The 2010-2011 Canterbury earthquake sequence: from paleoseismology to policy

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SESE, Arizona State University, April 6, 2016

THE UNIVERSITY OF MELBOURNE

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

EQC EARTHQUAKE COMMISSION KŌMIHANA RŪWHENUA

Christchurch City Council

GNS SCIENCE TE PŪ AO

The Prime Minister's Science Prizes

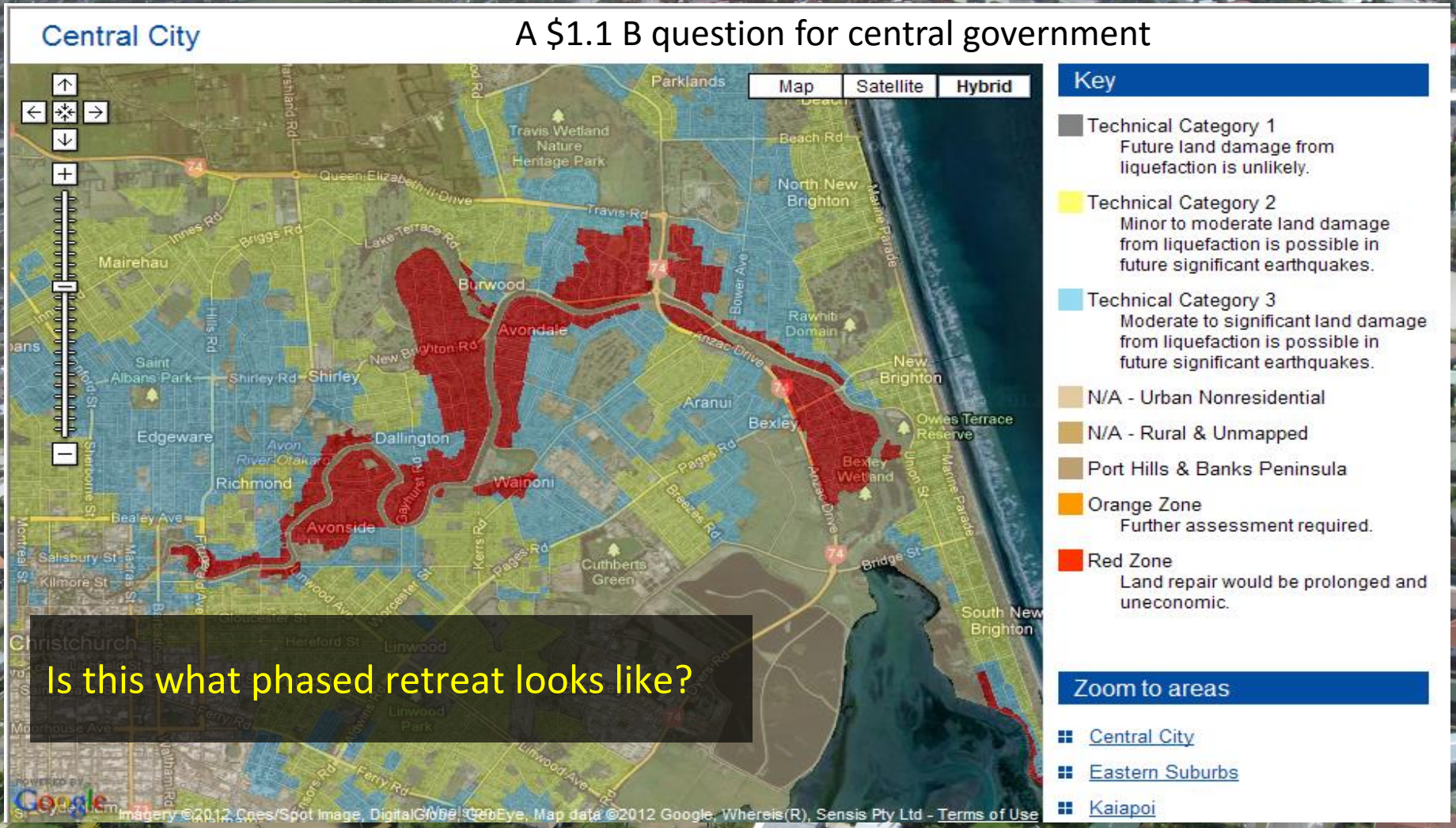
FULBRIGHT NEW ZEALAND TE TŪĀPAPA MĀTAURANGA O AOTEAROA ME AMERIKA

Tonkin & Taylor

SMC NZ Science Media Centre

QuakeCoRE Centre for Earthquake Resilience

Christchurch: The Color-Coded City

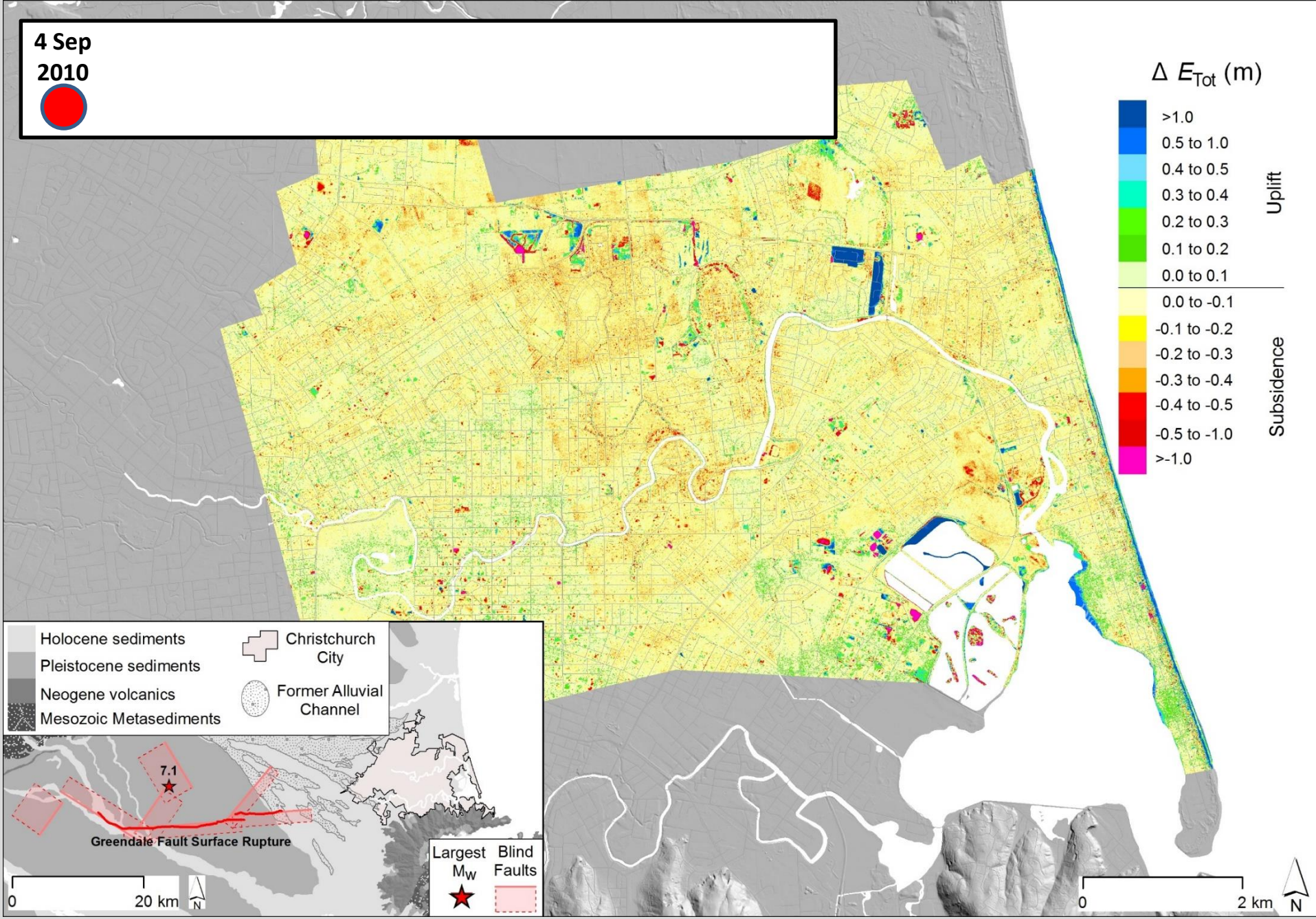


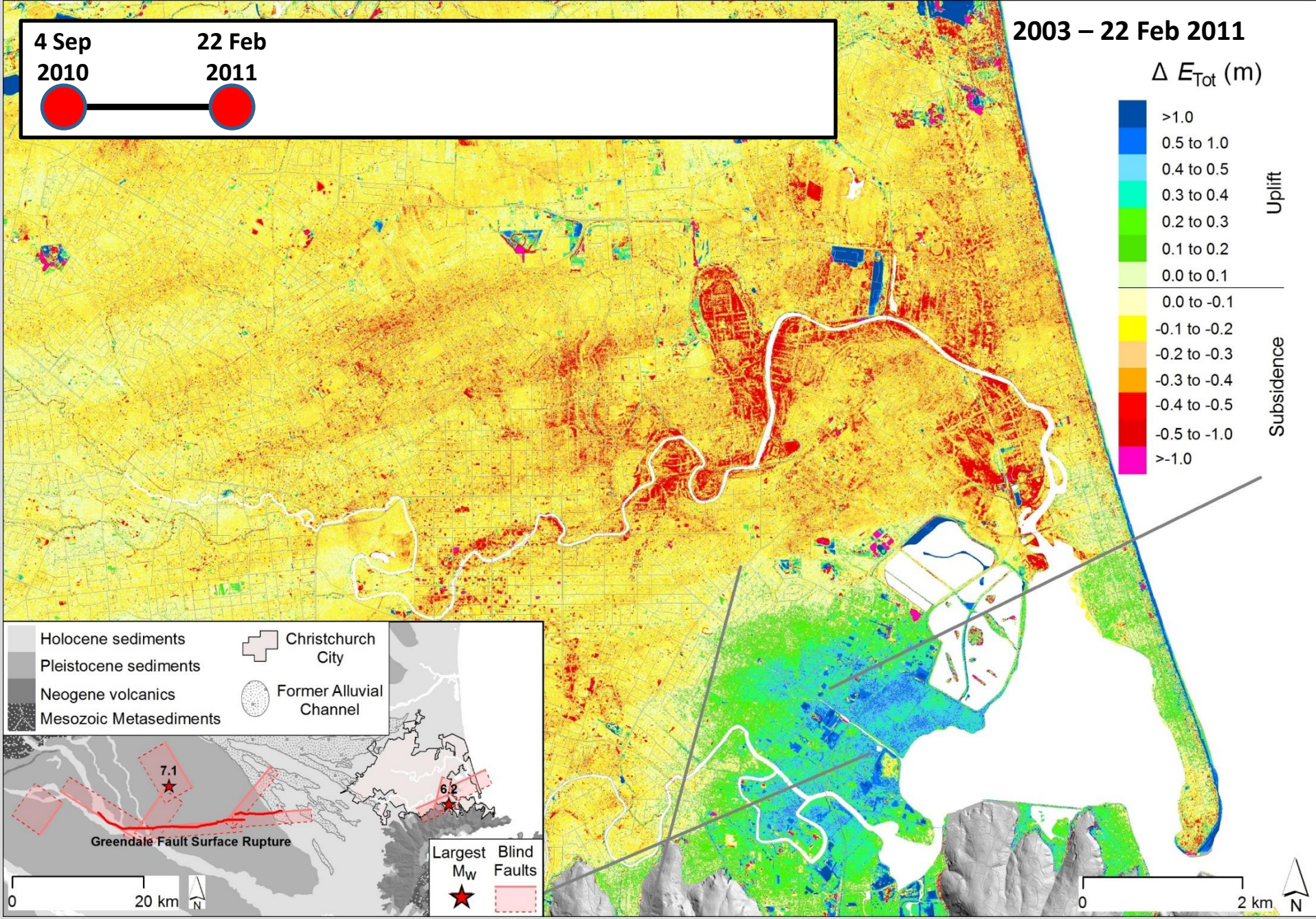
Is this what phased retreat looks like?

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)

Christchurch: The Sinking City

Hughes, M., Quigley, M., van Ballegooy, S., Deam, B., Bradley, B, Hart, D., Measures, R., (2015) The sinking city: Earthquakes increase flood hazard in Christchurch, New Zealand, *GSA Today*


4 Sep
2010
Δ E_{Tot} (m)
>1.0
0.5 to 1.0
0.4 to 0.5
0.3 to 0.4
0.2 to 0.3
0.1 to 0.2
0.0 to 0.1
Uplift
0.0 to -0.1
-0.1 to -0.2
-0.2 to -0.3
-0.3 to -0.4
-0.4 to -0.5
-0.5 to -1.0
>-1.0
Subsidence
0
2 km
N
Holocene sediments
Pleistocene sediments
Neogene volcanics
Mesozoic Metasediments
Christchurch City
Former Alluvial Channel
7.1
Greendale Fault Surface Rupture
0
20 km
N
Largest M_W
Blind Faults


4 Sep 2010
22 Feb 2011
2003 – 22 Feb 2011
Δ E_{Tot} (m)
>1.0
0.5 to 1.0
0.4 to 0.5
0.3 to 0.4
0.2 to 0.3
0.1 to 0.2
0.0 to 0.1
Uplift
0.0 to -0.1
-0.1 to -0.2
-0.2 to -0.3
-0.3 to -0.4
-0.4 to -0.5
-0.5 to -1.0
>-1.0
Subsidence
Holocene sediments
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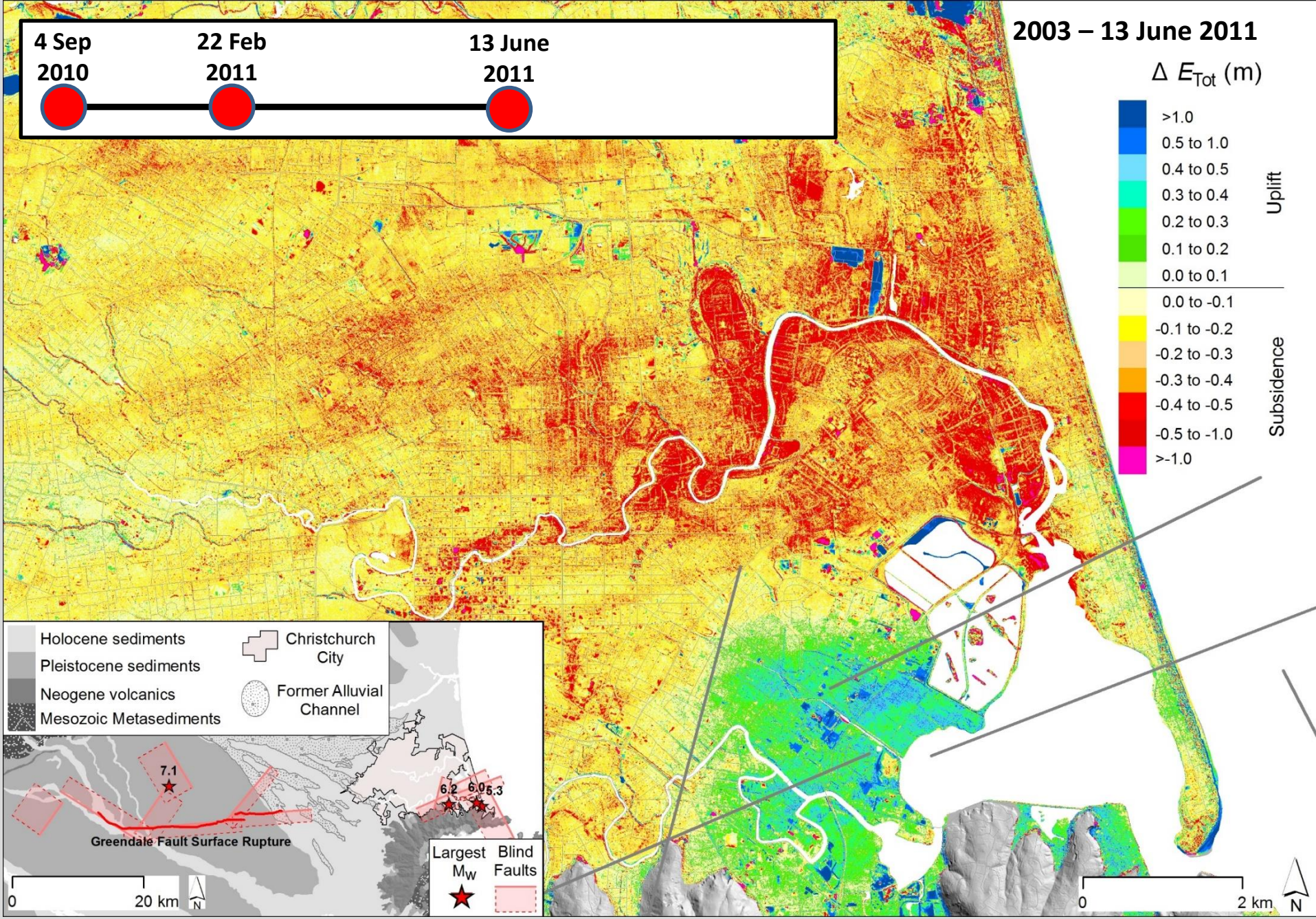
Mesozoic Metasediments
Christchurch City
Former Alluvial Channel
7.1
6.2
Greendale Fault Surface Rupture
Largest M_W
Blind Faults
0
20 km
N
0
2 km
N


4 Sep 2010
22 Feb 2011
13 June 2011
2003 – 13 June 2011
Δ E_{Tot} (m)
>1.0
0.5 to 1.0
0.4 to 0.5
0.3 to 0.4
0.2 to 0.3
0.1 to 0.2
0.0 to 0.1
Uplift
0.0 to -0.1
-0.1 to -0.2
-0.2 to -0.3
-0.3 to -0.4
-0.4 to -0.5
-0.5 to -1.0
>-1.0
Subsidence
Holocene sediments
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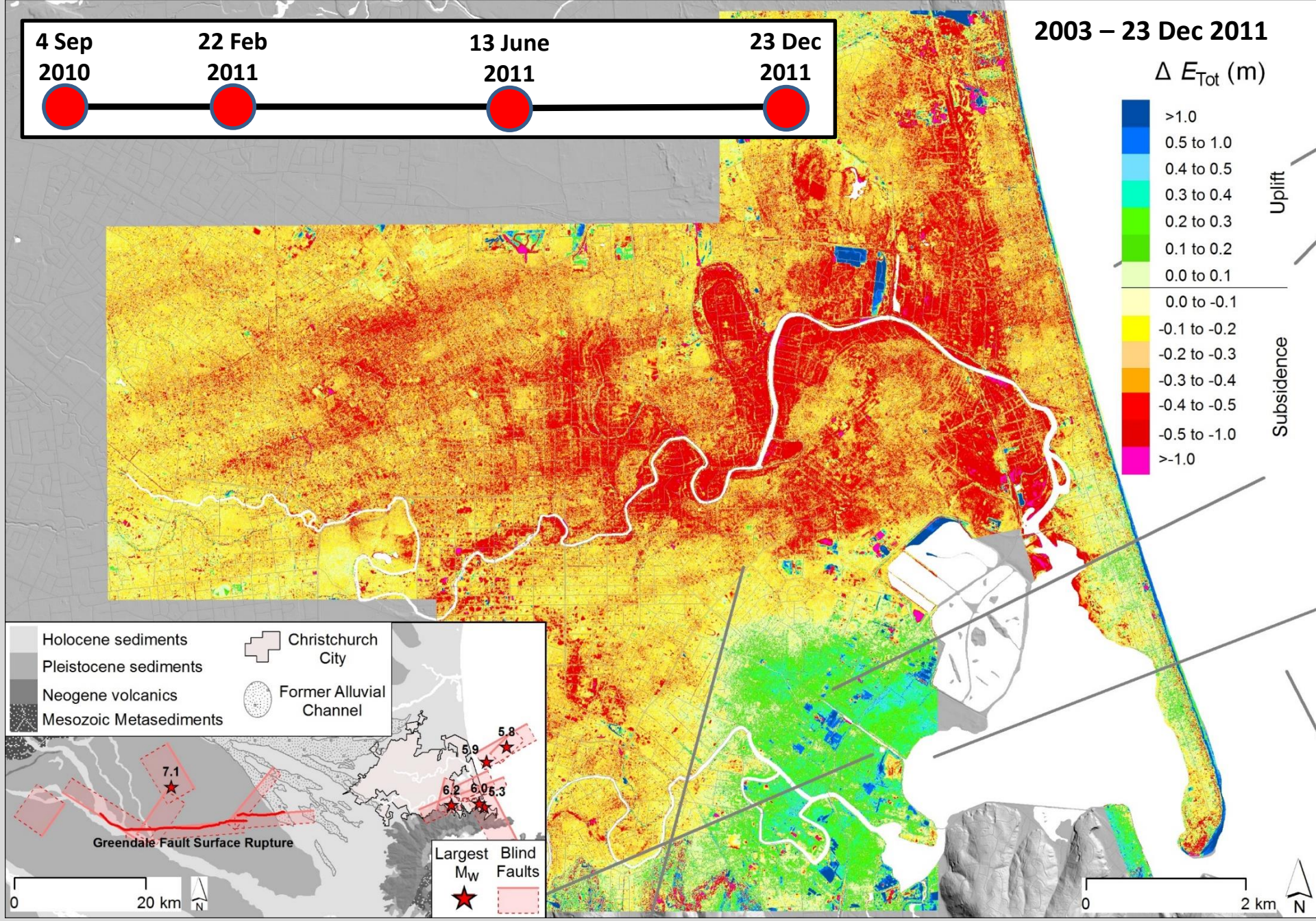
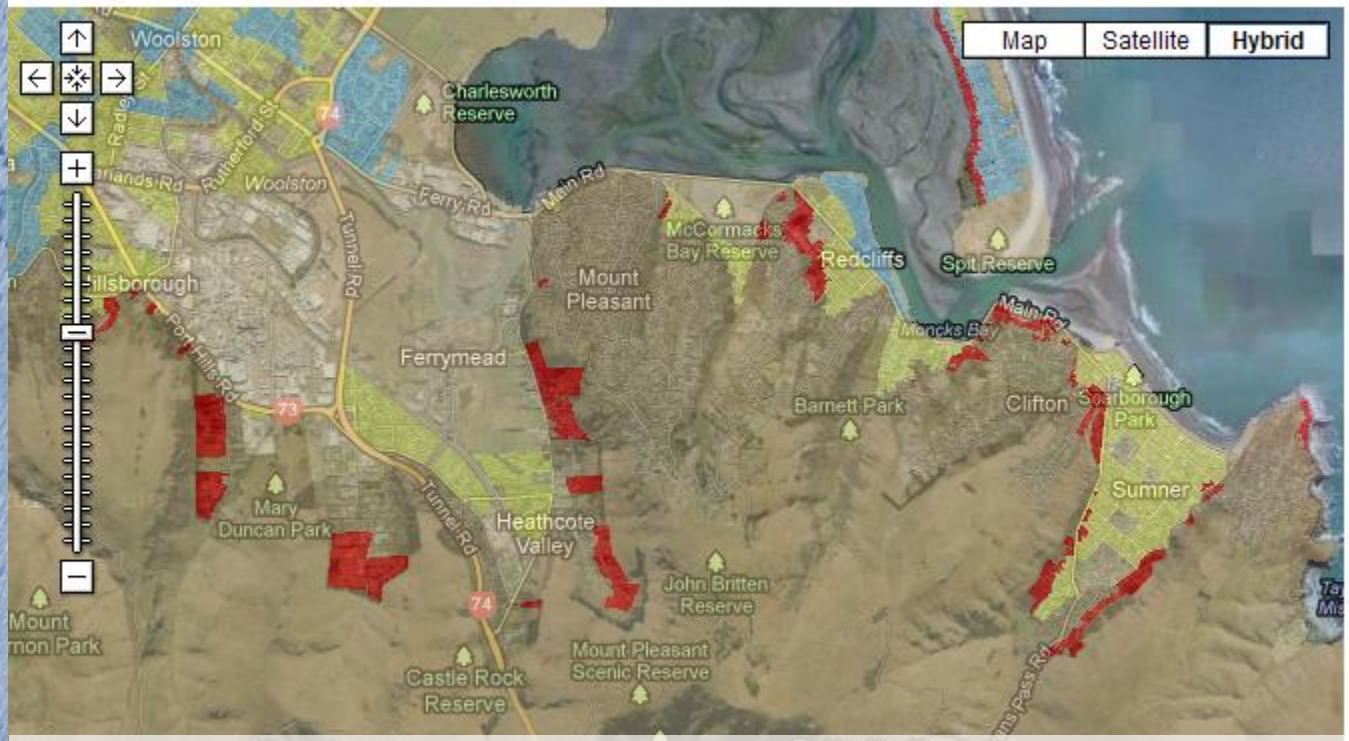
Christchurch City
Former Alluvial Channel
7.1
6.2
6.0
5.3
Greendale Fault Surface Rupture
Largest M_W
Blind Faults
0
20 km
N
0
2 km
N


4 Sep 2010
22 Feb 2011
13 June 2011
23 Dec 2011
2003 – 23 Dec 2011
Δ E_{Tot} (m)
>1.0
0.5 to 1.0
0.4 to 0.5
0.3 to 0.4
0.2 to 0.3
0.1 to 0.2
0.0 to 0.1
0.0 to -0.1
-0.1 to -0.2
-0.2 to -0.3
-0.3 to -0.4
-0.4 to -0.5
-0.5 to -1.0
>-1.0
Uplift
Subsidence
0
2 km
N
Holocene sediments
Pleistocene sediments
Neogene volcanics
Mesozoic Metasediments
Christchurch City
Former Alluvial Channel
7.1
5.8
5.9
6.2
6.0
5.3
Greendale Fault Surface Rupture
Largest M_W
Blind Faults
0
20 km
N

Central City



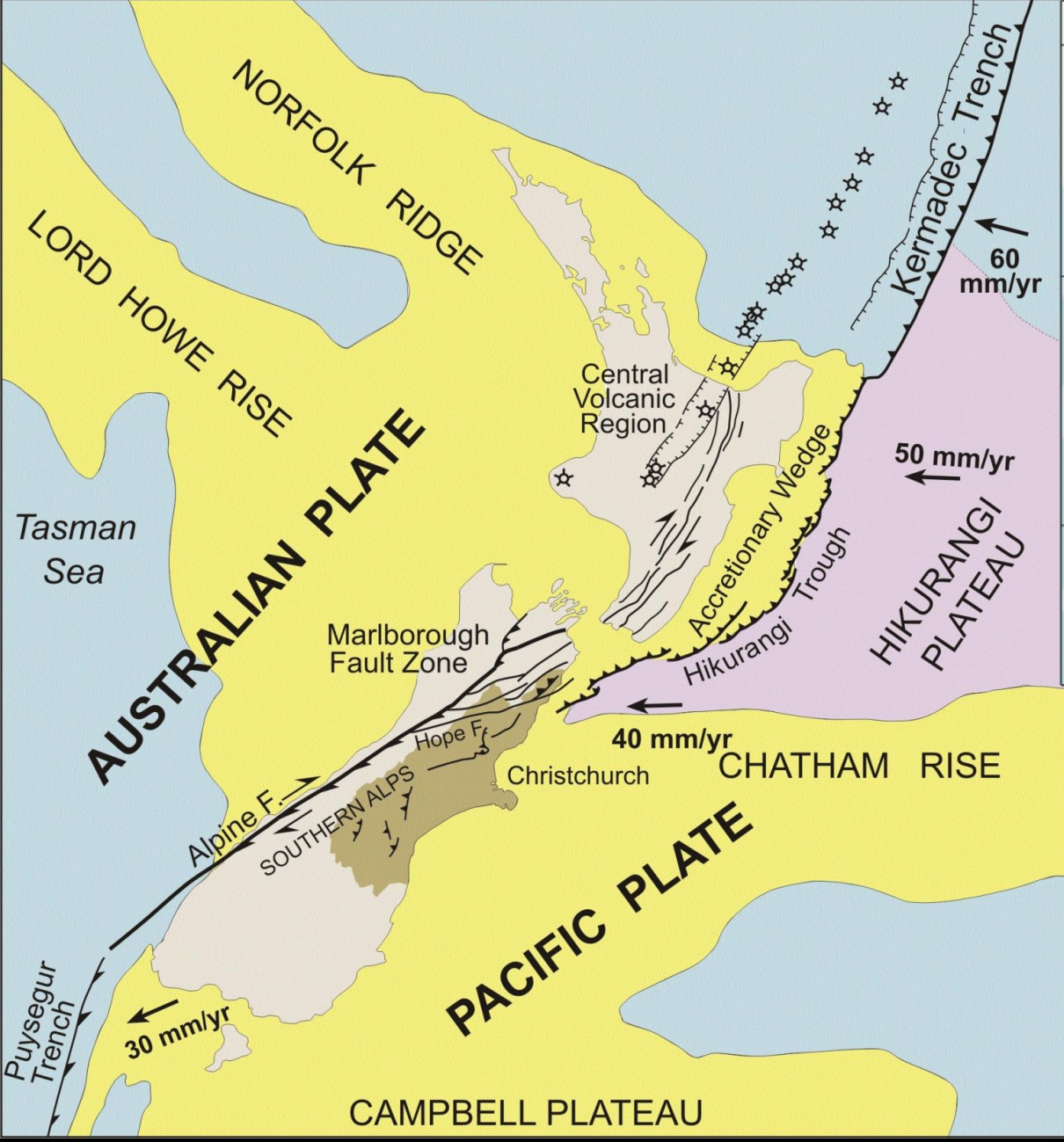
Key

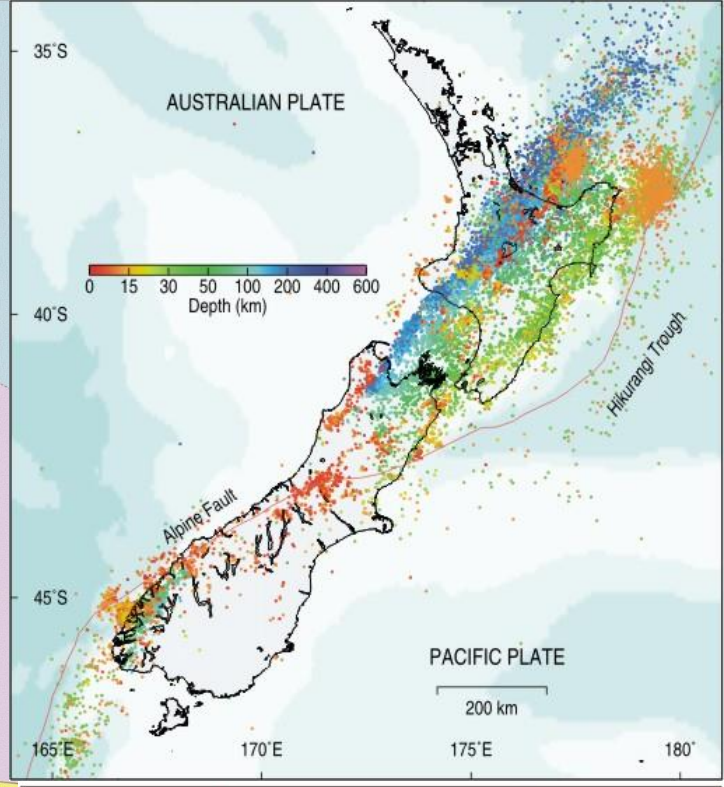
- Technical Category 1
  Future land damage from liquefaction is unlikely.
- Technical Category 2
  Minor to moderate land damage from liquefaction is possible in future significant earthquakes.
- Technical Category 3
  Moderate to significant land damage from liquefaction is possible in future significant 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.

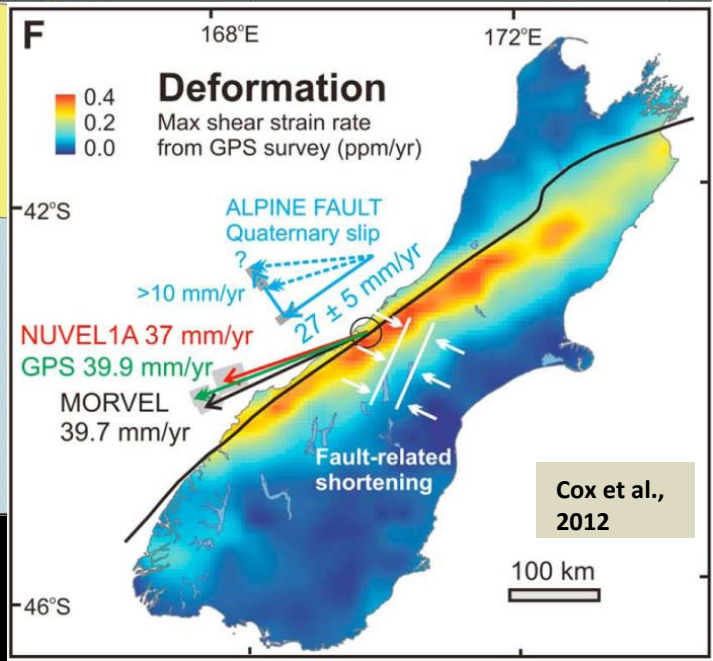
Christchurch: The Rockfall Prone City

Talk Outline

- Geologic, seismologic and societal context for the 2010-2011 Canterbury earthquake sequence
- CES environmental effects and paleoseismic precursors
- Can paleoseismology influence policy?
- Where to from here?

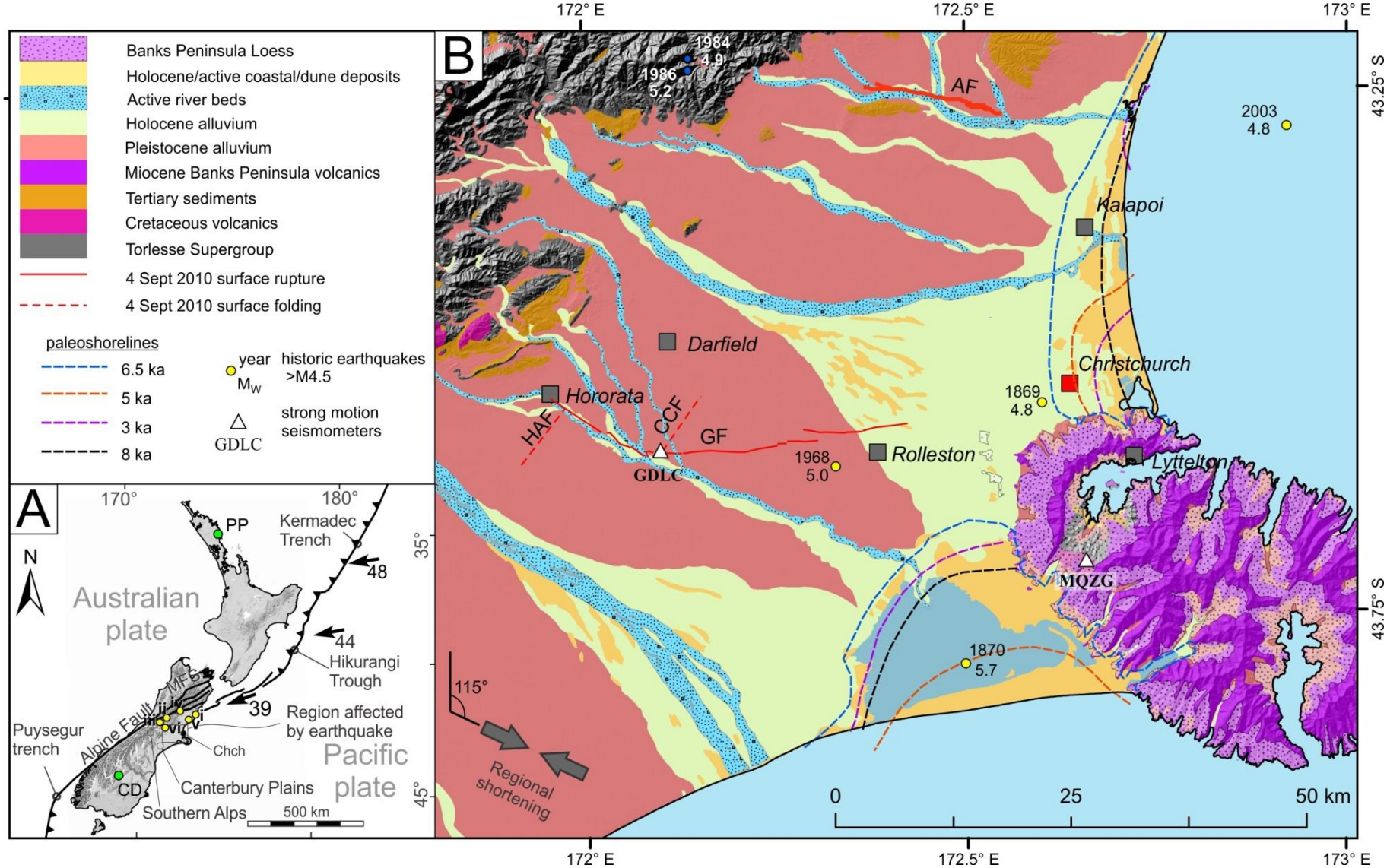






Cox et al., 2012

Geologic setting of NZ

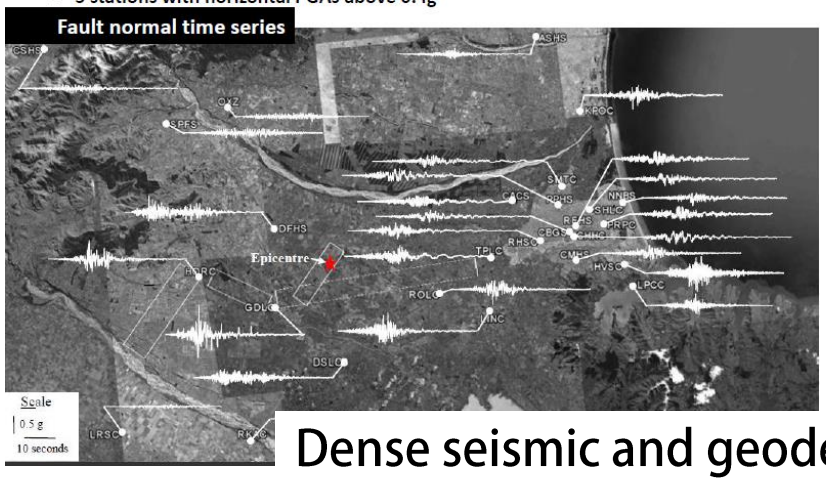


Christchurch: a city built mostly on Holocene sediments at the diffuse, modestly deforming, eastern periphery of a tectonically active orogen

Quigley et al., Tectonophysics, 2016

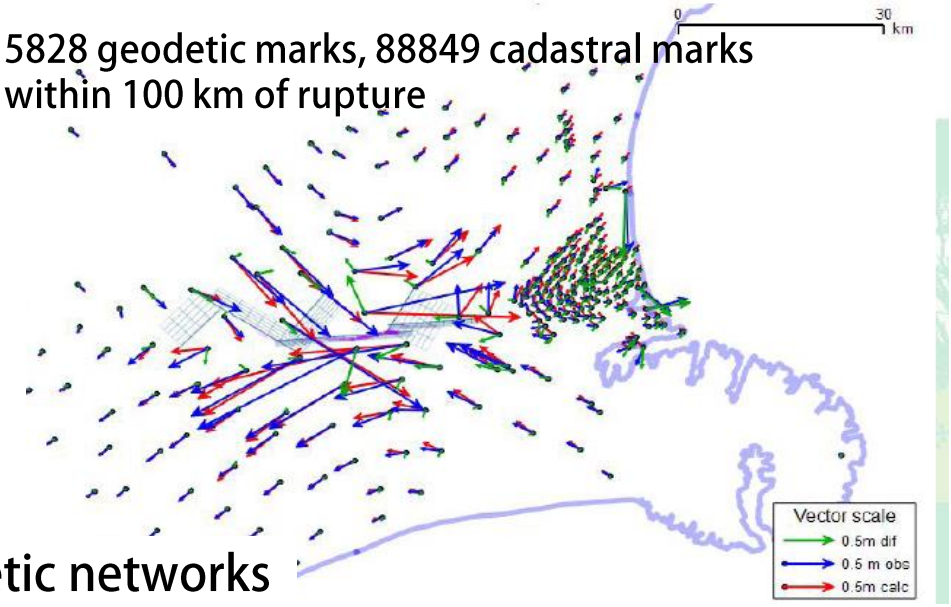
Ground motion characterization (4 Sept)

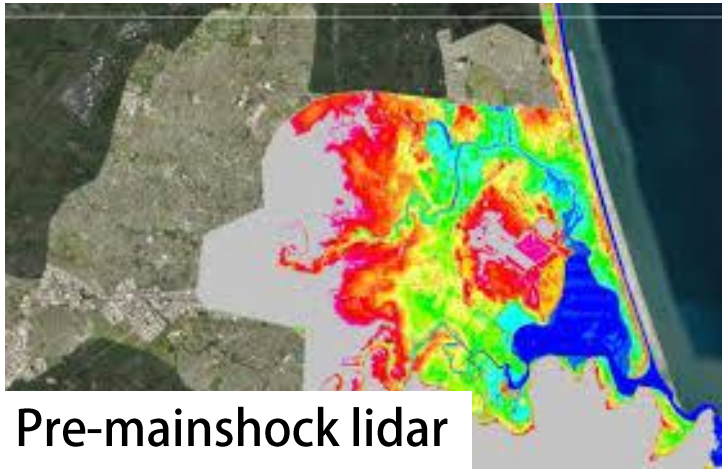
- 29 ground motion stations within 30km of the source
- Max values: horizontal PGA =0.76g, vertical PGA=1.30g, horizontal PGV=115cm/s
- 5 stations with horizontal PGAs above 0.4g



Dense seismic and geodetic networks

5828 geodetic marks, 88849 cadastral marks within 100 km of rupture



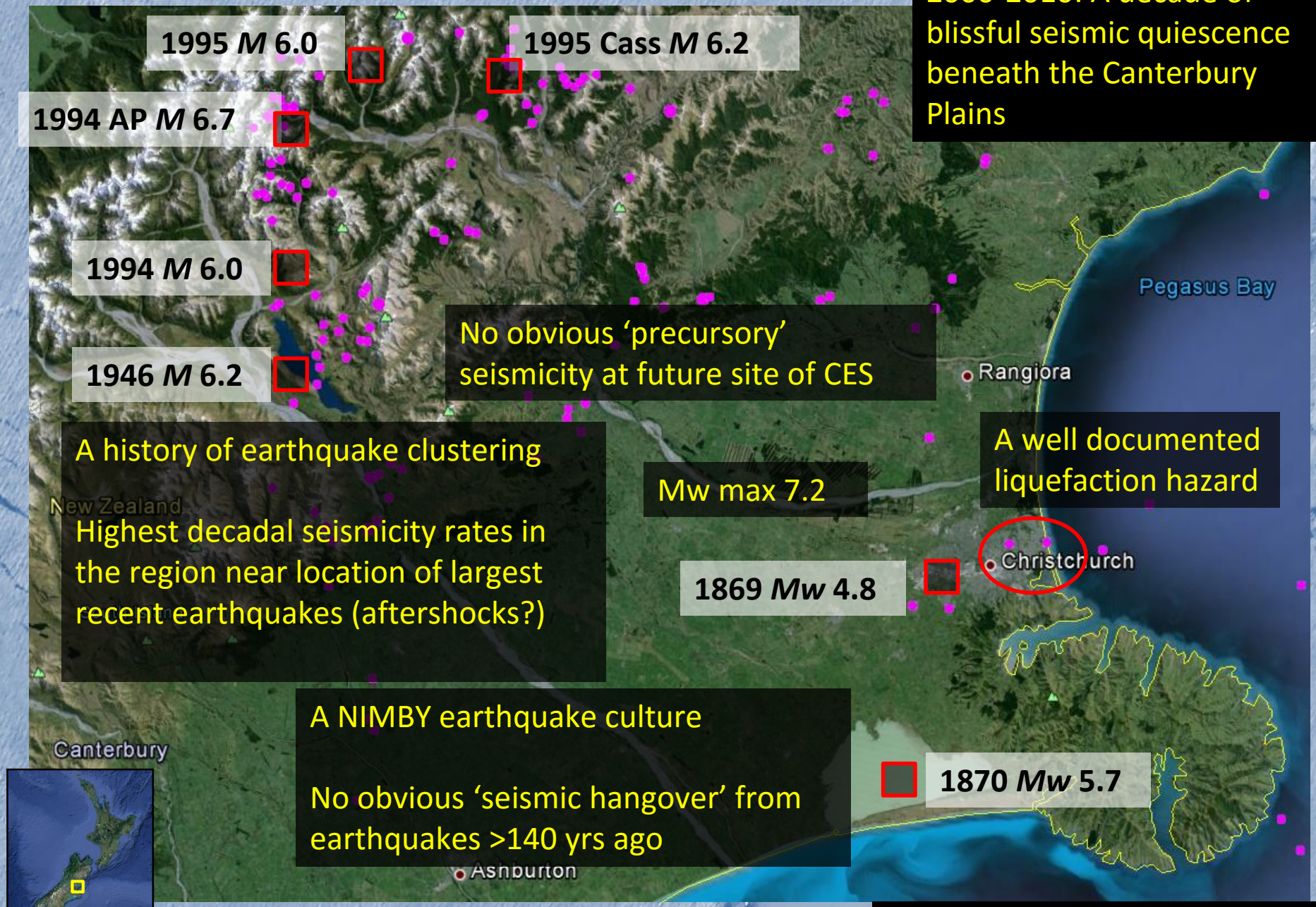


Pre-mainshock lidar

A flat agricultural grid in the epicentral region

Christchurch: a densely instrumented and gridded natural sandbox

Data source: Geonet



2000-2010: A decade of blissful seismic quiescence beneath the Canterbury Plains

No obvious 'precursory' seismicity at future site of CES

A history of earthquake clustering

Highest decadal seismicity rates in the region near location of largest recent earthquakes (aftershocks?)

Mw max 7.2

A well documented liquefaction hazard

A NIMBY earthquake culture

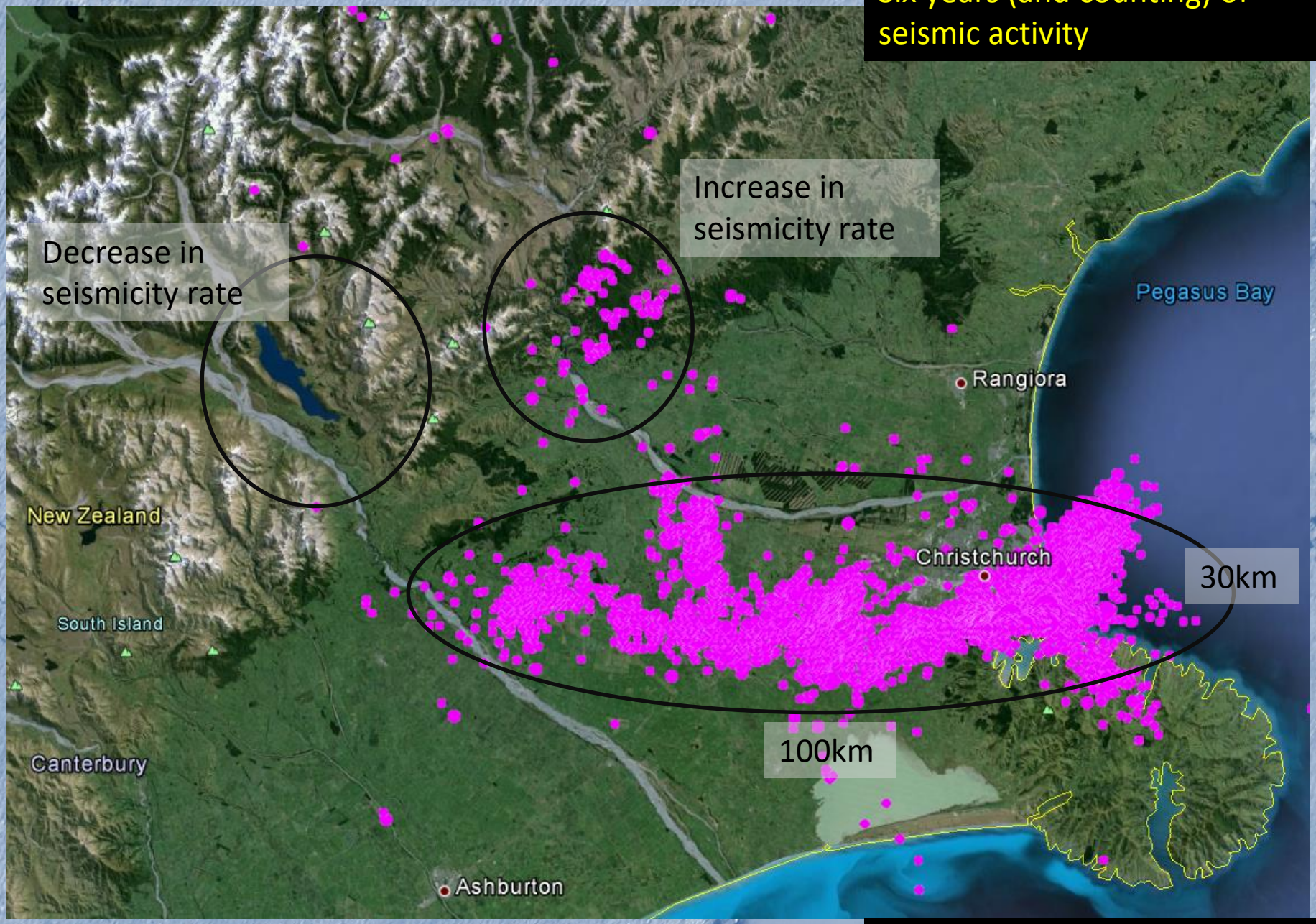
No obvious 'seismic hangover' from earthquakes >140 yrs ago

Seismologic and societal context

Seismicity Sept 1, 2000 to Sept 3, 2010
M ≥ 3.0, 0-15 km depth

Data source: Geonet

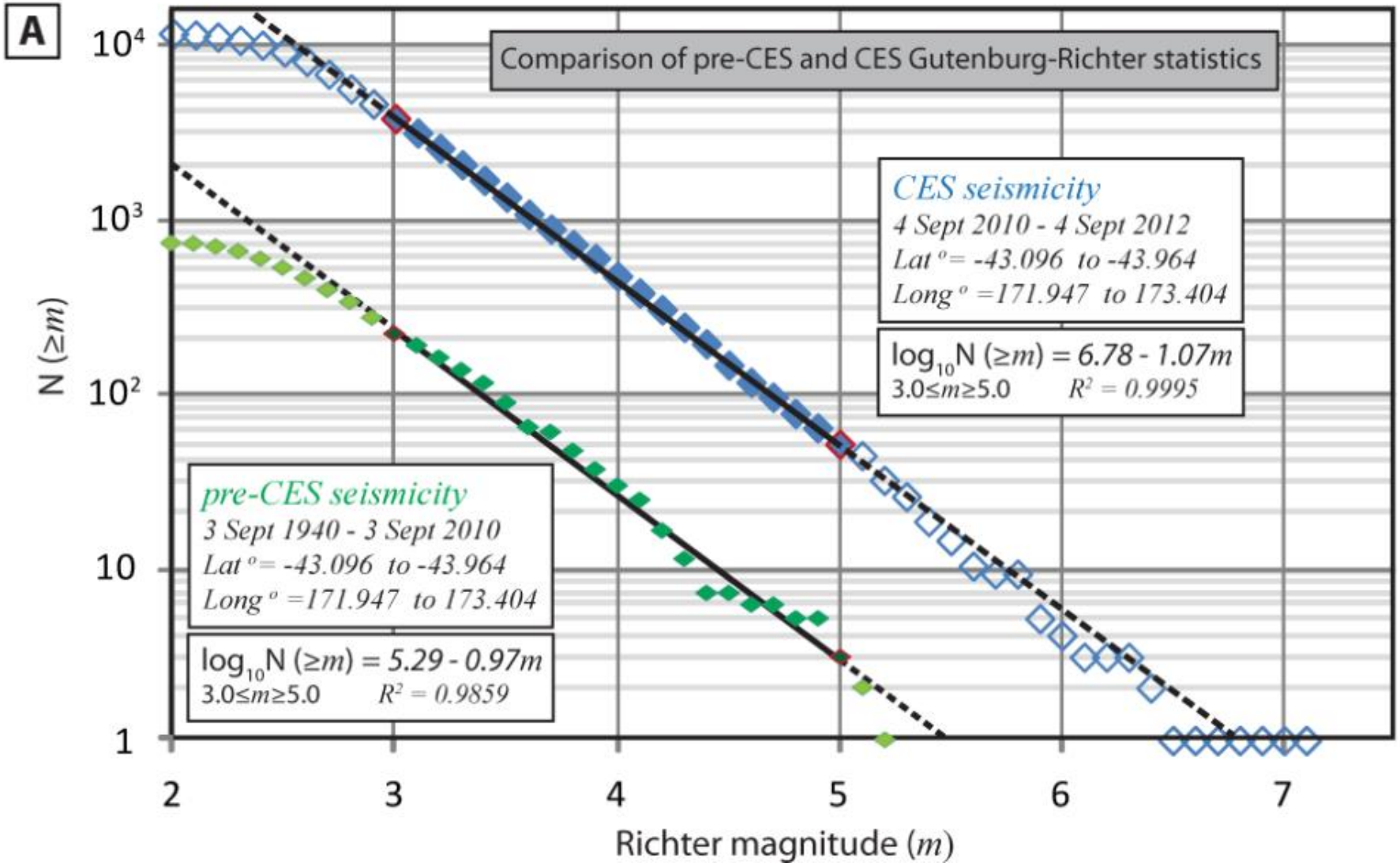
Six years (and counting) of seismic activity



Seismologic and societal context

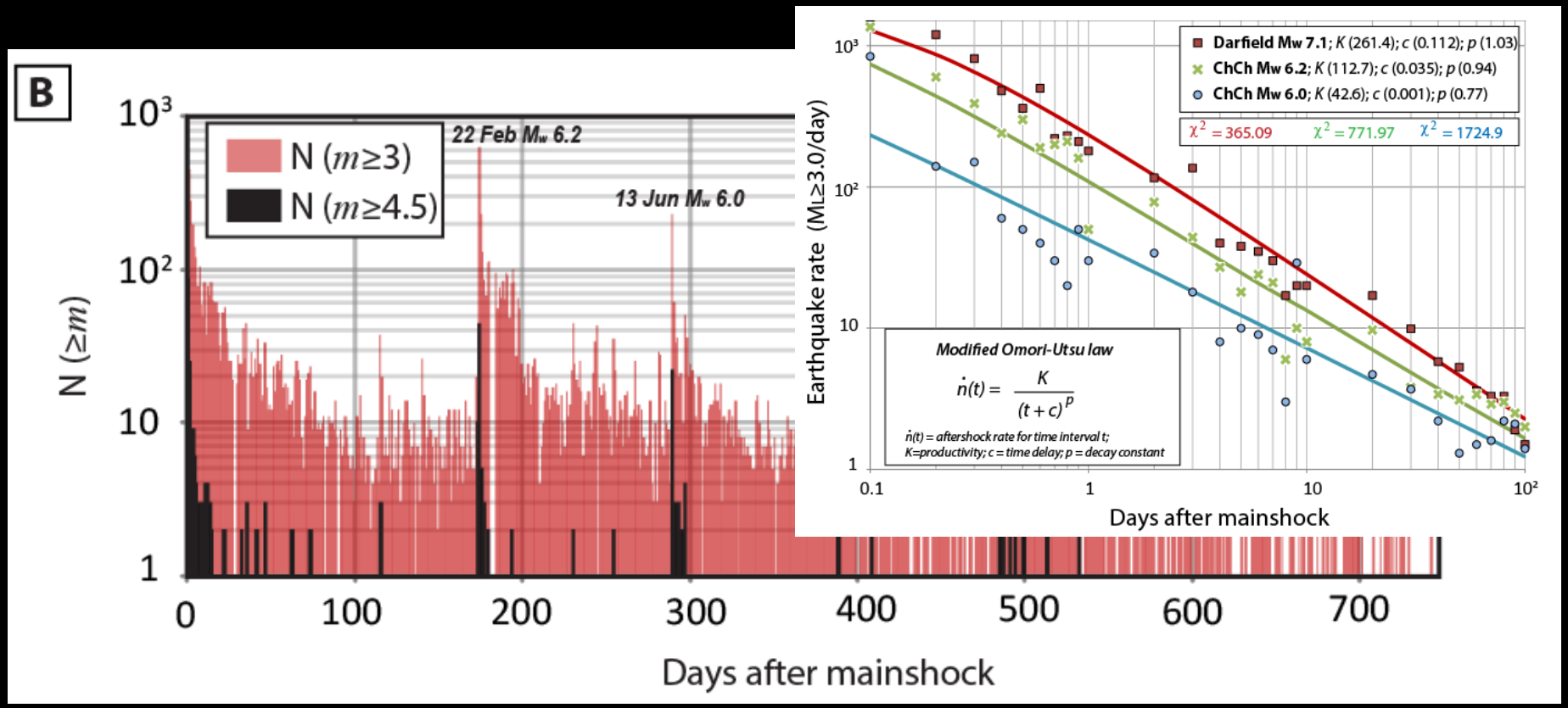
Seismicity Sept 4, 2010 to July 1, 2013
M ≥ 3.0, 0-15 km depth

G-R scaling of the CES and the preceding 60 yrs of seismicity in the same region



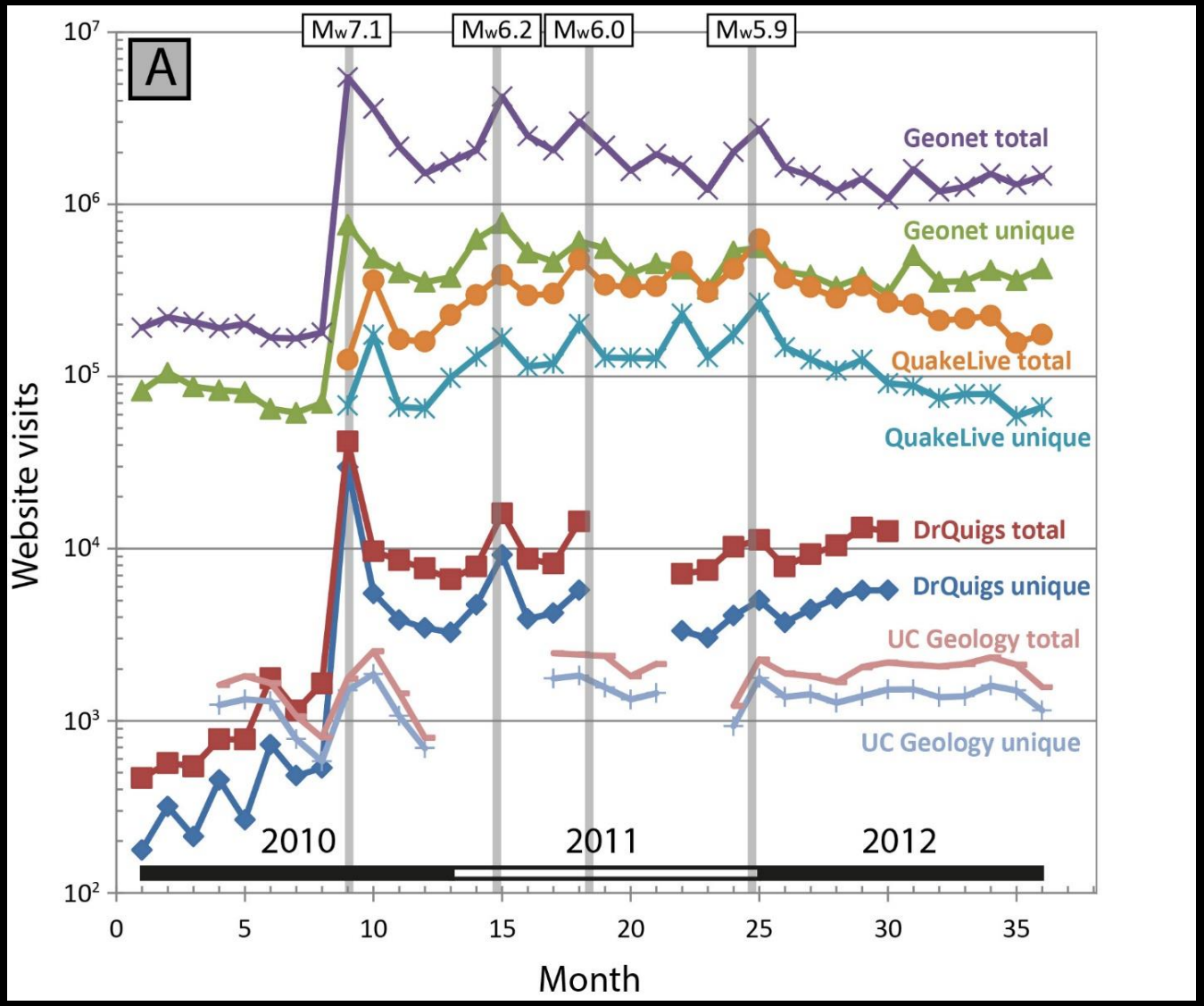
Quigley et al. 2016

Modified Omori's Law Scaling:
The most likely time for a damaging earthquake to occur is immediately after a damaging earthquake has occurred

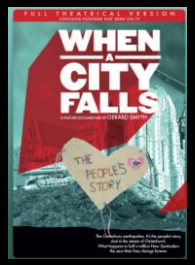


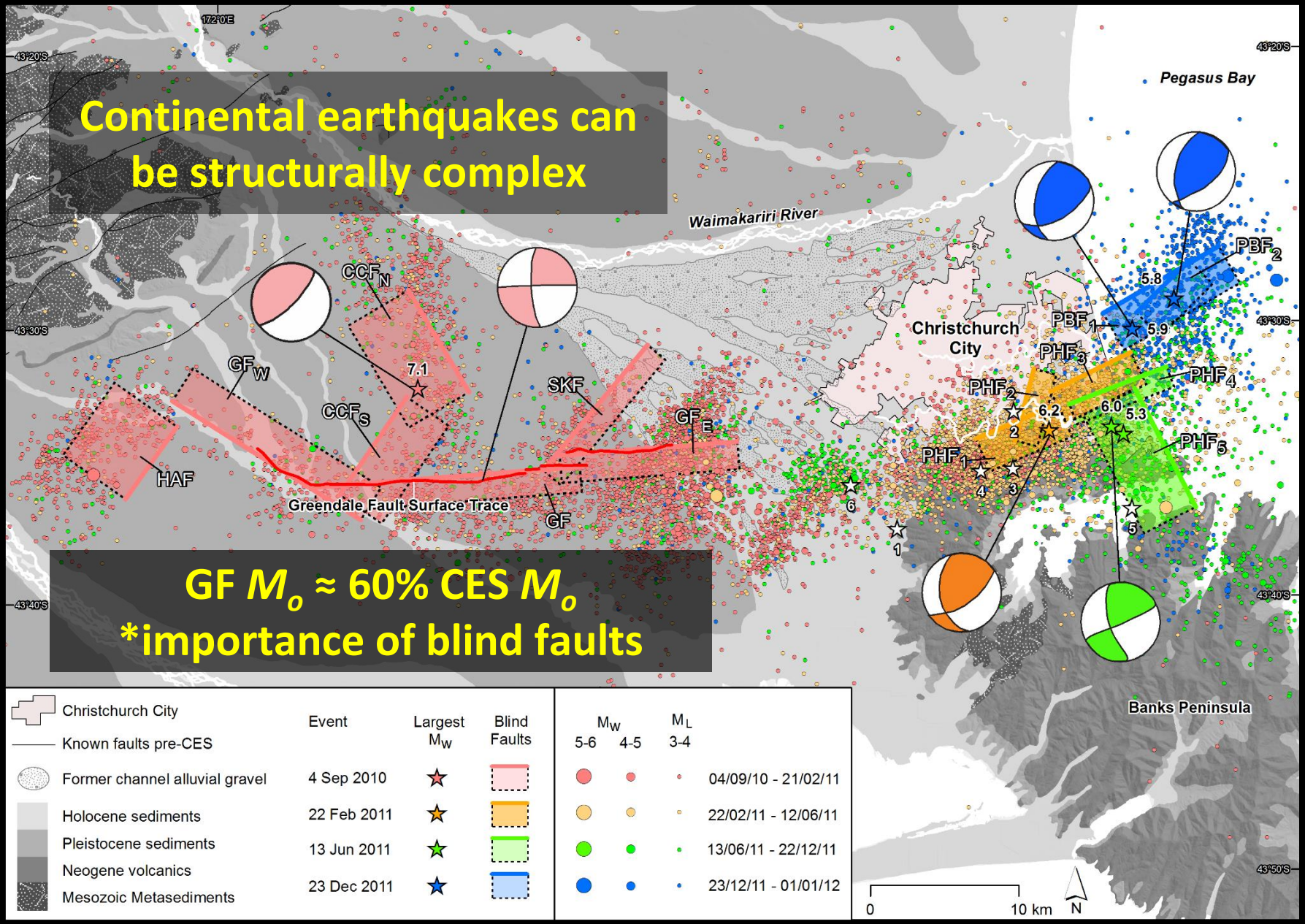
Search and rescue, building inspections, land use planning, science communication

Quigley et al, 2016



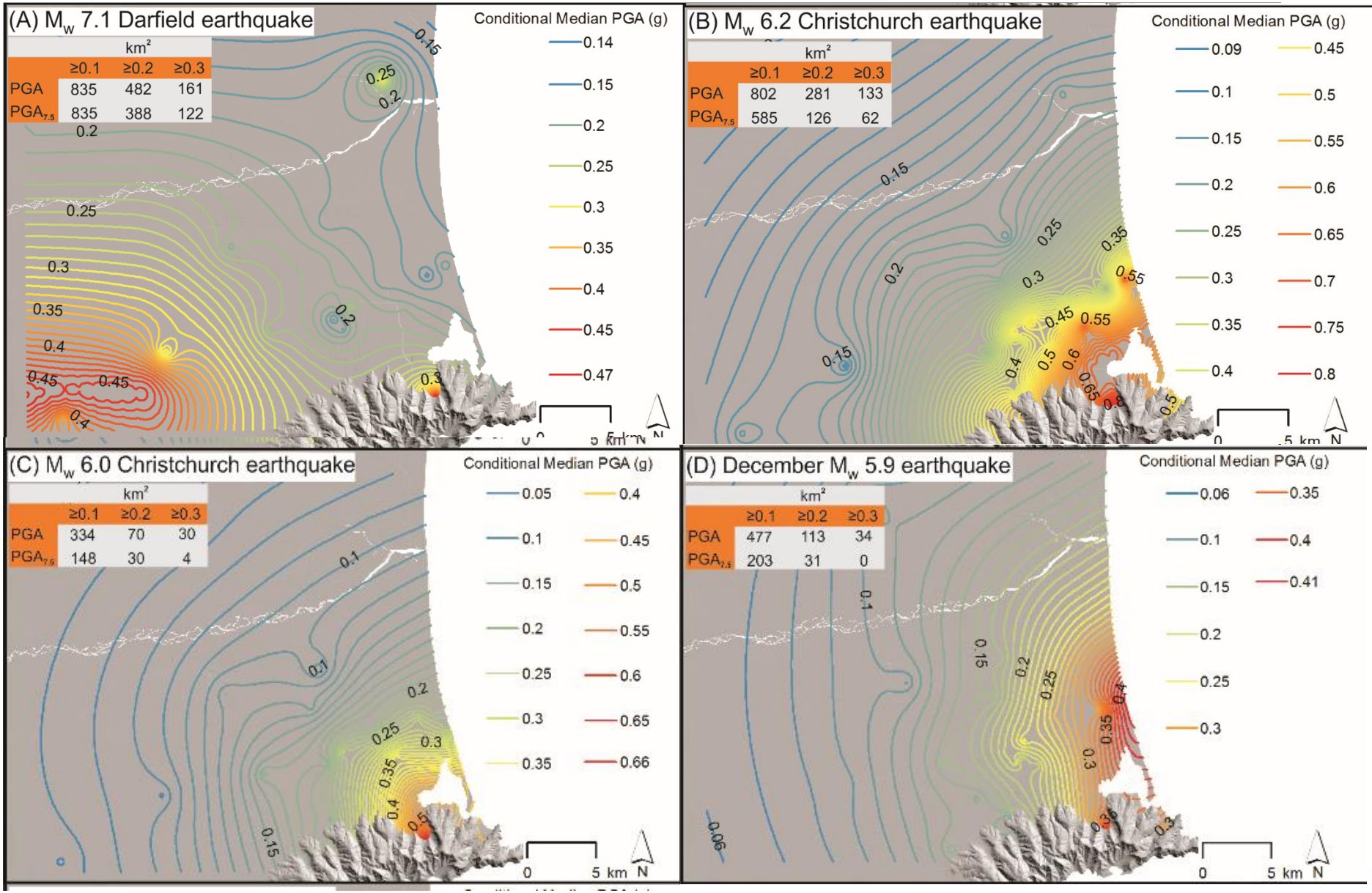
Predicting earth science website traffic in natural disasters using a modified Omori-Utsu law for aftershock decay





The 2010-2011 Canterbury Earthquake Sequence

Quigley et al., Tectonophysics, 2016



Blind fault earthquakes can represent highest shaking hazard

Quigley et al., Tectonophysics, 2016

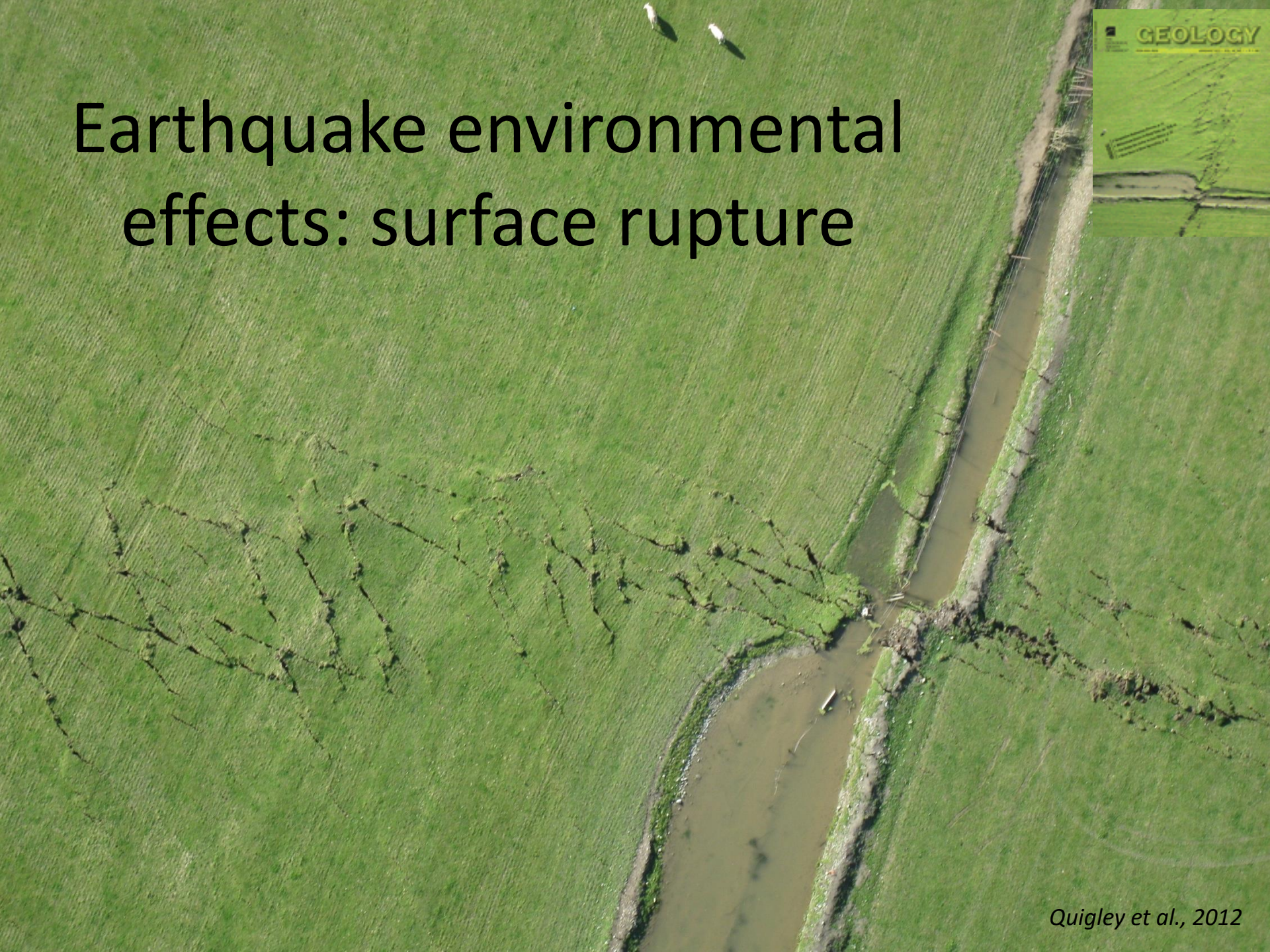
Earthquake comparisons: Counting the costs

	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

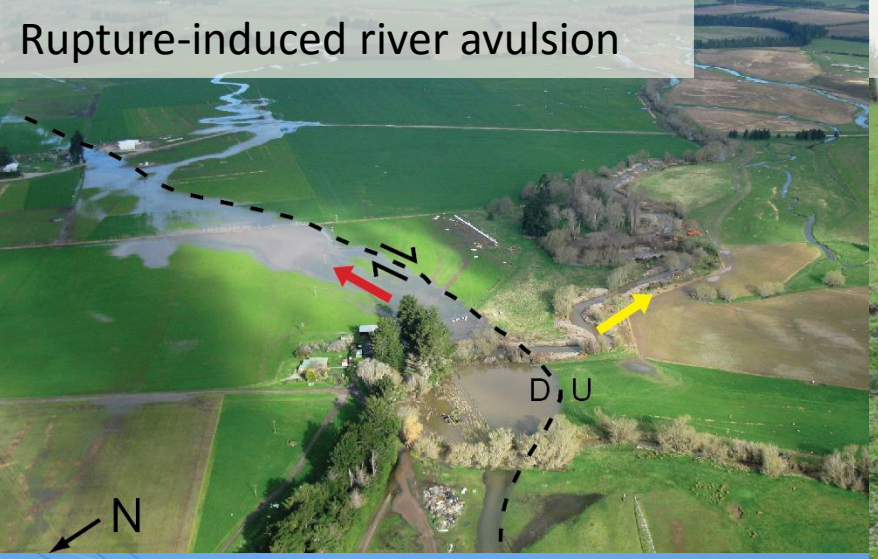
Loss of life and most damage occurred in an 'aftershock'
Most fatalities in two building collapses – building stock performed well from life safety perspective but poorly from a 'post-event functionality' perspective
Five geologic fatalities

Berryman, 2012

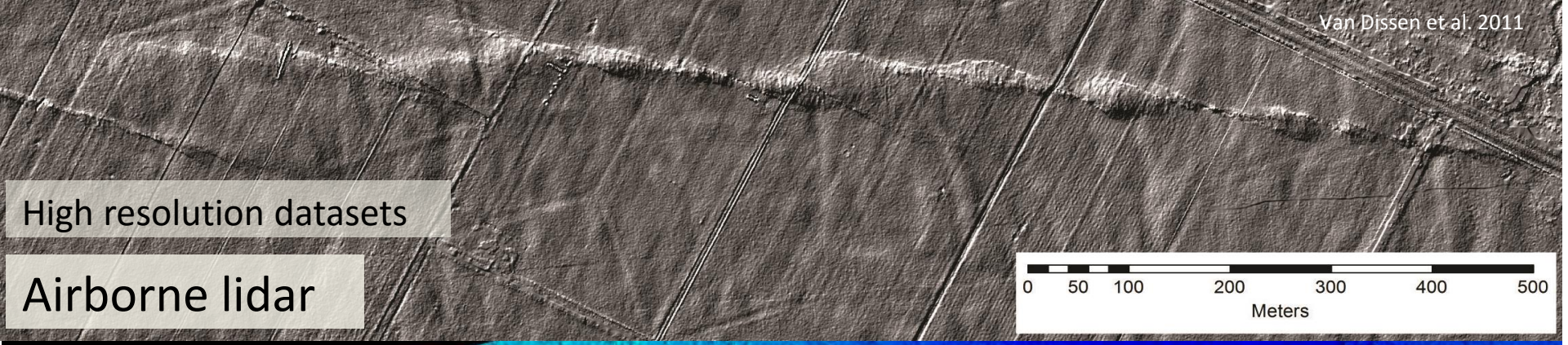
Earthquake environmental effects: surface rupture

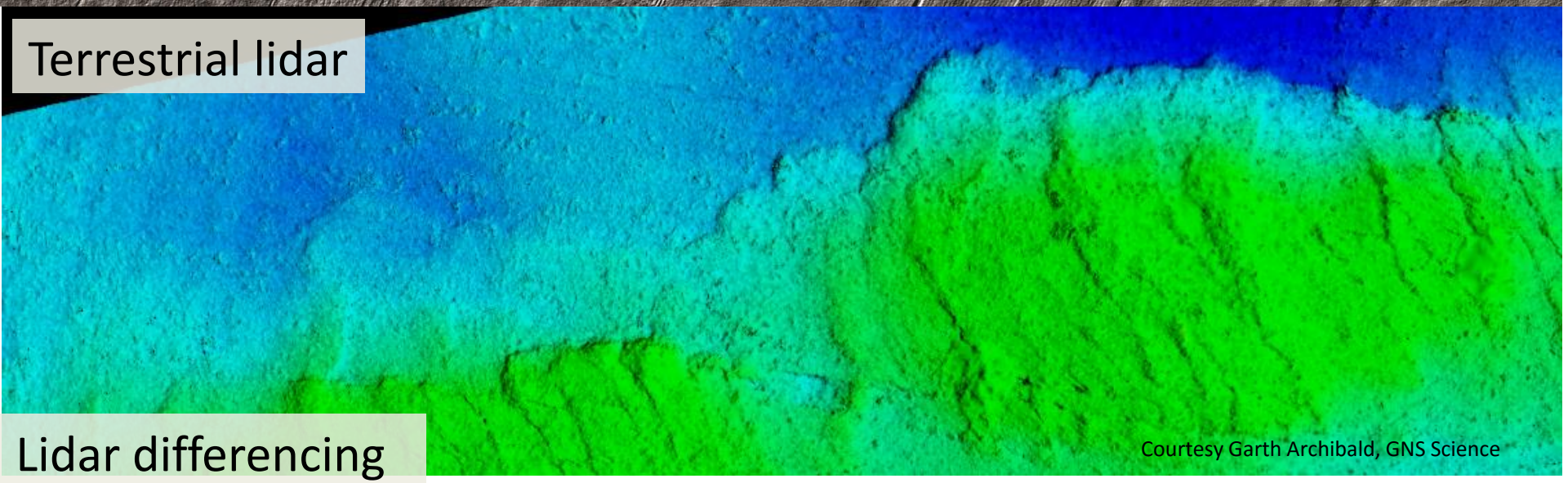


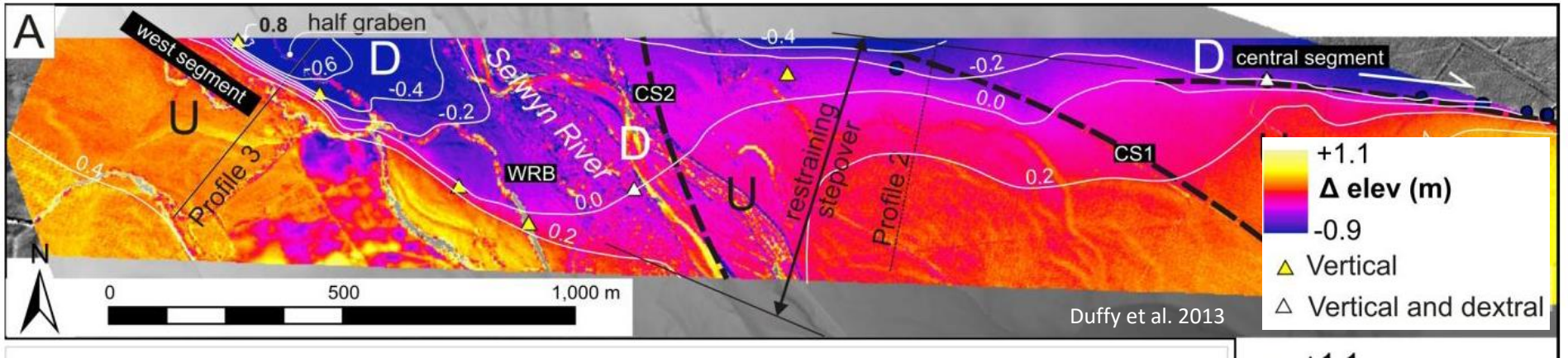
Quigley et al., 2012

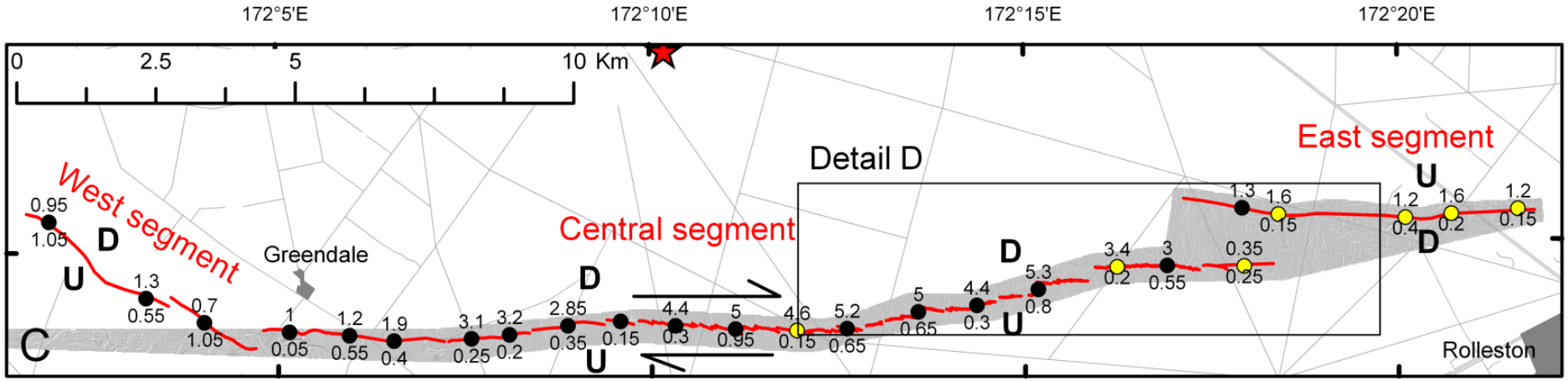


Characterisation of fault rupture displacements, impacts, and future hazards

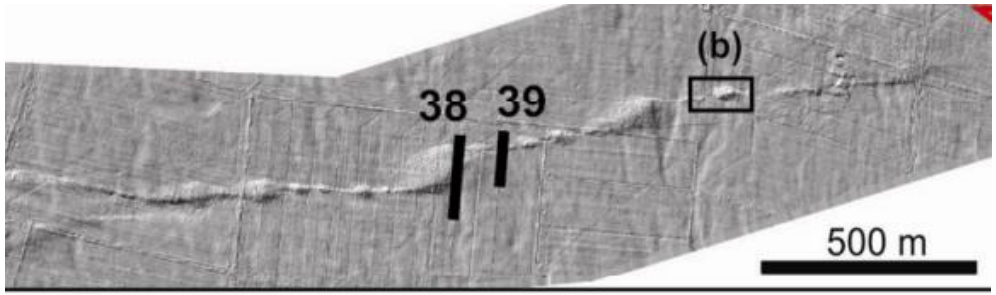

Van Dissen et al. 2011
High resolution datasets
Airborne lidar
0 50 100 200 300 400 500
Meters

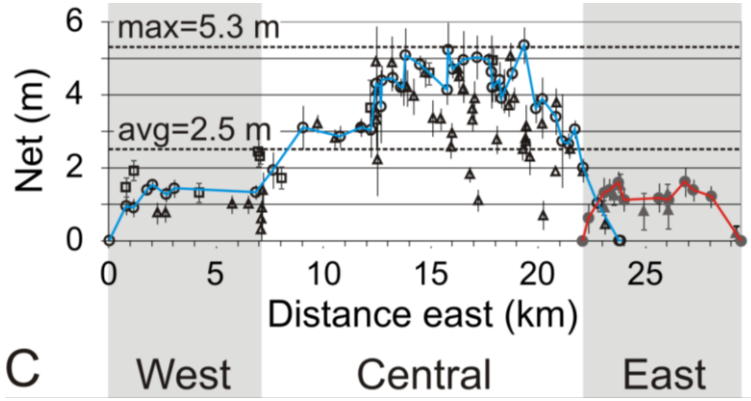

Terrestrial lidar
Courtesy Garth Archibald, GNS Science

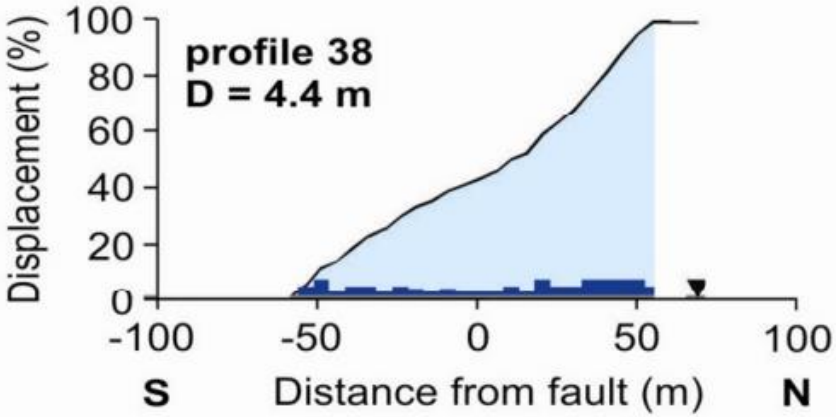

Lidar differencing
A
west segment
half graben
0.8
-0.6
D
-0.4
-0.2
U
Selwyn River
CS2
D
WRB
0.0
0.2
U
restraining stepover
Profile 2
Profile 3
0.4
-0.4
-0.2
0.0
0.2
D
central segment
CS1
N
0 500 1,000 m
+1.1
Δ elev (m)
-0.9
Vertical
Vertical and dextral
Duffy et al. 2013

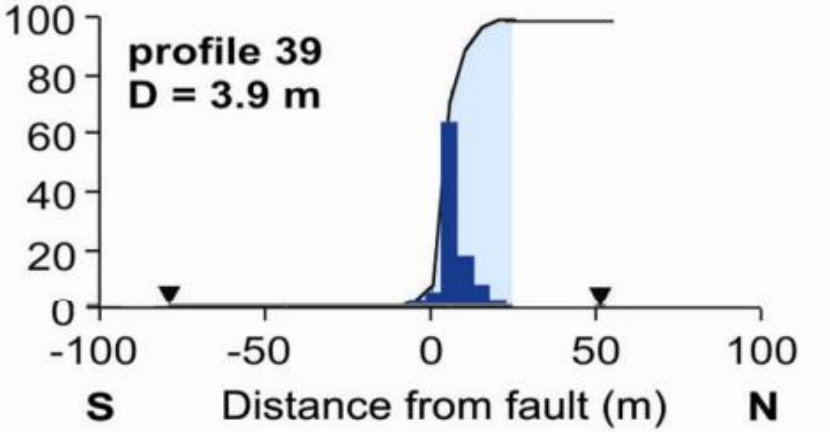


Controls on fault rupture morphology



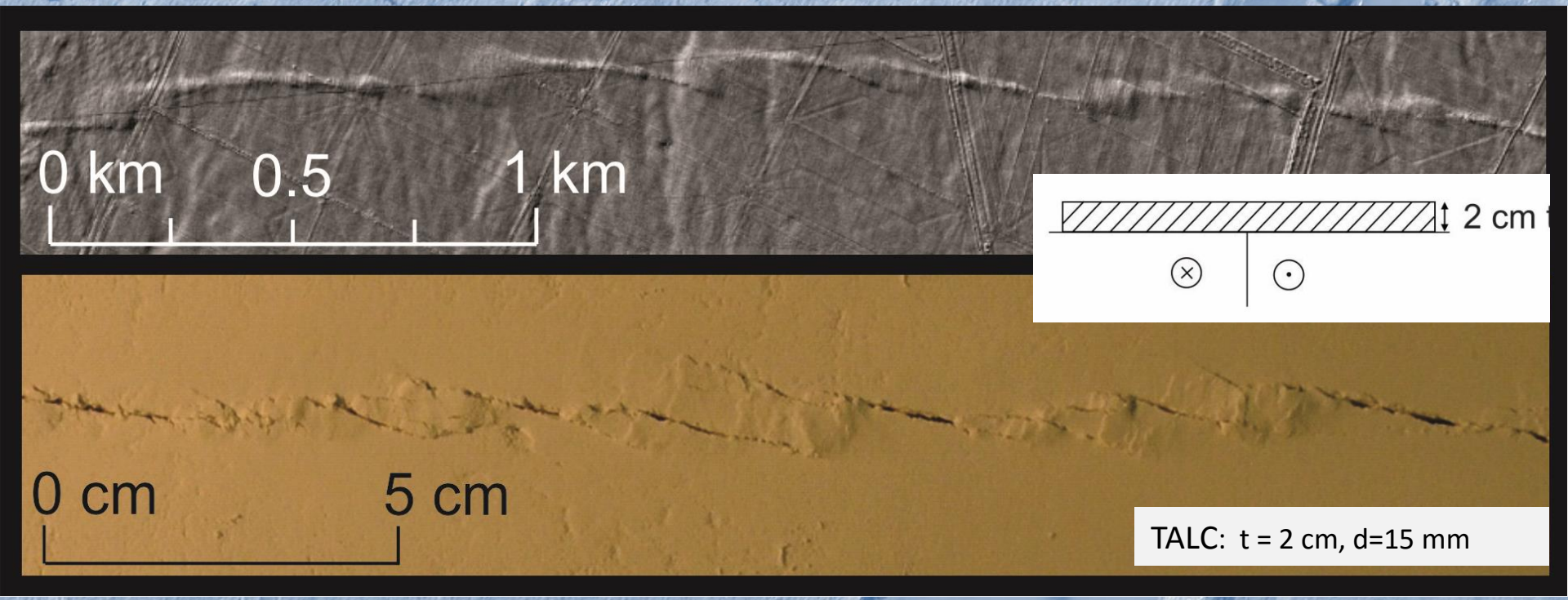






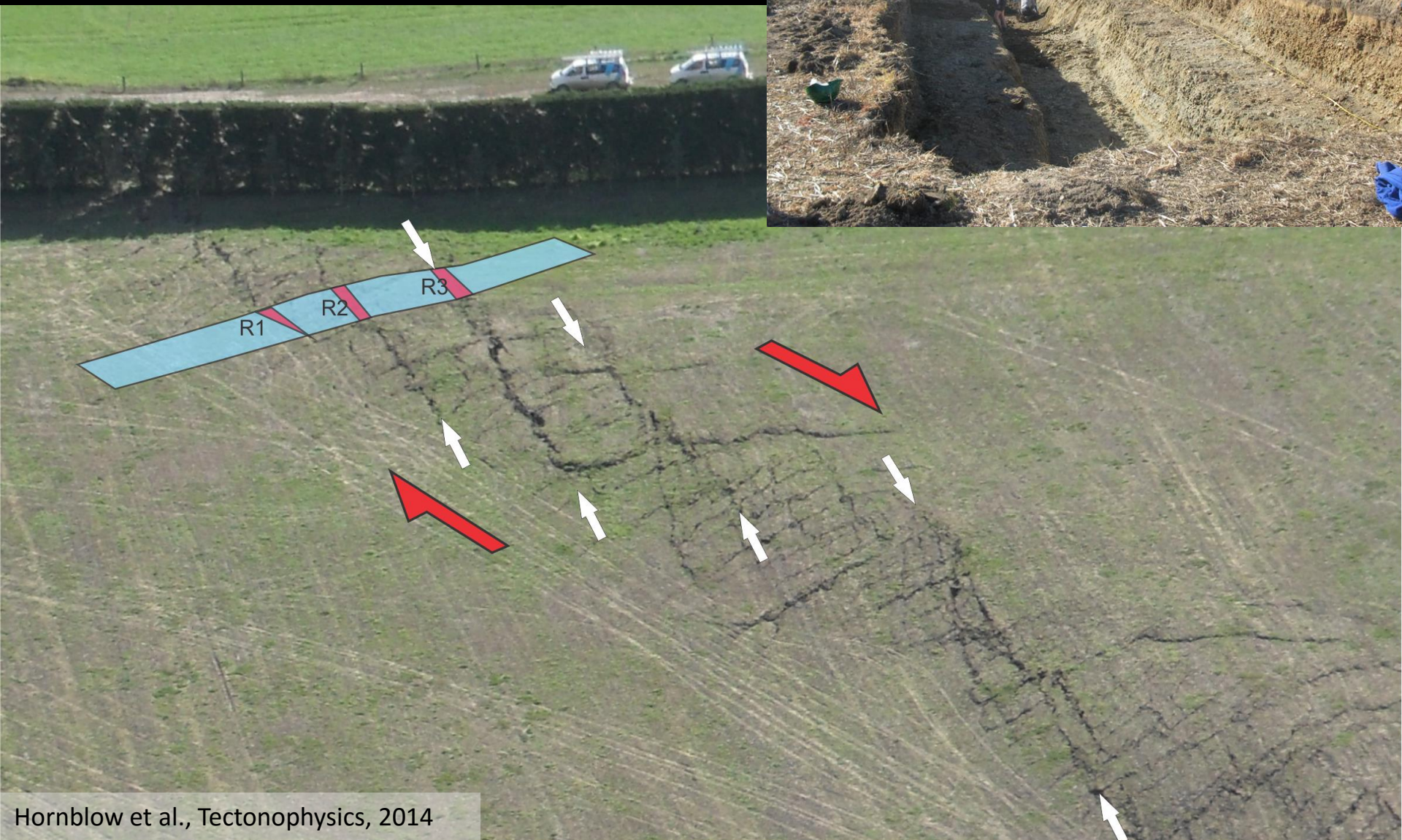
Analogue modelling of surface ruptures:

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?
Predicting rupture morphologic evolution

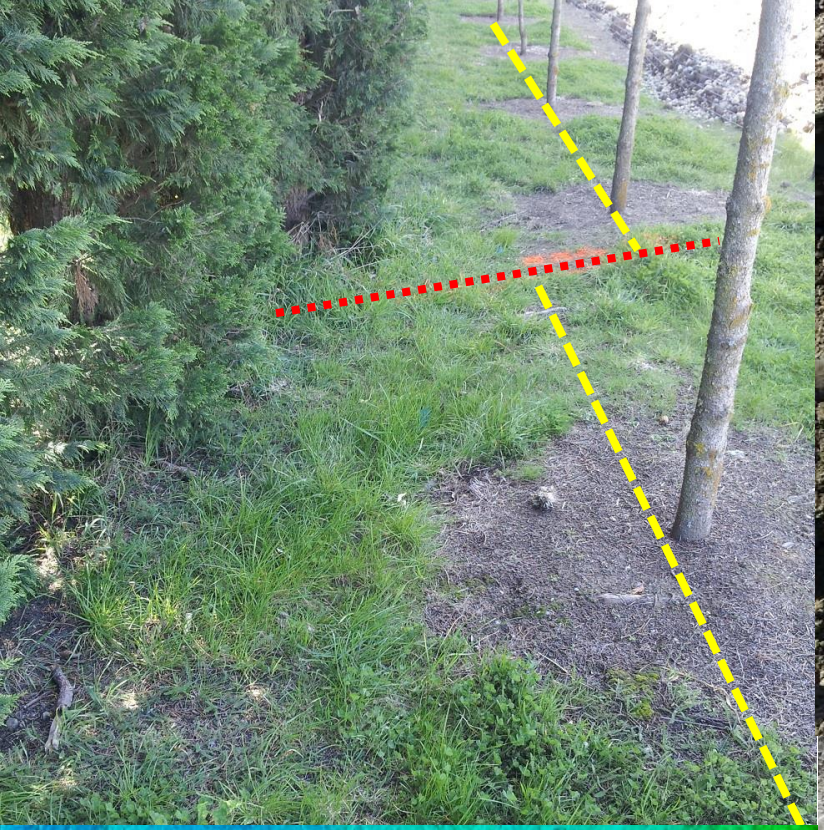


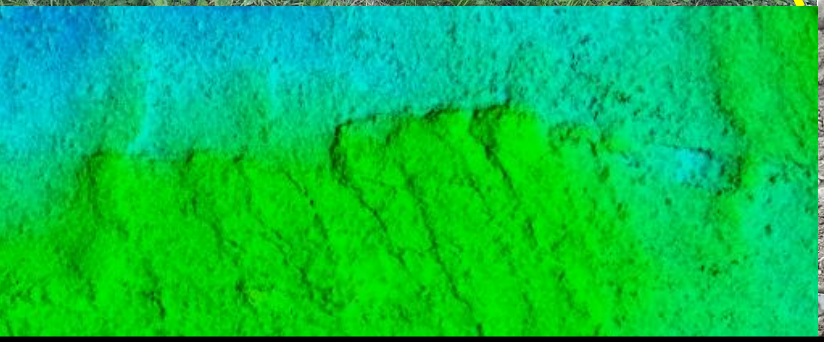
Sasnett, 2013

Fault rupture behaviour in time and space



Hornblow et al., Tectonophysics, 2014



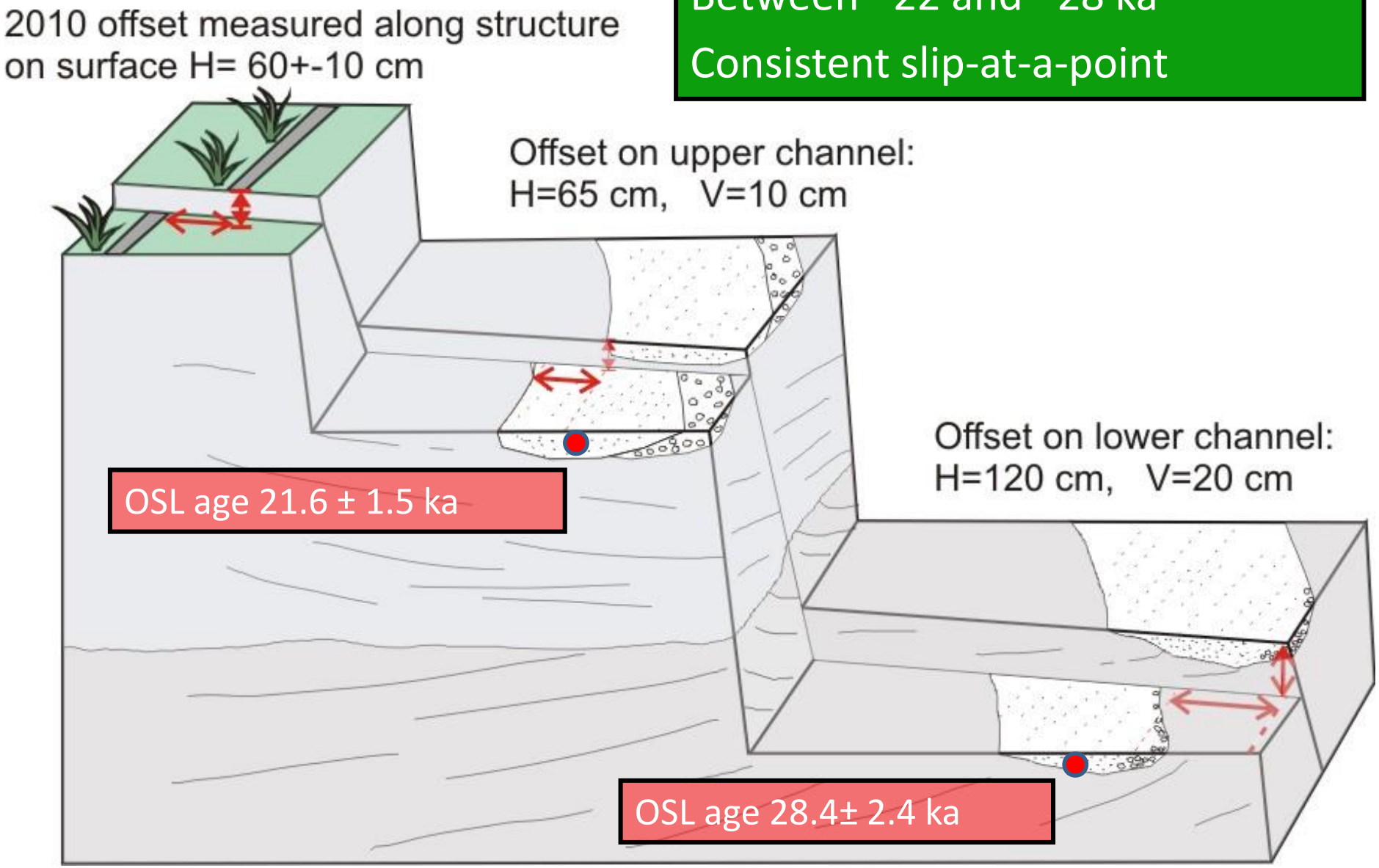


Digging laterally along fault to expose paleochannel cross-sections and measure piercing points (channel facies and margins)

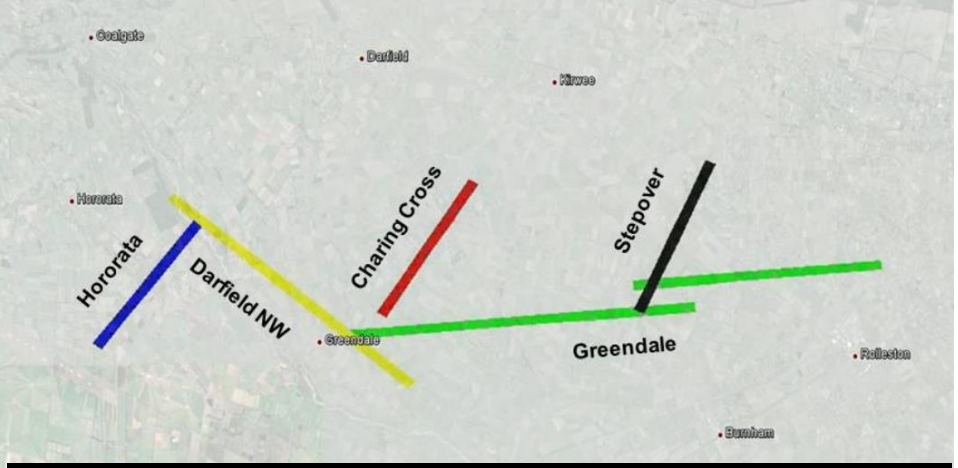
The penultimate earthquake:

Between ~22 and ~28 ka

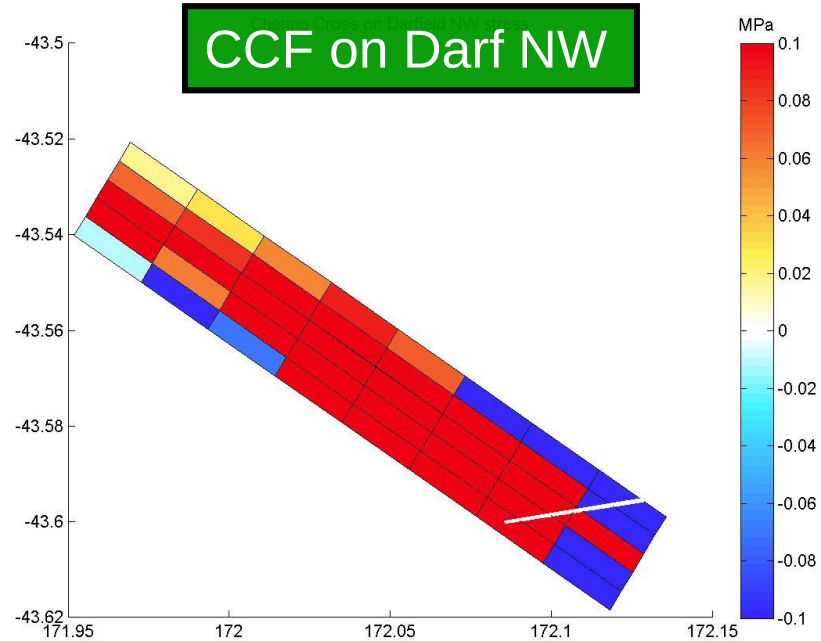
Consistent slip-at-a-point

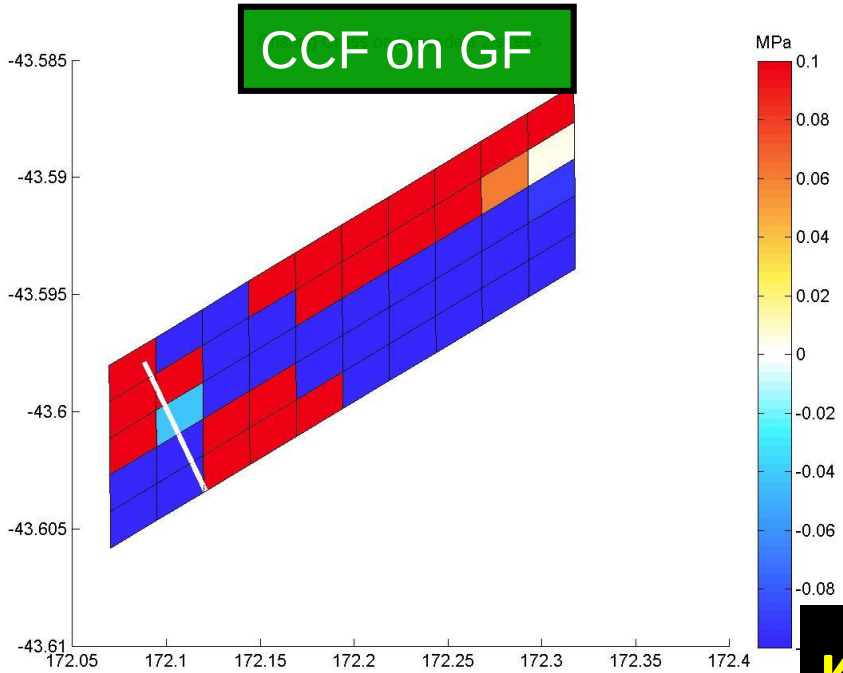


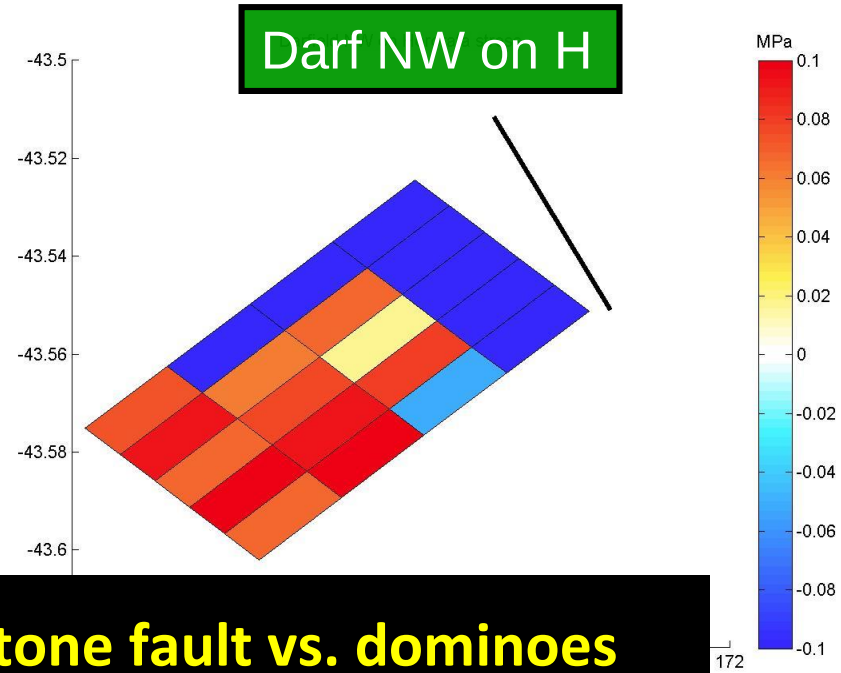
Hornblow et al., Tectonophysics, 2014



Coulomb 'static' stress evolution for rupture initiating on CCF





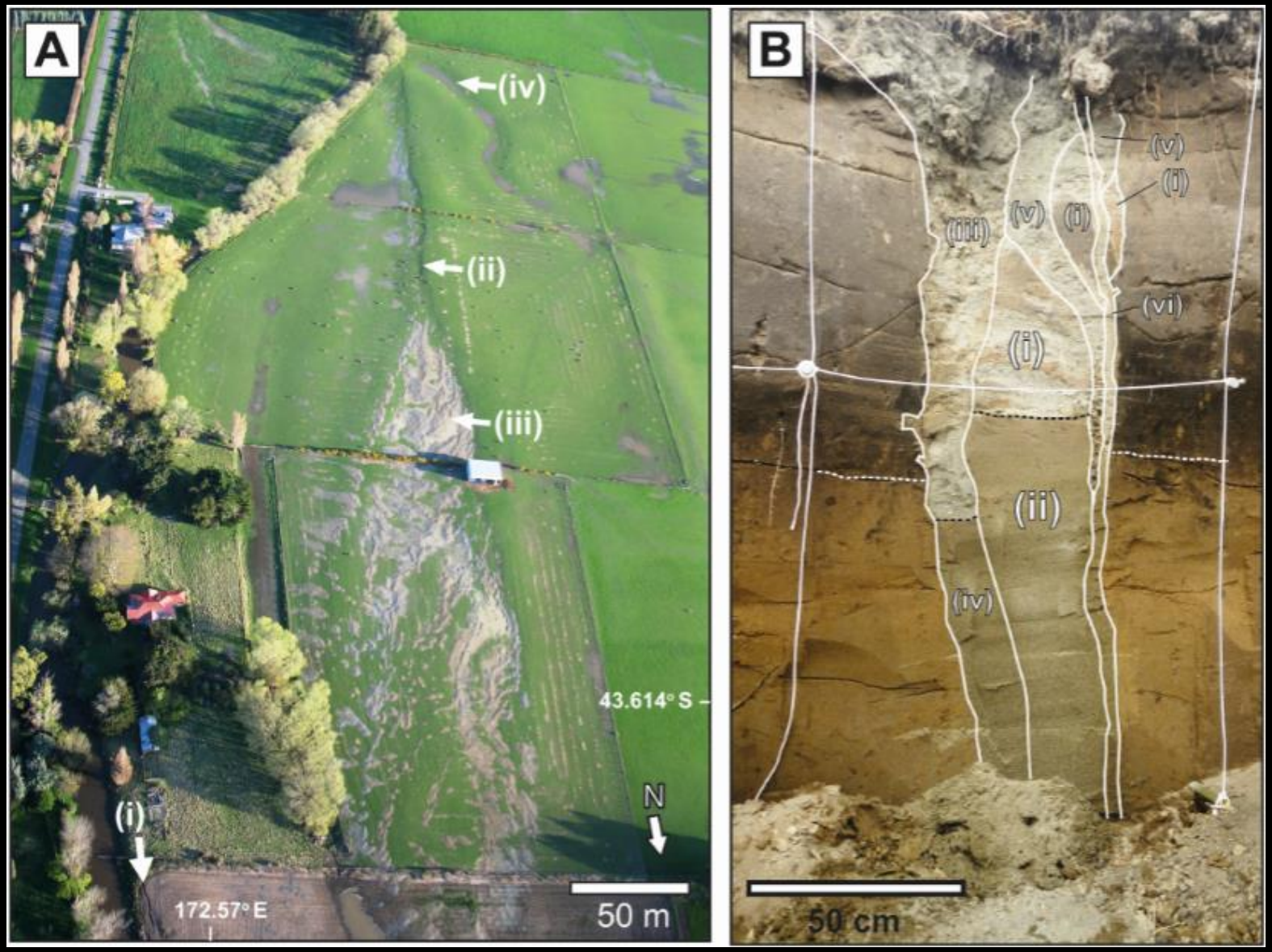


Keystone fault vs. dominoes

Courtesy: Abigail Jimenez, Sandy Steacy

Liquefaction

Geologic expressions of liquefaction



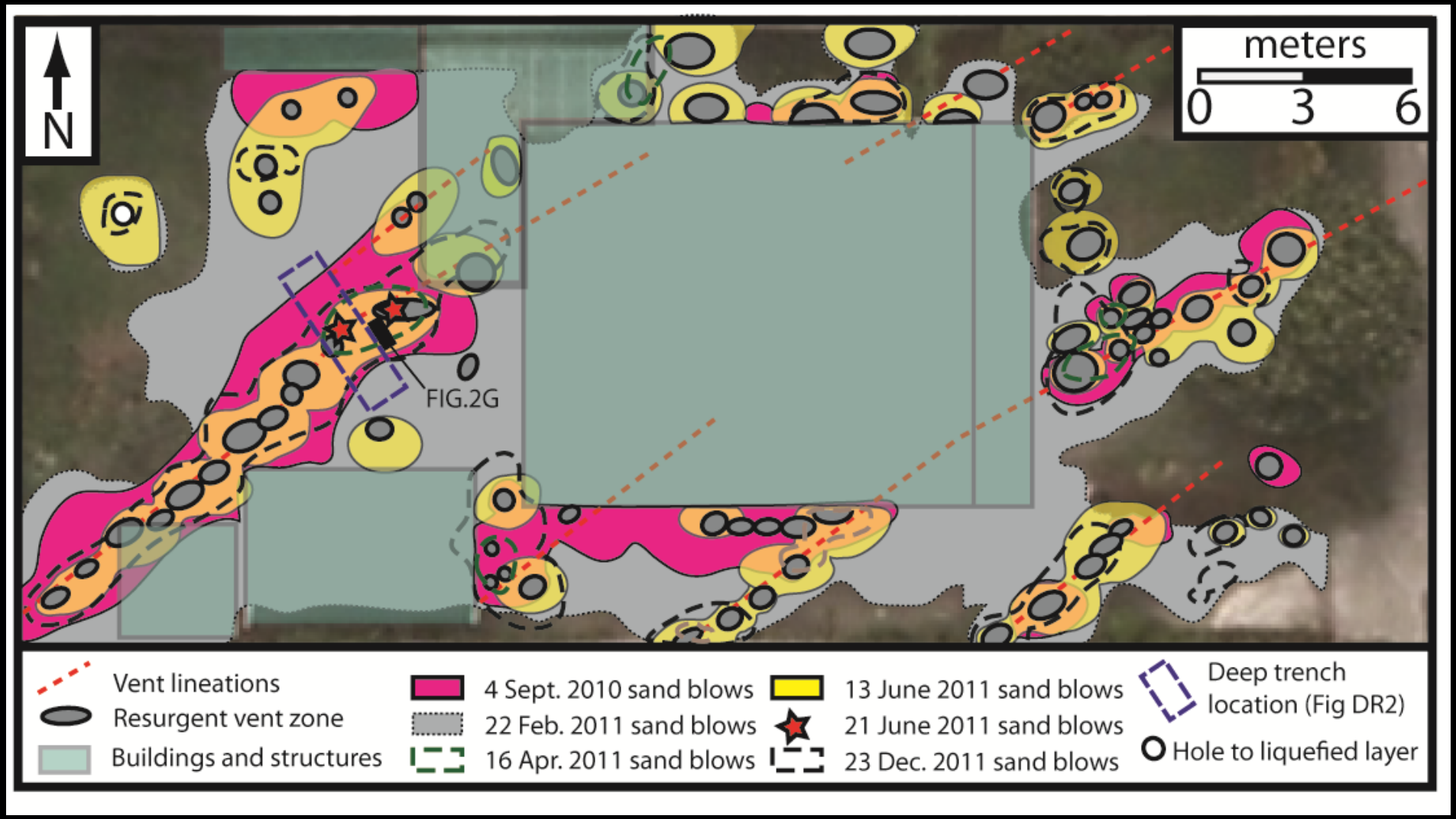
Quigley et al Tectonophysics

Avonside Liquefaction Laboratory: severe and recurrent liquefaction

11 episodes in Christchurch during 2010-2011 CES

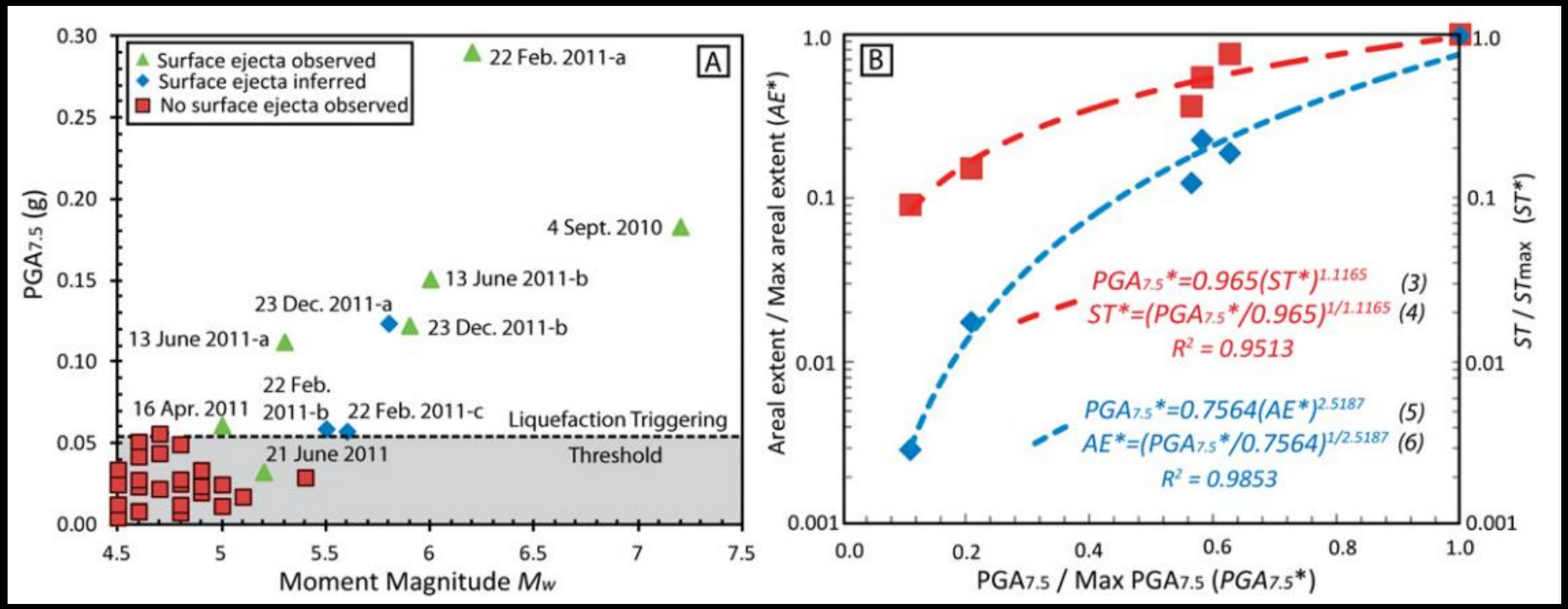
Quigley, M., Bastin, S., and Bradley, B., (2013) Recurrent liquefaction in Christchurch, New Zealand during the Canterbury earthquake sequence, *Geology 41 (4) p. 419-422.*

Relationship between earthquake M_w, shaking intensity, and surface expression of liquefaction and land damage



Quigley, M., Bastin, S., and Bradley, B., (2013) Recurrent liquefaction in Christchurch, New Zealand during the Canterbury earthquake sequence, *Geology 41 (4) p. 419-422.*

Definition of liquefaction-triggering PGA, improved understanding of recurrent liquefaction, and development of new empirical equations with predictive capacity

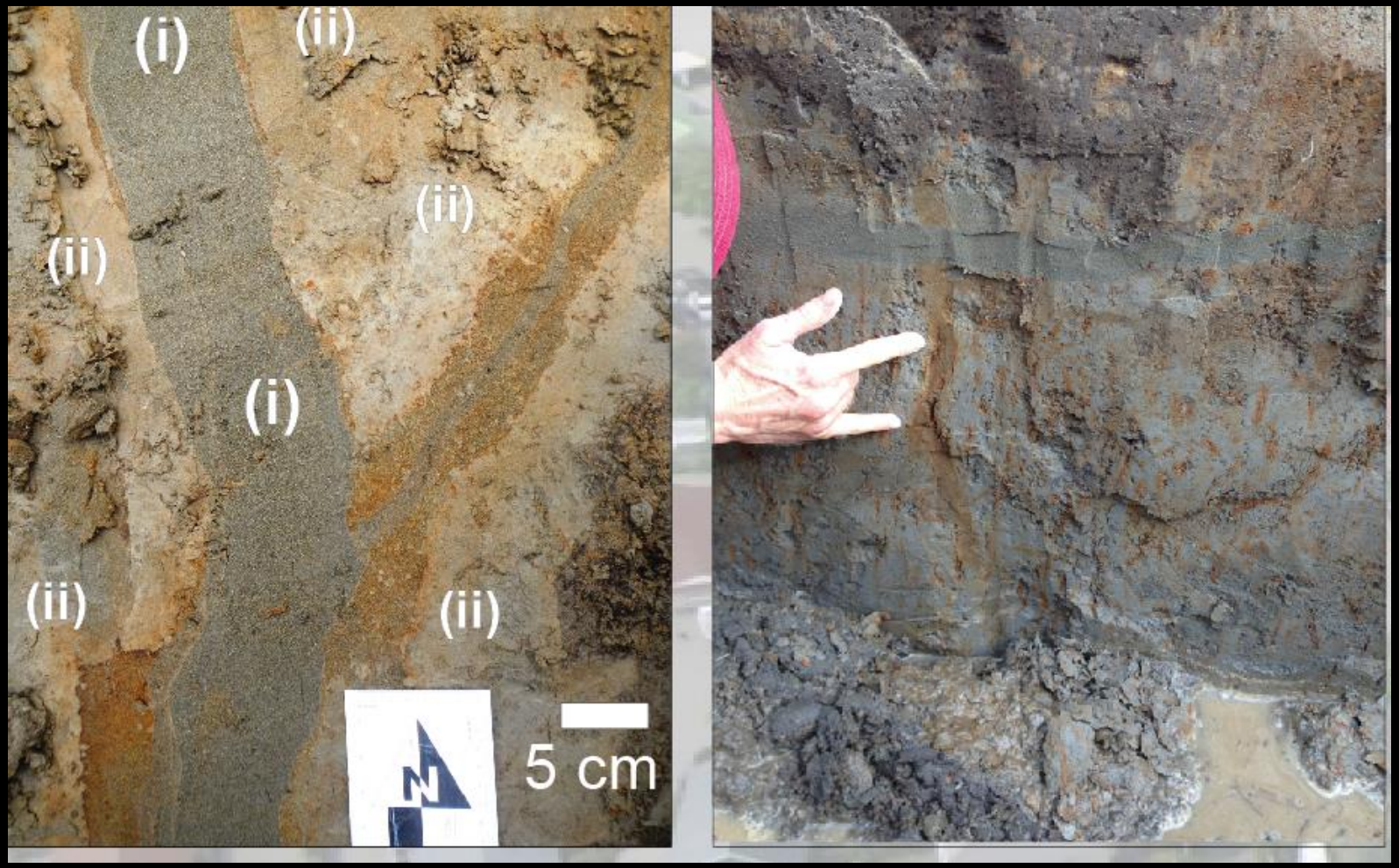


Quigley, M., Bastin, S., and Bradley, B., (2013) Recurrent liquefaction in Christchurch, New Zealand during the Canterbury earthquake sequence, *Geology 41 (4) p. 419-422.*

Paleoliquefaction investigations

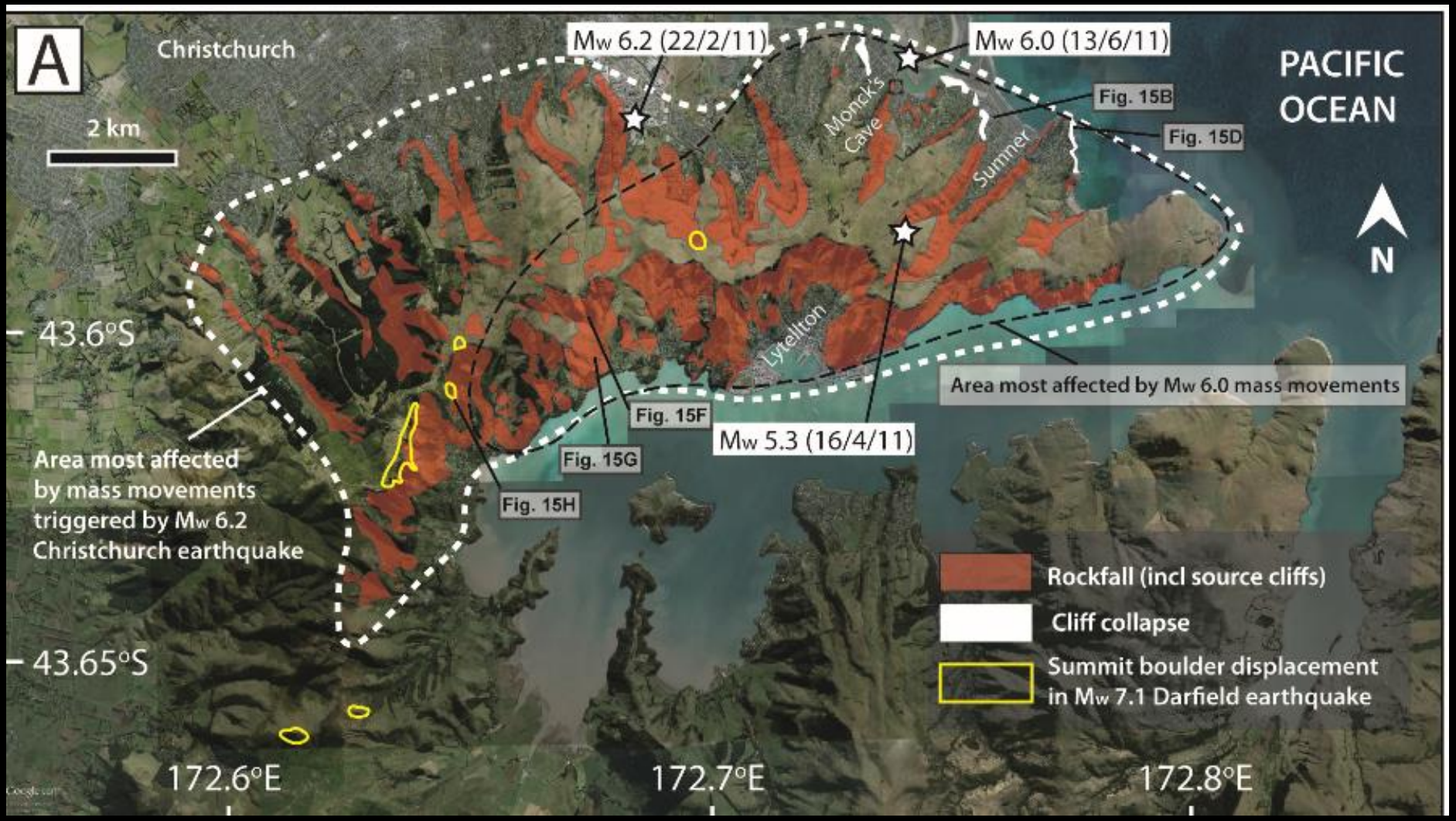
Predicting site responses under future seismic loading

Delineating hazardous areas



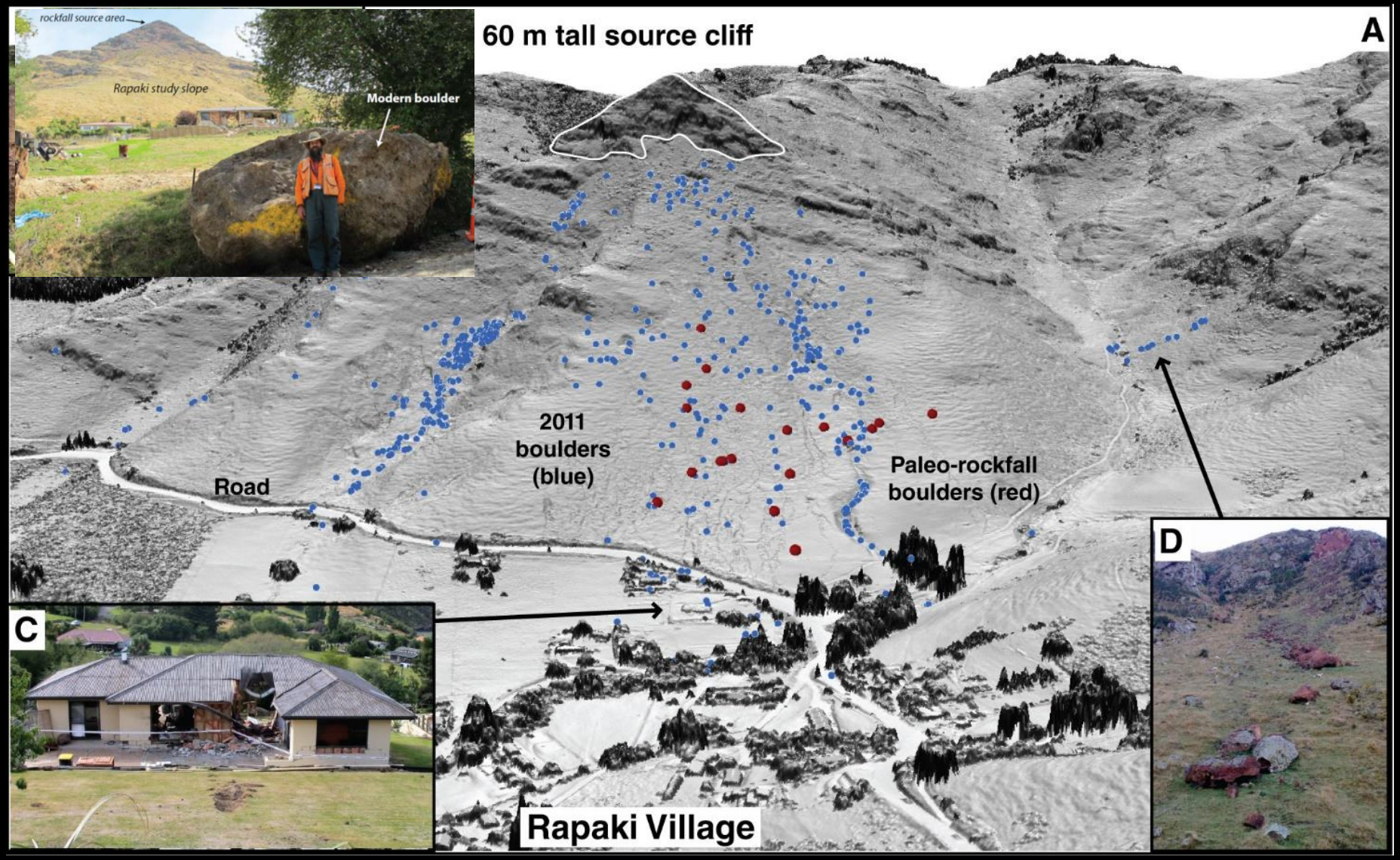
Bastin et al., GSAB, 2015

Rockfall



Recurrent rockfall and cliff collapse during the 2010-2011 Canterbury earthquake sequence

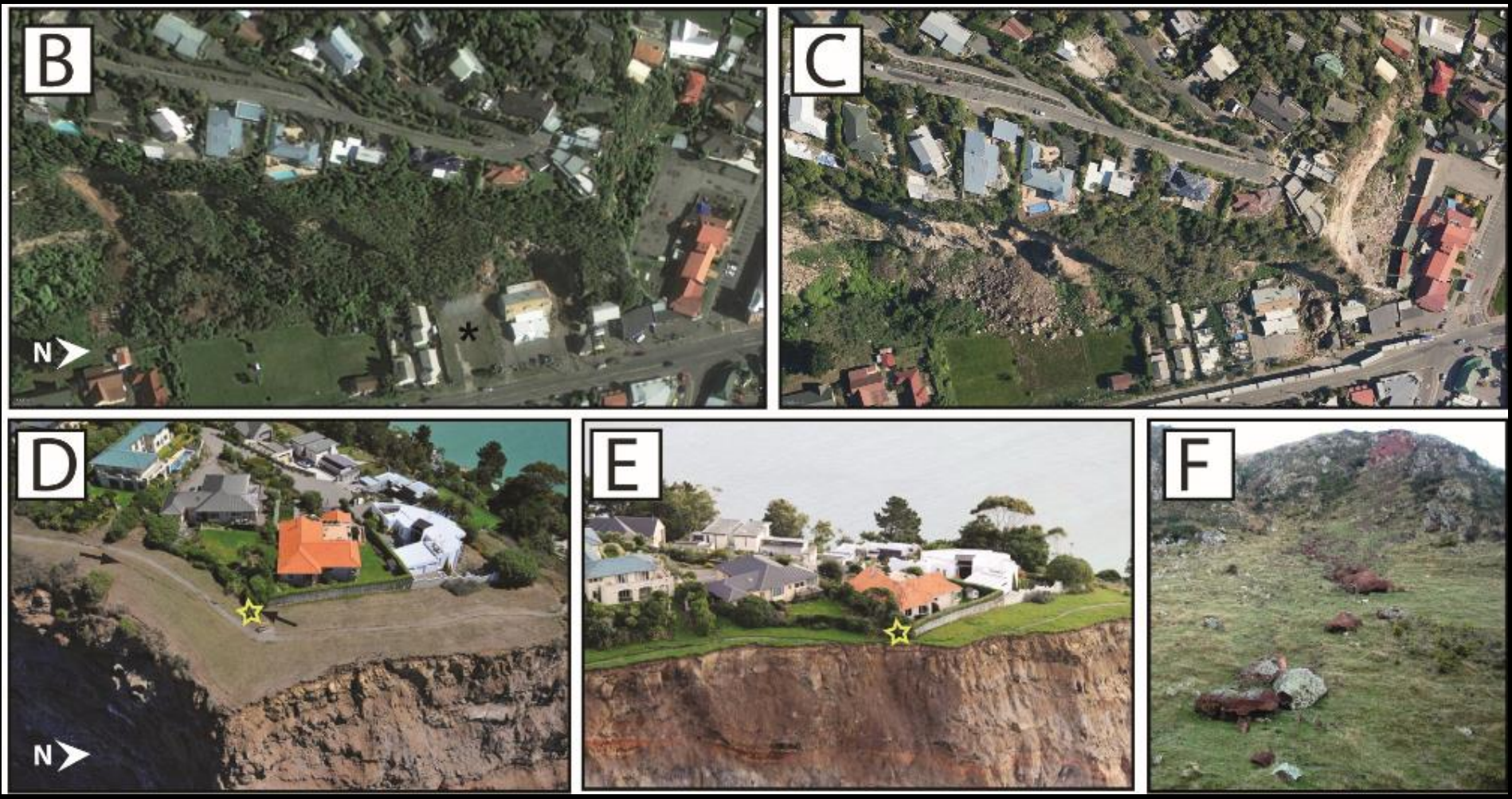
Massey et al., *Eq Spectra, 2014* Mackey and Quigley, *Geology, 2014;* Quigley et al., *Tectonophysics, 2016*



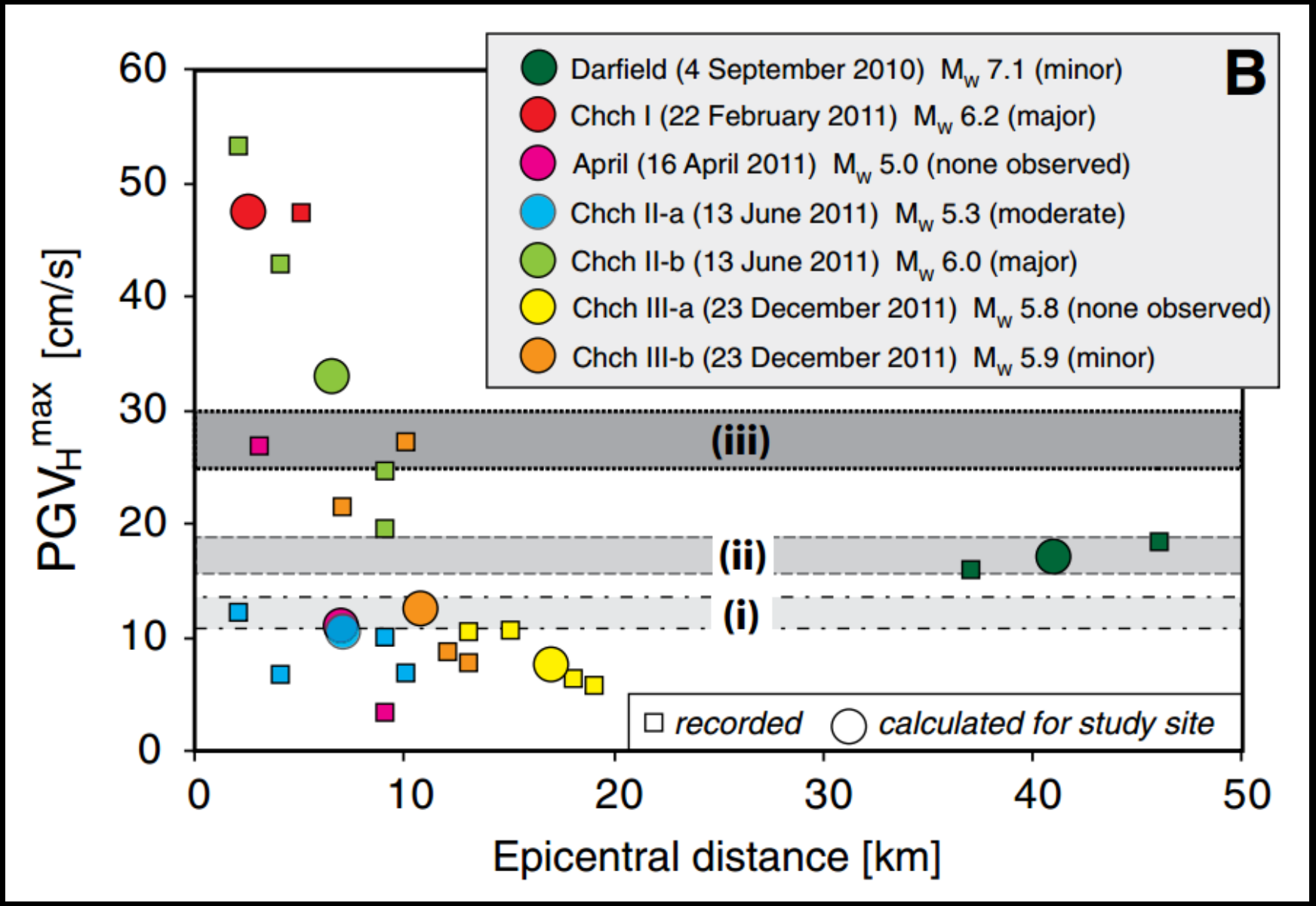
Rockfall and boulder roll

Mackey, B., and Quigley, M., (2014) Strong proximal earthquakes revealed by cosmogenic ^{3}He dating of prehistoric rockfalls, Christchurch, New Zealand, *Geology*

Cliff collapse, fatalities, and near misses



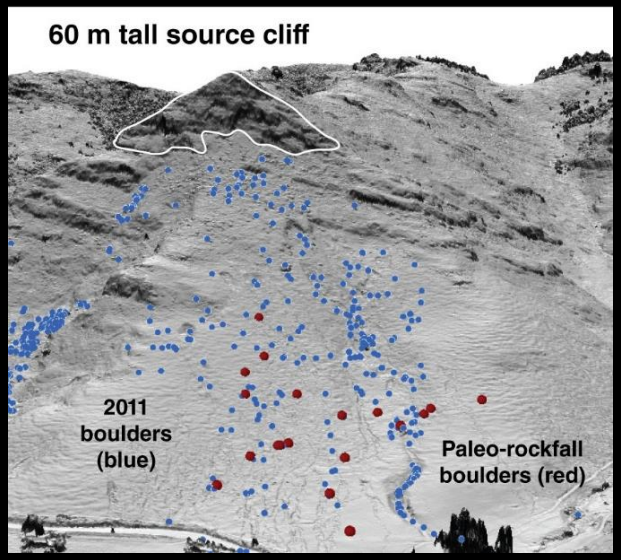
Quigley et al., *Tectonophysics, 2016*

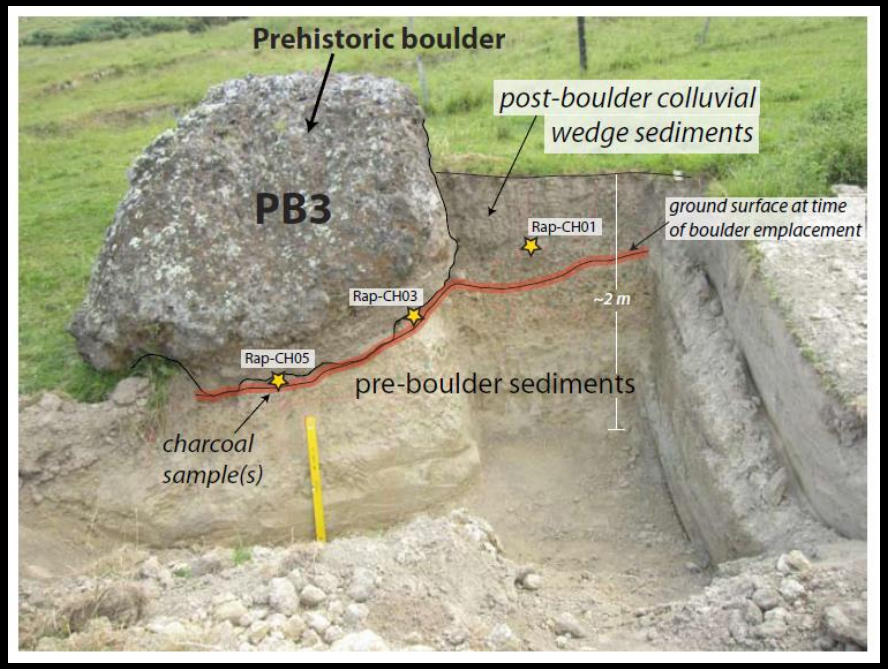


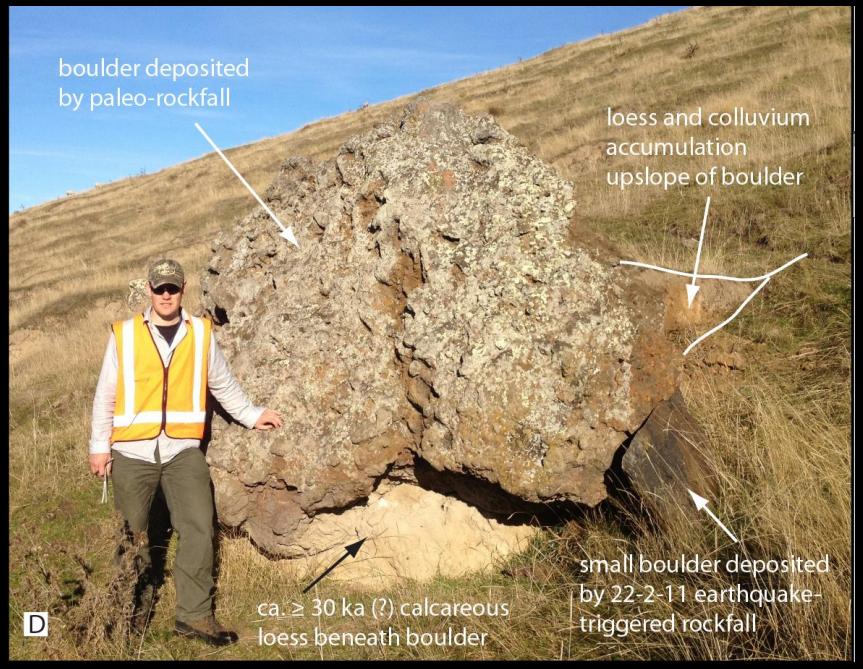
Empirically-defined calculations of seismologic thresholds for rockfall triggering for different rockmass fragility

Mackey and Quigley, Geology, 2014

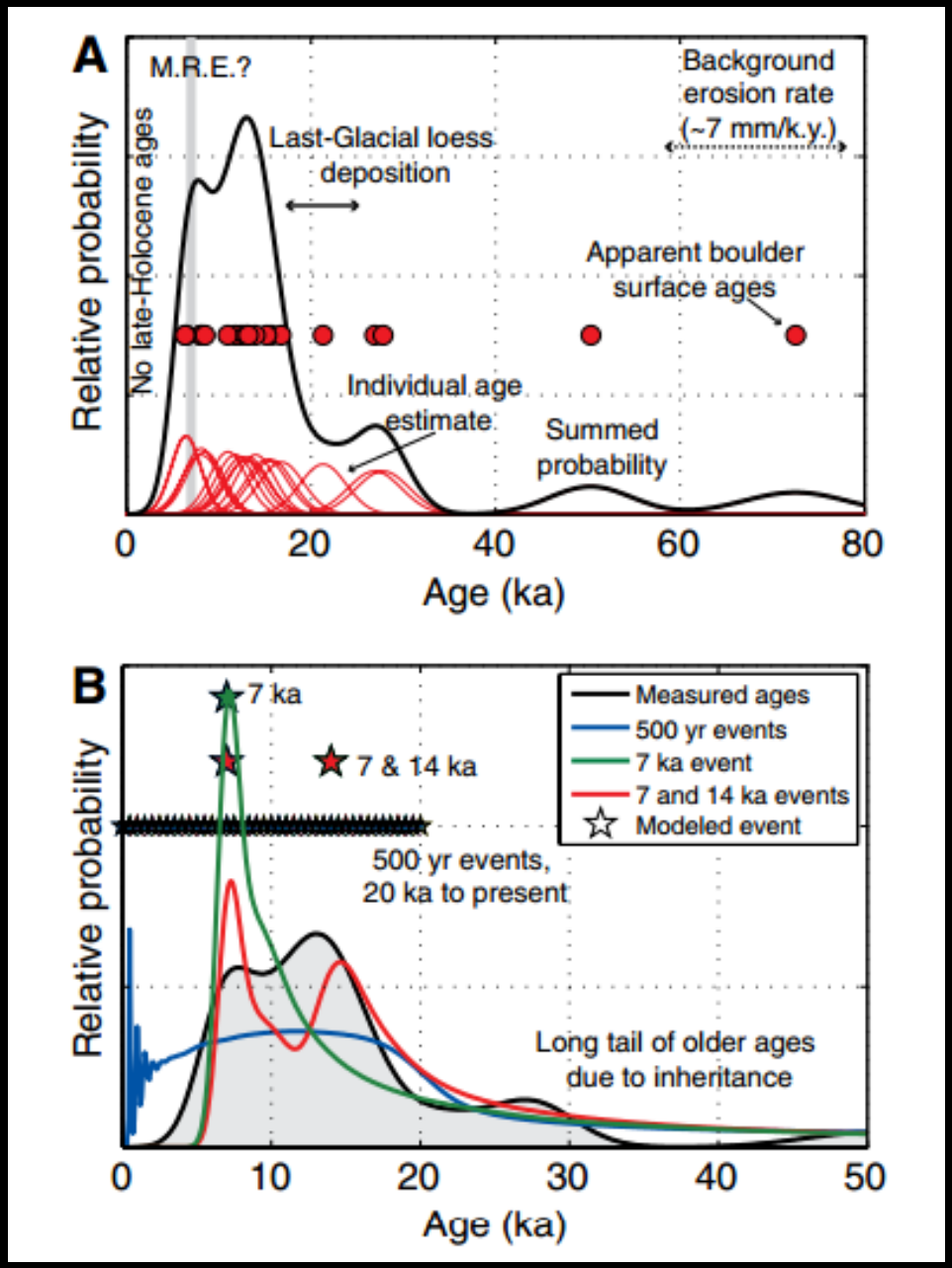
Paleo-rockfall deposits





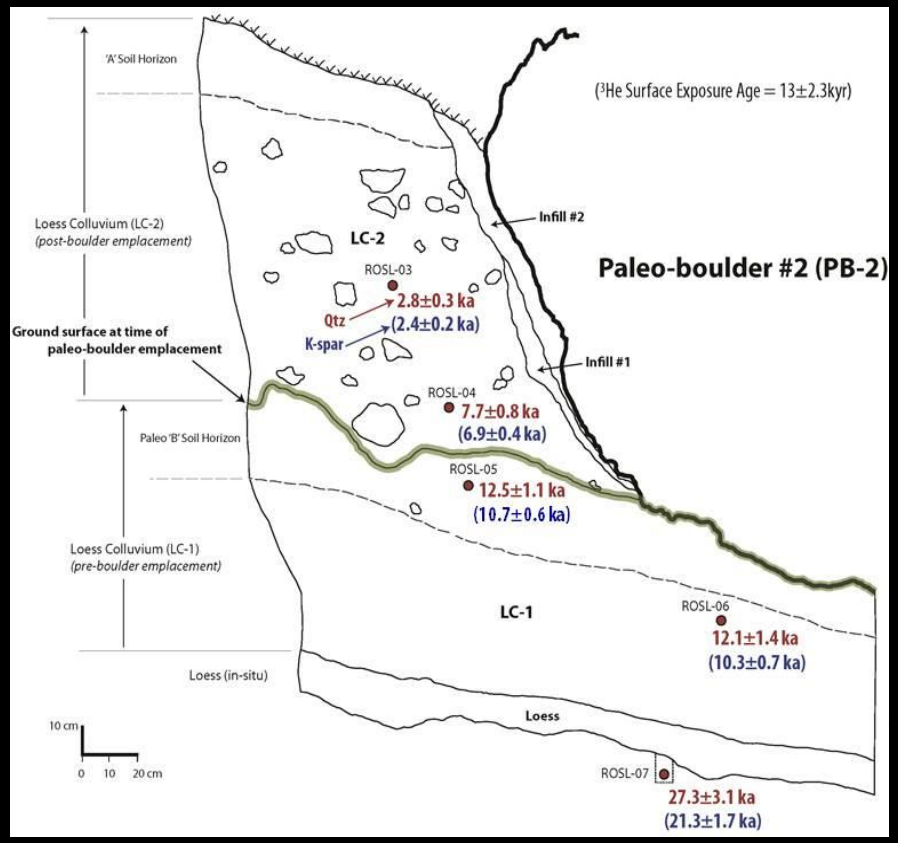


Mackey and Quigley, 2014 Geology; Borella et al. in review, Nat Geosci



Cosmogenic ^{3}He dating of paleo-boulder surfaces as proxy for emplacement age

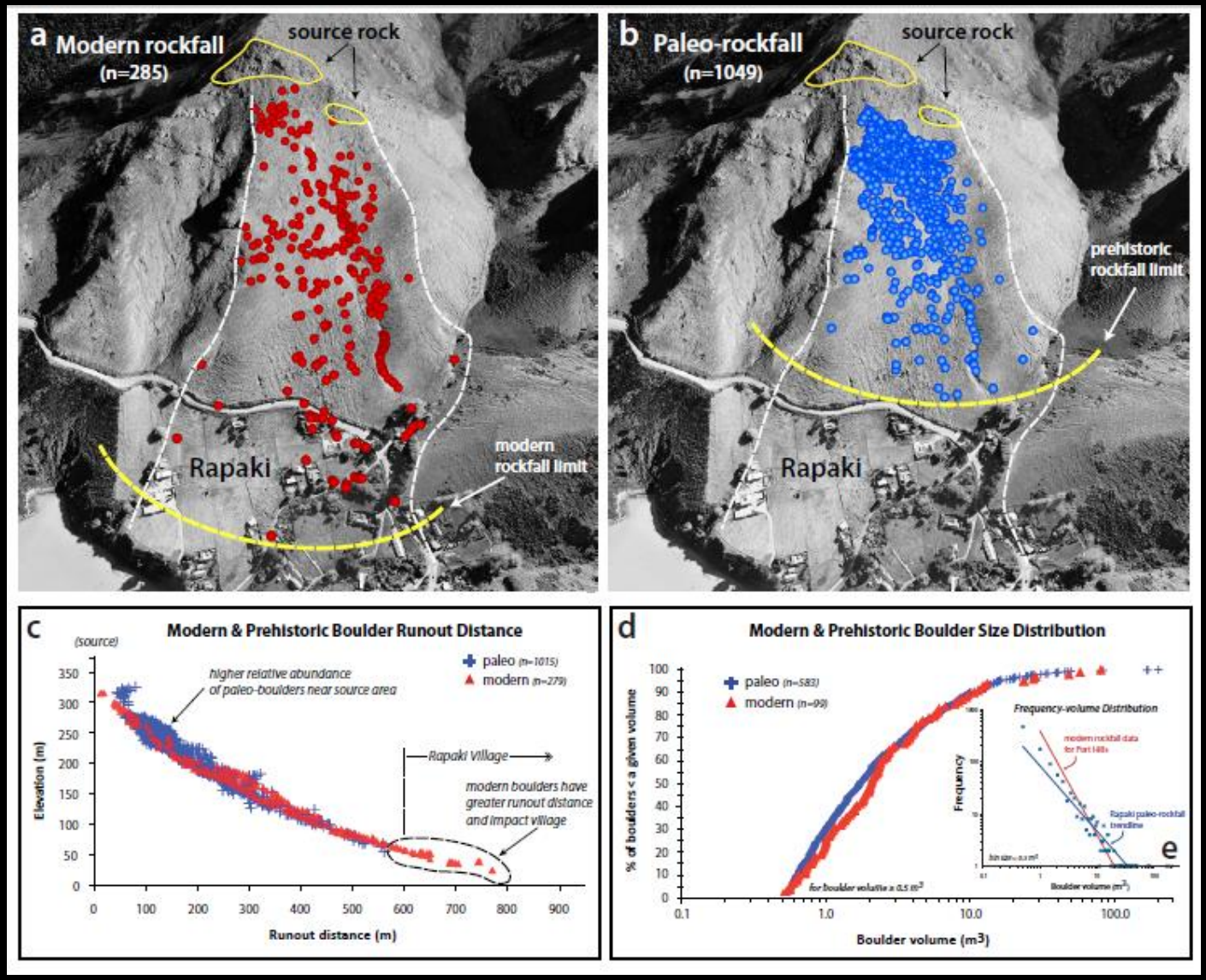
Mackey, B., and Quigley, M., (2014) Strong proximal earthquakes revealed by cosmogenic ^{3}He dating of prehistoric rockfalls, Christchurch, New Zealand, *Geology*



OSL, IRSL and ^{14}C dating of colluvium underlying and aggraded upslope of boulders

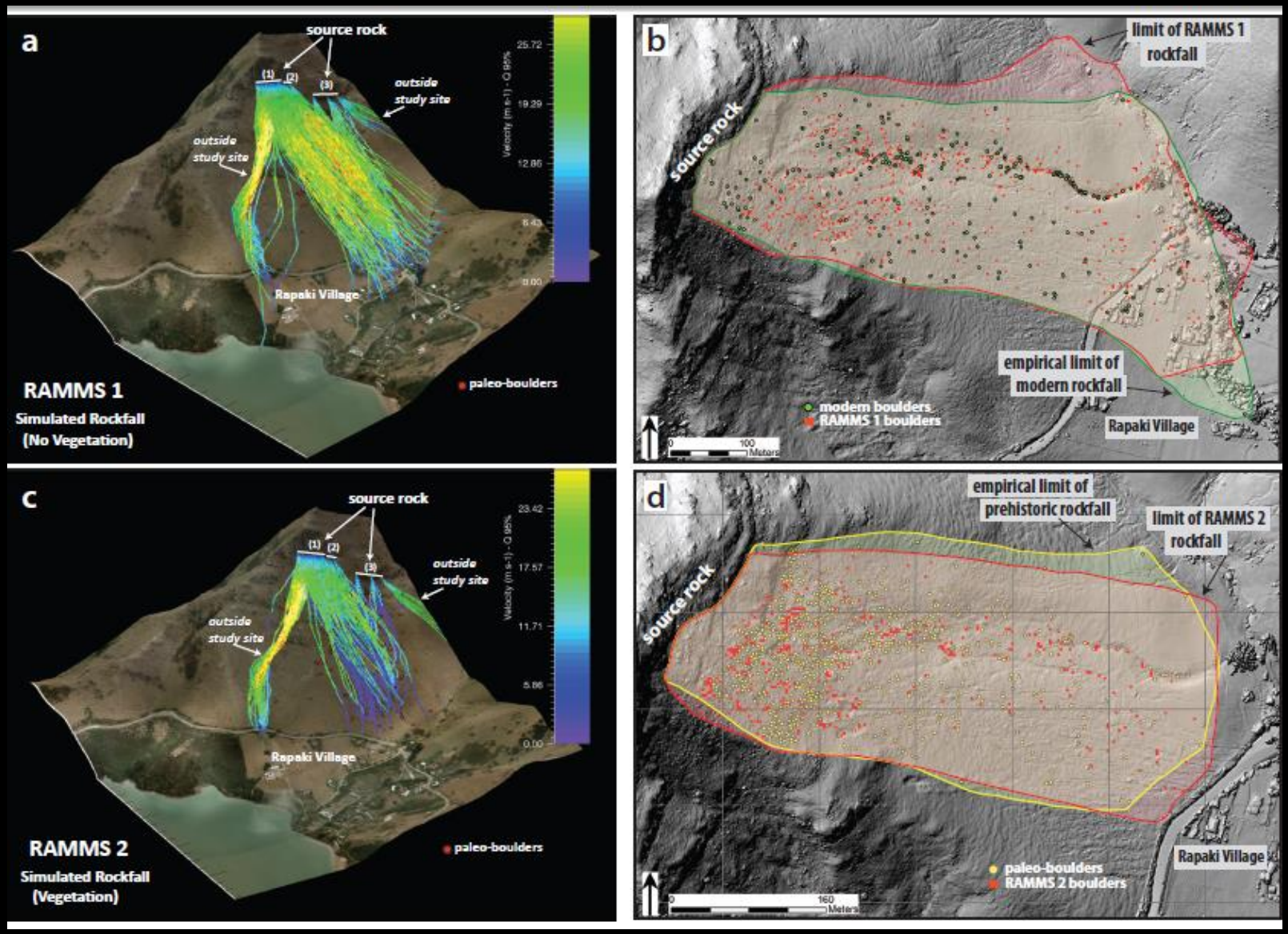
Sohbati et al 2016; Borella et al., 2016

Comparison of paleo- and contemporary rockfall distributions



Borella, J., Quigley, M., Vick, . (in review) Anthropocene rockfalls exceed limits of prehistoric predecessors, *PNAS*

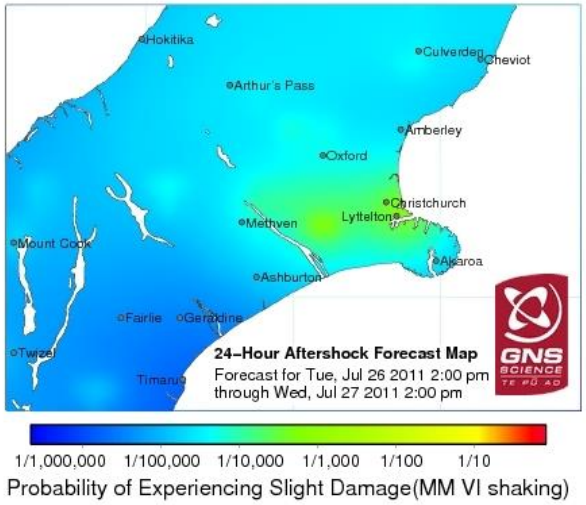
Modelling of paleo- and contemporary rockfall distributions



Borella, J., Quigley, M., Vick, . (in review) Anthropocene rockfalls exceed limits of prehistoric predecessors, *PNAS*

Paleoseismology and land use planning

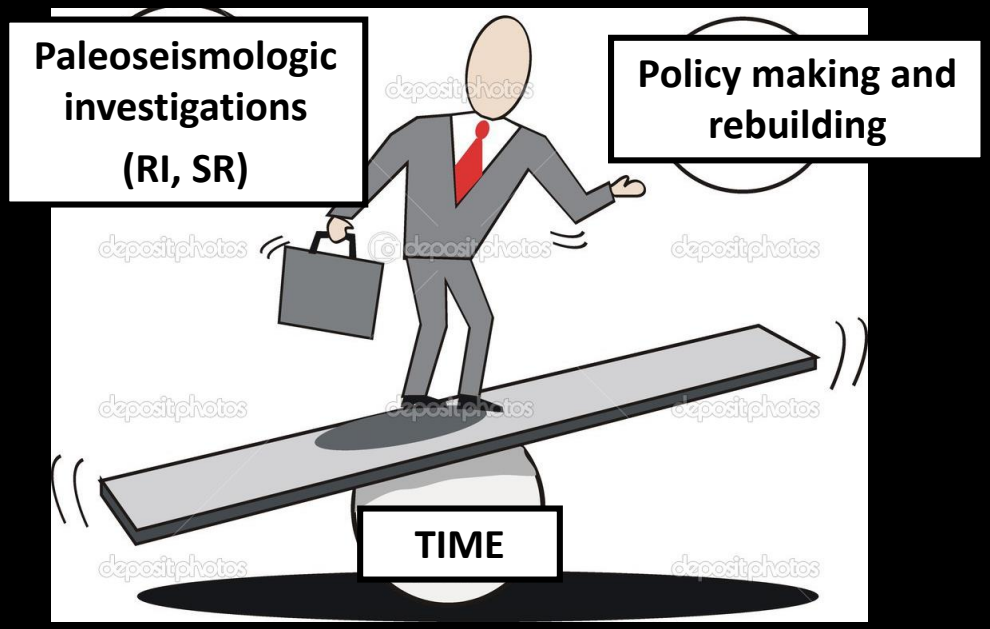
Bad decisions and implementation of operational earthquake forecasting



	Canterbury region long-term probabilities		
	One year: July 15 2011 - July 14 2012		
Magnitude range	Expected range	Expected average	Probability
5.0 - 5.4	0 - 5	1.9	85%
5.5 - 5.9	0 - 3	0.9	45%
6.0 - 6.4	0 - 1	0.2	15%
6.5 - 6.9	0 - 1	0.07	7%
7.0 - 7.9	0 - 1	0.02	2%

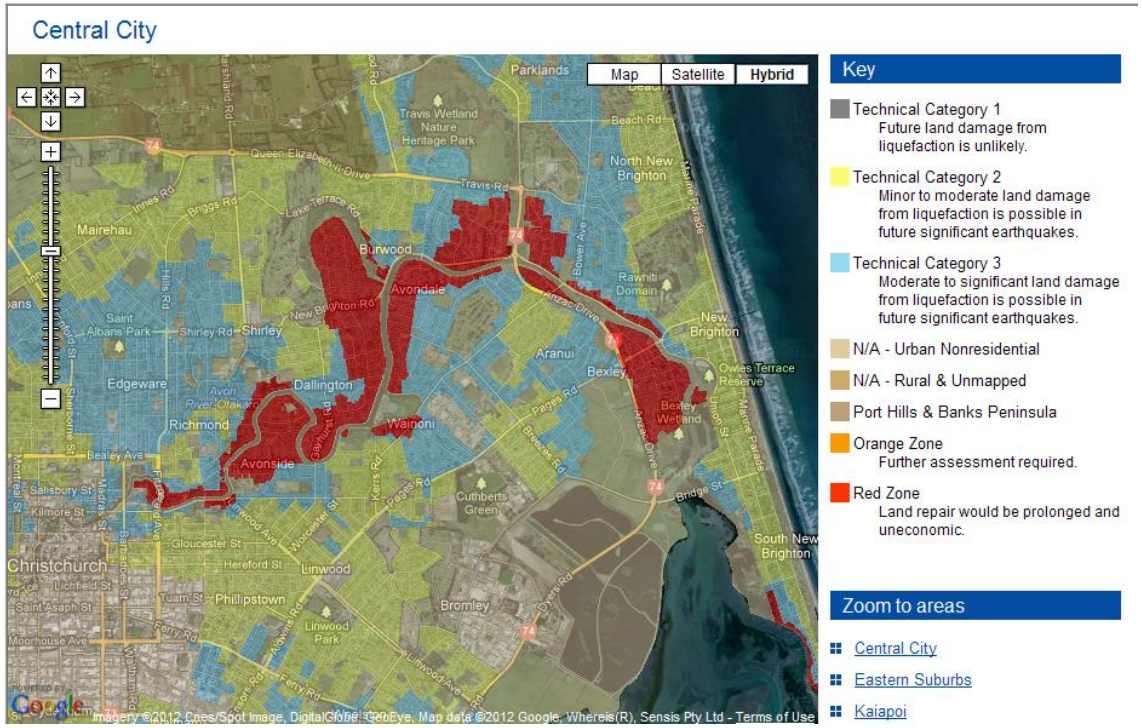
This table was last u

Fault zone land use policy: the race against recovery

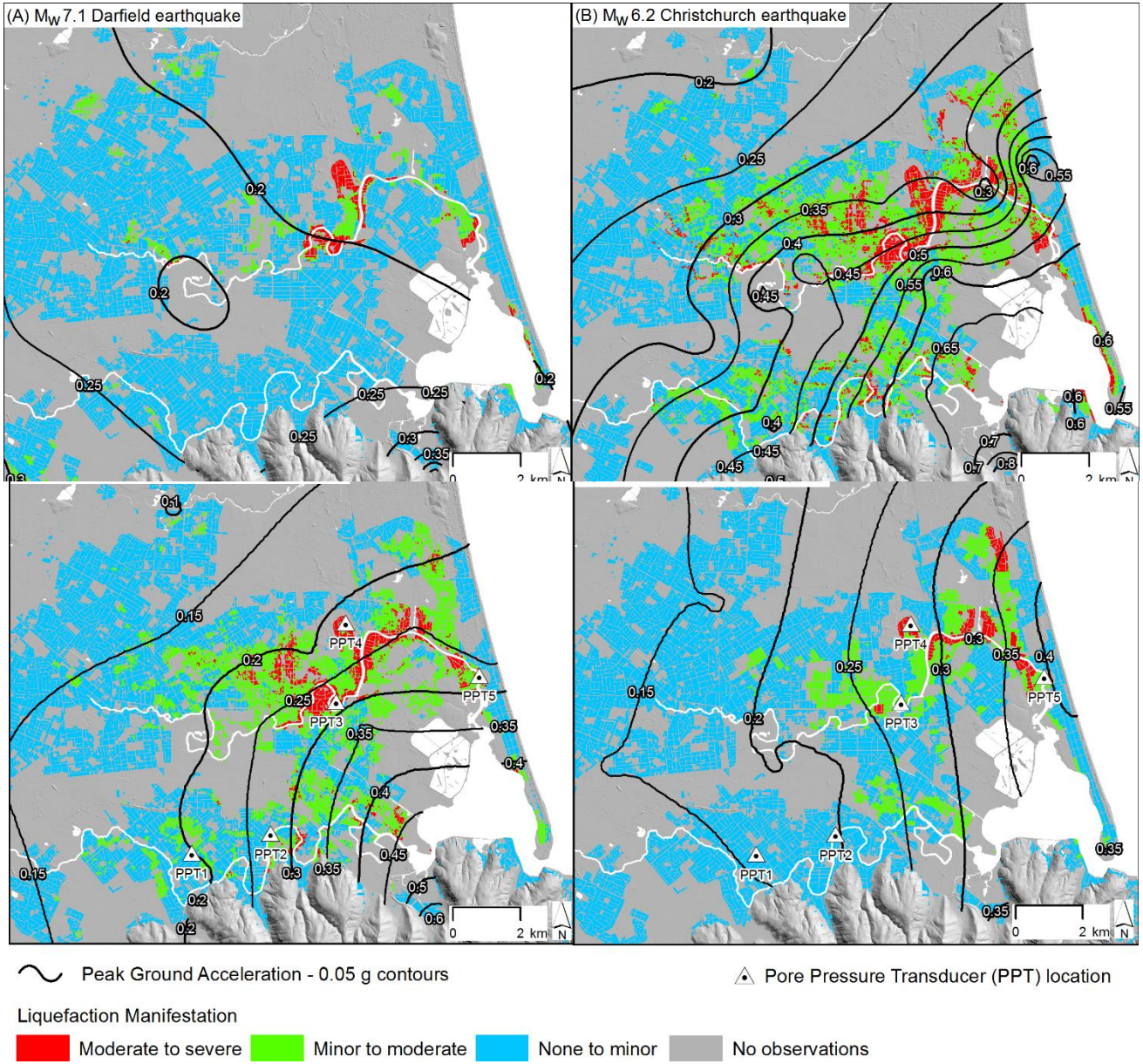


Liquefaction: ‘red zone’ criteria

- significant and extensive area wide land damage;
- success of engineering solutions may be uncertain in terms of design, its success and possible commencement, given the ongoing seismicity;
- any repair would be disruptive and protracted for landowners.



Probabilistic assessment of liquefaction in the next 50 years based on earthquake forecasting models and liquefaction triggering thresholds



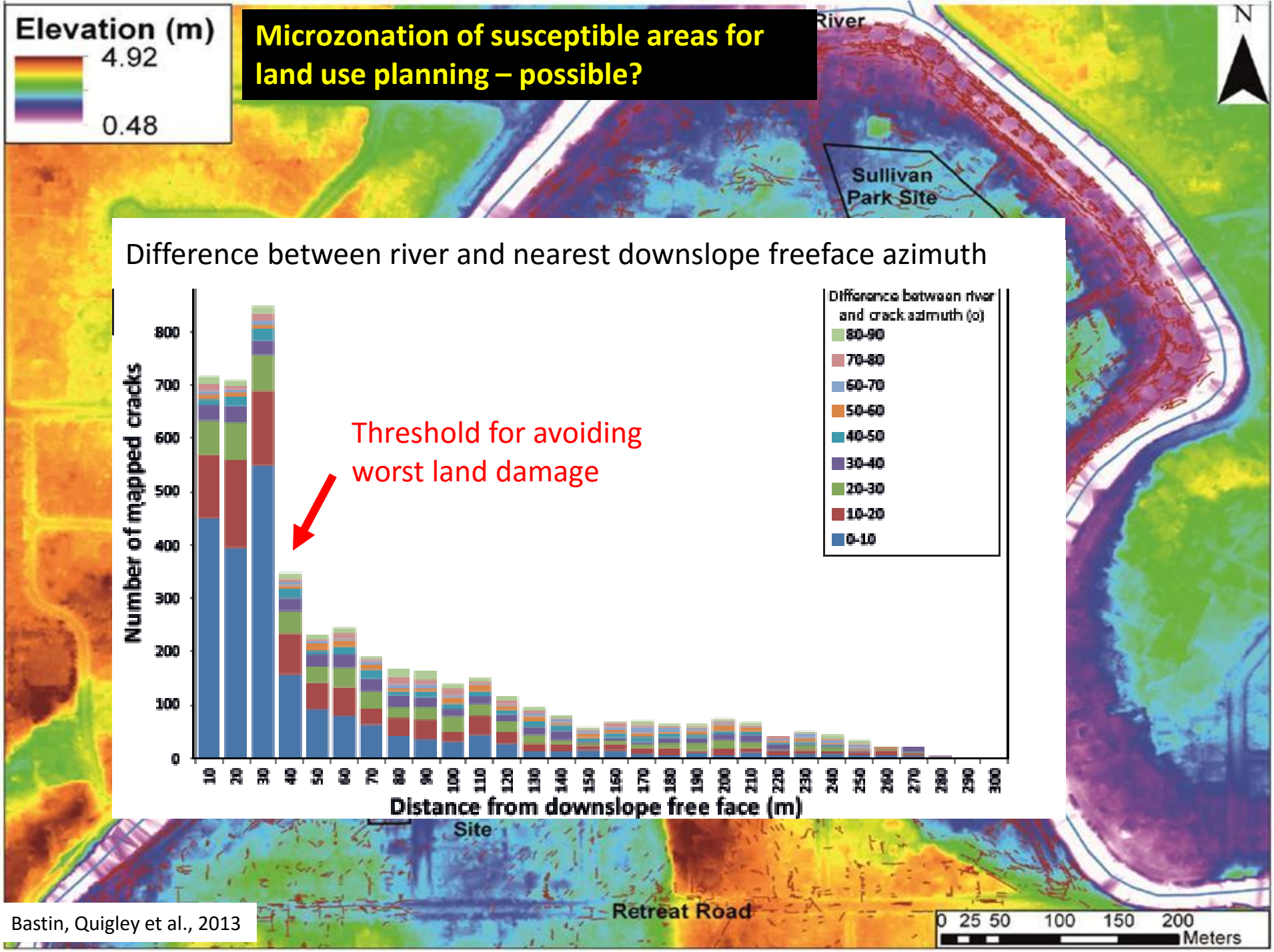
Independent paleoseismic tests of earthquake forecasts:

Targeted paleoliquefaction studies based on susceptibility (site conditions)

RED = multiple liquefaction episodes in last 2 kyr

GREEN = no evidence for liquefaction

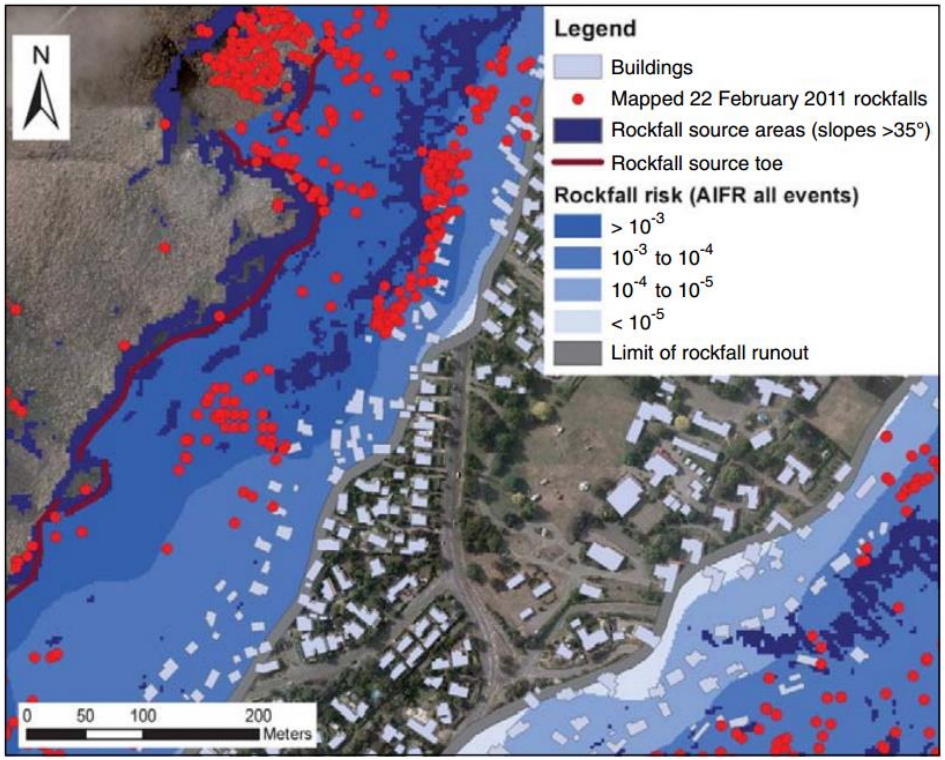
Microzonation of susceptible areas for land use planning – possible?

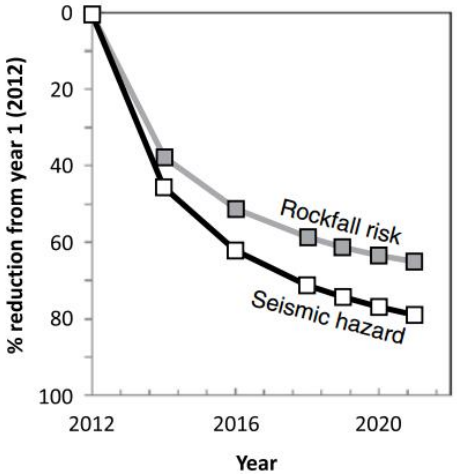


Difference between river and nearest downslope freeface azimuth

Bastin, Quigley et al., 2013

Rockfall: ‘red zone’ criteria and societal tolerance





(b)

AIFR

Rockfall event

Person in boulder path

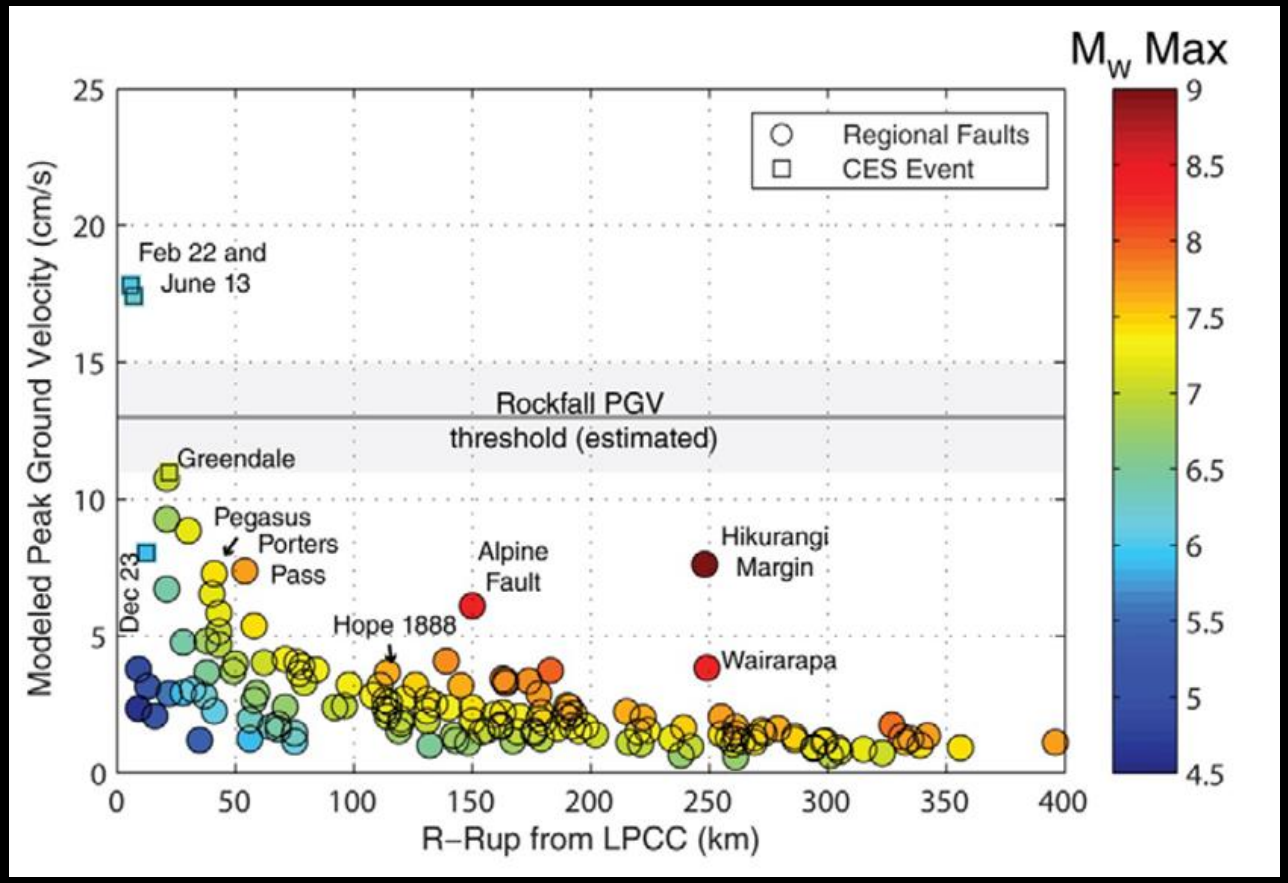
Person killed if hit

$$R_{(LoL)} = \boxed{P_{(H)}} \times P_{(S:H)} \times P_{(T:S)} \times V_{(D:T)},$$

Person present when event occurs

Massey et al. 2014

Delineation of seismic sources capable of rockfall generation using empirical thresholds and GMPEs: The tension between statistical forecasts and geology



Mackey, B., and Quigley, M., (2014) Strong proximal earthquakes revealed by cosmogenic ^{3}He dating of prehistoric rockfalls, Christchurch, New Zealand, *Geology*

Limitations to paleoseismic data

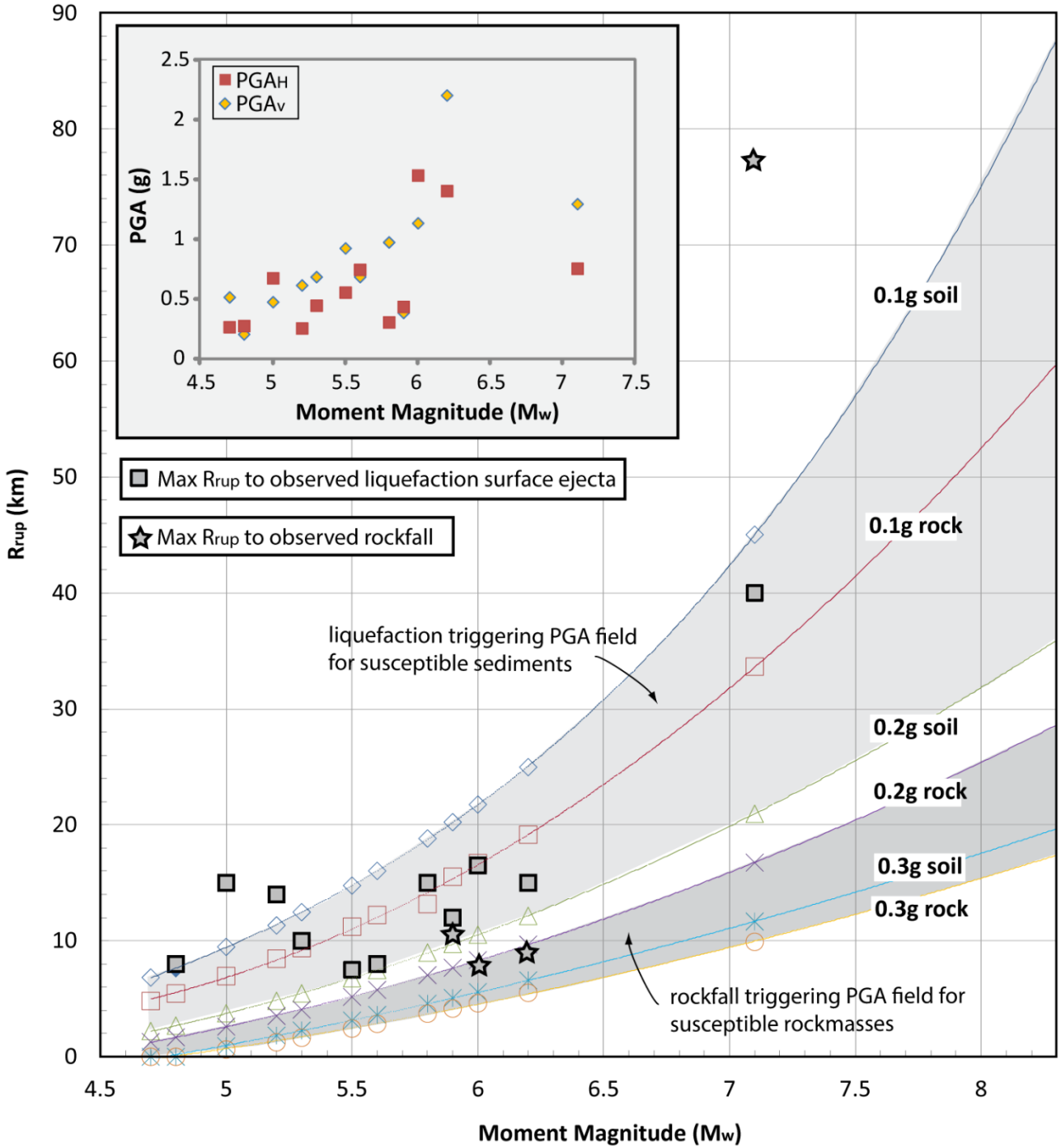
- Applicability of one study site to another unstudied site
- Distinguishing clustered from single events
- Coarse temporal resolution of geology compared to rebuilding / engineering timeframes
- Easily comprehended geologic uncertainties compared to statistic uncertainties

http://www.chchplan.ihp.govt.nz/wp-content/uploads/2015/03/Natural-Hazards-Part.pdf

"Dr. Quigley could not dismiss outright the possibility of future strong earthquakes, and said *even though we find very little evidence for that from a geologic perspective we cannot completely discount that possibility*."

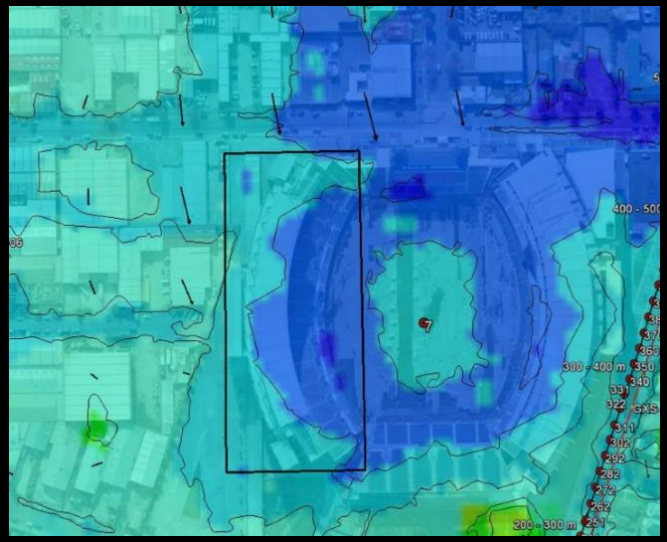
http://www.chchplan.ihp.govt.nz/wp-content/uploads/2015/03/Natural-Hazards-Part.pdf

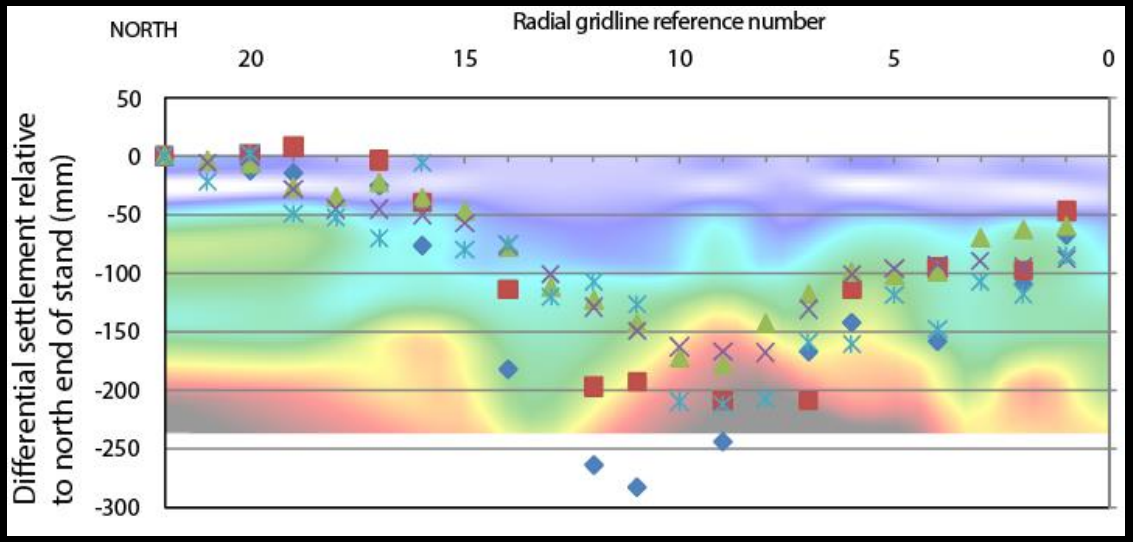
Where to from here?

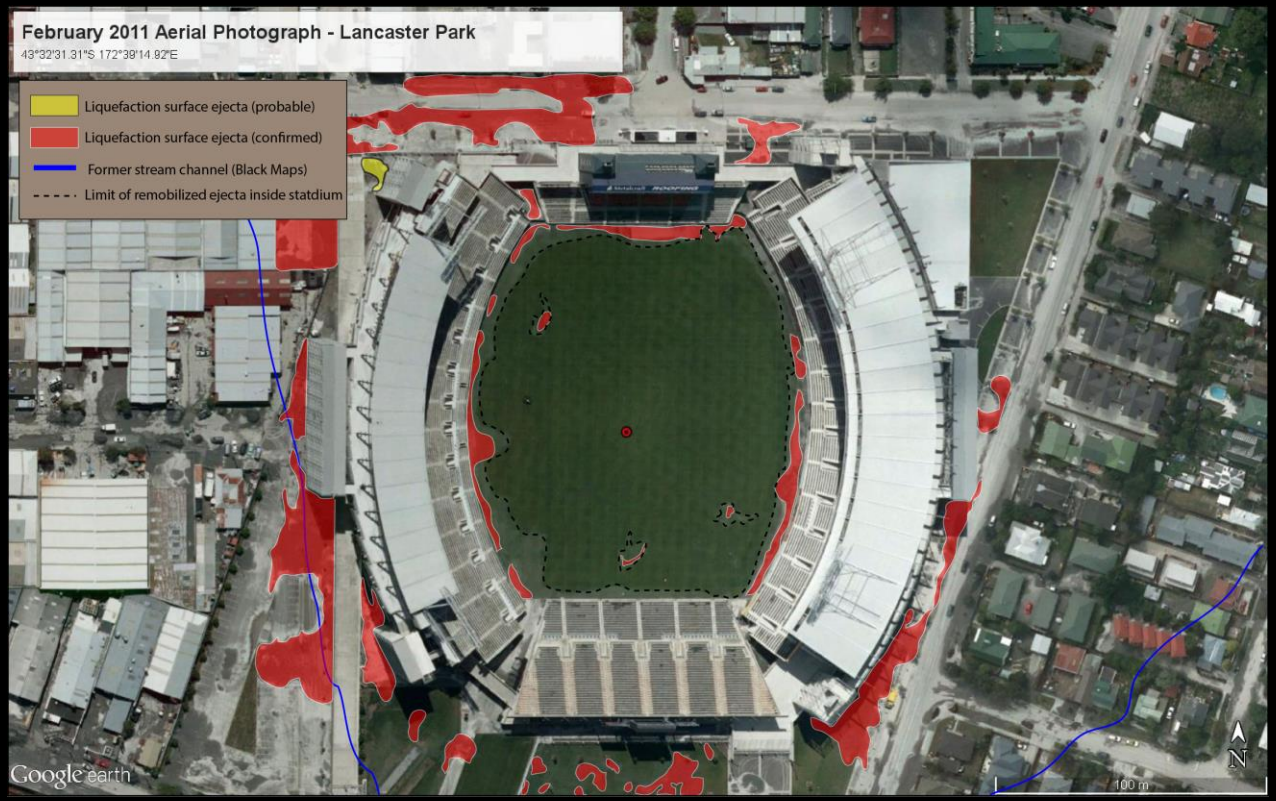


Predicting the impacts of future earthquakes under different site conditions and seismic characteristics

Quigley et al., 2016







APPLIED EARTH SCIENCE FOR INSURANCE CLAIMS:

Geologic controls on ground deformation and building damage and pre-CES seismicity

Conclusions

- The 2010-2011 CES is one of the best recorded earthquake sequences in history; combination of seismologic and geodetic data with field observations provides empirical evidence of triggering thresholds for earthquake effects
- Every environmental effect observed during the 2010-2011 CES had a paleoseismic predecessor of similar severity and extent; these were all identified retrospectively
- The recurrence intervals and severity of different effects vary as a function of phenomenon, seismologic thresholds and age
- Paleoseismic data could have been better utilized prior to development, but it is challenging to implement many paleoseismic datasets into land use planning during the recovery and rebuild phase
- Science has richly informed short-term policy in this instance; will it do so in the future?

Additional reading

Bastin, S., Quigley, M. et al. (2016) Late Holocene liquefaction at sites of contemporary liquefaction during the 2010-2011 Canterbury Earthquake Sequence, New Zealand, *Bulletin of the Seismological Society of America*, doi: BSSA-D-15-00166.

Quigley, M., et al. (2016) The 2010-2011 Canterbury earthquake sequence: environmental effects, seismic triggering thresholds, and geologic legacy, *Tectonophysics*, doi: 10.1016/j.tecto.2016.01.044.

Bastin, S., Quigley, M. et al. (2015) Paleoliquefaction in Christchurch, New Zealand, GSA Bulletin, B31174-1.

Hughes, M., Quigley M., et al. (2015) The sinking city: Earthquakes increase flood hazard in Christchurch, New Zealand, GSA Today 25, 3, 4-10

Hornblow, S., Quigley, M., et al.. (2014) Paleoseismology of the 2010 Mw 7.1 Darfield (Canterbury) earthquake source, Greendale Fault, New Zealand, *Tectonophysics,* 637, 178-190

Mackey, B., and Quigley, M. (2014) Strong proximal earthquakes revealed by cosmogenic 3He dating of prehistoric rockfalls, Christchurch, New Zealand, *Geology,* 42 (11), 975-978

Egan, C.J., and Quigley, M., (2014) Dancing earthquake science assists recovery from the Christchurch earthquakes, *Research in Dance Education,* 16(2), 161-183.

Quigley, M. et al. (2012) Surface rupture during the 2010 Mw 7.1 Darfield (Canterbury, New Zealand) earthquake: implications for fault rupture dynamics and seismic-hazard analysis, *Geology* 40 (1) p. 55-59.

Quigley, M., et al. (2013) Recurrent liquefaction in Christchurch, New Zealand during the Canterbury earthquake sequence, *Geology 41 (4) p. 419-422.*

Duffy, B., Quigley, M., et al. (2013) Fault kinematics and surface deformation across a releasing bend during the 2010 MW7. 1 Darfield, New Zealand, earthquake revealed by differential LiDAR and cadastral surveying, *GSA Bulletin 125 (3-4) p. 420-431* [