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

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2013 Hochstetter Lecture
A decade of blissful seismic quiescence beneath the Canterbury Plains

No obvious ‘seismic hangover’ from earthquakes >140 yrs ago

A NIMBY earthquake culture

A history of earthquake clustering

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

No obvious ‘precursory’ seismicity at future site of CES

Data source: Geonet
Three years (and counting) of intense seismic activity

Data source: Geonet

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

Decrease in seismicity rate
Increase in seismicity rate
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**

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<tr>
<td><strong>Epicentre¹</strong></td>
<td>30 km W</td>
<td>10 km SE</td>
<td>10 km SE</td>
<td>10 km E</td>
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<tr>
<td><strong>Time²</strong></td>
<td>4:36 am</td>
<td>12:51 pm</td>
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<td>3:18 pm</td>
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<tr>
<td><strong>Max PGA³</strong></td>
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<td>To older brick &amp; URM</td>
<td>All pre-1970s &amp; several modern buildings with eccentric design</td>
<td>Further residential damage in Port Hills &amp; already damaged CBD buildings</td>
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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.
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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
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<td><strong>Prob</strong></td>
<td>1/475 yr</td>
<td>1/12,000 yr</td>
<td>1/1,000 yr</td>
<td>1/300 yr</td>
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<tr>
<td><strong>%</strong></td>
<td>0.2</td>
<td>0.008</td>
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**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?

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)

A $1.1 B question for central government
Modern houses built immediately above and below seacliffs

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

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.
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)
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

Van Dissen et al. 2011

Duffy et al. 2013
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 RUPTURE LENGTH (GEODETECTIC / SEISMOLOGIC) ~48 km
Mw 6.9-7.0

COMBINED SUBSURF RUP LENGTH (GEODETECTIC / SEISMOLOGIC) ~86 km
Mw 7.1

Importance of understanding how geologic record of active faulting rel to subsurface rupture potential:

\[ E \text{ Mw 7.1} = 6 \times E \text{ Mw 6.6} \]
>100 field measurements, 1000s of potential strain markers

- Fault displacements
- Thresholds between bending and breaking
Greendale Fault

Mw 7.4 from scaling rel
Why?

Lots of surface slip?
Slip distribution?
Measurement technique?

Quigley et al 2012
Nothing really anomalous in slip distribution

Some indication that fault interactions may have increased coseismic slip
Relation between fault area and seismic moment for large and great earthquakes (Kanamori & Anderson 1975)

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?

\[
\Delta \sigma^0 = (\mu/C) \times (D/W) = 13.9\pm3.7 \text{ MPa}
\]
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

- 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 uniformly dipping basement fault
Multi layer model best replicates m-scale surface rupture morphology
Surface complexities created with simple, planar uniformly dipping basement fault beneath layered ‘strata’
• 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
**Reactivated structures**

- Successive ‘active fracture’ mapping at successive strain increments

- Which structures are most reactivated and thus best targets for trenching?
• Synthetic trenches – Low angle (Riedel) fractures best targets, but complex relationships possible

• Supported by trenching?
Greendale Fault
paleoseismology project

Hornblow et al
- Many surface fractures terminate in uppermost 30-50 cm (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

2010 offset measured along structure on surface H= 60+/-10 cm

Offset on upper channel: H=65 cm, V=10 cm

OSL age 21.6 ± 1.5 ka

Offset on lower channel: H=120 cm, V=20 cm

OSL age 28.4± 2.4 ka

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

CCF on Darf NW

CCF on GF

Darf NW on H

Courtesy: Abigail Jimenez, Sandy Steacy (Ulster)
Coulomb ‘static’ stress evolution for rupture initiating on GF

GF on CCF
GF on H
GF on Darf NW
Coulomb ‘static’ stress evolution for rupture initiating on Darf NW

Darf NW on H

Darf NW on CCF

Darf NW on GF
Other rupture scenarios (Mw max): Fault connectivity and rupture potential
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

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.
Modified from Green et al. 2011

- Epicentral distance for shallow to intermediate depth earthquakes (focal depth < 50 km)
- Epicentral distance for intermediate to deep earthquakes (focal depth > 50 km)
- Distance from fault feature for all depth earthquakes

Ambraseys (1988) magnitude bound relation using distance to fault

Ambraseys (1988) magnitude bound relation using epicentral distance

Darfield earthquake

19 Oct 2010 aftershock

Avonside study site
- Liquefaction features observed
- Liquefaction features inferred
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 characteristics 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, distance from free face, elevation, etc

Targeted lateral spreading cracks for paleoliquefaction investigations

Difference between river and nearest downslope freeface azimuth

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).

ca.1910 anthropogenic layer

545 ± 18 $^{14}$C age

Bastin et al., 2013
Liquefaction of Sullivan’s Park sometime between 1880s and 1920s

Weathered lamb bone pit: ca. 1881
Opening of wool scouring factory

Lamb bone pit: ca. early 1900s

Oxidized paleodike

Interfingering with flood deposit

Modern feeder dike

Suspects

Bastin et al., 2013
Rockfall / Boulder Roll Hazard

22-2-11 boulders deposited 'weathered-side-down'

22-2-11 boulders deposited 'weathered-side-up'

Mackey and Quigley
Quigley et al

boulder deposited by paleo-rockfall

loess and colluvium accumulation upslope of boulder

c. ≥ 30 ka (?) calcareous loess beneath boulder

small boulder deposited by 22-2-11 earthquake-triggered rockfall
A mid Holocene rockfall event incorporating ‘fresh’ and pre-exposed material?
No evidence for ‘random’ temporal occurrence
No evidence for Alpine Fault earthquakes
Future challenges
An analogous eq (sequence) could happen at any time anywhere else in New Zealand: have you personalized your hazard?

-100s of mapped active faults

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

Nicol et al. (2011)
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