Widespread Triggering of Slow Slip Events following the Mw7.8 Kaikōura Earthquake: Implications for Earthquake Forecasting

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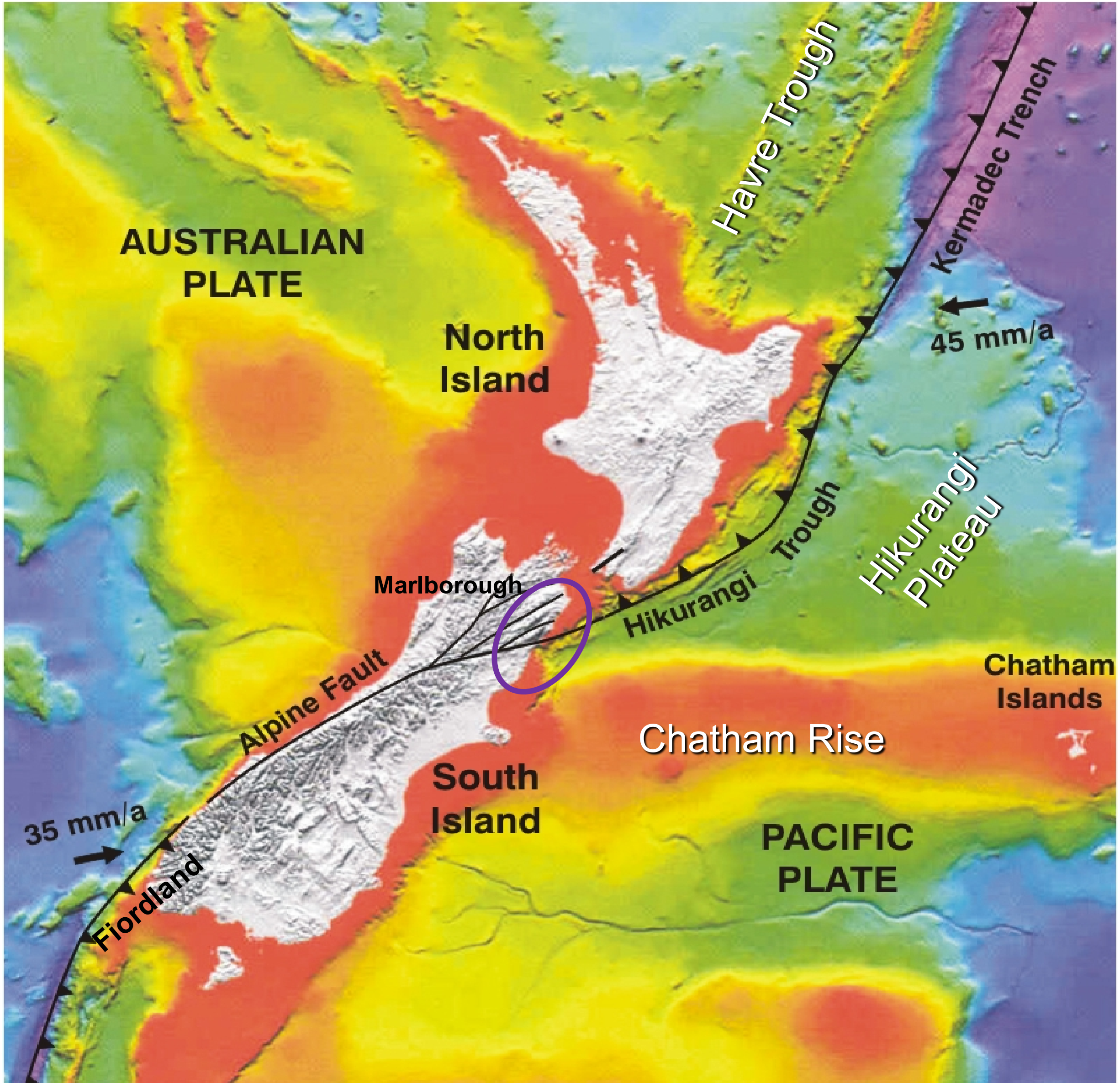
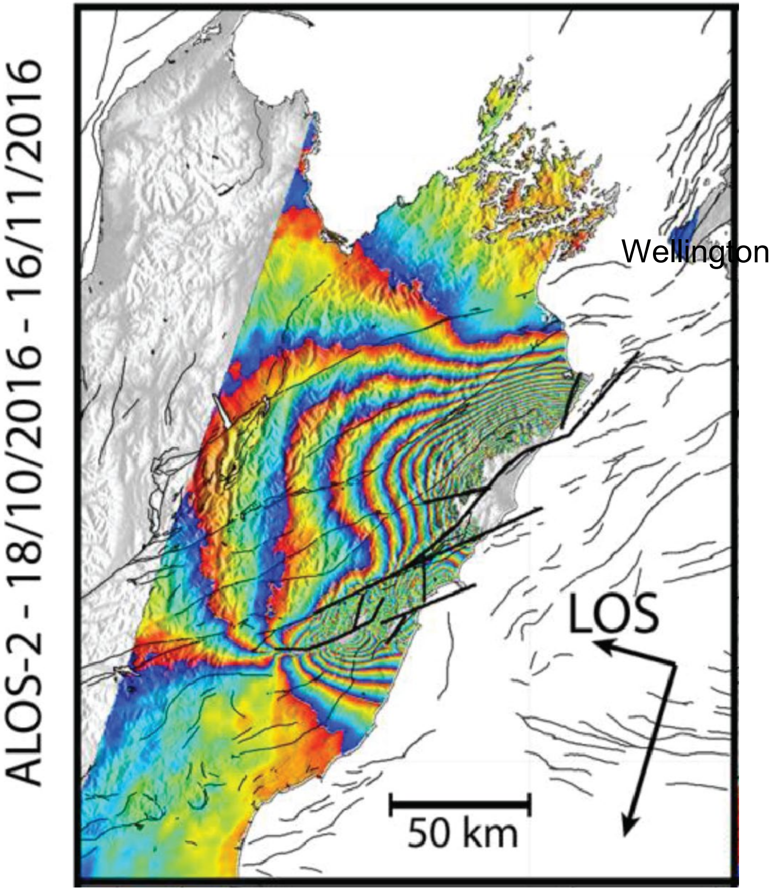
New Zealand's tectonic setting

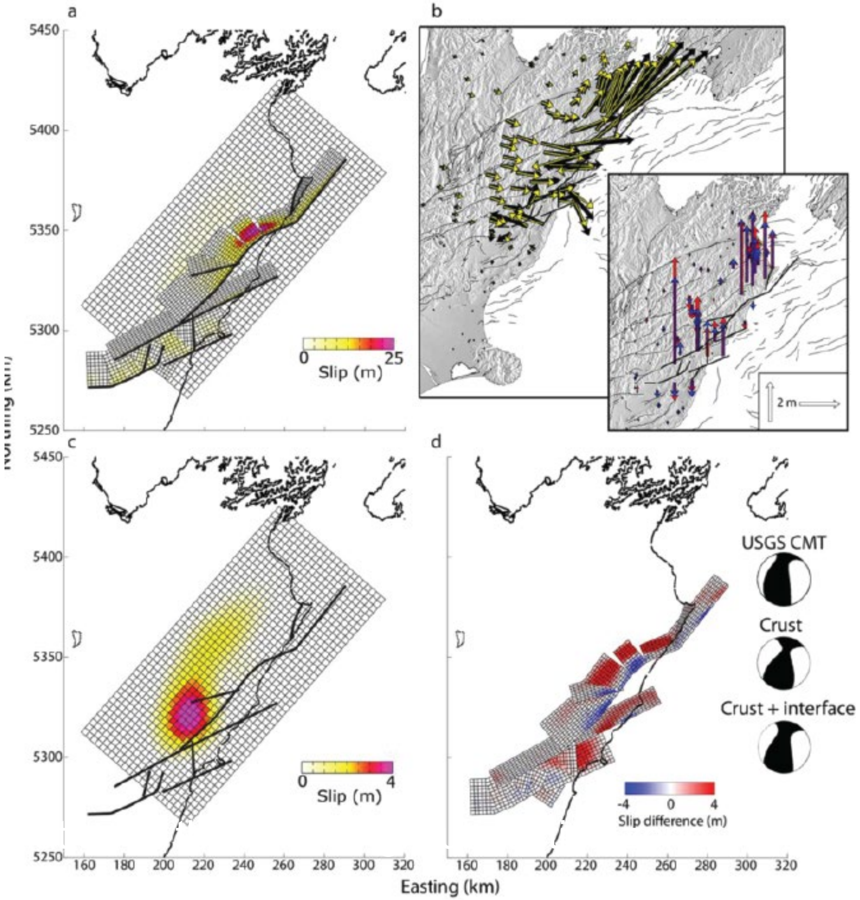
The 14 Nov 2016 M7.8 Kaikōura earthquake occurred in a complex tectonic transition from strike-slip on the Alpine Fault to subduction of the Pacific Plate beneath the eastern North Island



The M7.8 Kaikōura earthquake, 14 November 2016—a highly complex, multifault rupture

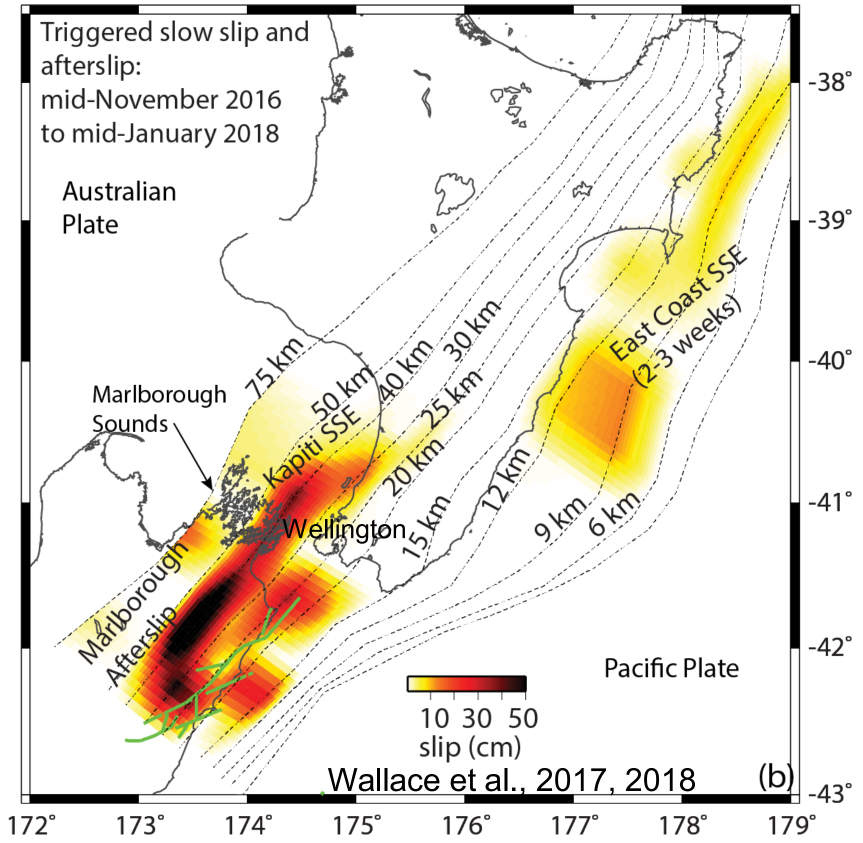


Rupture initiated in south and propagated 150 km to north, stopping ~30 km south of NZ's capital city

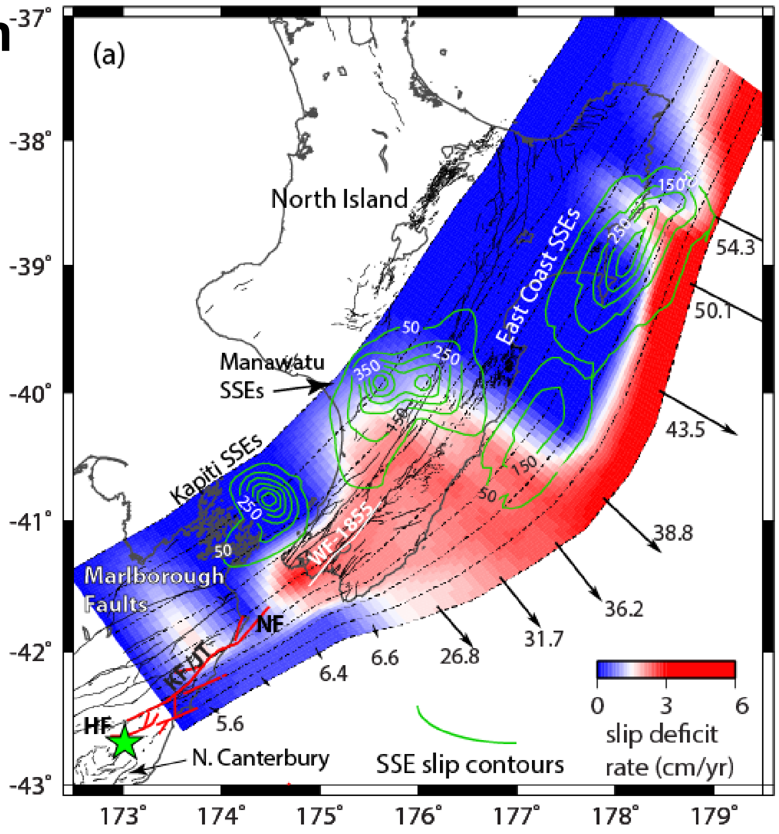


Hamling et al., 2017, Science

Large-scale slow slip and afterslip triggered by the Kaikōura earthquake on much of the Hikurangi subduction zone



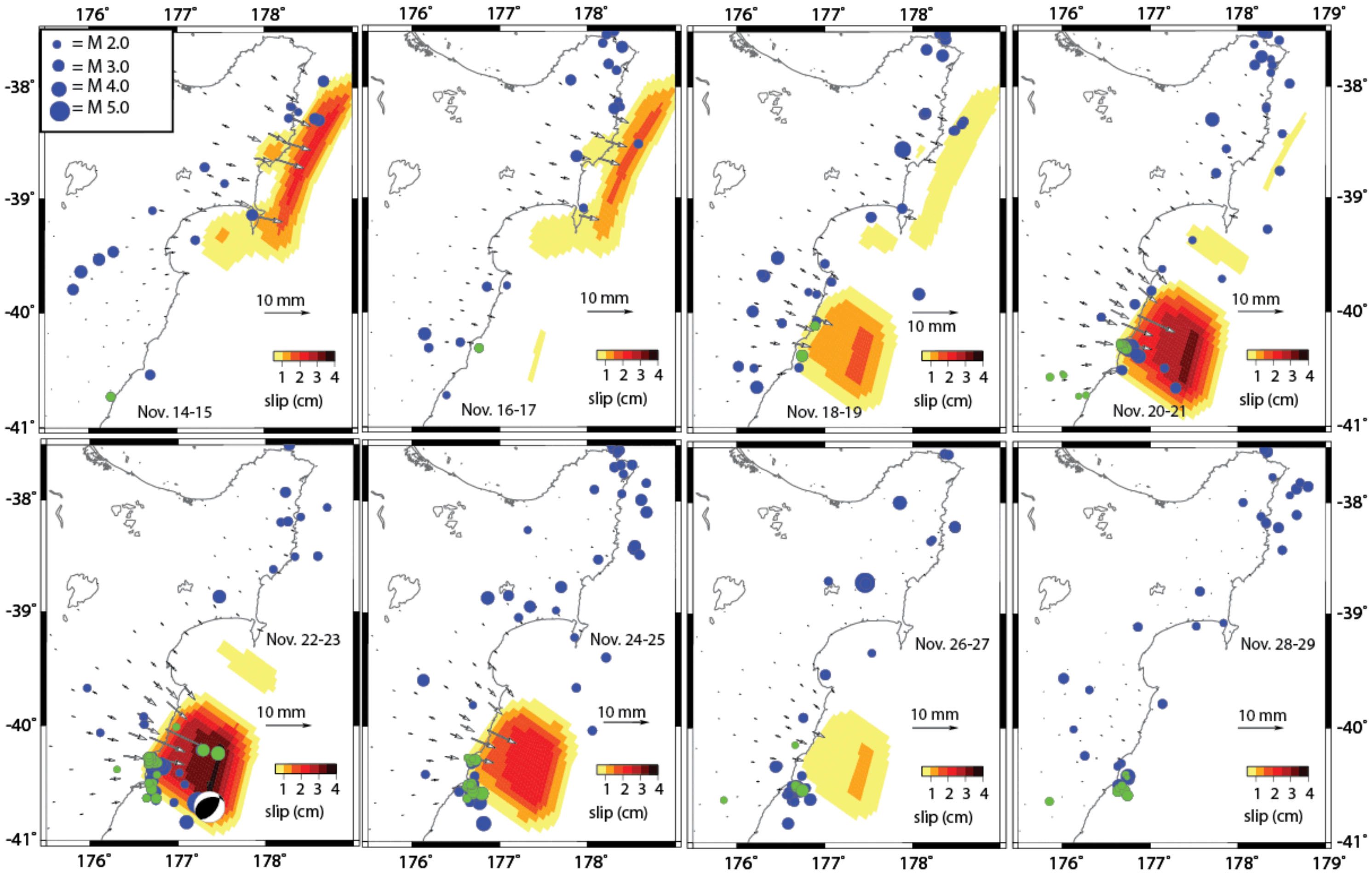
Interseismic coupling on subduction zone



Simultaneous slow slip encircled the locked portion of the Hikurangi subduction interface—this raised major concern about potential for a megathrust earthquake

Afterslip= Mw 7.4; Kapiti=Mw 7.1; East Coast=Mw 7.1

Lots of seismicity on subduction zone related to East Coast SSE during the 2 weeks after the Kaikōura earthquake, including an Mw 6.1 thrust event



Wallace et al., 2017

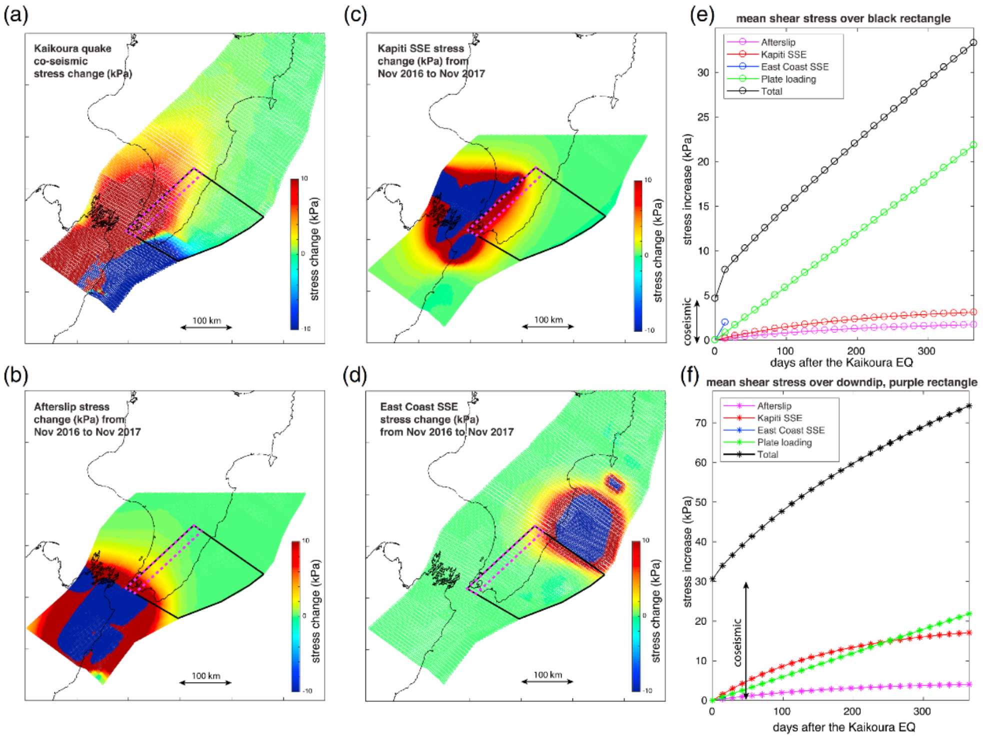
Slow slip and afterslip on the Hikurangi subduction interface following Kaikoura
What does this mean for future seismicity?

- First time we have ever seen simultaneous rupture of most of NZ’s slow slip regions
- The locked portion of the subduction interface beneath Wellington and the lower North Island was being loaded at a higher rate than we’ve ever seen before—both from the Kaikoura earthquake and subsequent SSEs
- No existing models were available to convert SSE observations to future rates of earthquakes
- **Lots of concern, but what does it all mean...**

The New Zealand Government demanded immediate numbers on how the slow slip changes our earthquake forecasts

Big implications for decisions about fast-tracking major roading & infrastructure works, response planning for Wellington, public awareness, etc.

Shear stress changes on interface from EQ and SSEs



Kaneko et al., 2018

Locally, shear stress increase on locked zone near Wellington was more than 0.5 MPa

What does this mean for future large events? Probability of M>=7.8 in the next year: 1st estimate – December 2016

EEPAS (+STEP/ETAS)	Seismicity rate increase during past NZ slow slip events	ARTS: R. Robinson's earthquake simulator	Paeloseismic Data	National Seismic Hazard Model
Large rate increase over 10 years 30% prob of M>7 in 1 year 3% prob of M>7.8 in 1 year	~2 times increase on average. As large as 15, as little as ½ 1/3 had significantly increased rates (southern SSE) Mostly GR-ish but some odd shapes Largest SSE triggered EQ in NZ: M6.1 (11/17)	2% probability of M>7.8 following another M7.8	Paleoseismic data illustrate a temporal correlation (±30-50yrs) between **some** past large earthquakes on crustal faults and subduction earthquakes Direction of correlation? Large uncertainties	~0.5-0.8% M7.8+/year in the region

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A rapidly convened expert elicitation panel converged on a 5% probability of M7.8 *or larger* within the next year in Central New Zealand

For December 2016-December 2017 period

This is approximately 10 times greater than the "peace-time" probabilities in the seismic hazard model and is an almost double the probability from just the effect of the Kaikoura earthquake alone (from statistical forecasts).

SSE Forecasting Model Building Procedure: 2nd estimate, Nov 2017

Probability estimated subjectively for central New Zealand by an international expert panel using a range of observations and models

- Models constructed June – November 2017
- Evaluated by two expert panel workshops
  - September 2017 (at SCEC) → initial model evaluation and suggestions for improvement
  - November 2017 → 2 day workshop to evaluate models and estimate probabilities
- Use of structured expert elicitation procedure with expert calibration (we tested the international experts!)

SSE Forecasting Model Building Procedure: 2nd estimate, Nov 2017

The models:

- Multiple observations of seismicity during past SSE (~ 2x seismicity rate increase during SSE)
- Statistical forecasting models (**10+ models**, recurrence-based, Omori, and other clustering models)
- SSE equivalent-magnitude statistical forecasting models (scaled down to reflect low rate increases)
  - SSE magnitude scaled based on Omori
  - Scaled based on Rate-State
- ARTs: Synthetic seismicity simulator (static & dynamic coulomb)
- Simple physical model of subduction earthquake occurrence
- Paleoseismic data (extremely limited)
- National Seismic Hazard Model

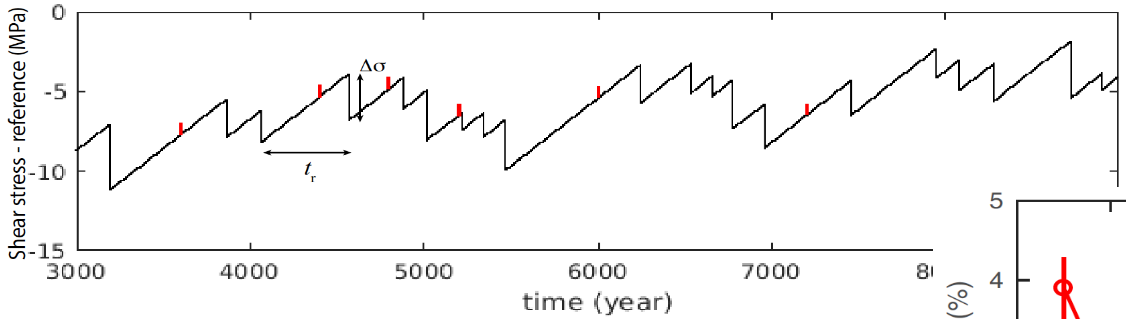
Simple physical model (Kaneko et al., 2018, GRL)

Estimating probability of large **subduction** EQs following SSEs involves 3 steps:

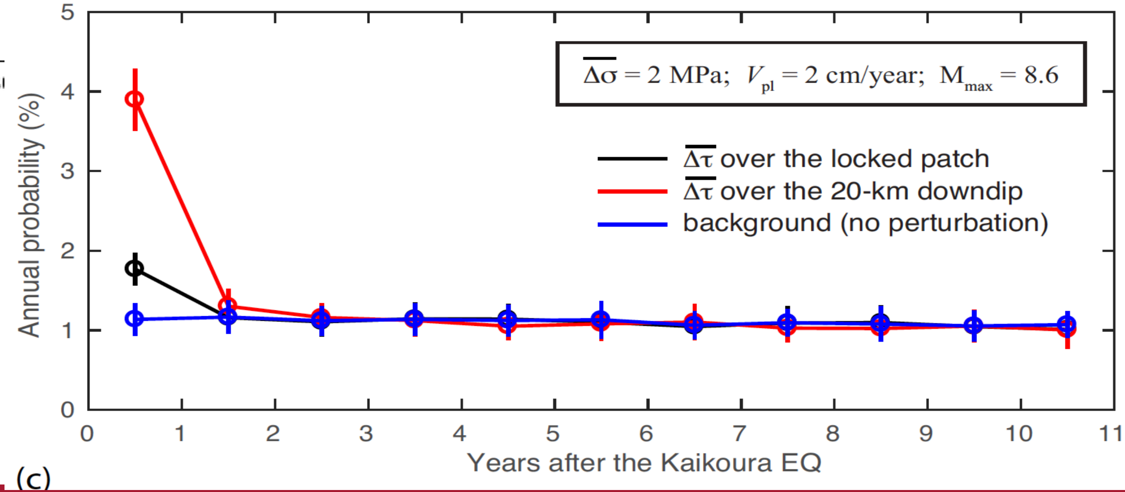
(1) Estimate stress changes on the megathrust due to Kaikoura EQ and SSEs

(2) Develop a synthetic earthquake catalogue over 1 million years (based on distributions of subduction earthquake stress drops, coupled with steady interseimic loading)

(3) Apply total stress perturbation from Kaikoura EQ + SSEs to the synthetic catalogue and compute the probability of a large earthquake for specific periods following that perturbation



Each dot (below) corresponds to mean of 50 runs with the vertical bar corresponding to plus-minus one standard error/deviation

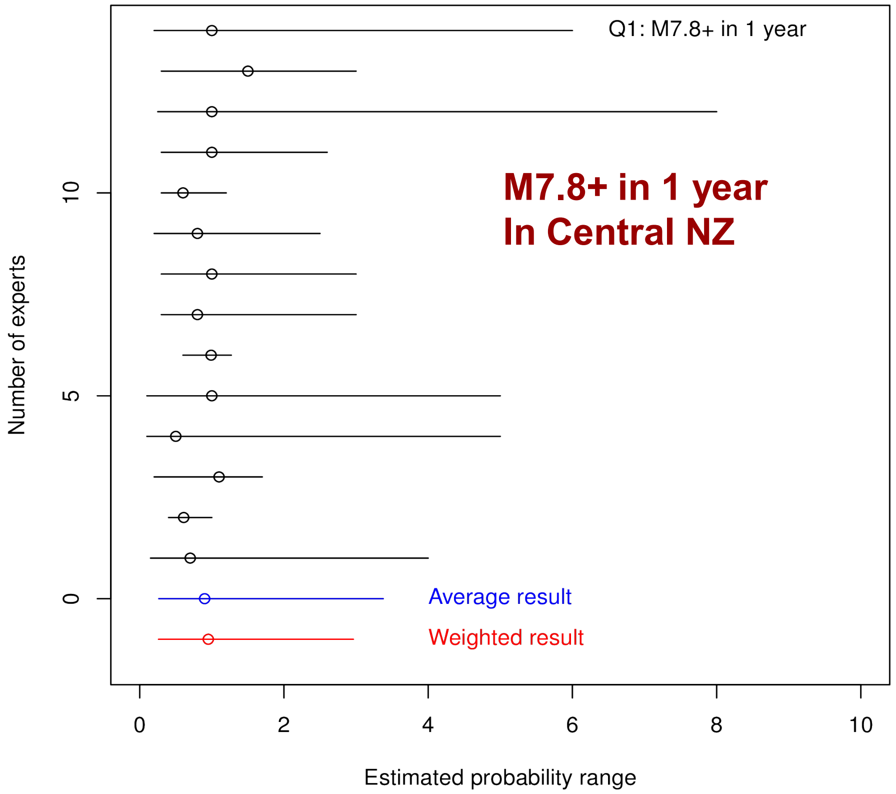


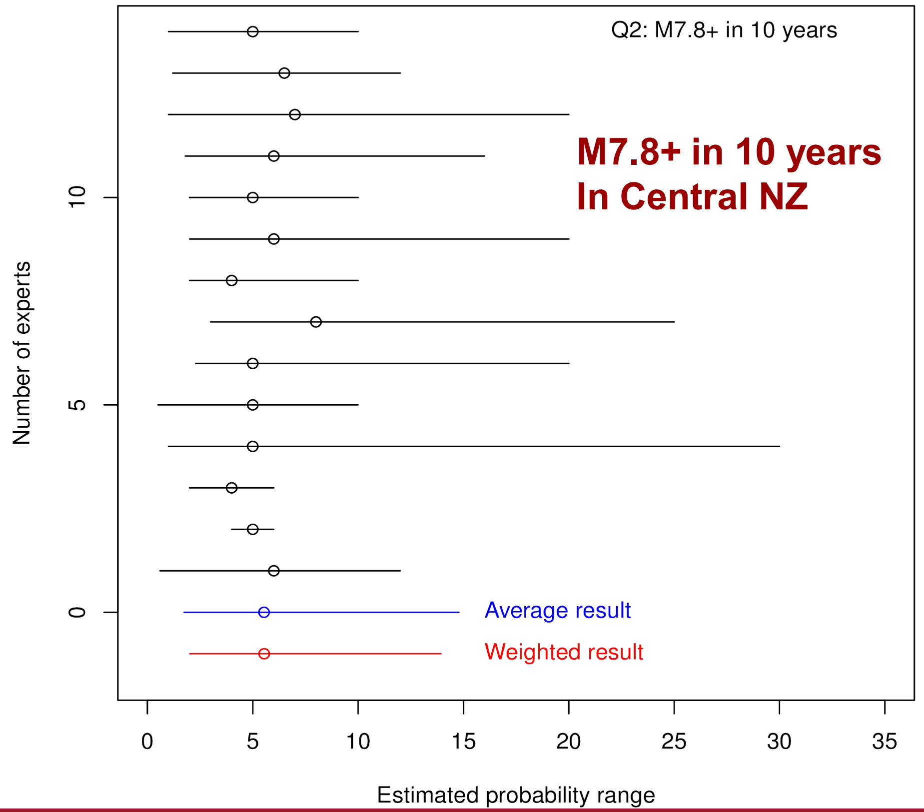
Annual probability decays to the background level after 2 years (similar to the duration of SSEs)

The ratio of total stressing rate over stress drop of EQs controls the probabilities:
(74 kPa/year)/(2 MPa) = 3.7% per year; (34 kPa/year)/(2MPa) = 1.7% per year

Estimated probabilities were consistent across experts—we decided to have experts assign their own probabilities rather than weight specific models and combine them. This allowed for the possibility that the models we considered do not actually capture what is going on.

The results show very large uncertainties, and the experts appeared to rely strongly on statistical clustering models





Communicating the Probabilites

https://www.geonet.org.nz/earthquake/forecast/central_nz

- Direct to government (local/national)
- Media
- GeoNet webpage
- Direct engagement with stakeholders (insurance, engineers, etc)

Overall the revised forecast probabilities are almost twice as high as those from the NZ National Seismic Hazard Model for the same region

Forecast Probabilities for Large Events in Central New Zealand

	Magnitude Range	**Chance of occurrence: Range** (best estimate)
Within the *next year* *(Nov 2017-Nov 2018)*	**M7.8** or greater	**0.3% to 3%** (1%)
	M7.0 or greater	**2% to 14%** (6%)
Within the *next decade* *(Nov 2017+10 years)*	**M7.8** or greater	**2% to 20%** (7%)
	M7.0 or greater	**10% to 60%** (30%)

Conclusions and path forward

Understanding the influence of slow slip events on earthquake probabilities remains an extremely large challenge. Robust methods to address this are needed—ideally via several approaches, a mix of physics and statistics based.

We need to develop Operational Earthquake Forecasting models that incorporate transient slip events, and not just make *ad hoc* decisions (no more earthquakes in NZ, for a while please).

24 hr forecasts remain less useful. Weeks/months/years/decades are desired. What modelling is necessary to cover these time frames? Should forecasts be used in engineering design?

End-users in New Zealand are increasingly sophisticated in their understanding, demands and use of forecasting (we have also had a series of engagement workshops).

Responding to, and interacting with, end-user needs takes a considerable amount of time, effort and $.

Information is demanded quickly (same day, please!): calculation time is important.