A geodetic and seismic overview of the Kaikoura earthquake

Charles Williams, with contributions from Ian Hamling, Laura Wallace, Caroline Holden, Yoshi Kaneko, Rafael Benites, Bill Fry, Anna Kaiser, Annemarie Christophersen, Russ Van Dissen, Stephen Bannister, John Ristau, Sigrun Hreinsdottir, Matt Gerstenberger, and many others

GNS SCIENCE

TE PŪ AO

Most Important Aspect of the Kaikoura Earthquake

Yes, the cows are OK.

More details in the next talk.

Kaikoura Earthquake Summary

M_w 7.8
14 Nov. 12:03 AM (local)
Lasted ~2 minutes.
2 deaths, >20 injured.
Tsunami.
Coastal uplift
Many landslides.
$3-8 billion damage.

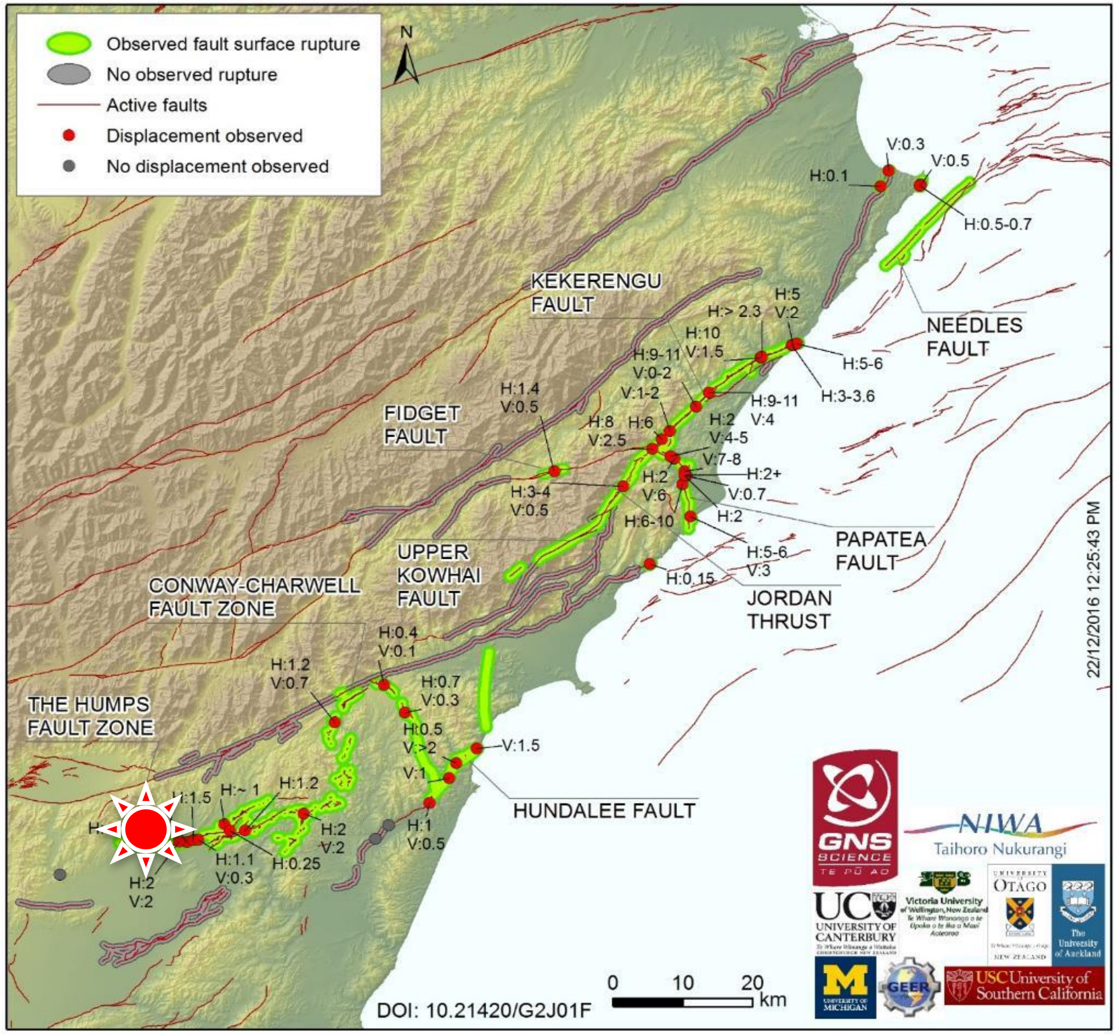
<u>**Approx. 180 km-long zone of rupturing:**</u>

Mainshock ~20 km south of Hope Fault

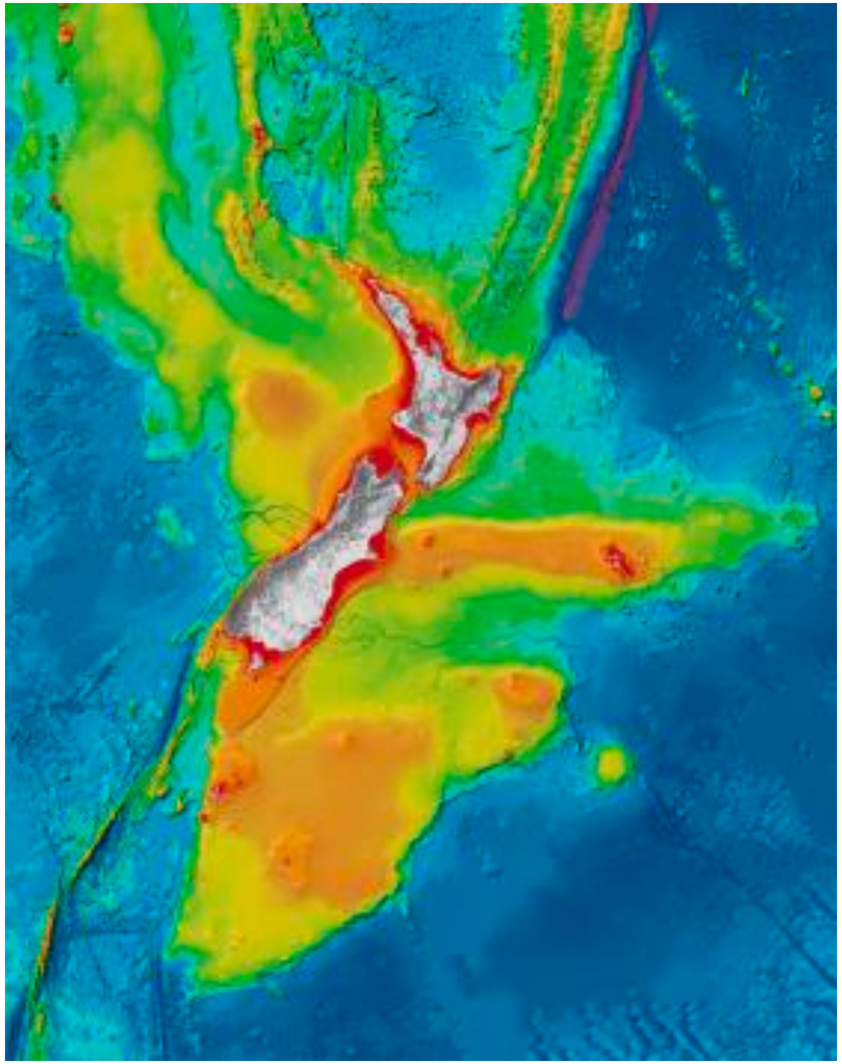
~15 km deep

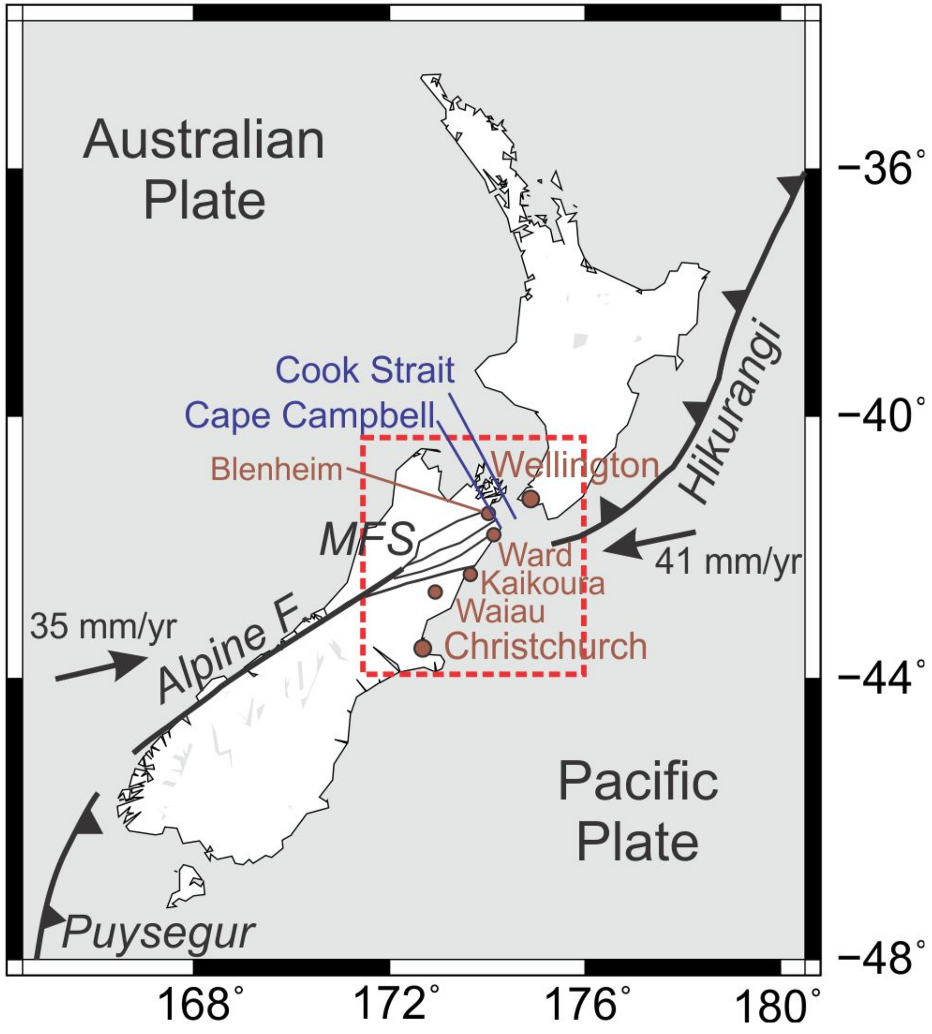
Rupture propagated NE as complex sequence

Arrested near Cape Campbell.



Tectonic Setting





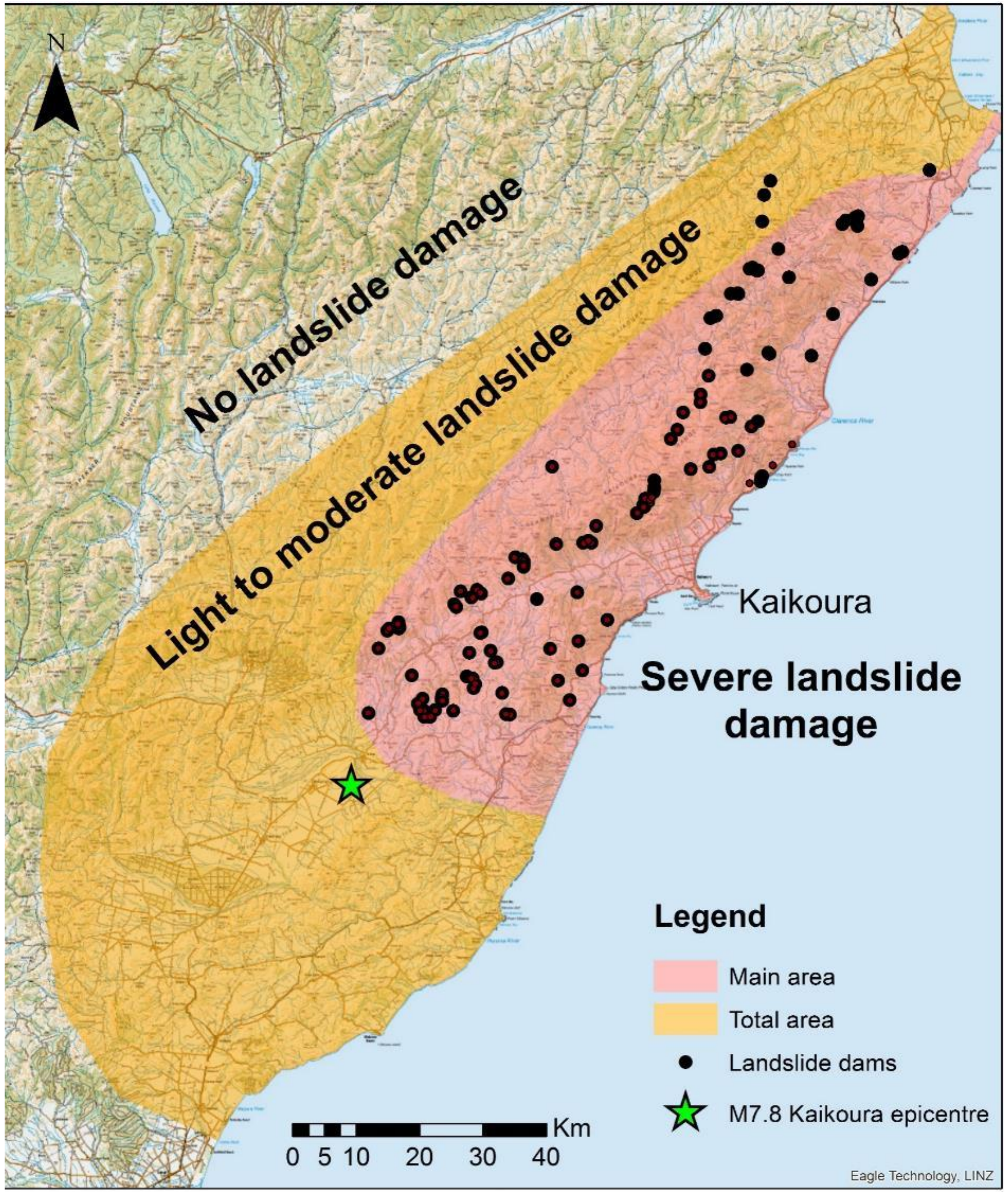
- Near-normal convergence along N. portion of Hikurangi
- Oblique convergence along S. portion
- Transition into Marlborough Fault System.
- Alpine Fault.
- Puysegur Subduction Zone with opposite sense of subduction.

Landslides

GNS estimates that 80,000 to 100,000 landslides were triggered by the earthquake and subsequent aftershocks.

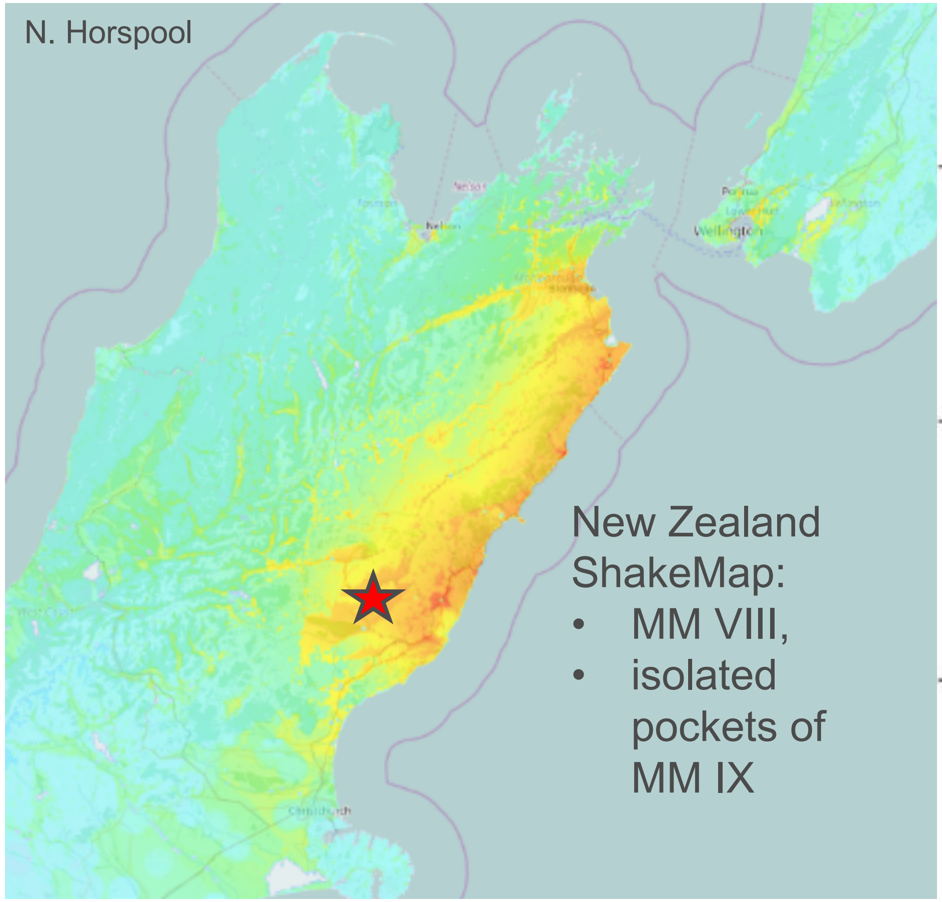
~50 of them yielded significant dams (lakes & ponds)

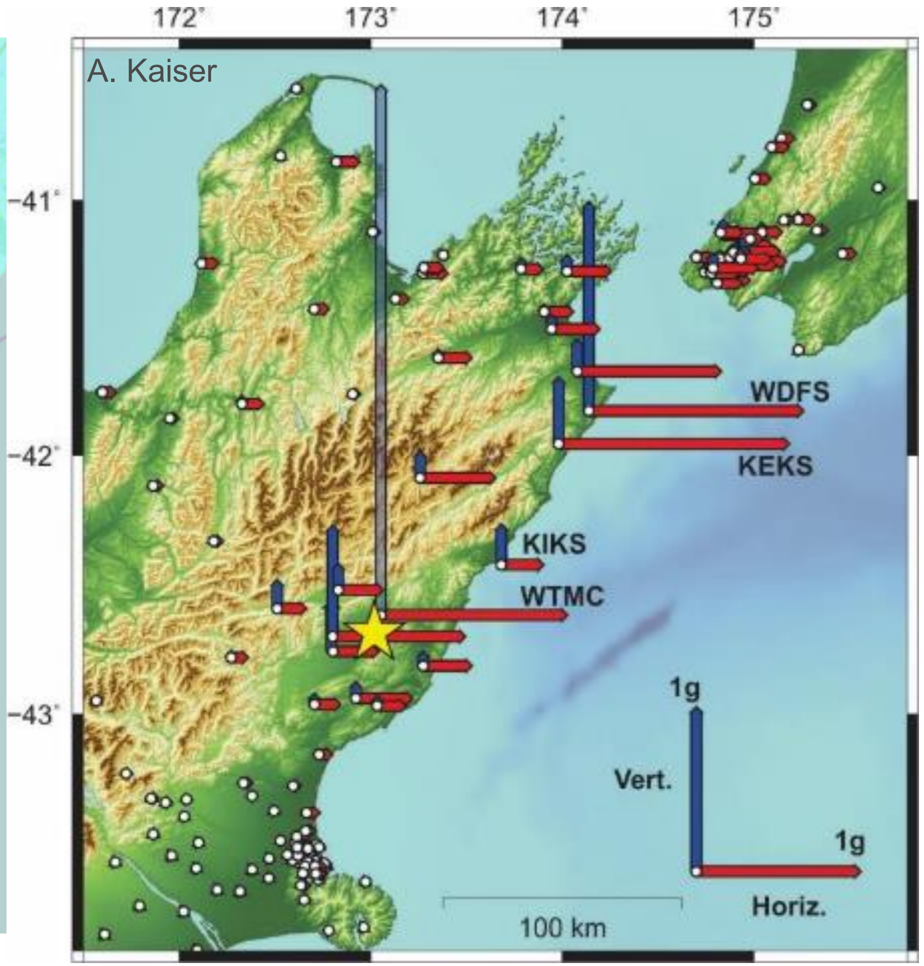
Greywacke landsdlide, State Highway 1



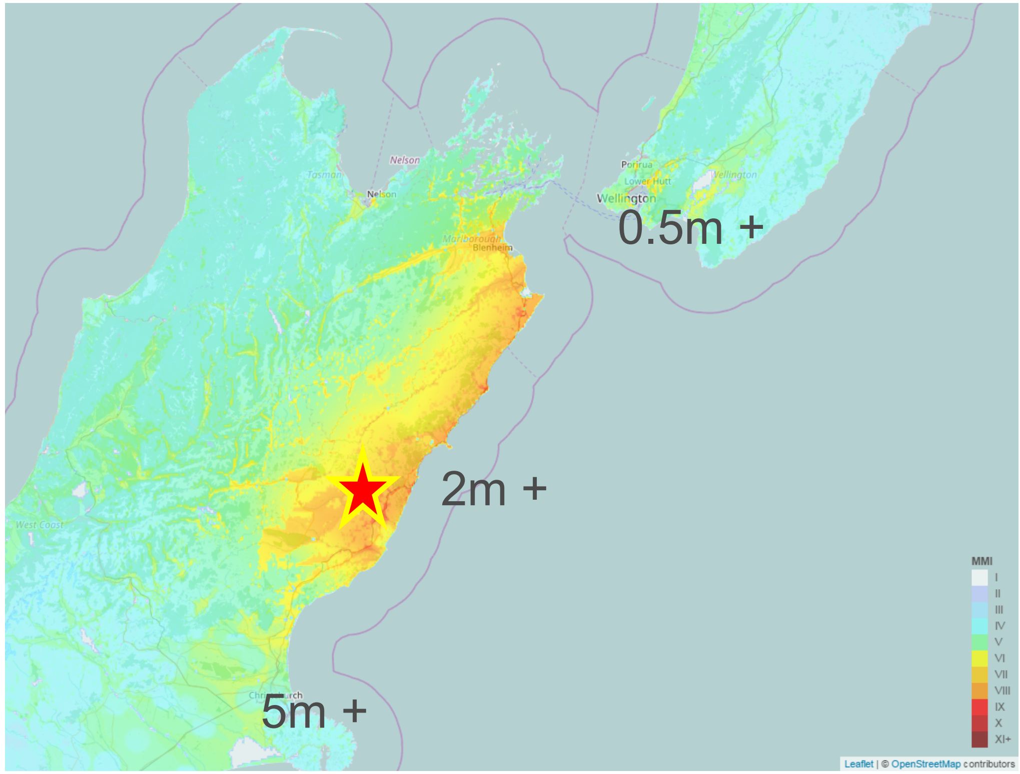
Ground Motions

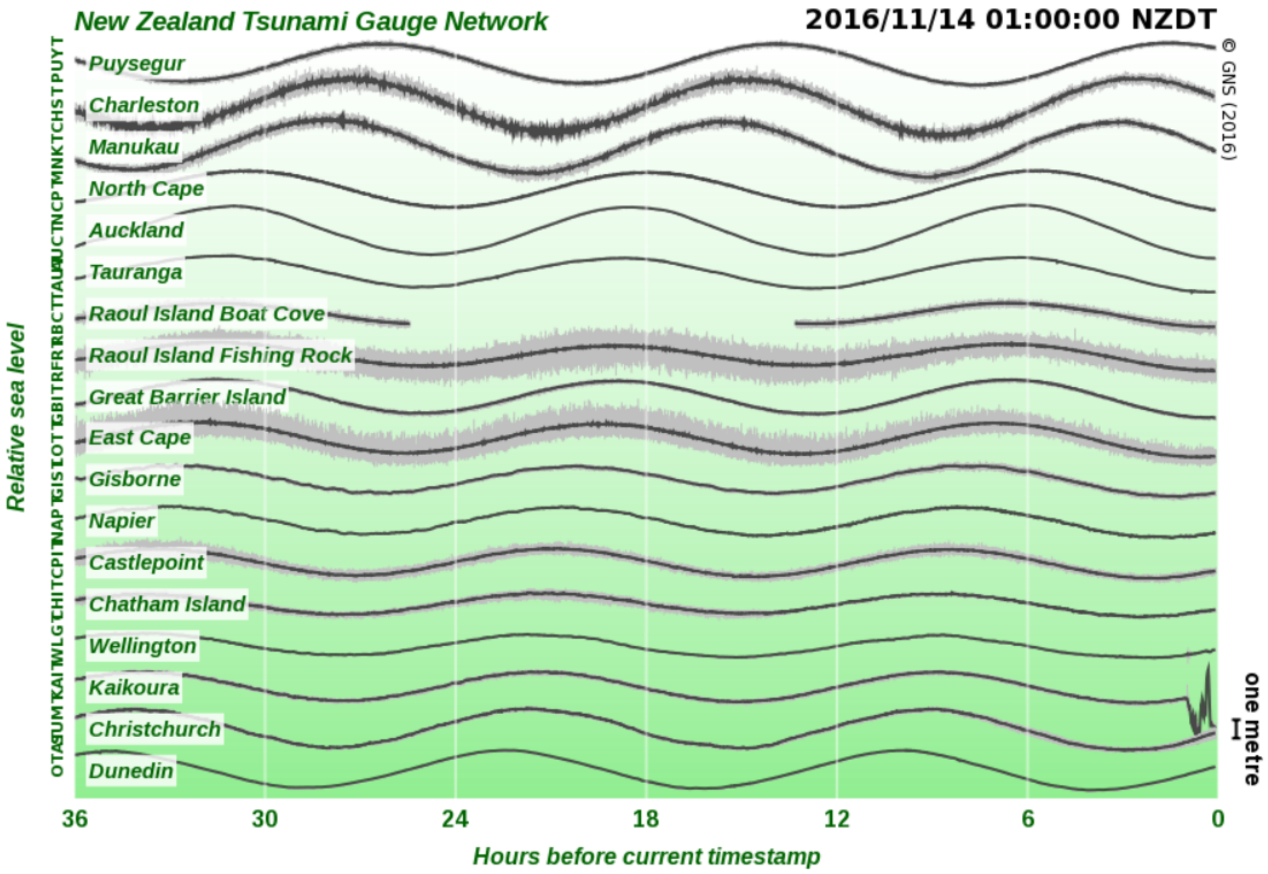
- Peak Ground Acceleration (PGA) confirmed > 1 g at both ends of rupture
- Ground shaking significantly lower in Christchurch than Wellington





Tsunami

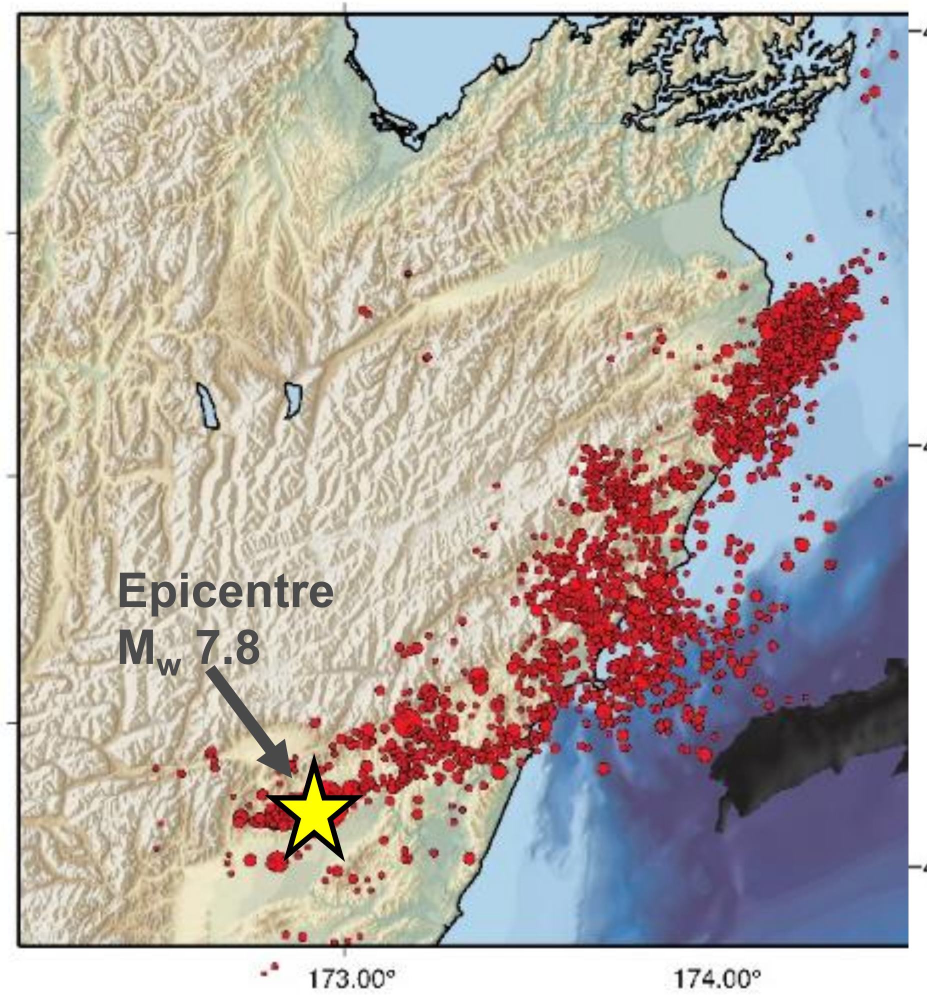


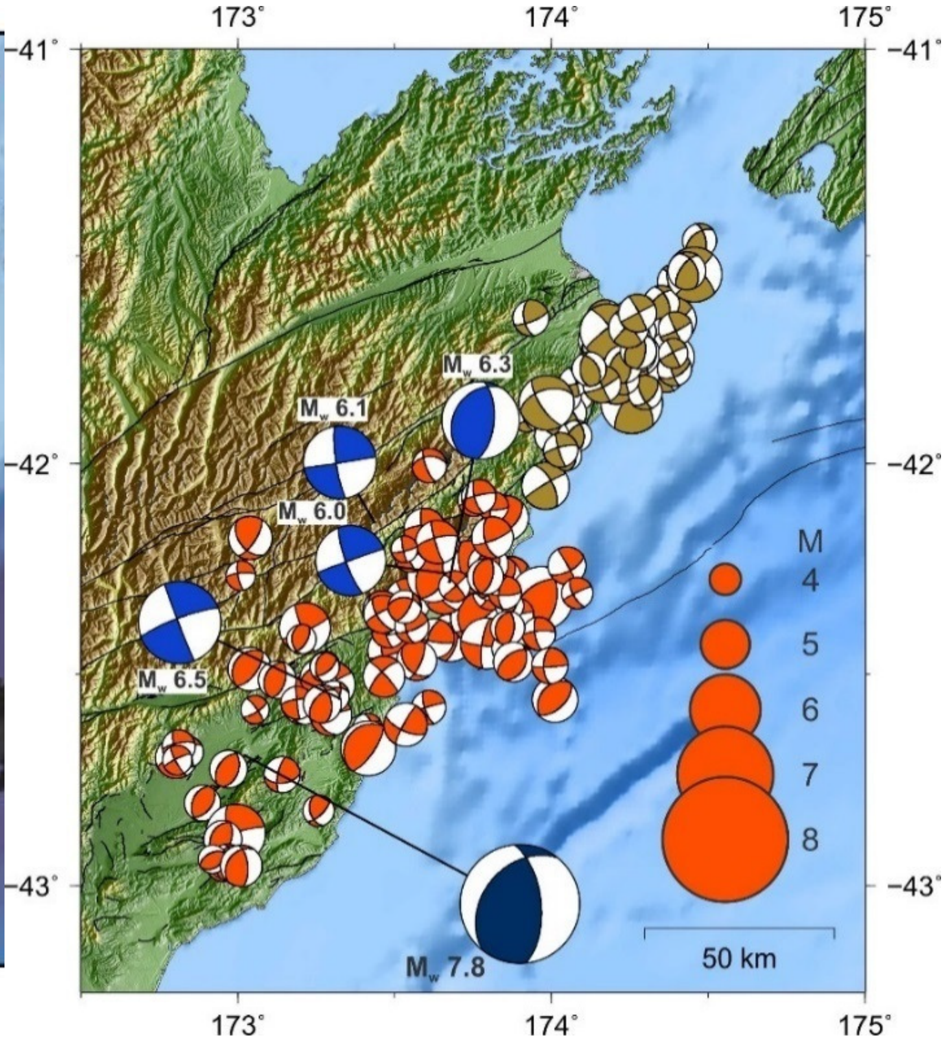


Tsunami waves were measured at tide gauges in Kaikoura, Wellington, Christchurch, and Castlepoint.

Preliminary tsunami modeling (e.g., *Hamling et al, accepted*) using travel time inversions suggest that the source was long-wavelength seabed deformation somewhere in the coastal region between Cape Campbell and the southern Kaikoura coast.

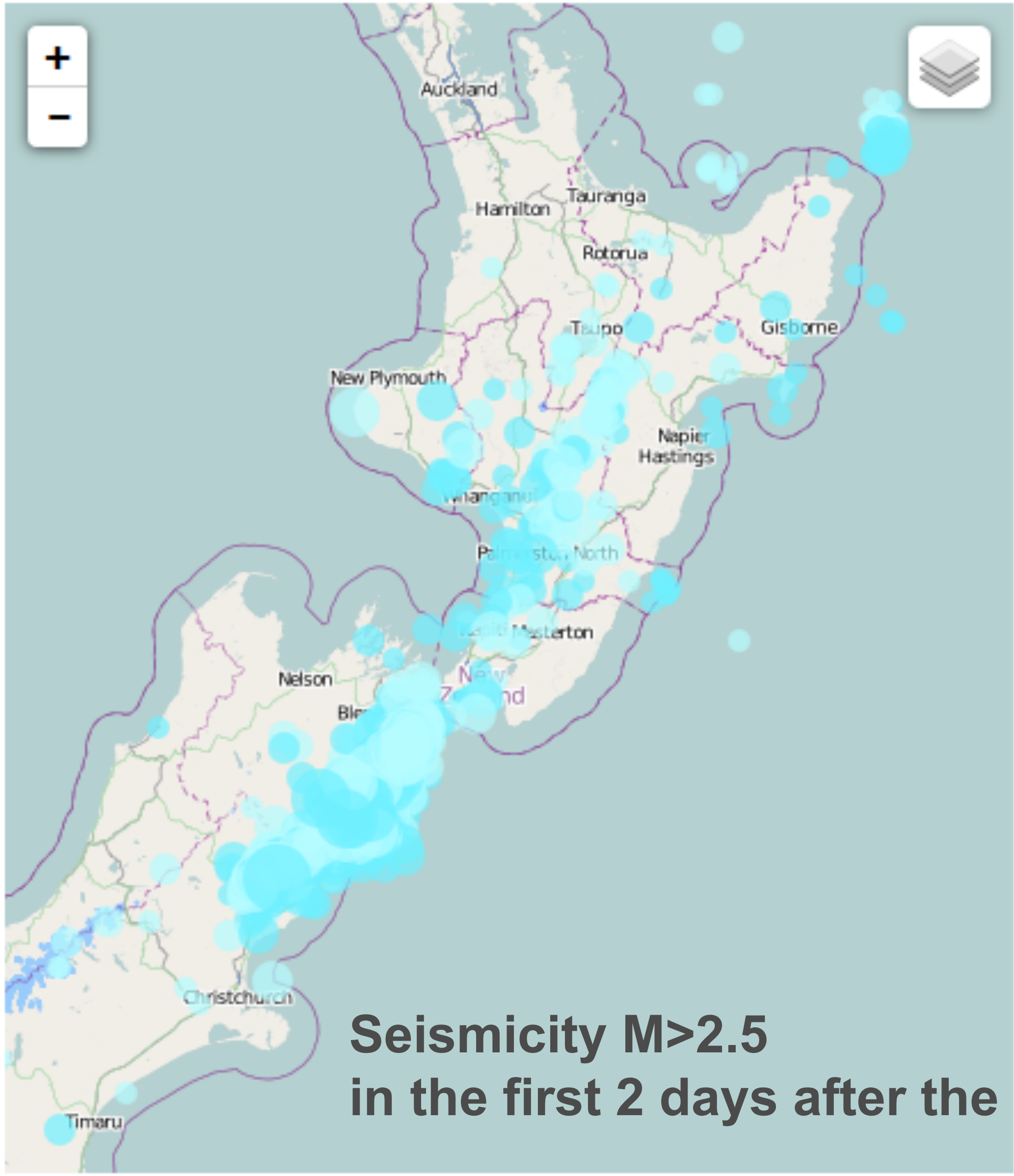
Earthquake Source: Aftershocks





Stephen Bannister

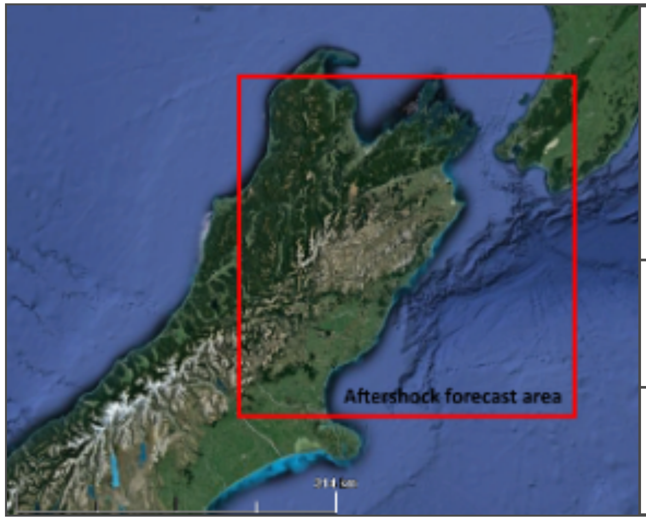
Seismicity Increase Immediately After the Earthquake



Seismicity M>2.5
in the first 2 days after the Mw7.8

- Most of the country affected
- Obvious effects of ‘forward directivity’

Kaikoura Earthquake Aftershock Probabilities
March 2017

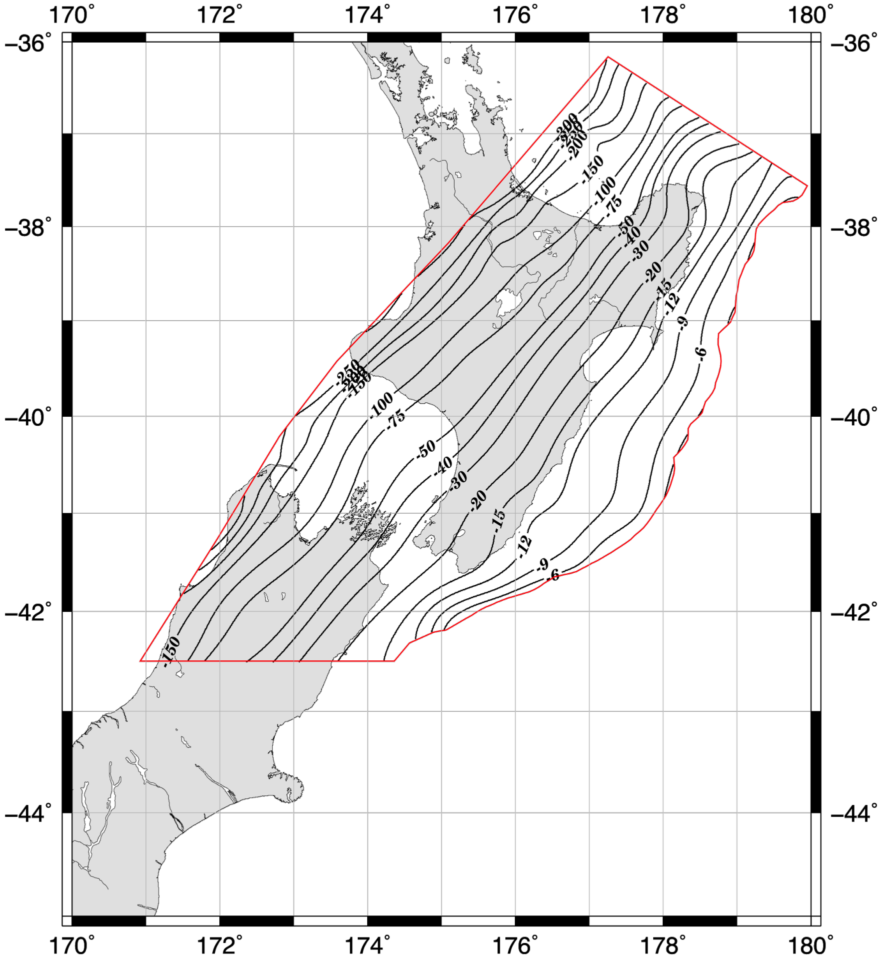


time	M 5.0-5.9 Probability of 1 or more M5.0-5.9	M 6.0-6.9 Probability of 1 or more M6.0-6.9	M ≥7 Probability of 1 or more M≥7
within 30 days	73%	15%	1%
within one year	>99%	68%	10%

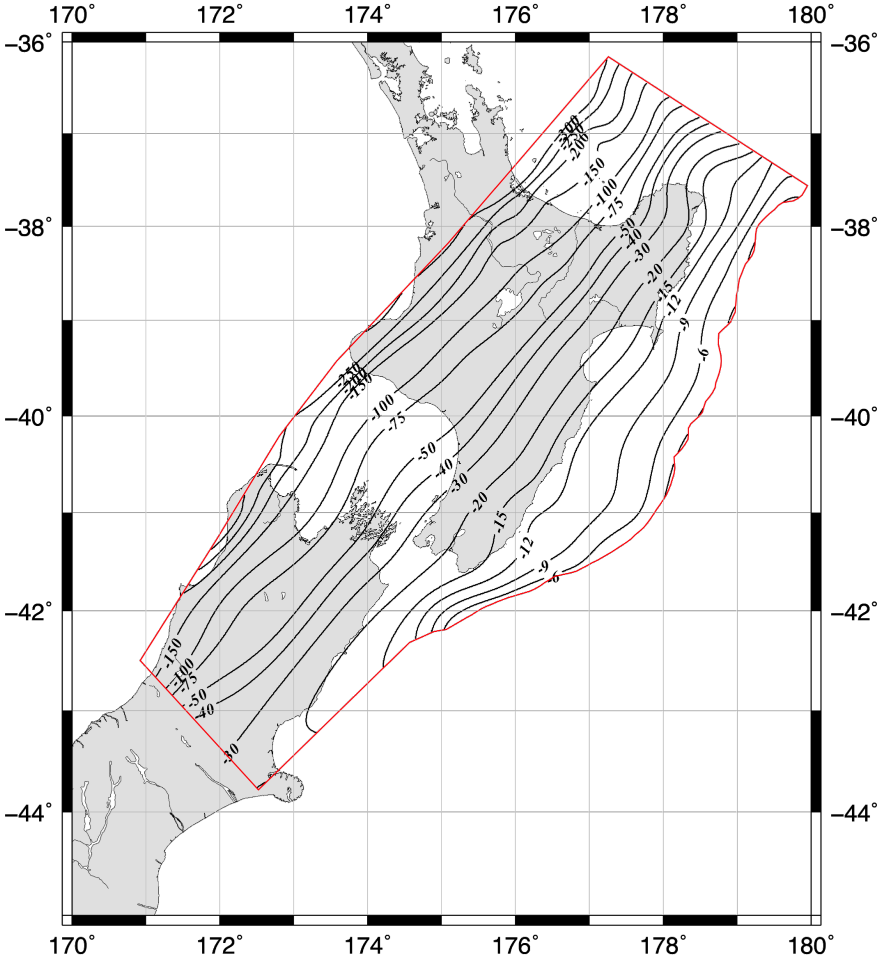
Rate of earthquakes of magnitude 6 and above:

- **Entire aftershock region**
  - About 5 times larger than normally expected for the month pre-Kaikoura
- **Wellington region**
  - 1.6 times larger than normal for the next month

Does the Hikurangi Subduction Zone Extend Further South?

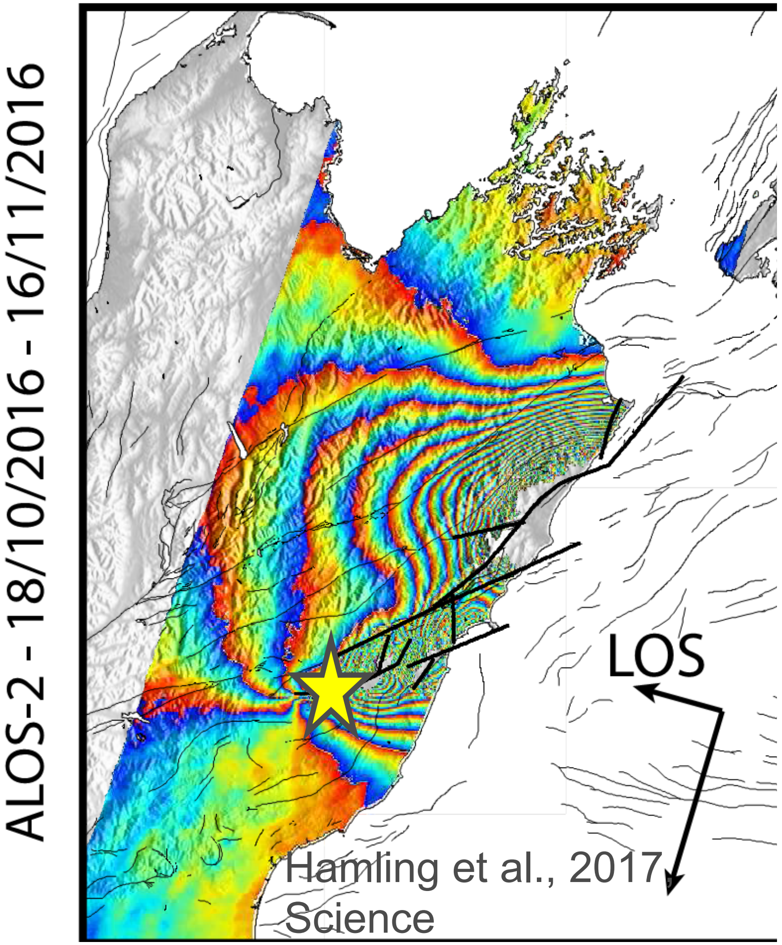


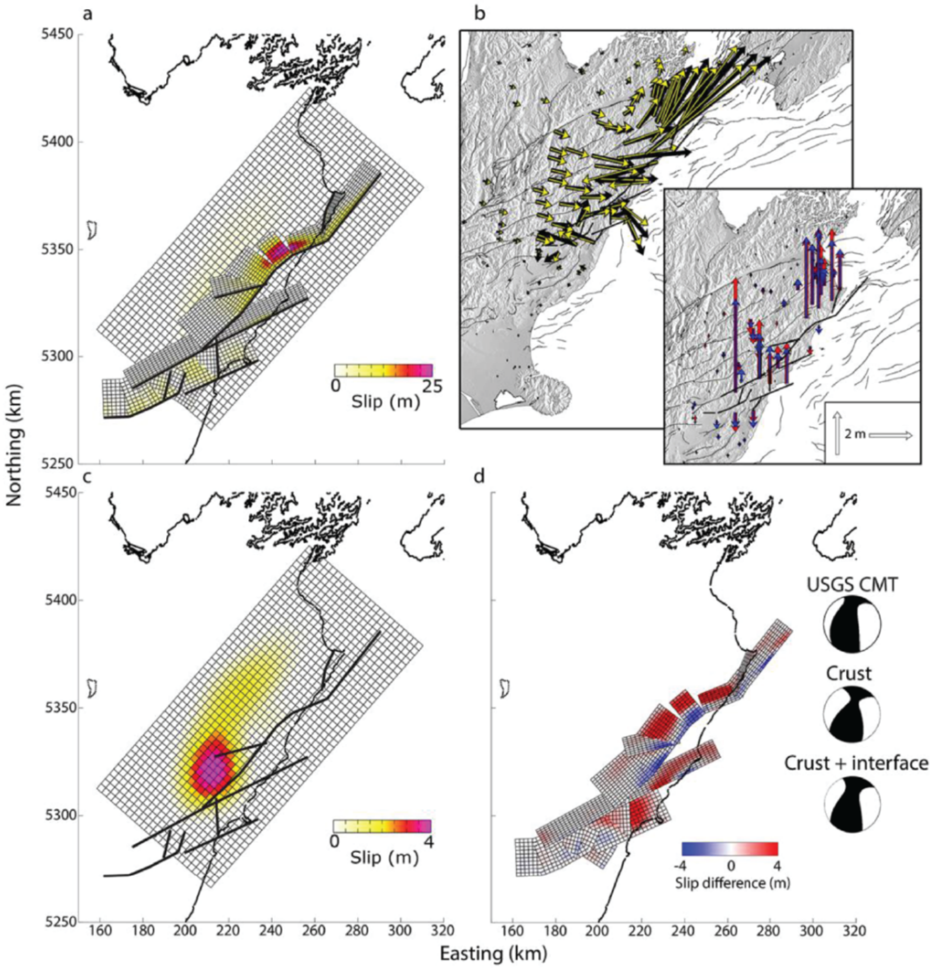
Williams et al., 2013



Extended version following earthquake

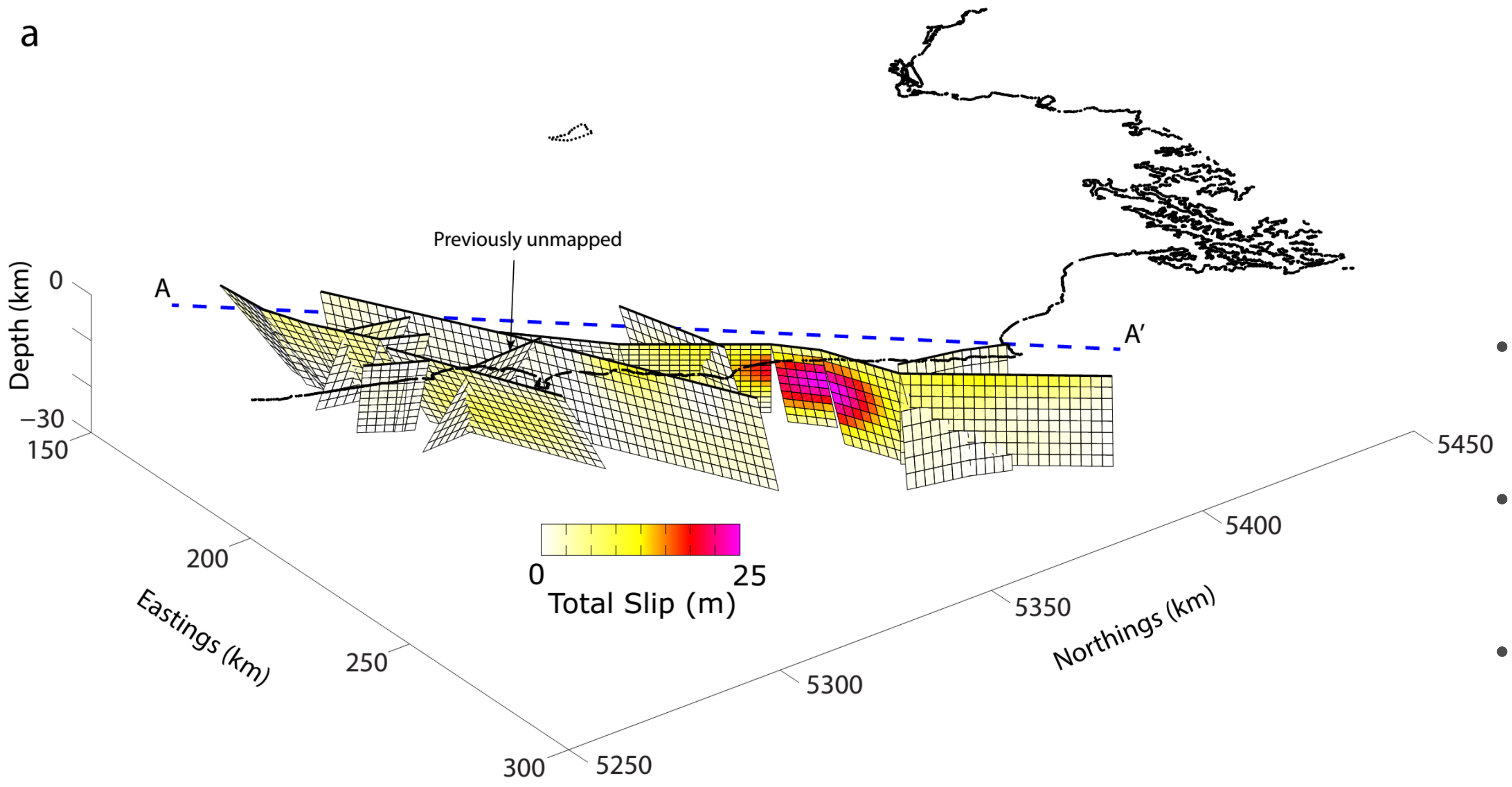
Geodetic Inversions Using InSAR and GPS (Ian Hamling)

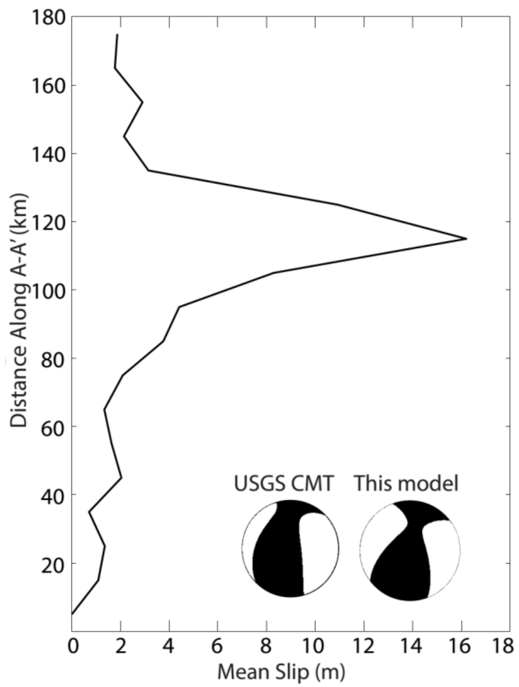




The earthquake's complexity was unprecedented--involving rupture on at least a dozen crustal faults. It is also possible that the earthquake ruptured the far southern end of the Hikurangi subduction zone beneath the northern South Island

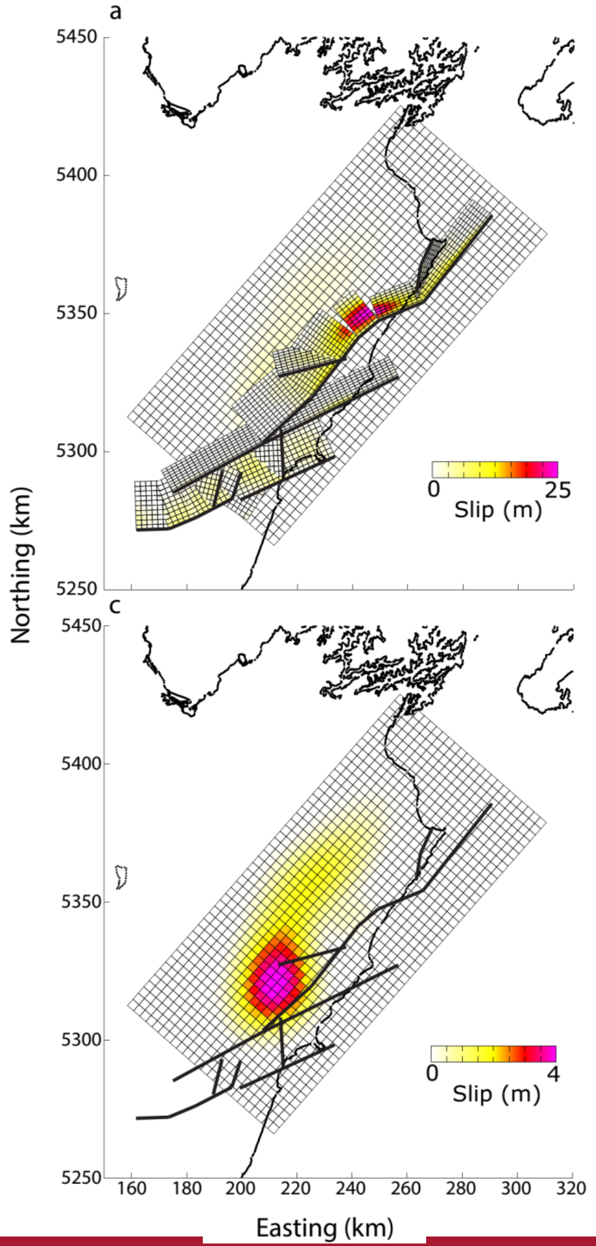
Inversion Results with Only Crustal Faults

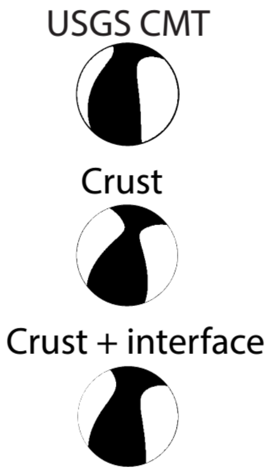


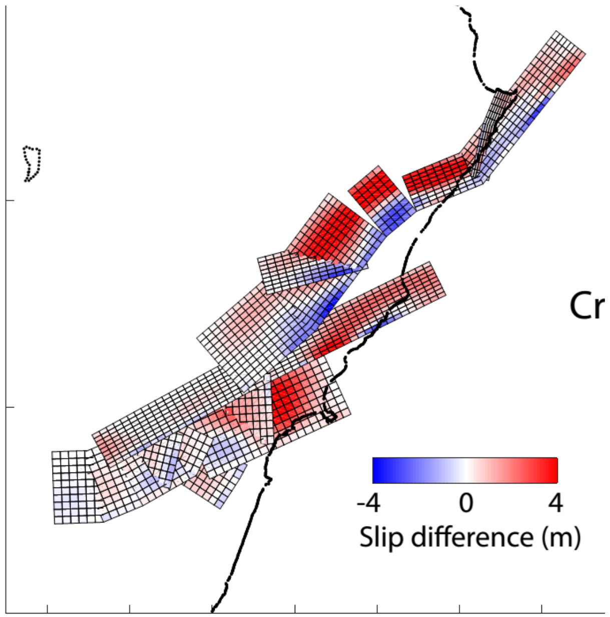


- Model requires 25 m of slip at 12-15 km depth along the deeper part of the Kekerengu fault.
- Predicted slip is consistent with field observations of surface rupture
- Although lower, slip of ~10 m is predicted at depth along the Humps and Hundalee segments in the south

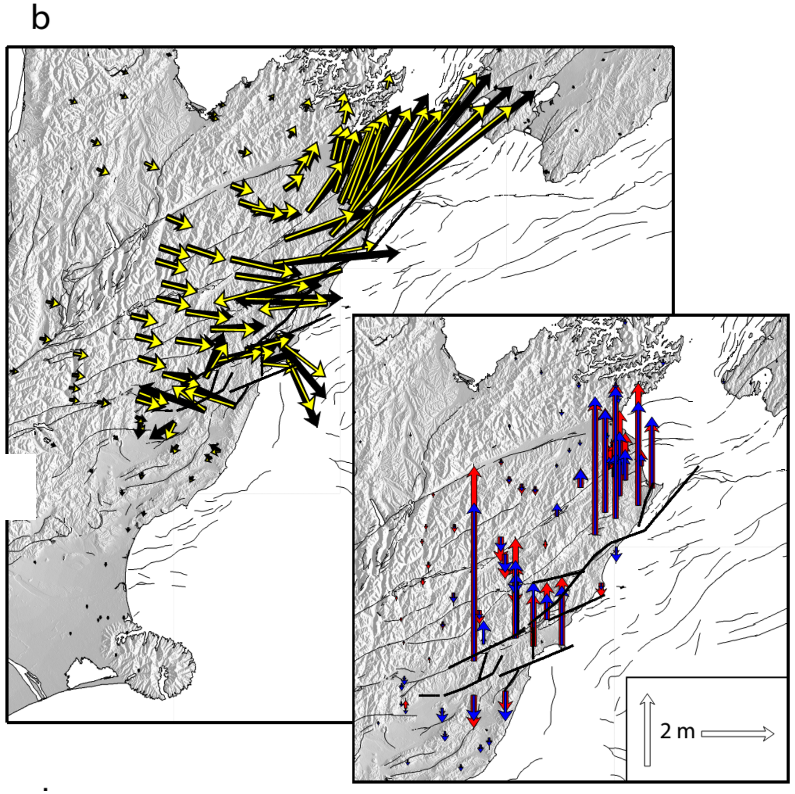
Was There Slip on the Southern Hikurangi?



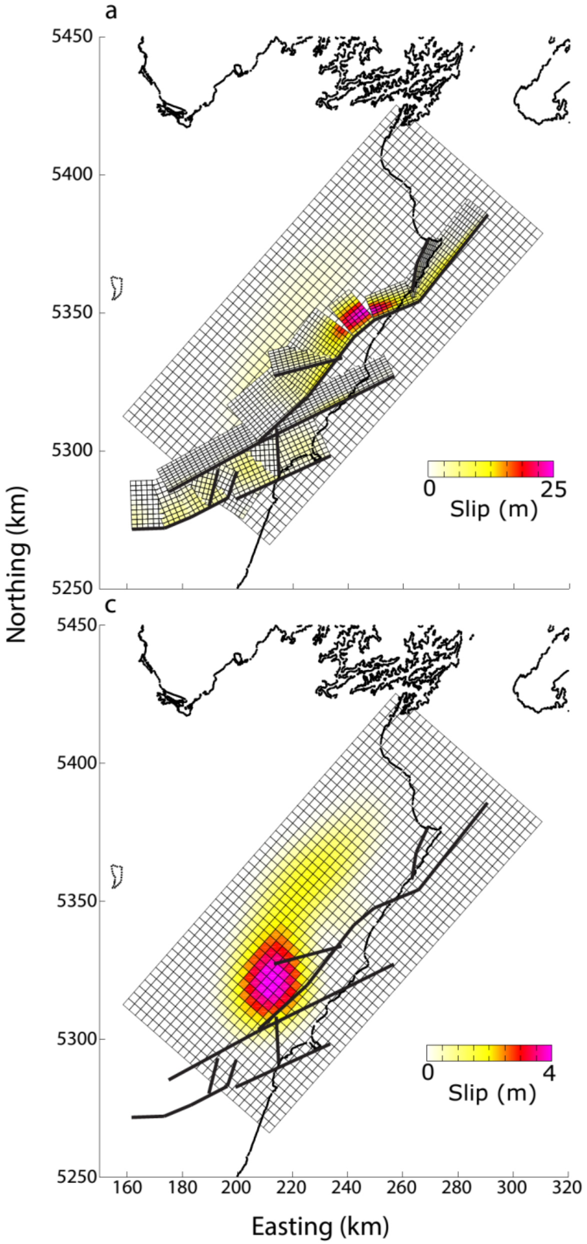


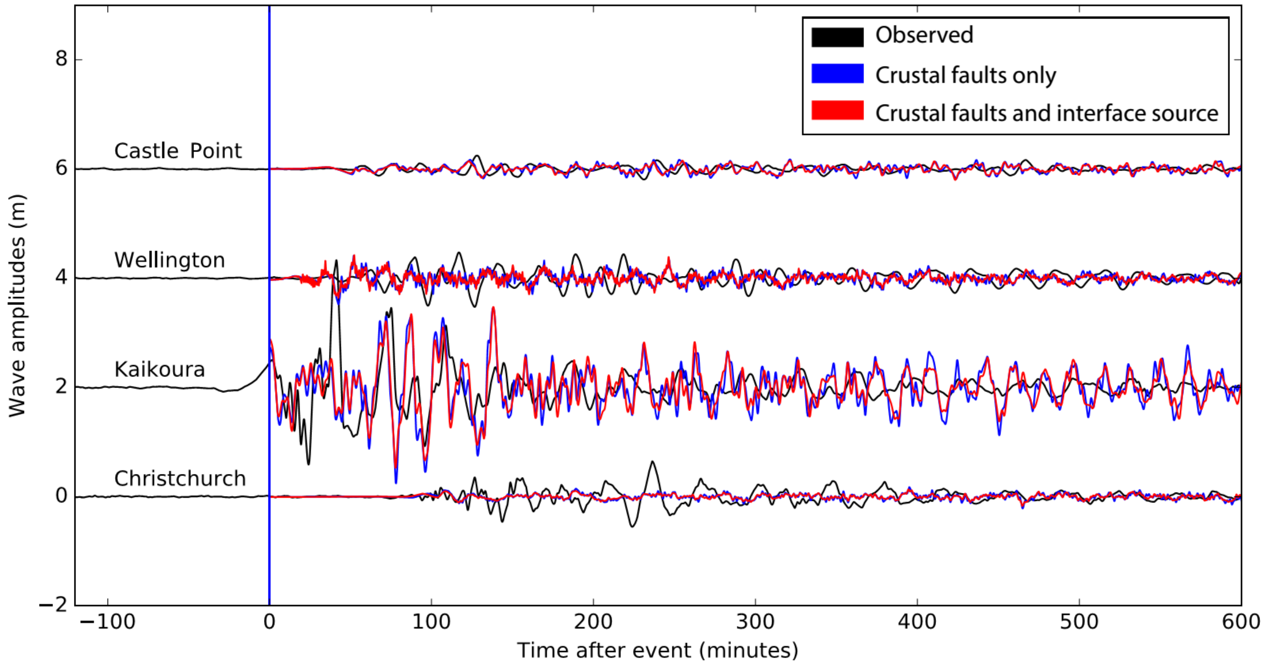


- With slip on the subduction interface, the focal mechanism becomes closer to the one derived from USGS W-phase inversion.
- Adding the subduction interface does not change the total misfit (<1%)
- Contribution of the interface to the overall moment is relatively minor (~15%)



Was There Slip on the Southern Hikurangi?





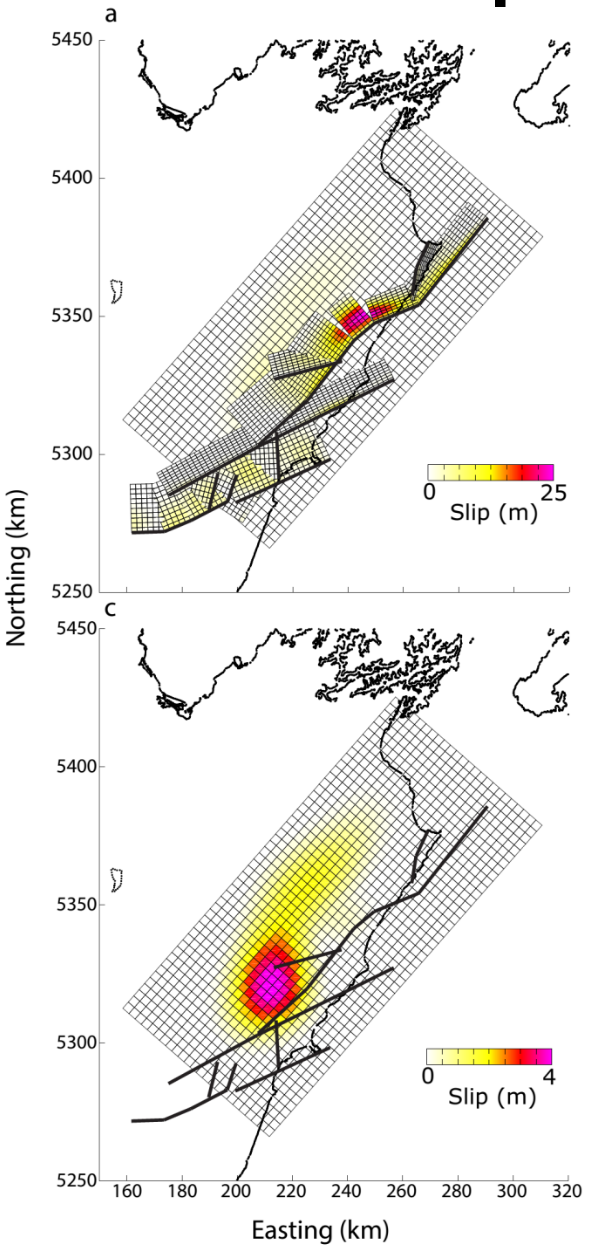
Can we fit the tsunami better??

Not really!

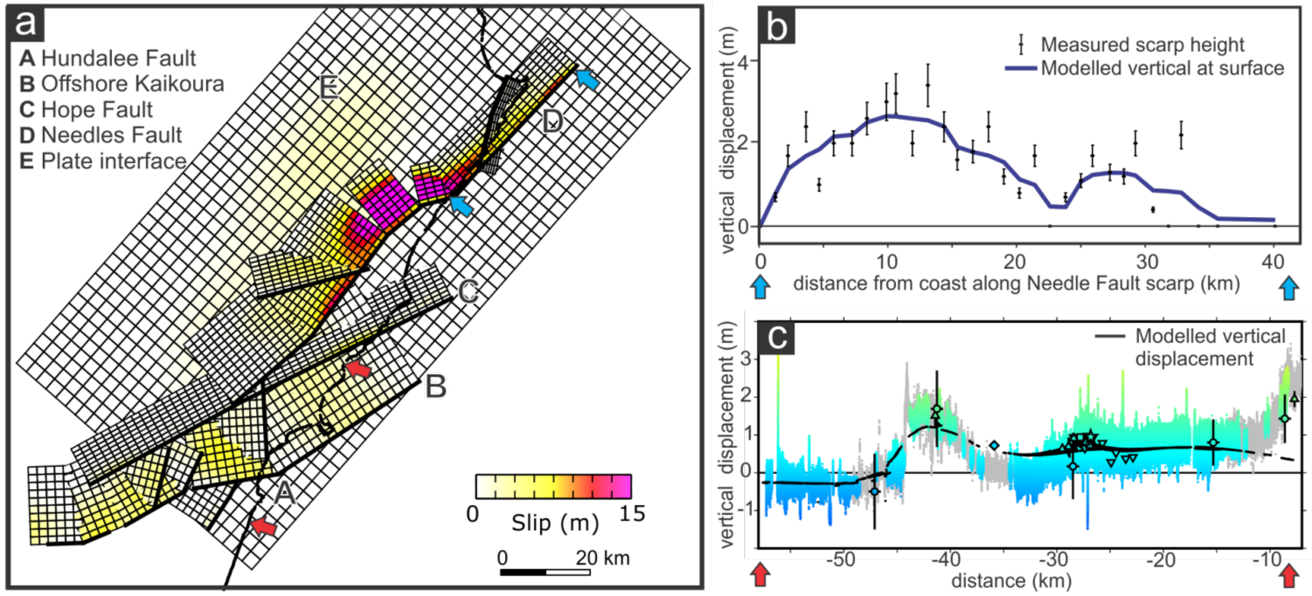
Still missing something??

Probably!

Was There Slip on the Southern Hikurangi?



Clark et al submitted



One option – crustal fault offshore.

To get broad uplift we require shallow dip ~ 30°

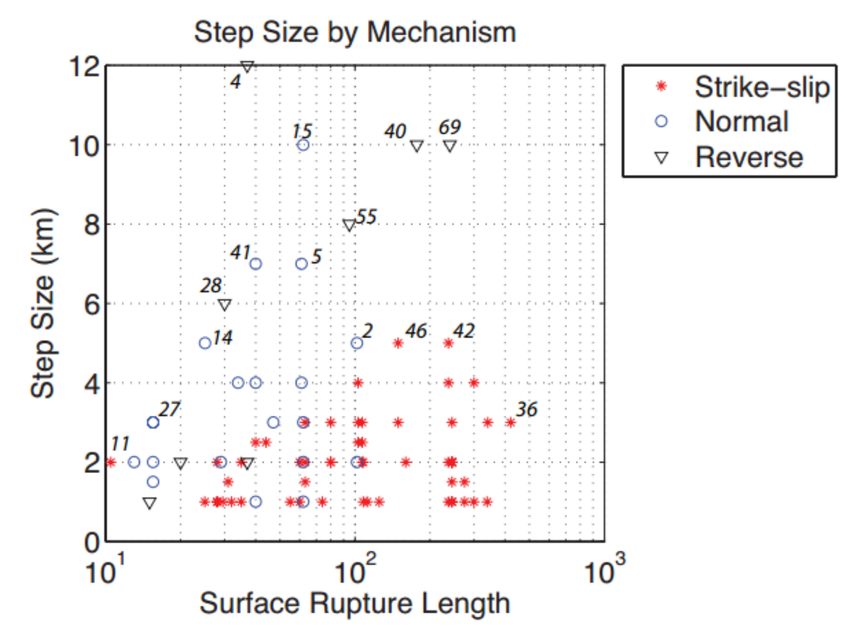
Not well constrained but removes some slip from interface.

Implications:

- The large apparent gap between southern and northern segments mean that it wouldn't have been a plausible scenario in most hazard models.

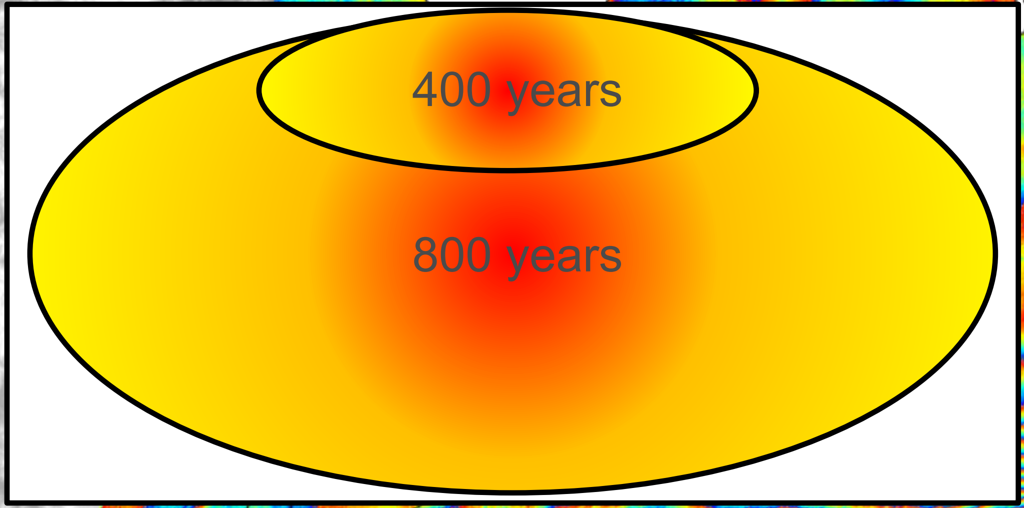
- We predict slip down to 25 km – at least 10 km more than allowed in NZ hazard models.

- Slip at depth vs surface slip: Kekerengu example
  - 10 m of surface slip
  - Average recurrence interval ~400 years
  - Slip rate ~25 mm/yr



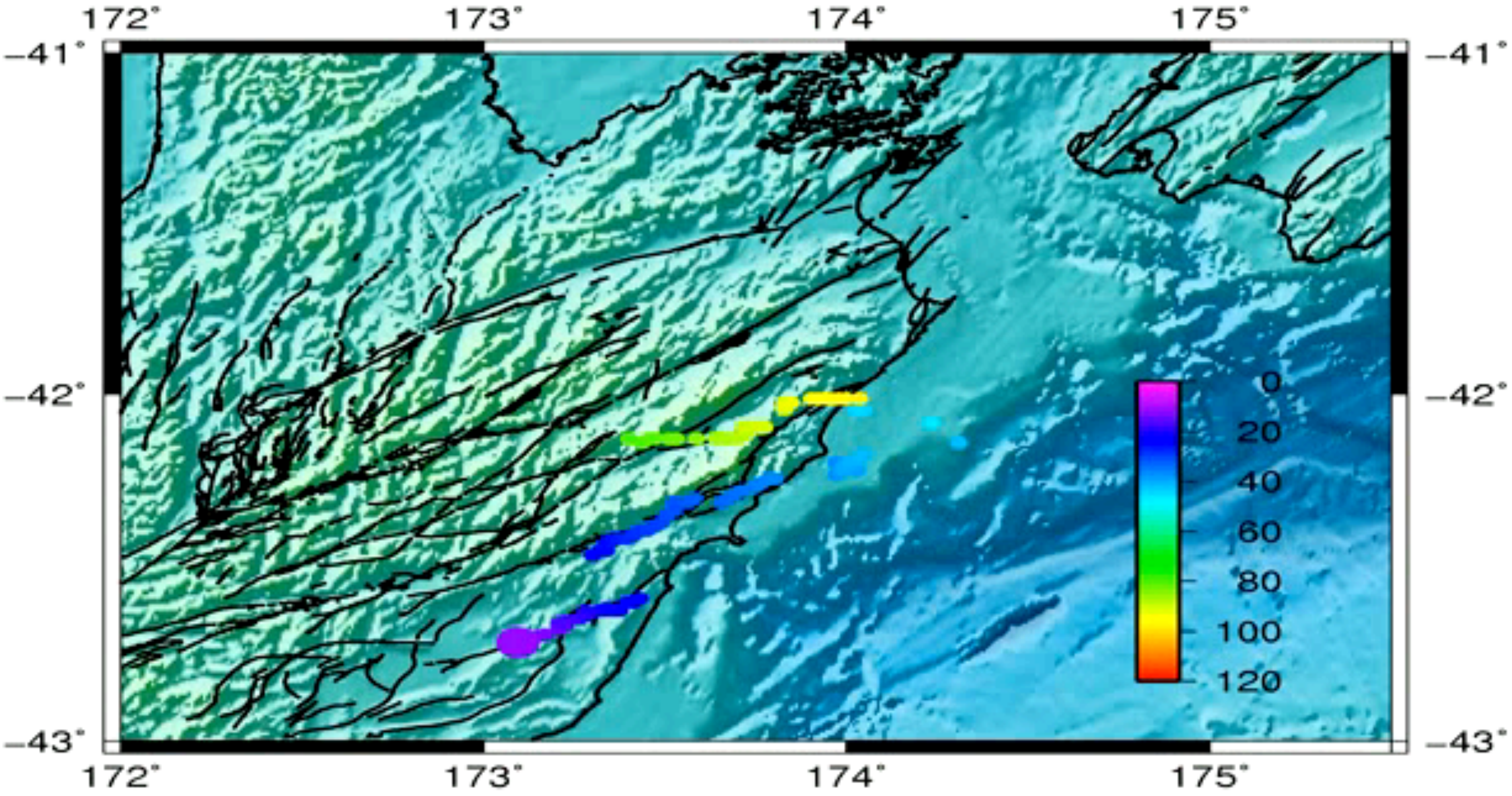
Biasi et al; 2016

Implications:



- **Slip at depth vs surface slip: Kekerengu example**
  - 20-25 m at depth in 2016 Kaikoura Earthquake
  - Options:
  - Average recurrence interval c. 400 years – slip rate ~50 mm/yr or recurrence interval 800 years

Video of Maximum Energy Release (Bill Fry)



Courtesy of Yoshi Kaneko

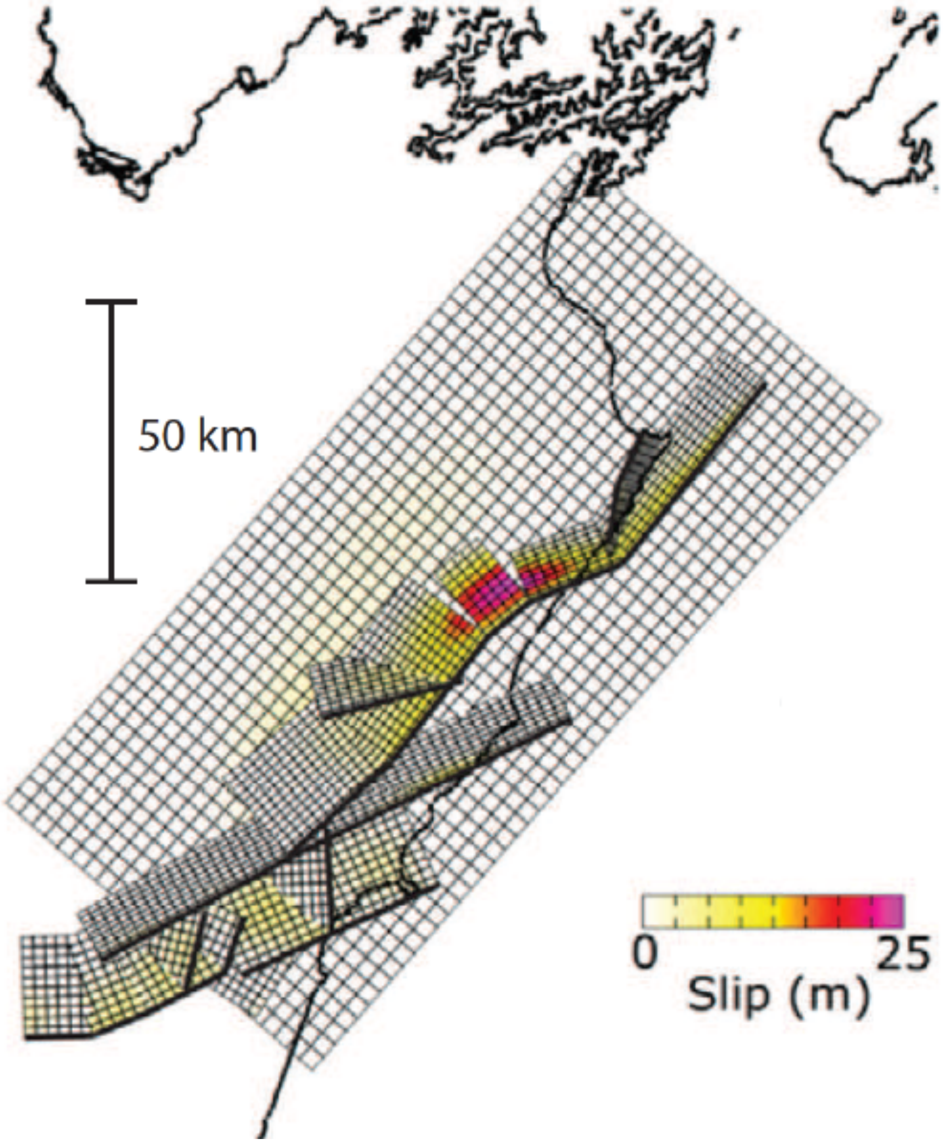
Kinematic source modeling

Finite fault represented by 3122 point sources with Gaussian source-time function with the half duration of 2.5 s

Geodetically-derived slip model (Hamling et al., submitted) as a constraint for the fault geometry and the final slip distribution

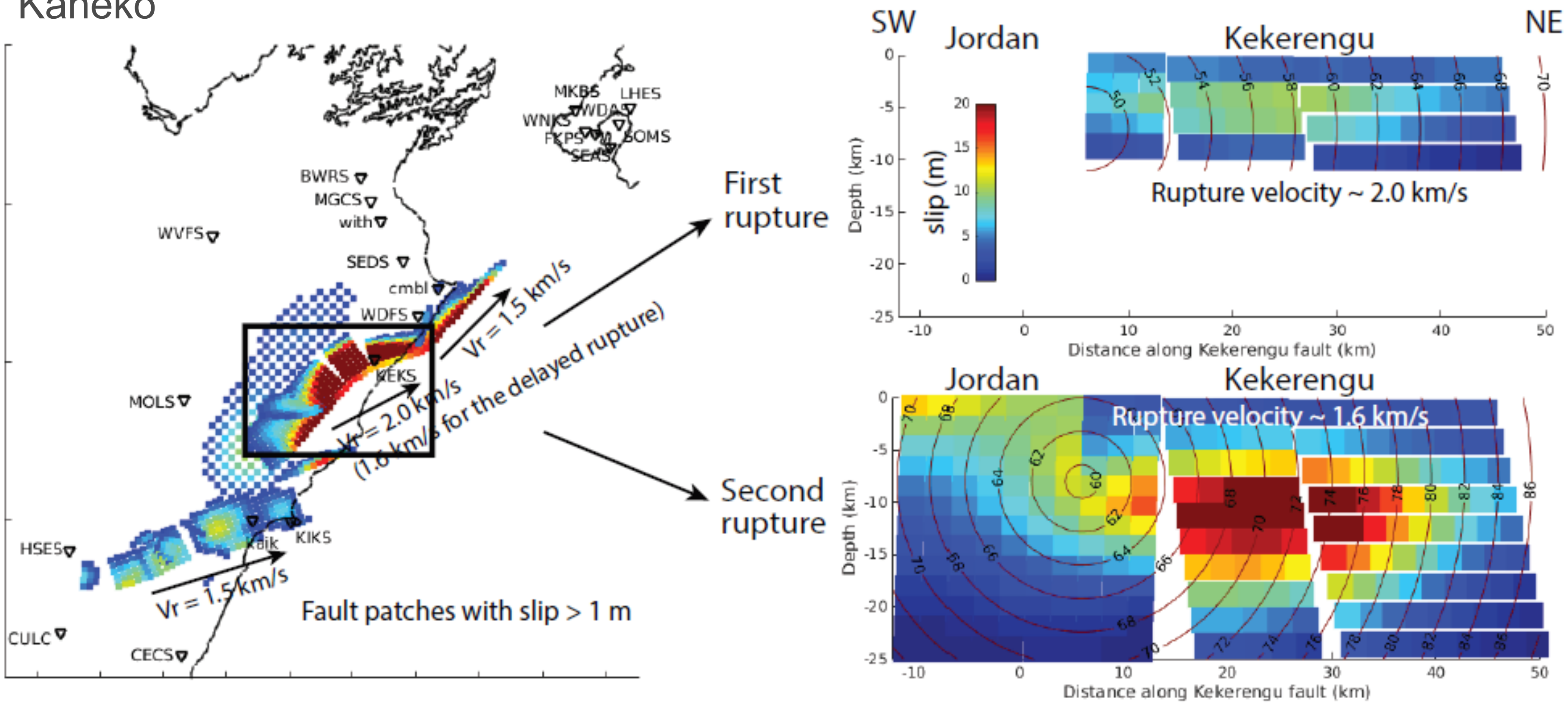
Only the rupture initiation times of fault segments are varied

Our finding: simple rupture propagating continously from the south to north cannot explain local strong-motion and high-rate GPS waveforms



Kinematic source modeling

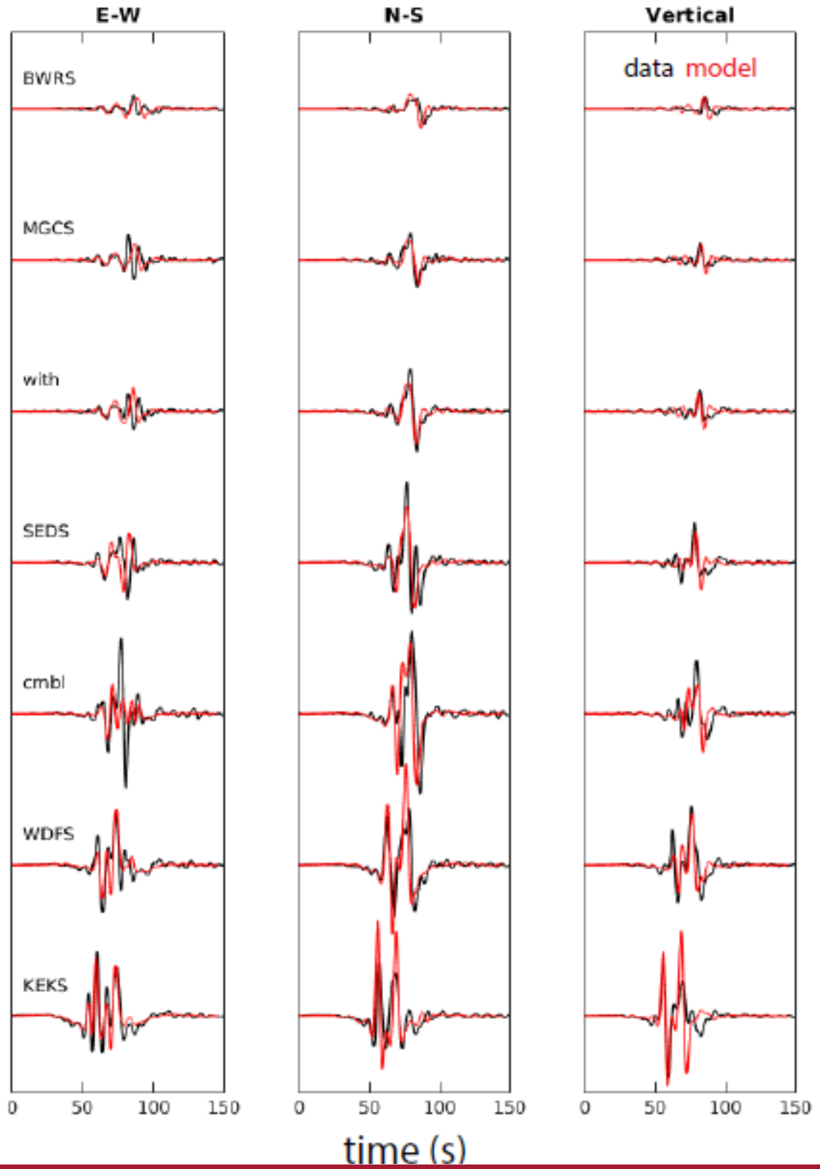
Courtesy of Yoshi Kaneko

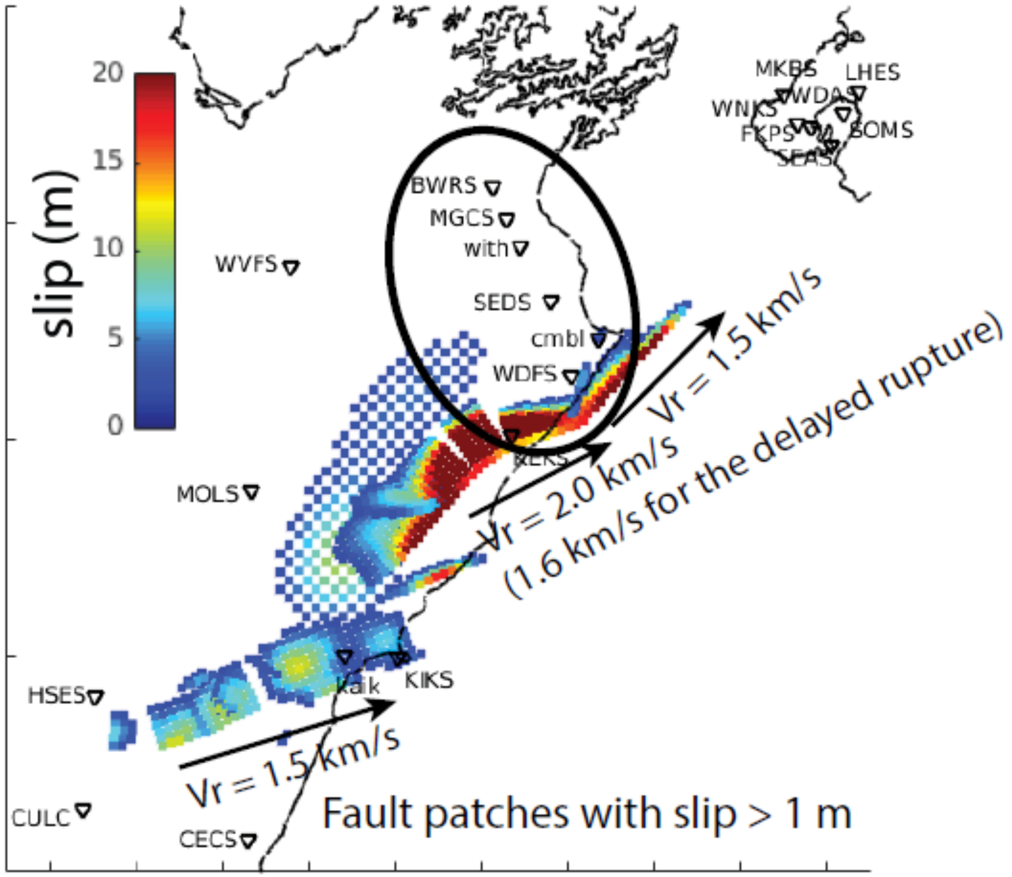


- Overall, the rupture velocity was relatively slow, ranging from 1.5 km/s to 2.0 km/s.
- The best-fit model indicates re-rupturing of a shallow portion of the Kekerengu fault
- On the southern Kekeregu fault, the first rupture began to propagate at 48 s after the origin time
- At 11 s later, the second (delayed) rupture nucleated on the same fault at ~10 km depth and broke a major asperity with ~20 m slip on the deeper segment

Kinematic source modeling

Northern stations Filter: 5 – 60 s



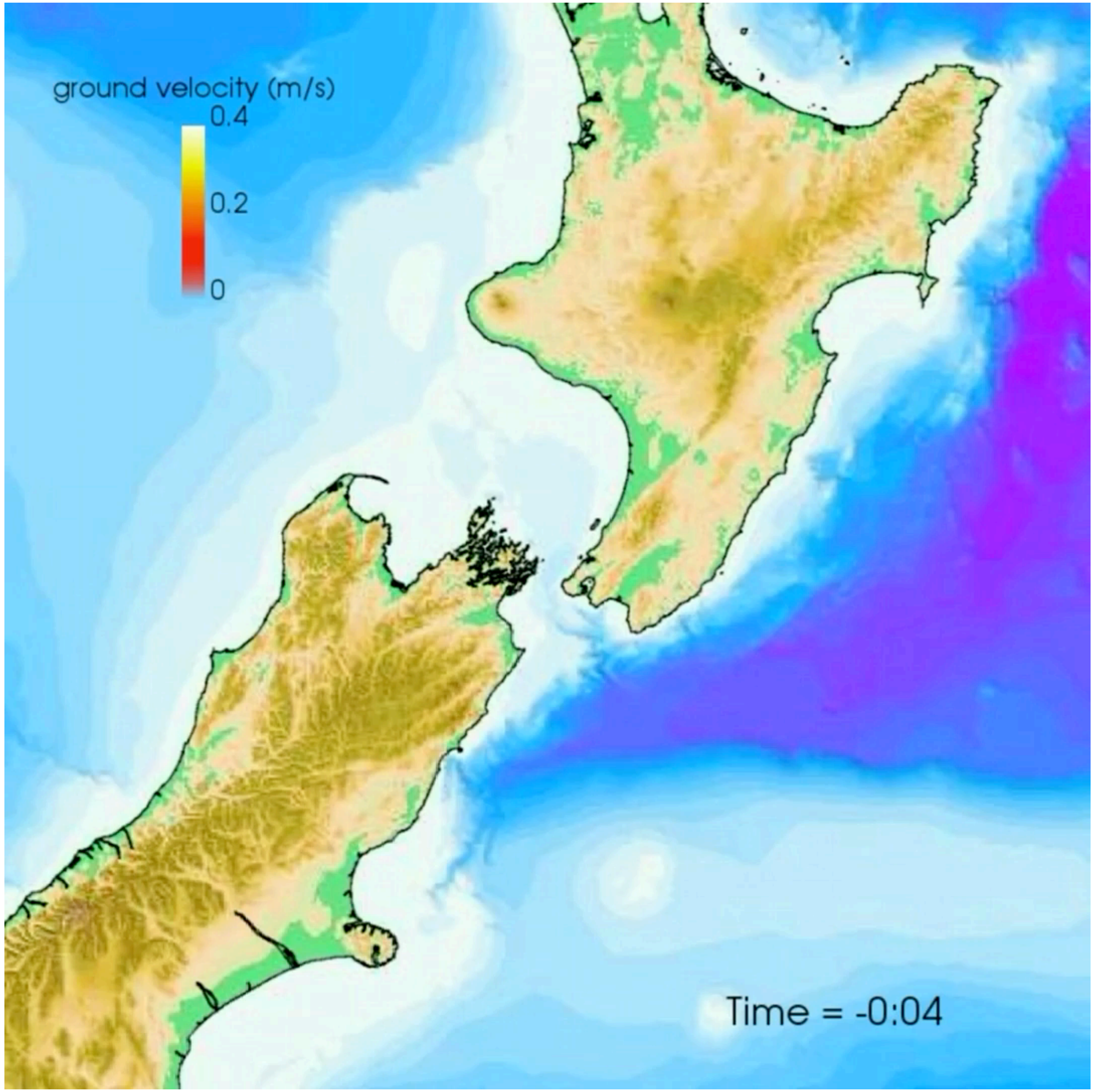


Kaikoura Modelled Surface Velocity and Tsunami Height Models (Yoshi Kaneko and Xiaoming Wang)

Kaikoura rupture model using SpecFEM.

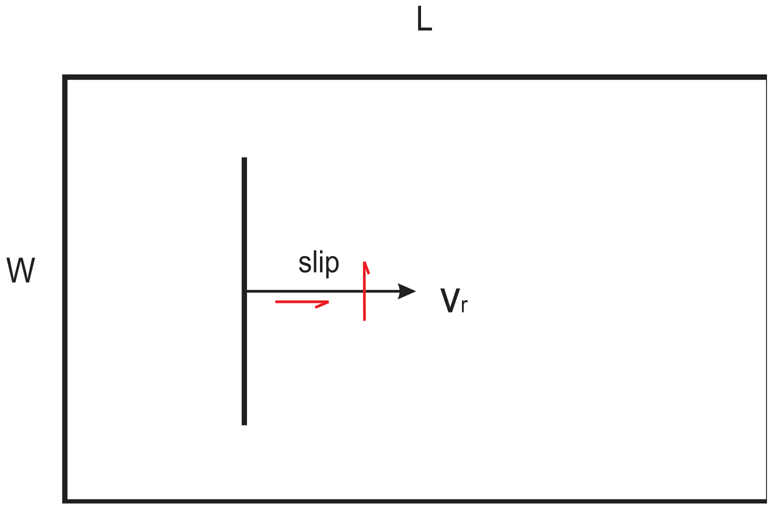
Surface deformation field serves as boundary conditions for tsunami model using Comcot.

[Kaikoura Earthquake simulation update]



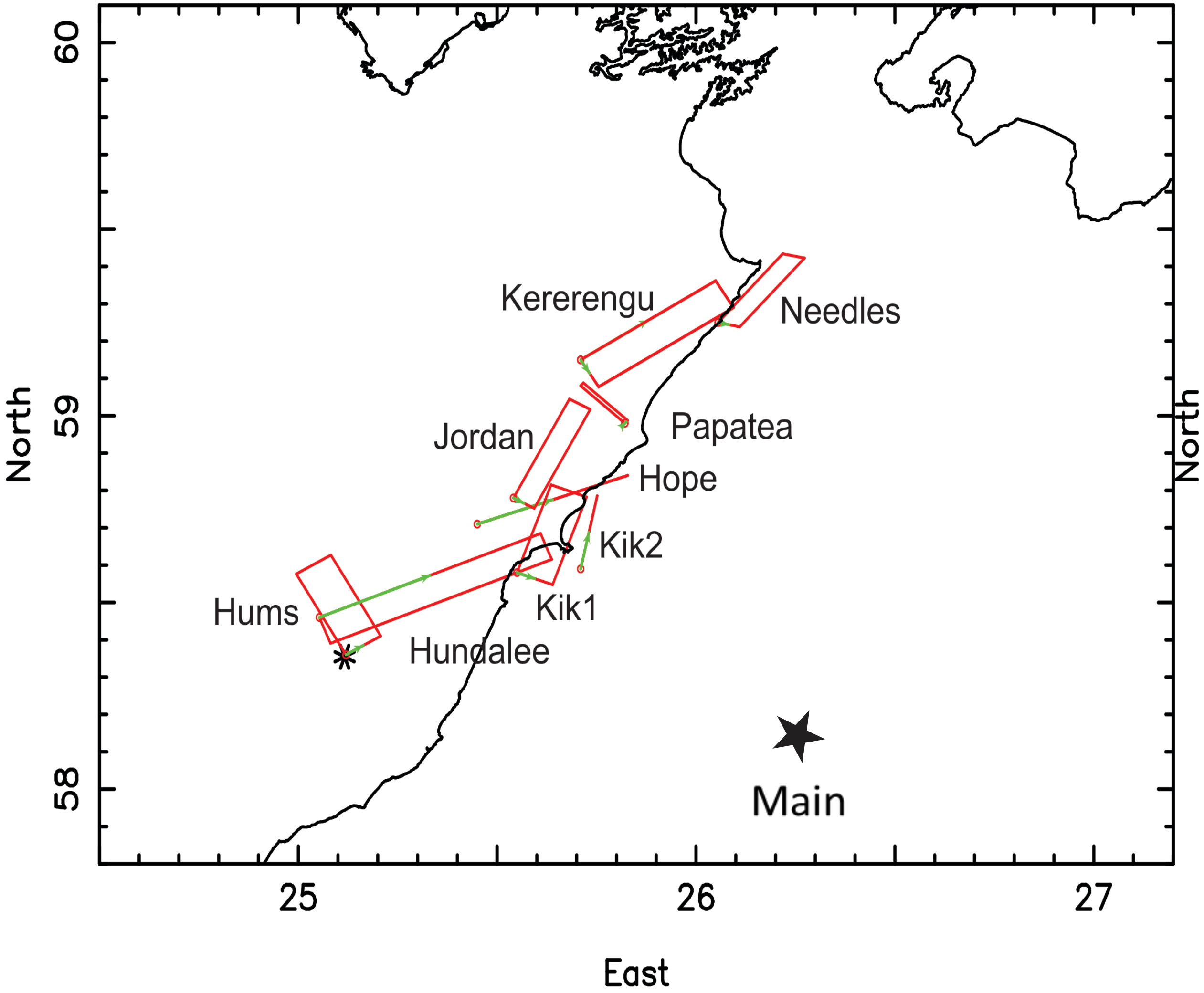
Modelling the near field strong ground motion during the Kaikoura earthquake (Rafael Benites)

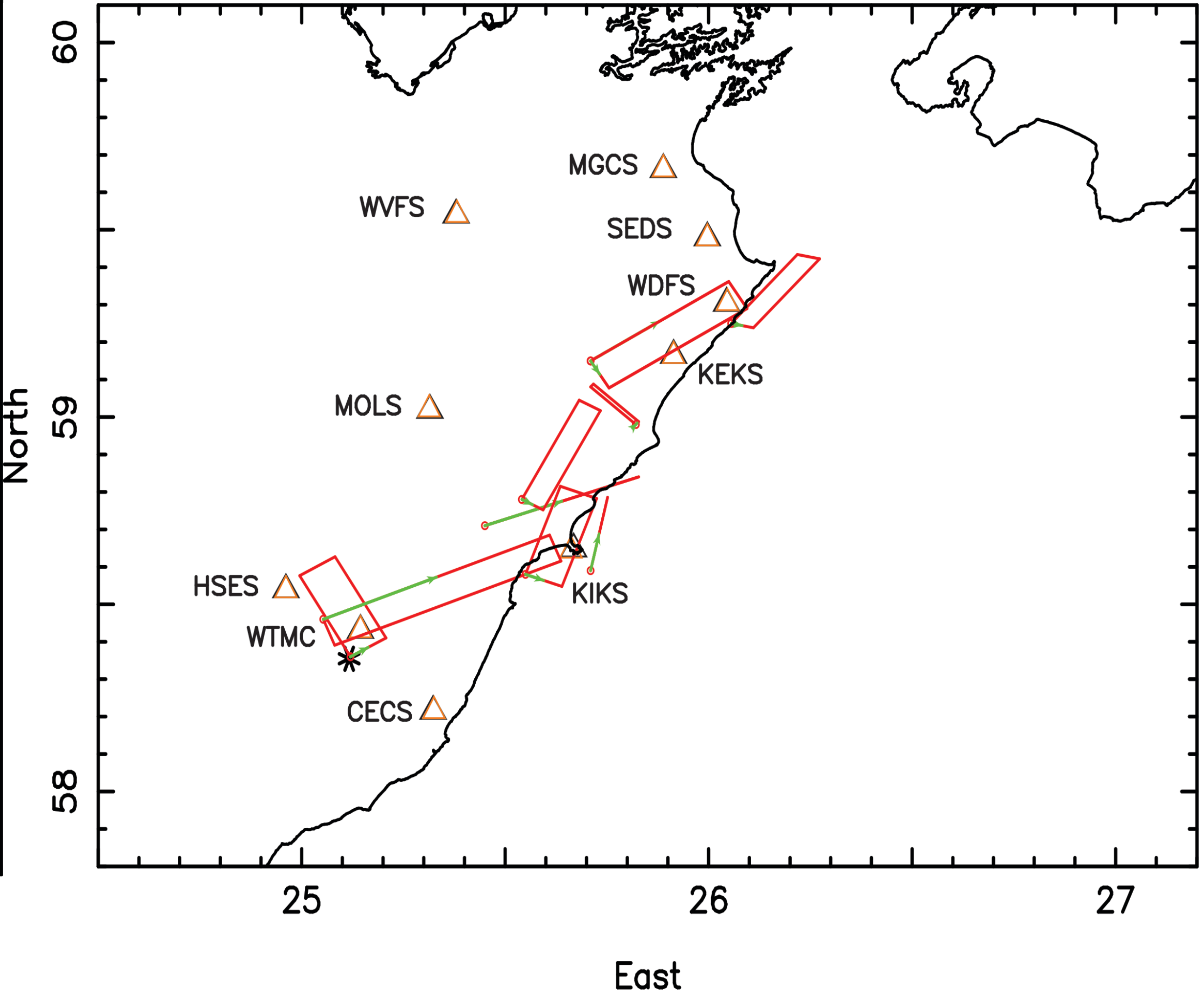
- **A Haskell type rupture is a rectangular fault of length L and width W, and uniform rupture with velocity Vr. The slip vector can be either parallel or perpendicular to the strike.**



A combination of Haskell faults representing a complex rupture

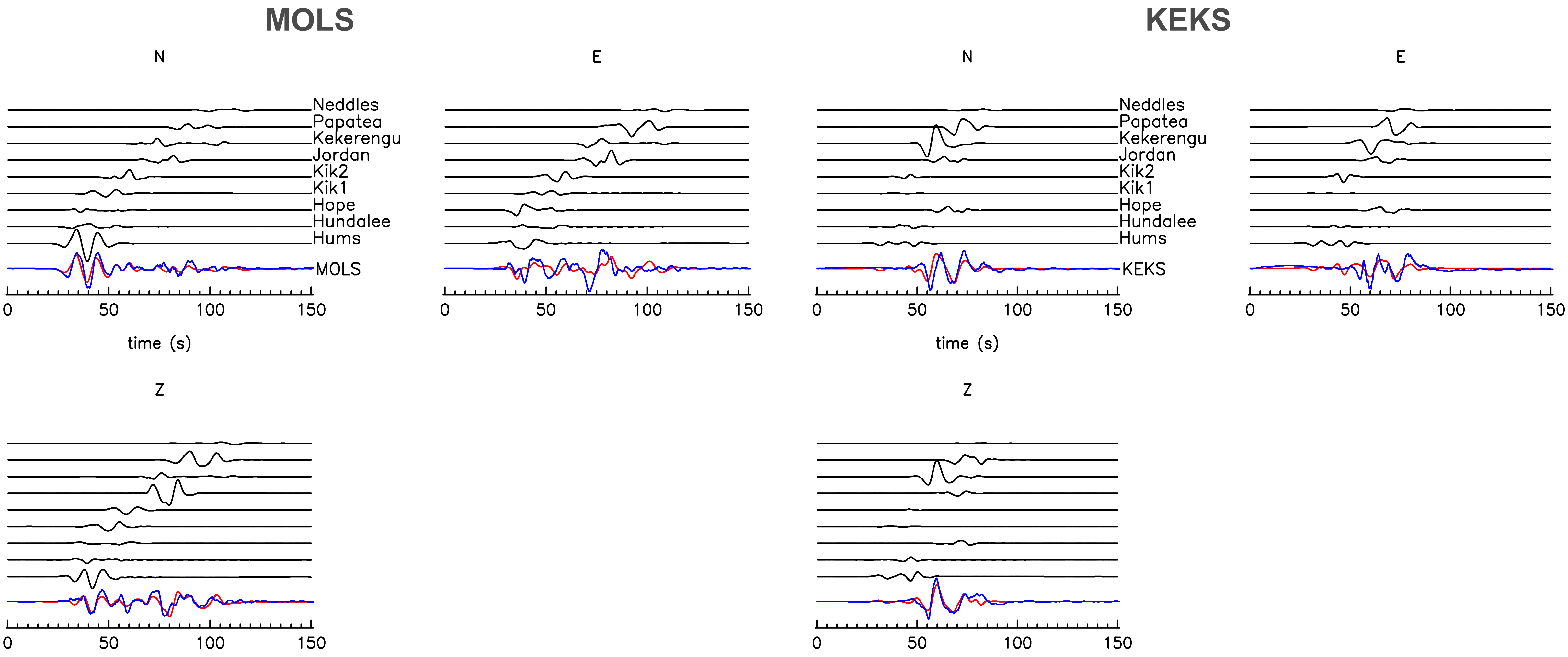
Fault and Station Distribution



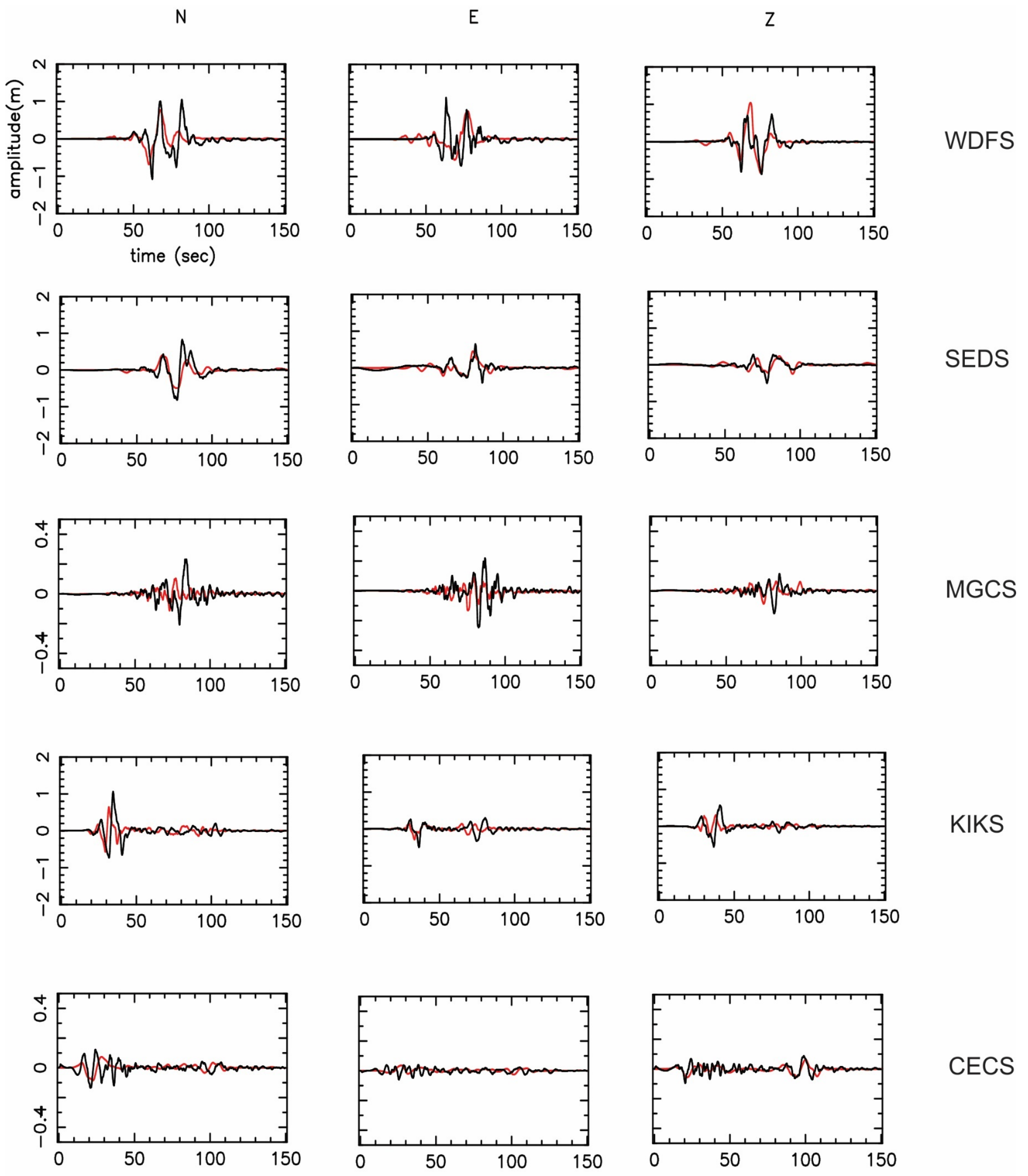


At each fault the dot at its deepest corner represents its nucleation point. The green arrow represents the slip directions.

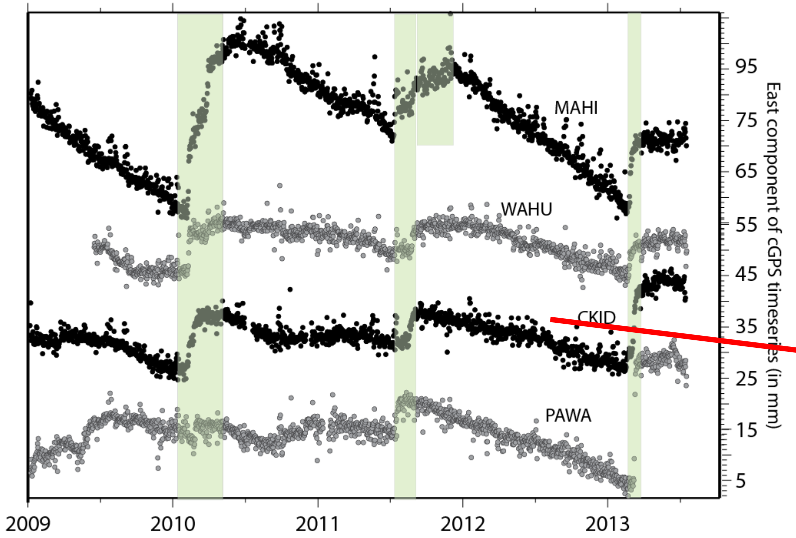
Contributions from Each Fault

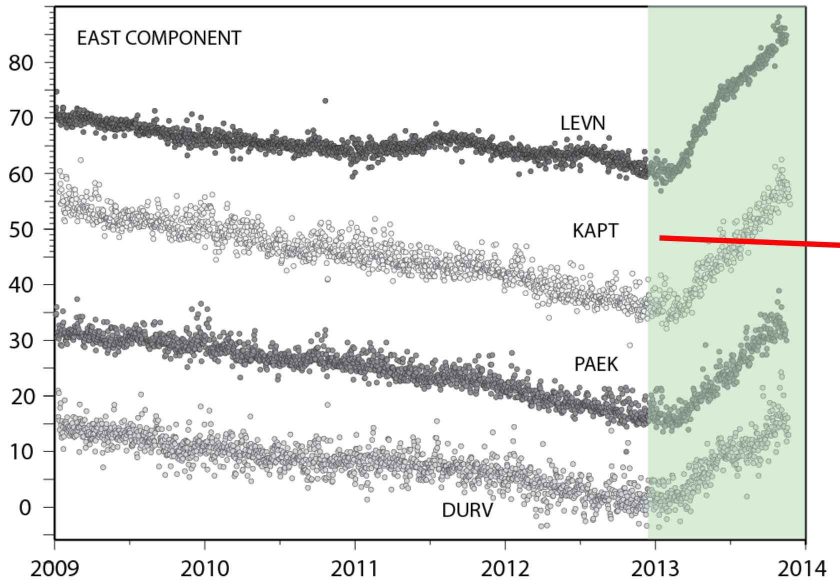


Observed and Predicted Waveforms at Other Sites

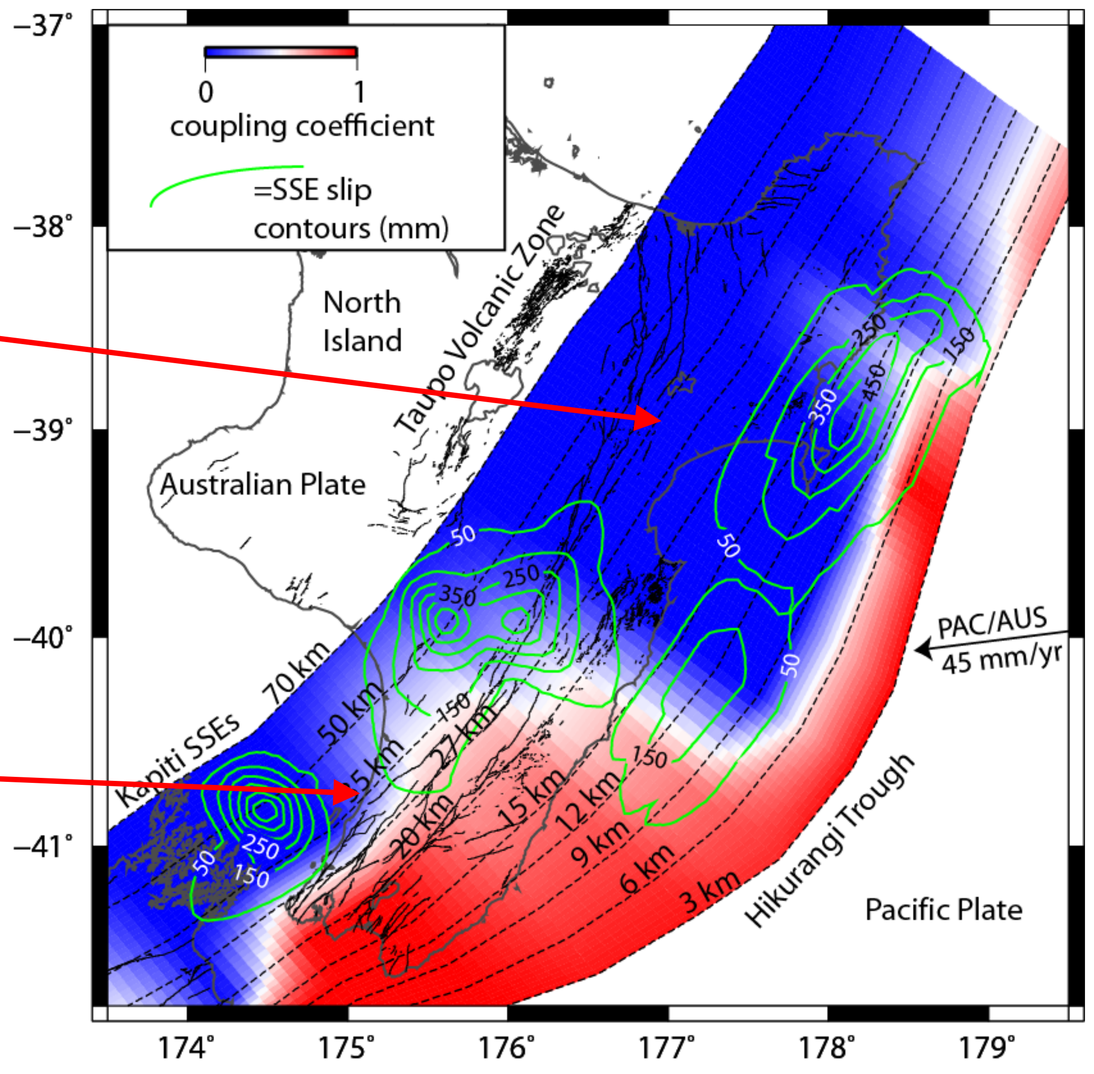


Triggered Slow Slip Following the Kaikoura Earthquake





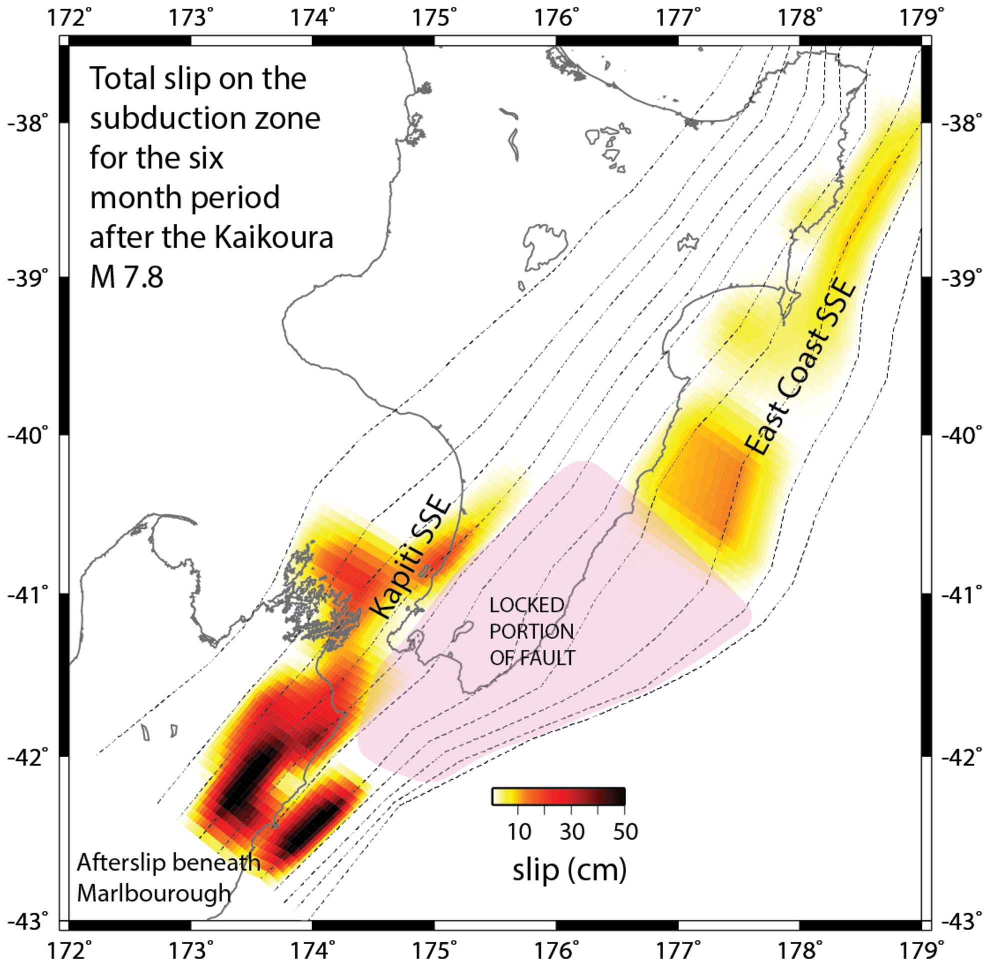
Large cGPS displacements of up to 3-4 cm



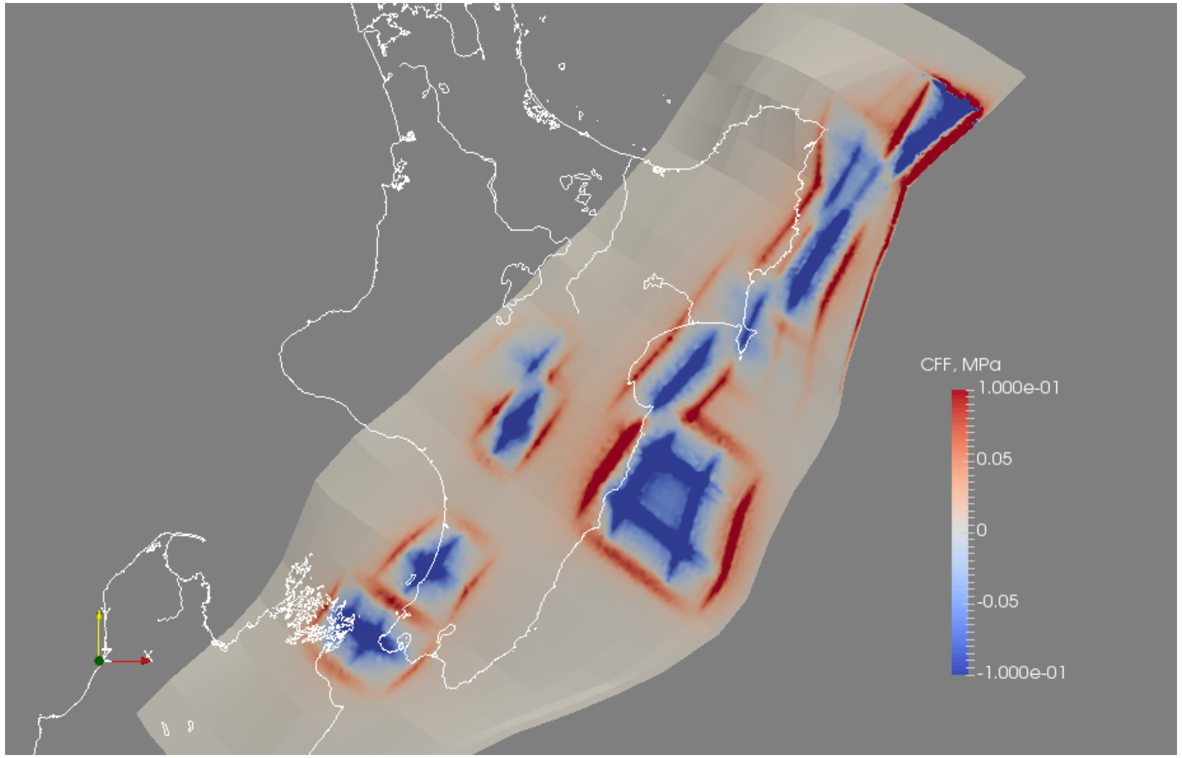
Green contours show cumulative slow slip between 2002 and 2012

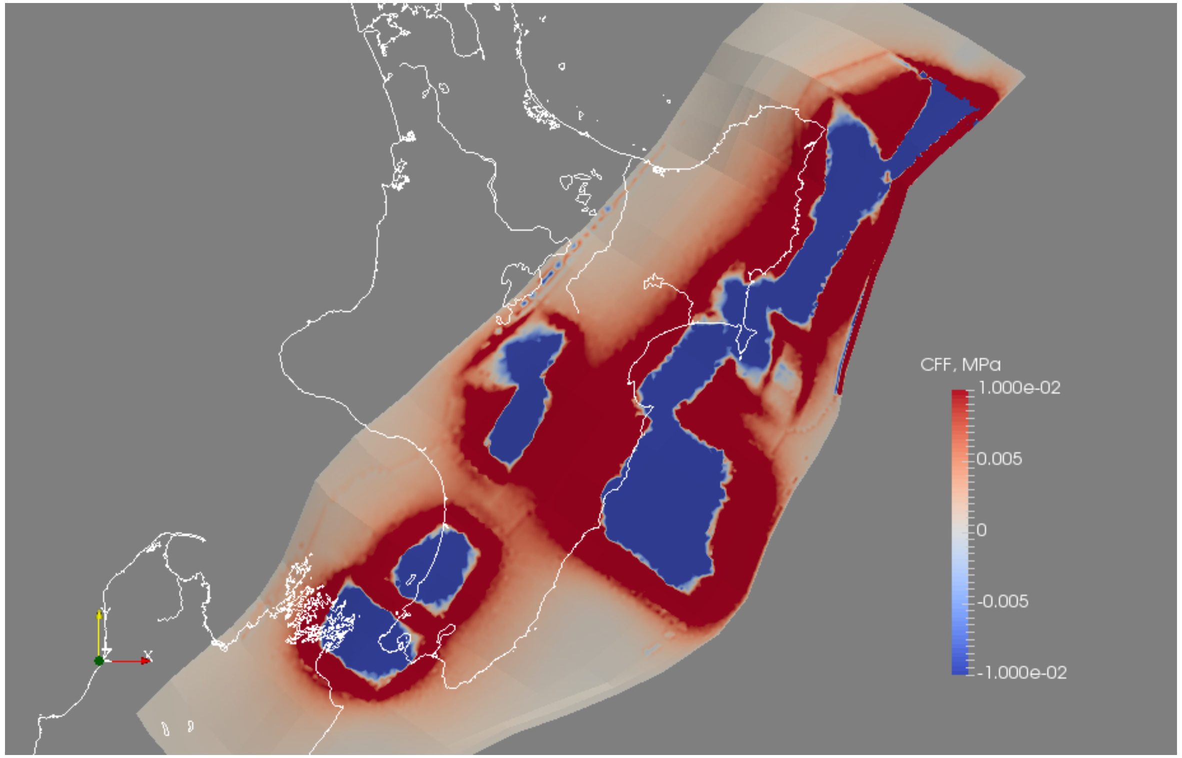
Slow slip and afterslip on the Hikurangi subduction interface following the Kaikoura M 7.8 earthquake

- Slow slip began within hours of the Kaikoura earthquake.
- SSEs continued for weeks (northern) to months (southern).
- Afterslip was also observed immediately following the earthquake that appears to be on a portion of the Hikurangi subduction thrust that was previously thought to be inactive.

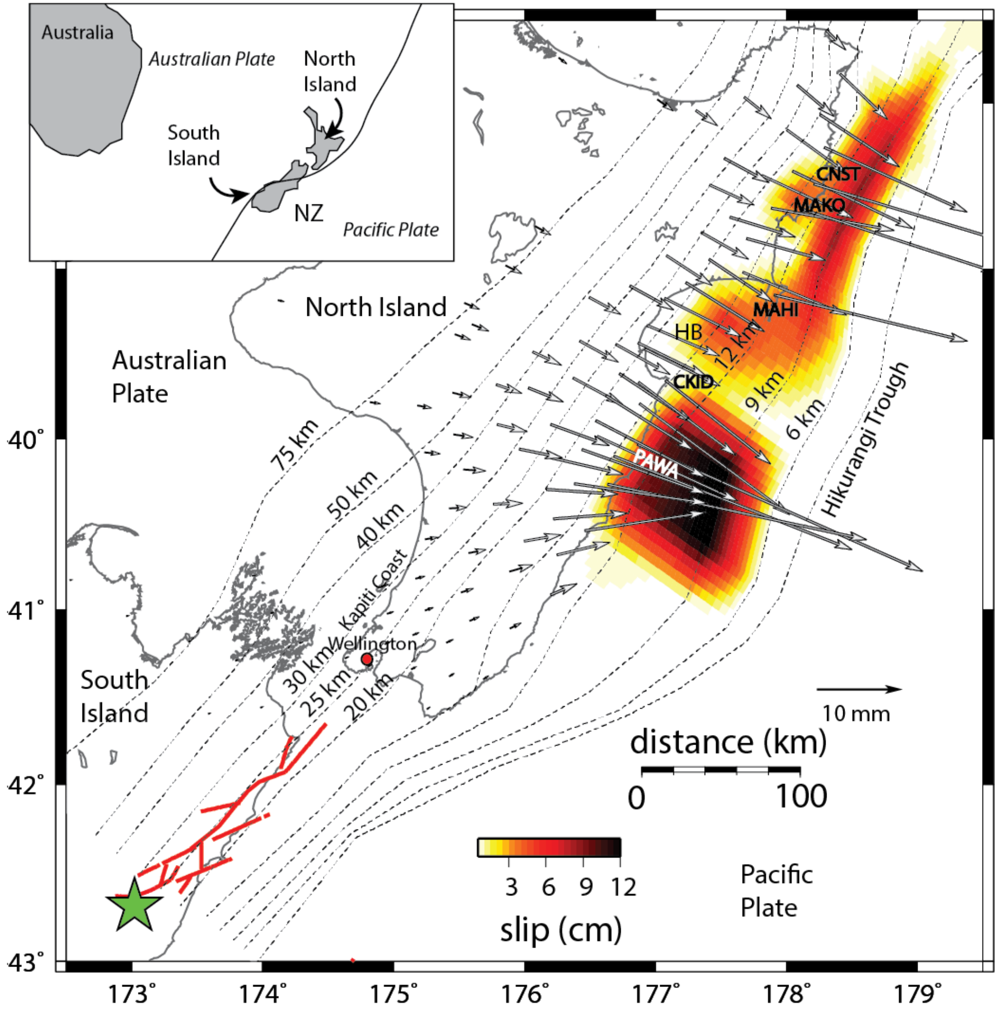


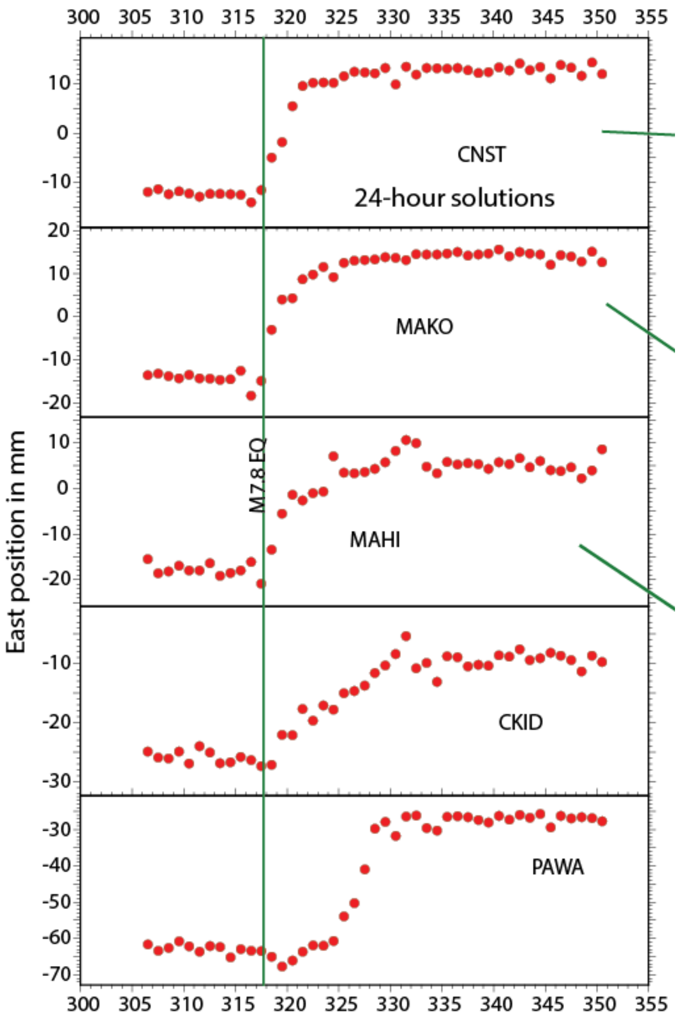
Coulomb Stresses from Initial SSE Models





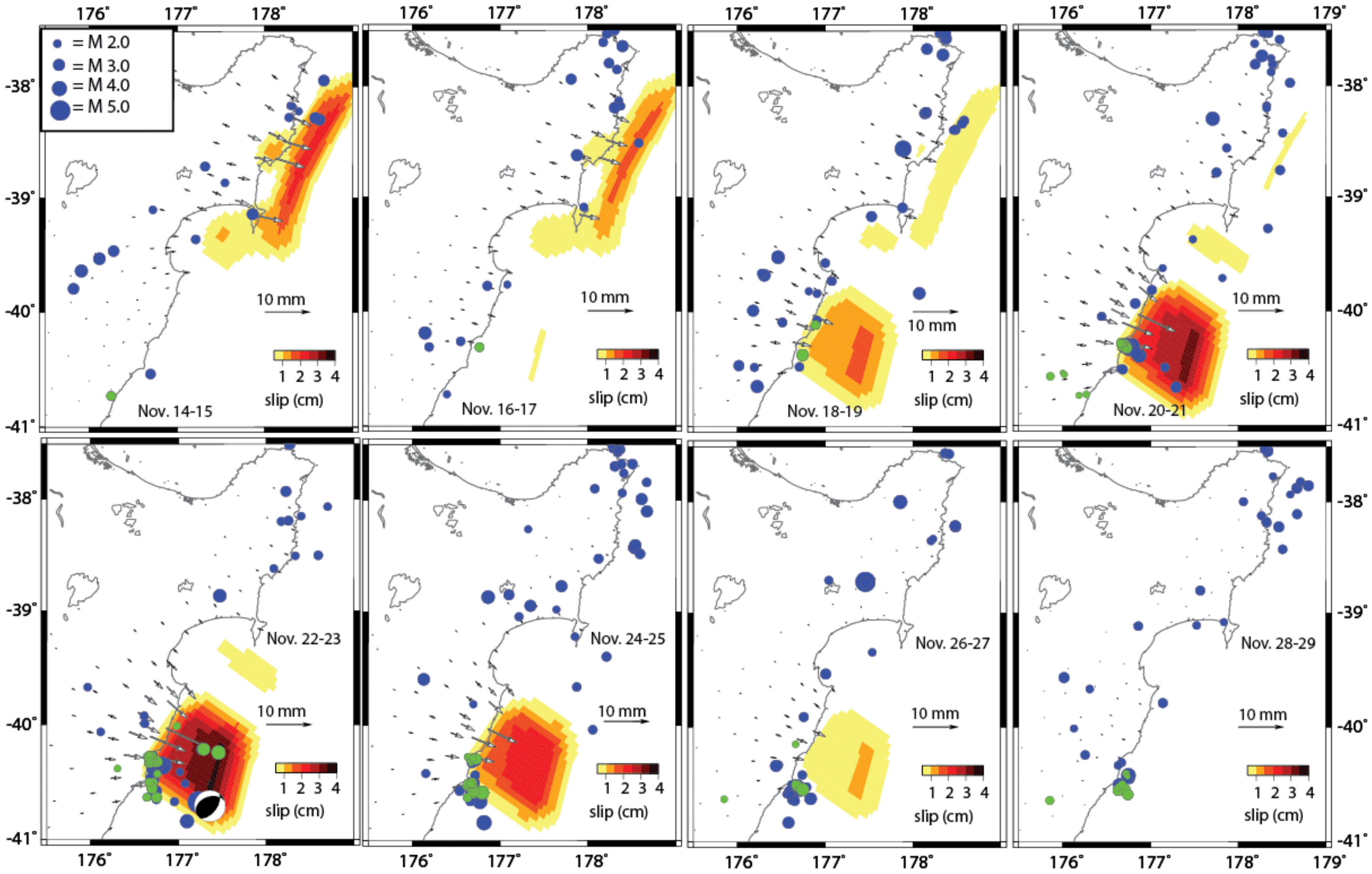
Shallow east coast SSE lasted 2-3 weeks and migrated south over that period. Slip was equivalent to a Mw 7.1





Abundant triggered seismicity (up to Mw 6.0) accompanied the triggered east coast SSE

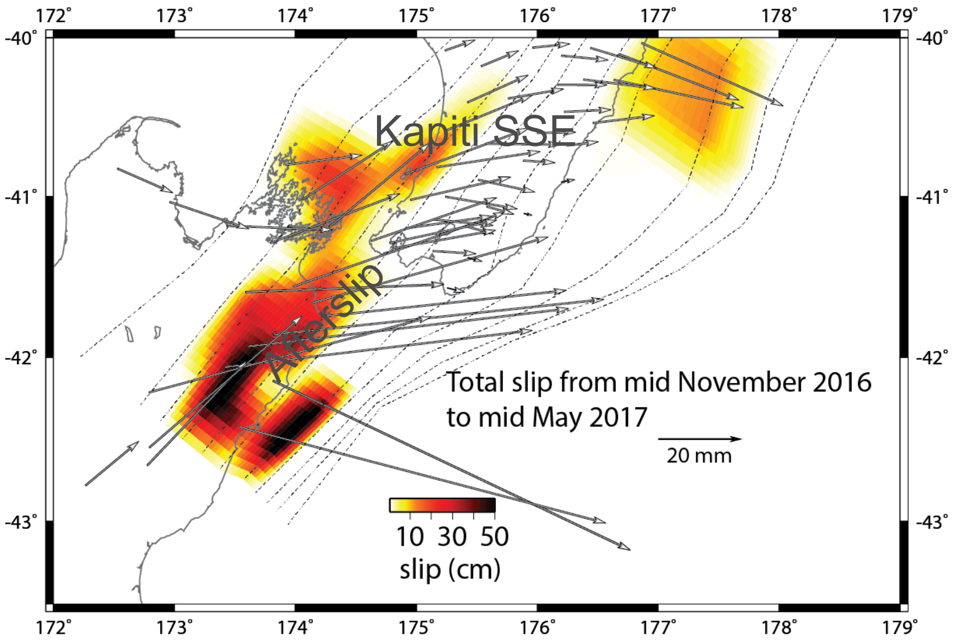
Time-dependent geodetic inversions using TDefnode

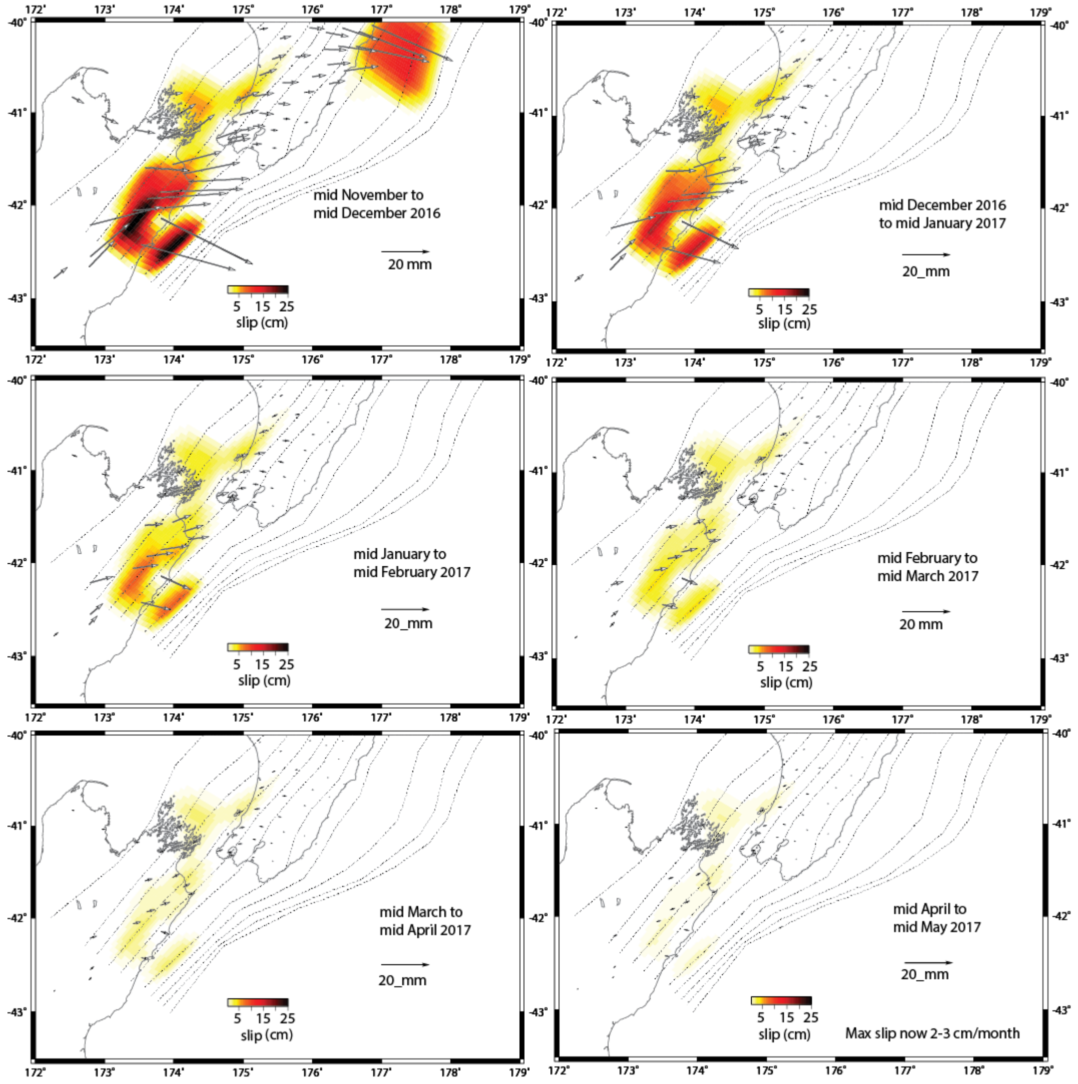


Repeater locations by Z. Peng and B. Fry

Wallace et al., in review

Large slow slip triggered at southern Hikurangi (Kapiti region) as well as afterslip on the interface beneath the northern South Island

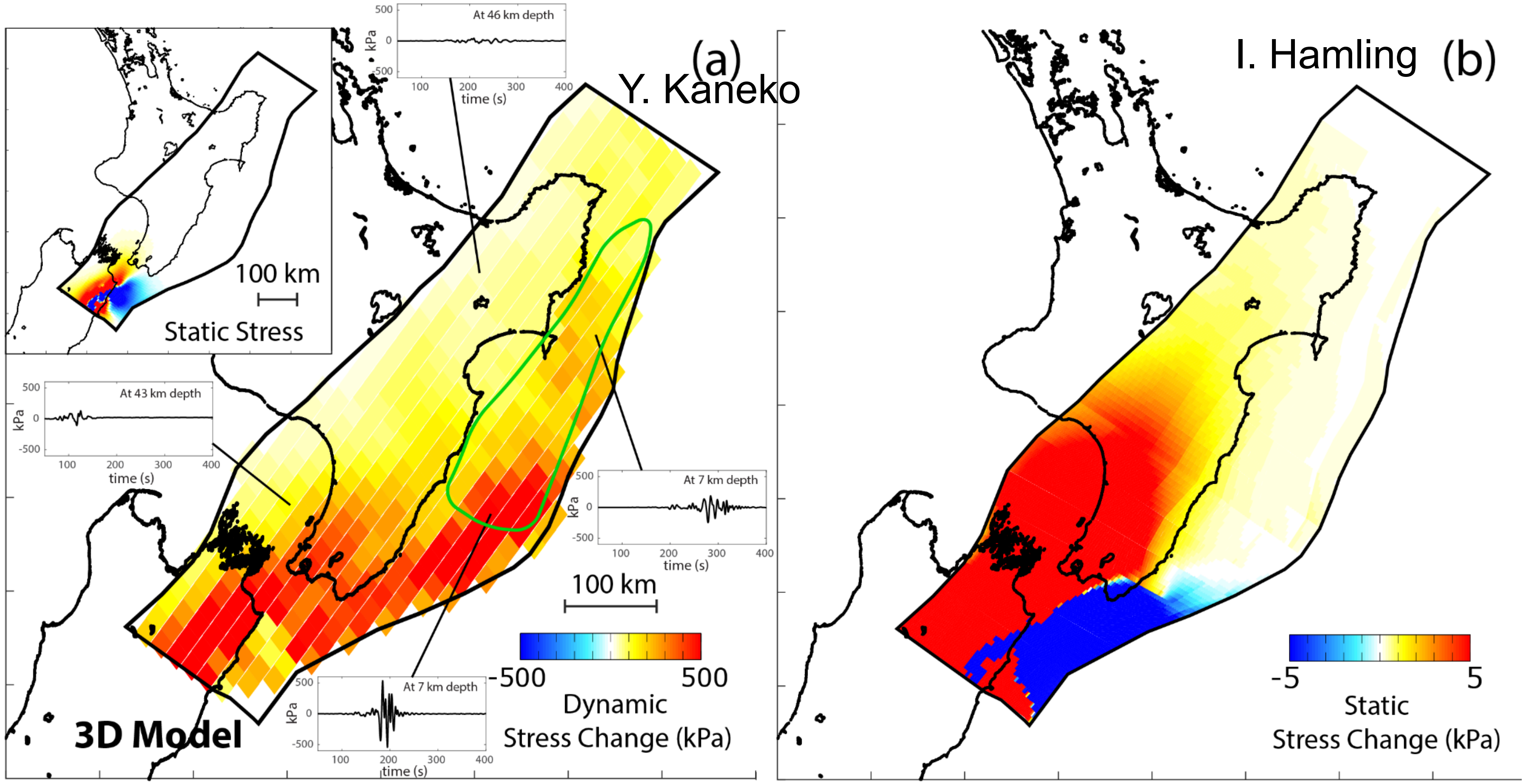




Time-dependent geodetic inversions (cGPS and InSAR) done with TDefnode. We also invert simultaneously for afterslip on the Kekerengu/Jordan Thrust and Needles Faults (not shown here)

First-ever clear example of subduction interface slip beneath the northern S. Island

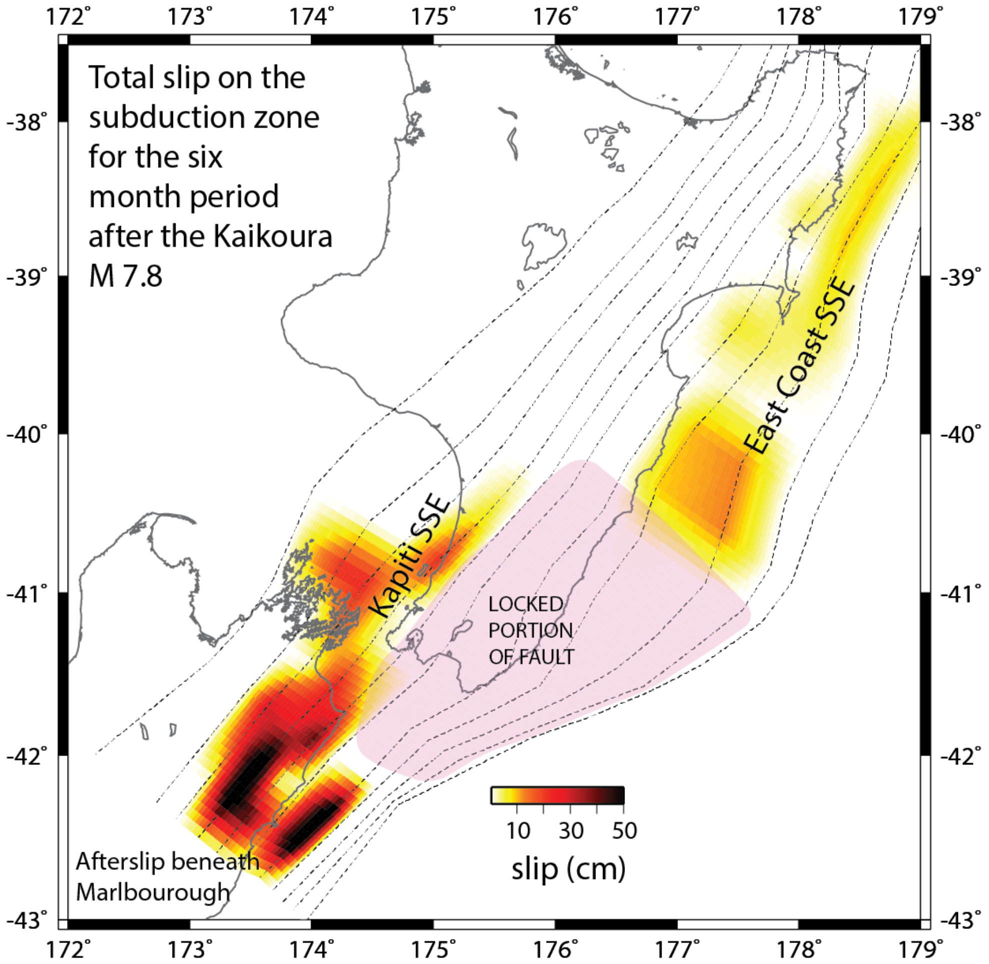
Dynamic vs. static stress changes as an SSE trigger

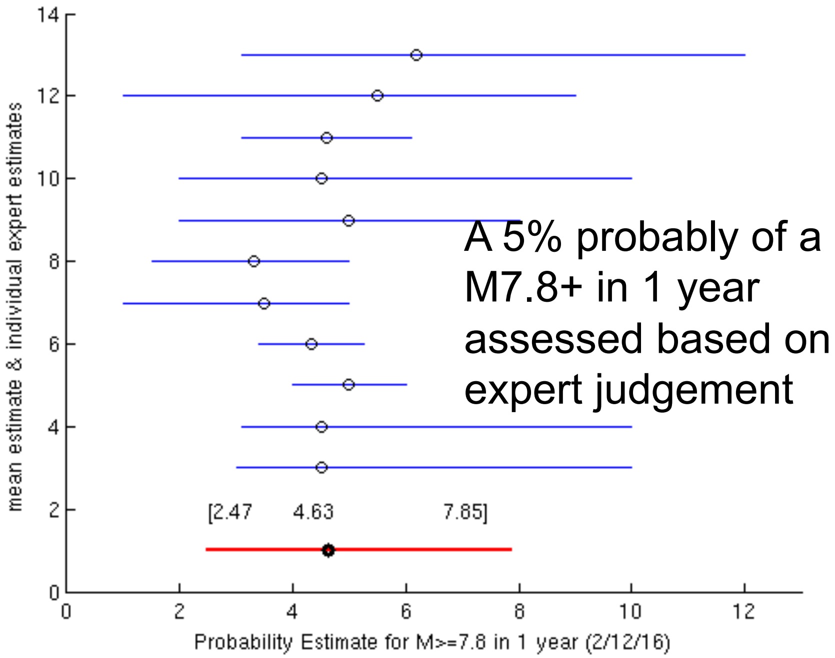


Dynamic stress changes likely driver of the shallow, east coast SSE, while deep, southern Hikurangi SSEs more likely driven by static stress changes.

Dynamic stress changes off east coast greatly enhanced by rupture directivity and the presence of low-velocity outer forearc overlying the shallow interface—the "basin effect" amplifies and increases duration of dynamic stressing

Implications for hazard going forward—SSEs and afterslip surrounding the locked megathrust



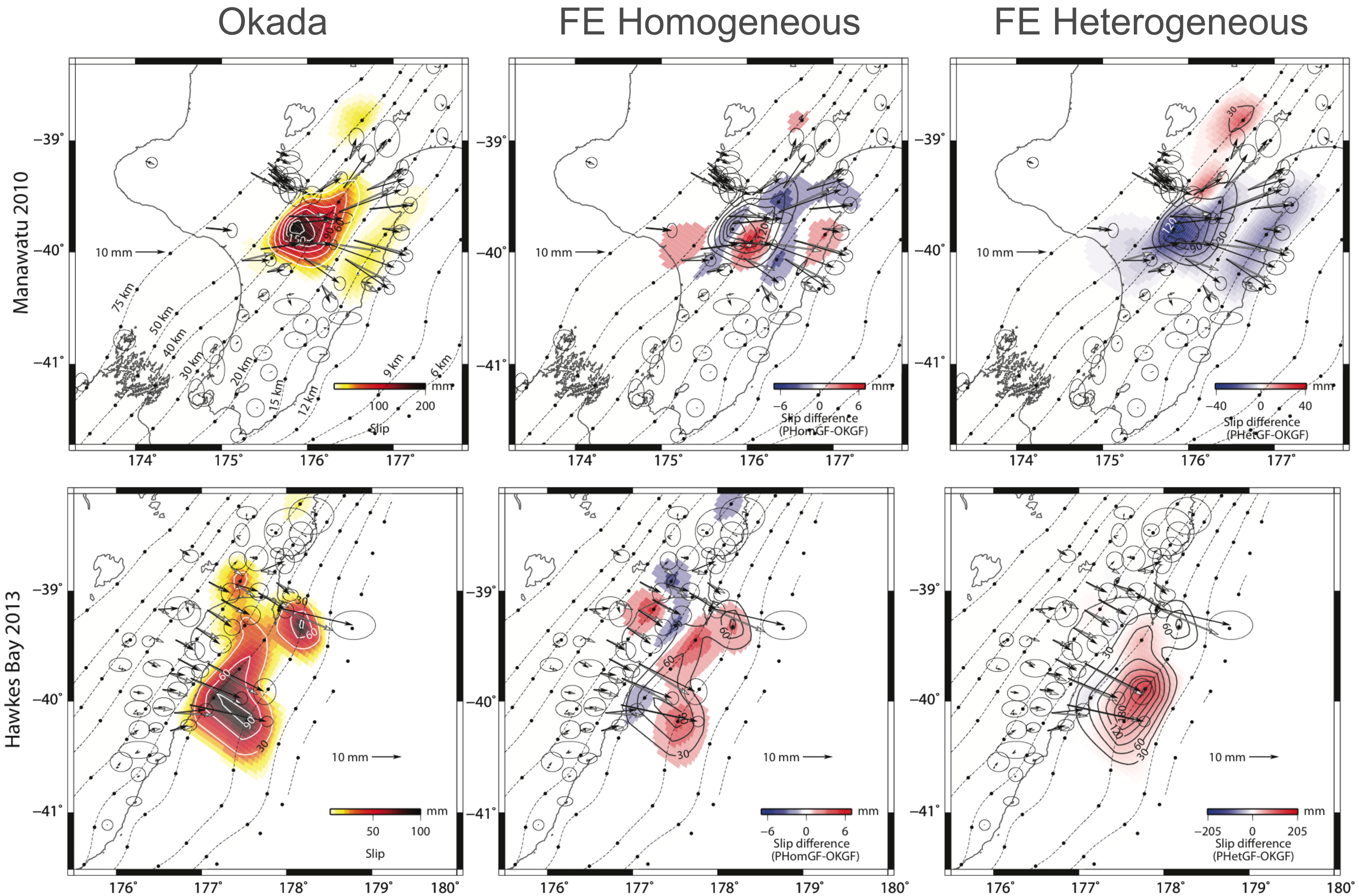


Reasoning based on a variety of lines of evidence, including: ~2x's increase in seismicity rates during past SSEs, STEP/EEPAS model forecasts, clustering in synthetic catalogs of NZ earthquakes simulated over many seismic cycles, and paleoseismic evidence for temporal clustering of Kekerengu fault and subduction earthquakes

Future Modeling Work

- Inversion of coseismic, afterslip, and SSEs using PyLith-generated Green's functions.
- Postseismic modeling of Kaikoura + afterslip.

Effects of material heterogeneity on SSE inversions



Williams and Wallace, 2015

Summary

- The Kaikoura earthquake was an incredibly complex event, rupturing at least 21 crustal faults.
- There was a long temporal and spatial gap during the event – extremely unlikely in most cases.
- It is possible that the event also ruptured a portion of the Hikurangi subduction thrust that was previously thought to be permanently locked.
- The earthquake triggered widespread SSEs, afterslip, and increased seismicity throughout New Zealand, primarily in the N. Island.
- The Kaikoura quake has increased the risk of large aftershocks significantly in surrounding regions, including Wellington.

Conclusions

- Widespread slow slip and afterslip occurred on the Hikurangi subduction zone during the weeks and months following the Kaikoura M7.8 earthquake
- East coast triggered SSEs are the clearest example ever recorded of immediate, long-distance dynamic triggering (>300 km) of large-scale SSEs
- Shallow east coast SSEs triggered by dynamic stress changes, which is enhanced by presence of low-velocity sedimentary wedge of outer forearc
- Deep, south Hikurangi SSEs were likely triggered by static stress changes
- We observe clear, large afterslip on the subduction interface beneath the northern South Island
- Assessing the impact of SSEs and afterslip on seismic hazard forecasts going forward is of extreme importance