Shattering a plate boundary: Complex multi-fault rupture during the 2016 Mw 7.8 Kaikoura earthquake, New Zealand.

A geodetic perspective!!

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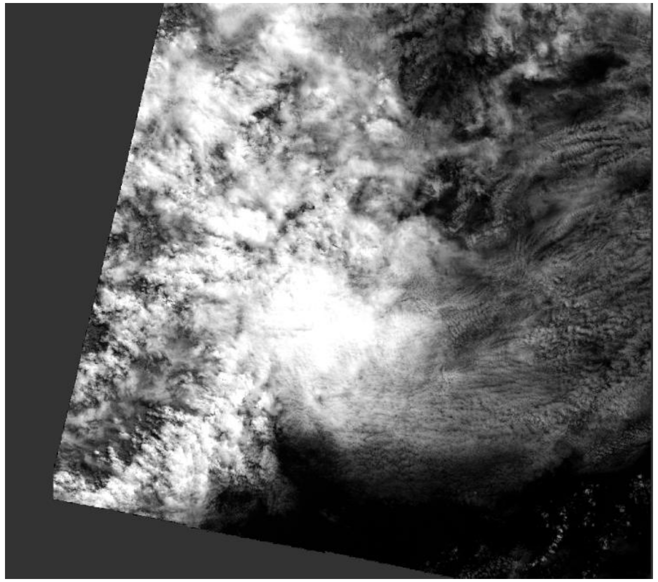
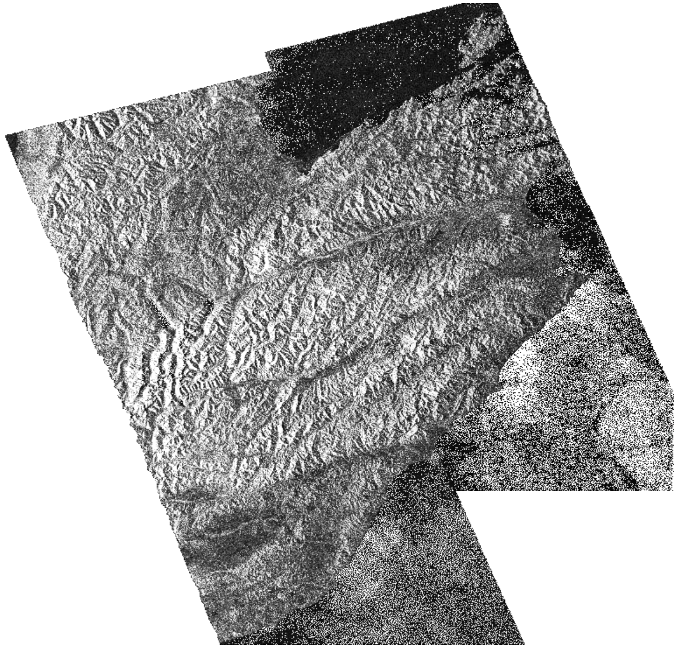
Outline:

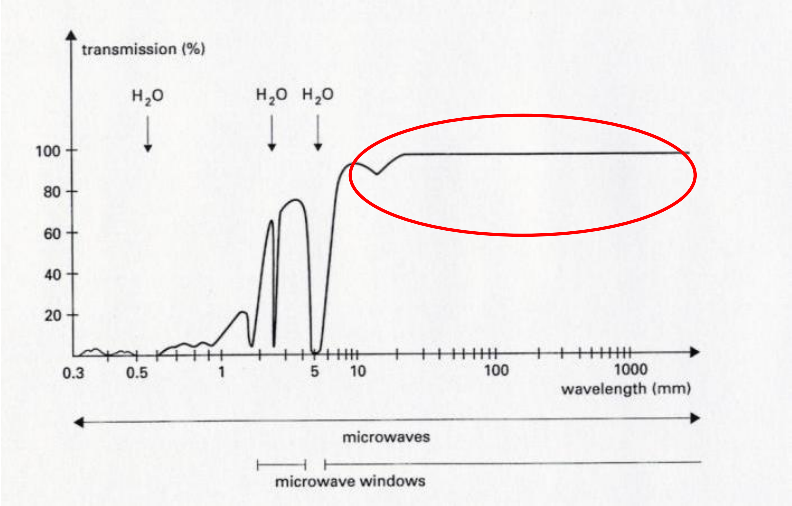
- **Satellite Radar Interferometry**
- **Geodetic observations of ground**
  - Mapping the Kaikoura rupture from space
  - Modelling of ground deformation to infer fault slip.
  - Early post-seismic deformation
- **Conclusions**

InSAR – Synthetic Aperture Radar Interferometry

- Utilises radar satellites orbiting at ~600-700 km.
- Radars operate at microwave frequencies with wavelengths of millimeters to meters. Like lasers, radars are coherent – they contain both amplitude and phase information
- Unlike optical satellites, radar can see through clouds and has its own illumination source.



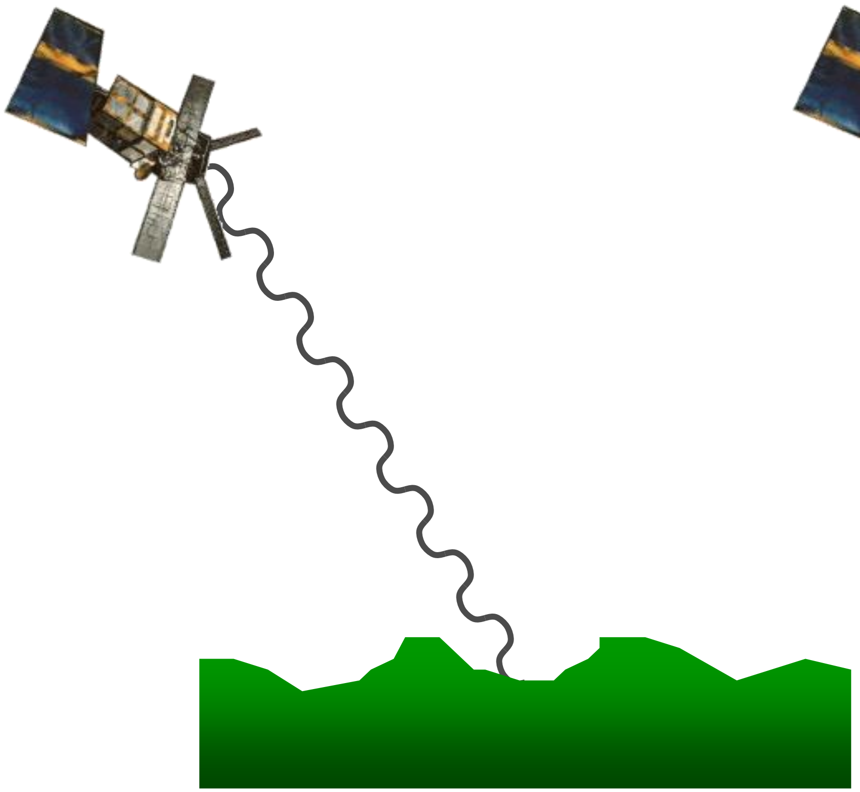




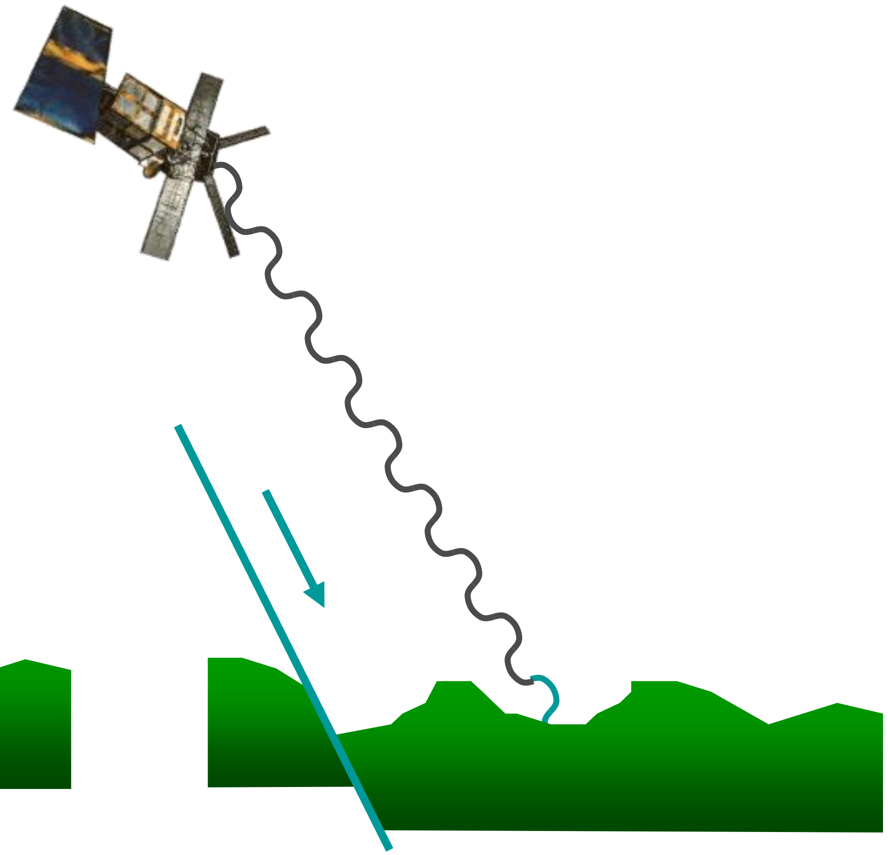
InSAR – how it works

Another two radar images taken at times t_1 and t_2 (after an earthquake)

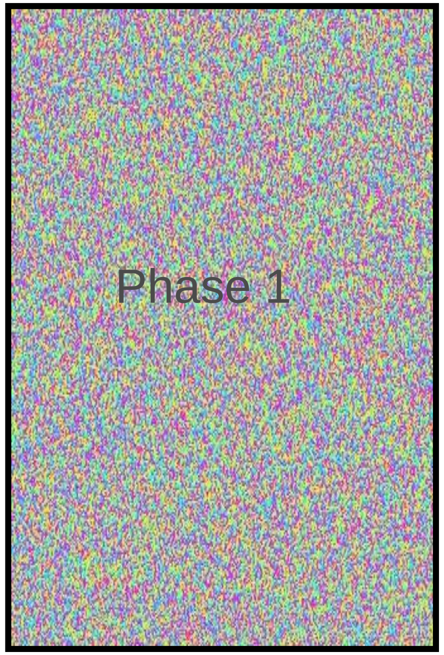
Before earthquake

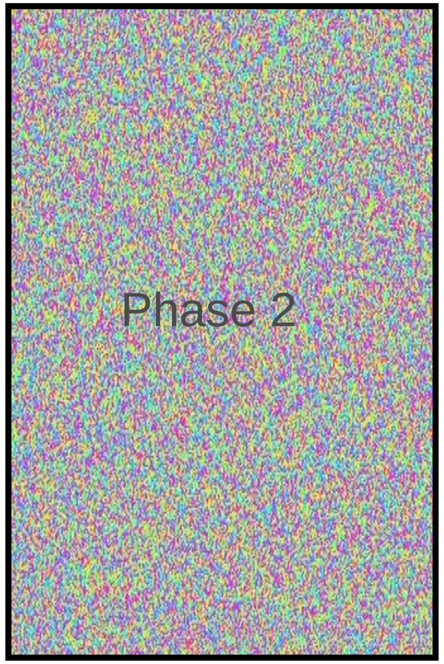


After earthquake

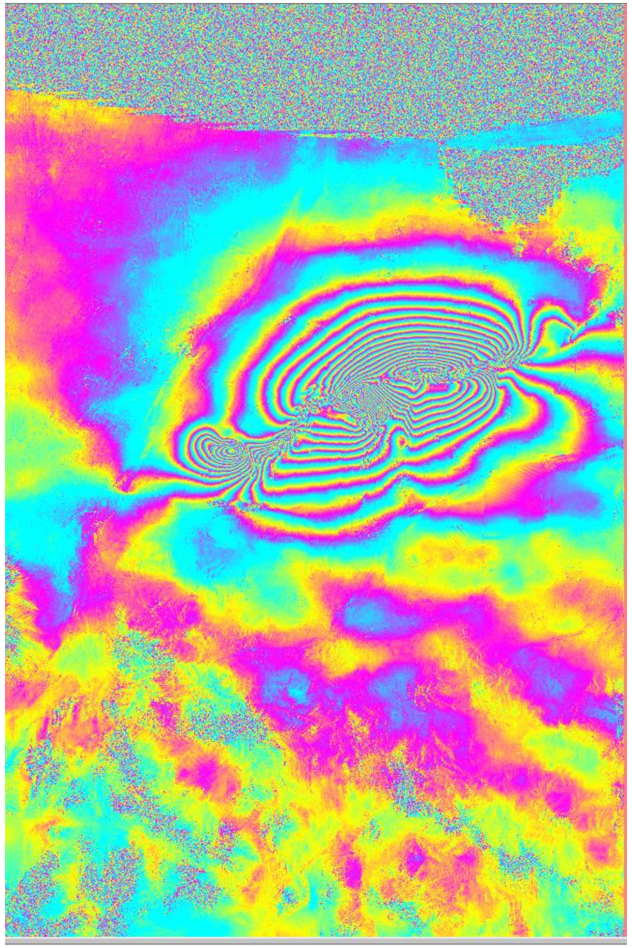


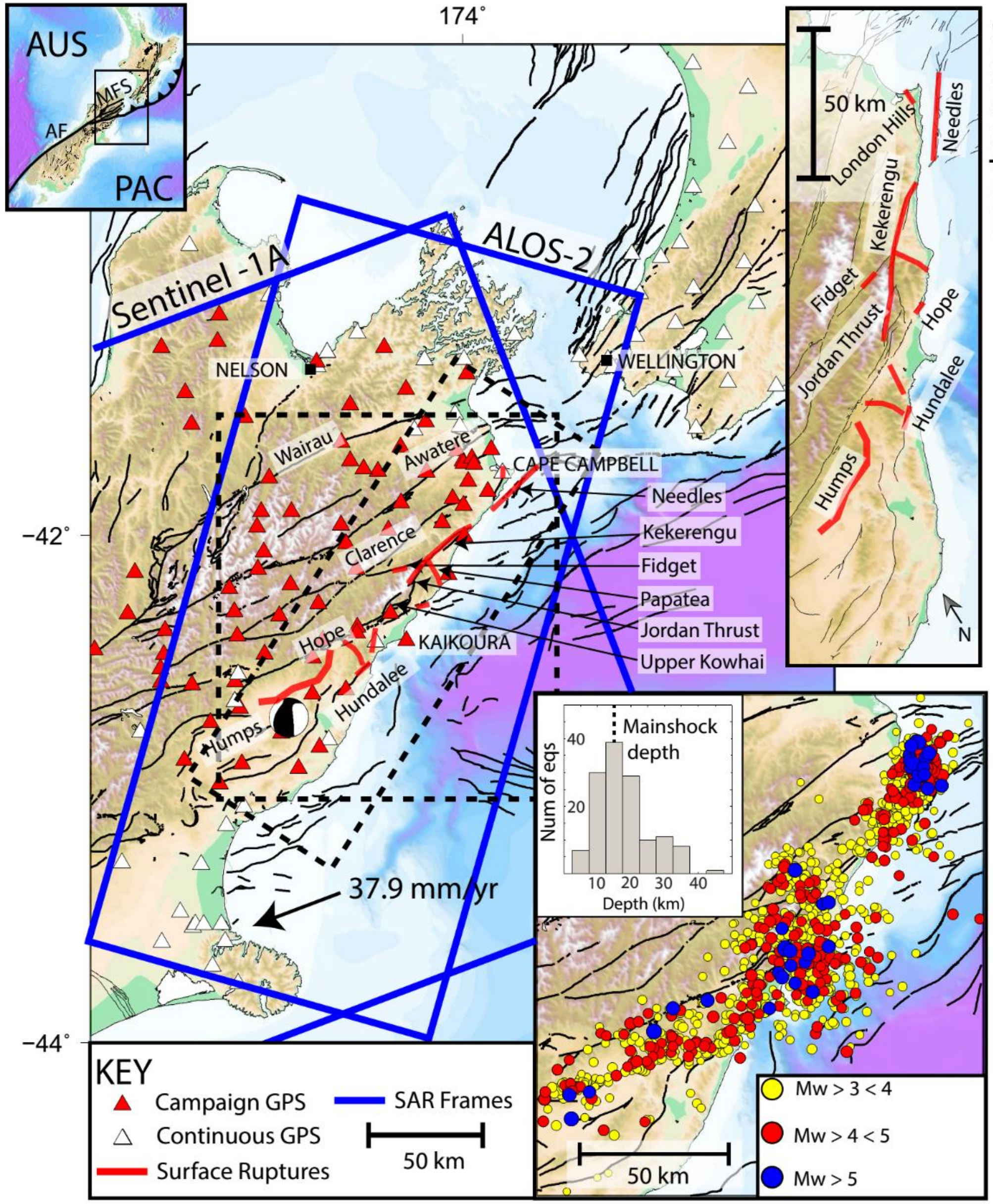
Amplitude

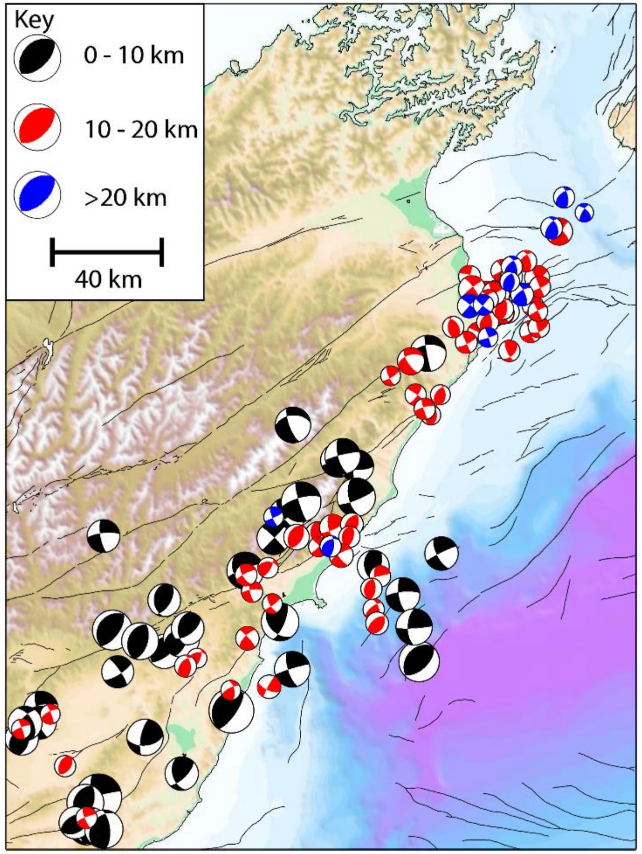




Take difference between Phase 1 and Phase 2

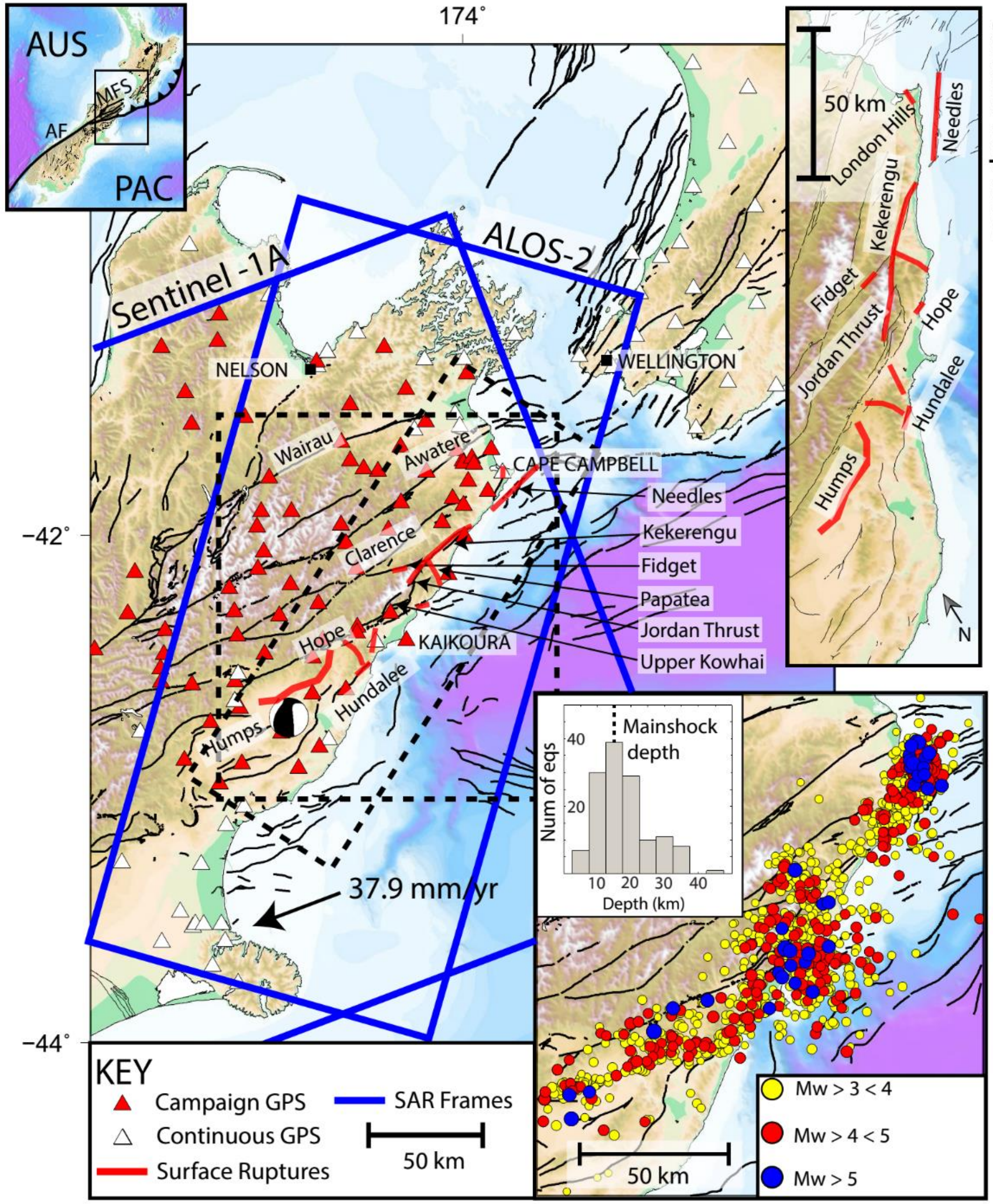


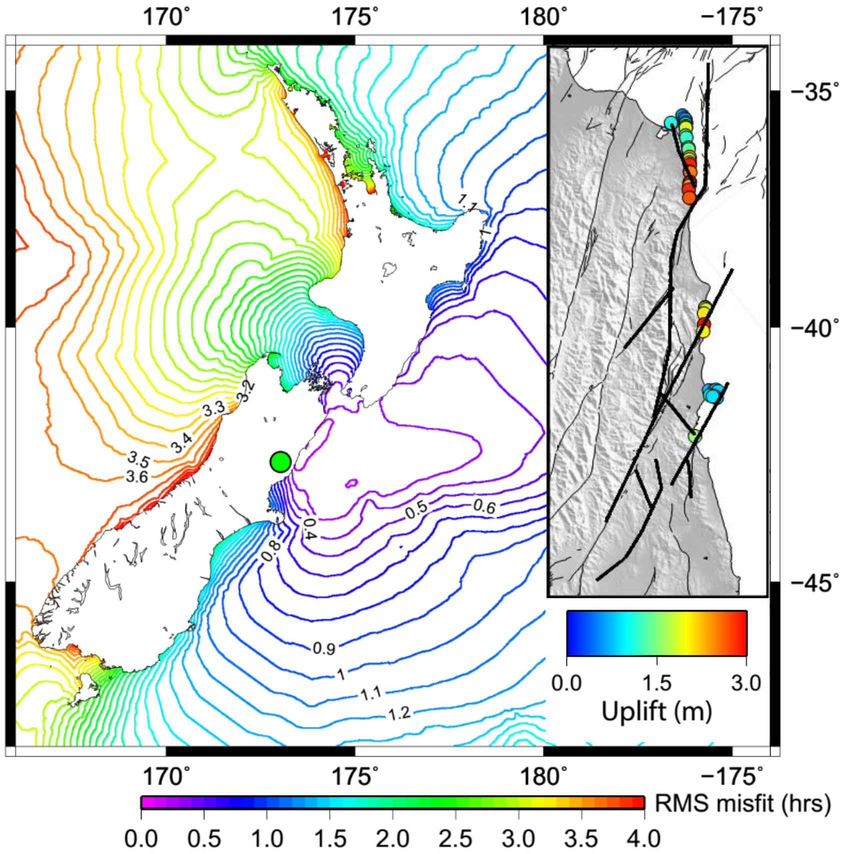




The rupture initiated in the south propagating northwards across a complex network of mapped and unmapped faults over a distance of ~180 km.

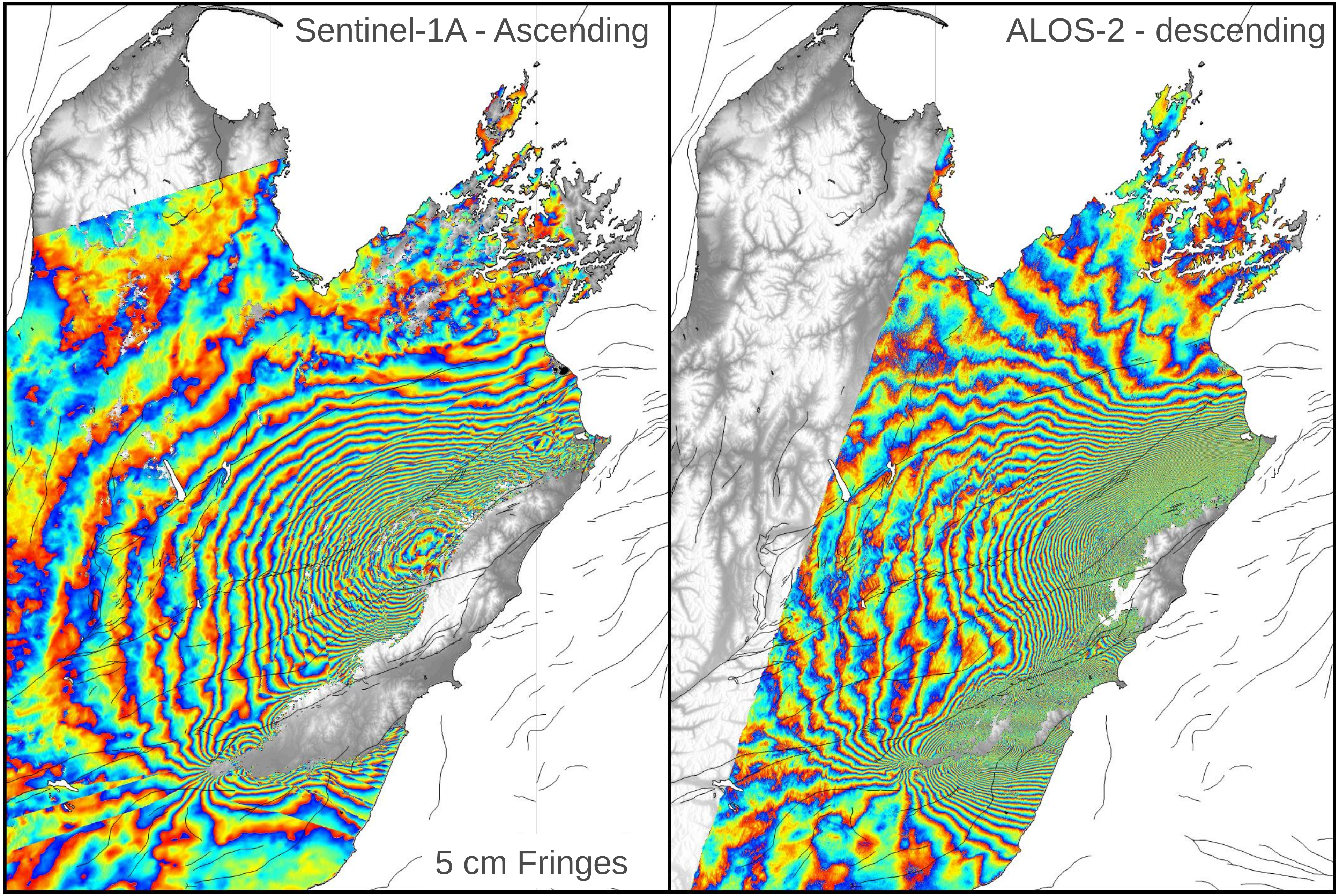
Aftershocks show a combination of strike slip and reverse mechanisms





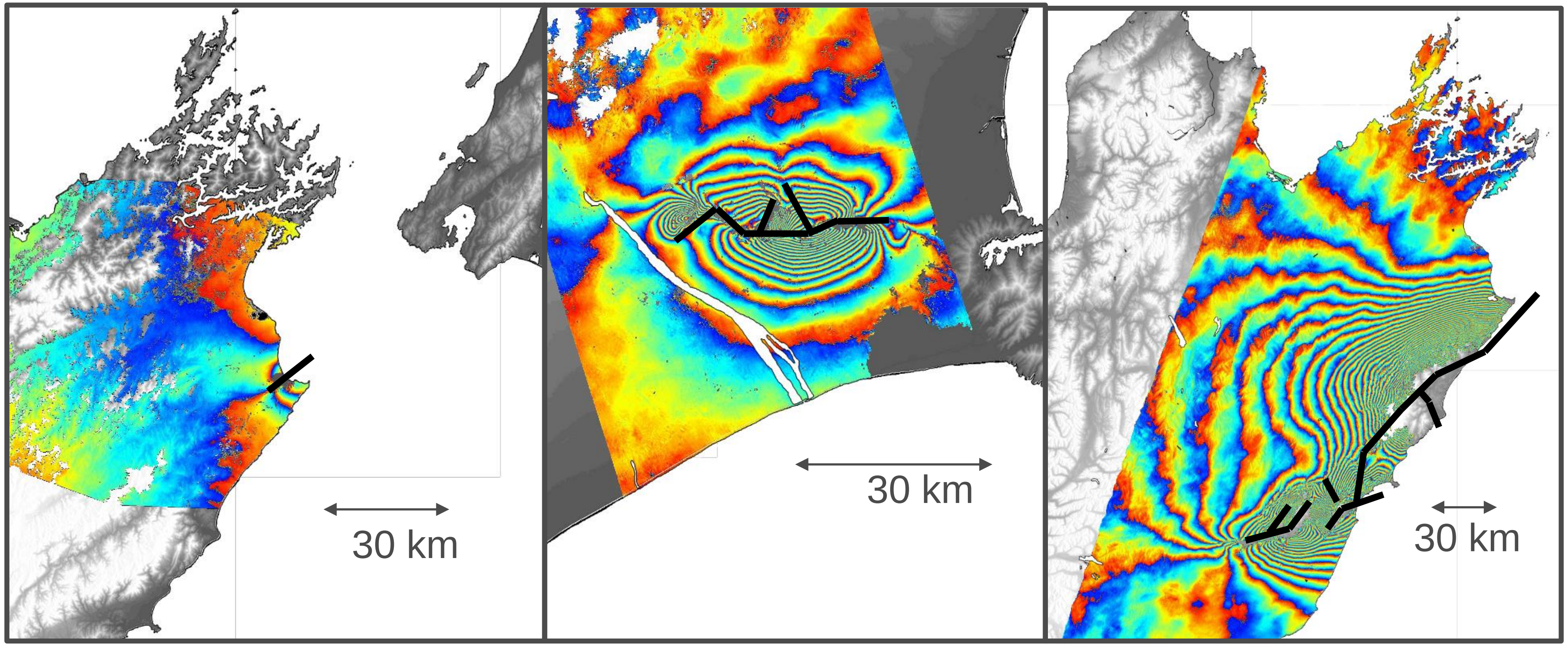
A local tsunami of up to 3 m was generated.

Travel time residuals indicate a source region somewhere between Kaikoura and Cape Campbell.



03/11/16 – 15/11/2016

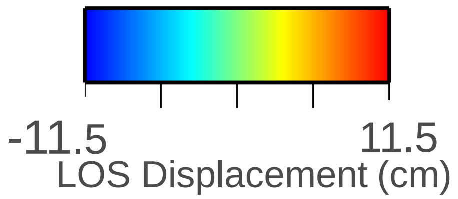
18/10/16 – 16/11/2016

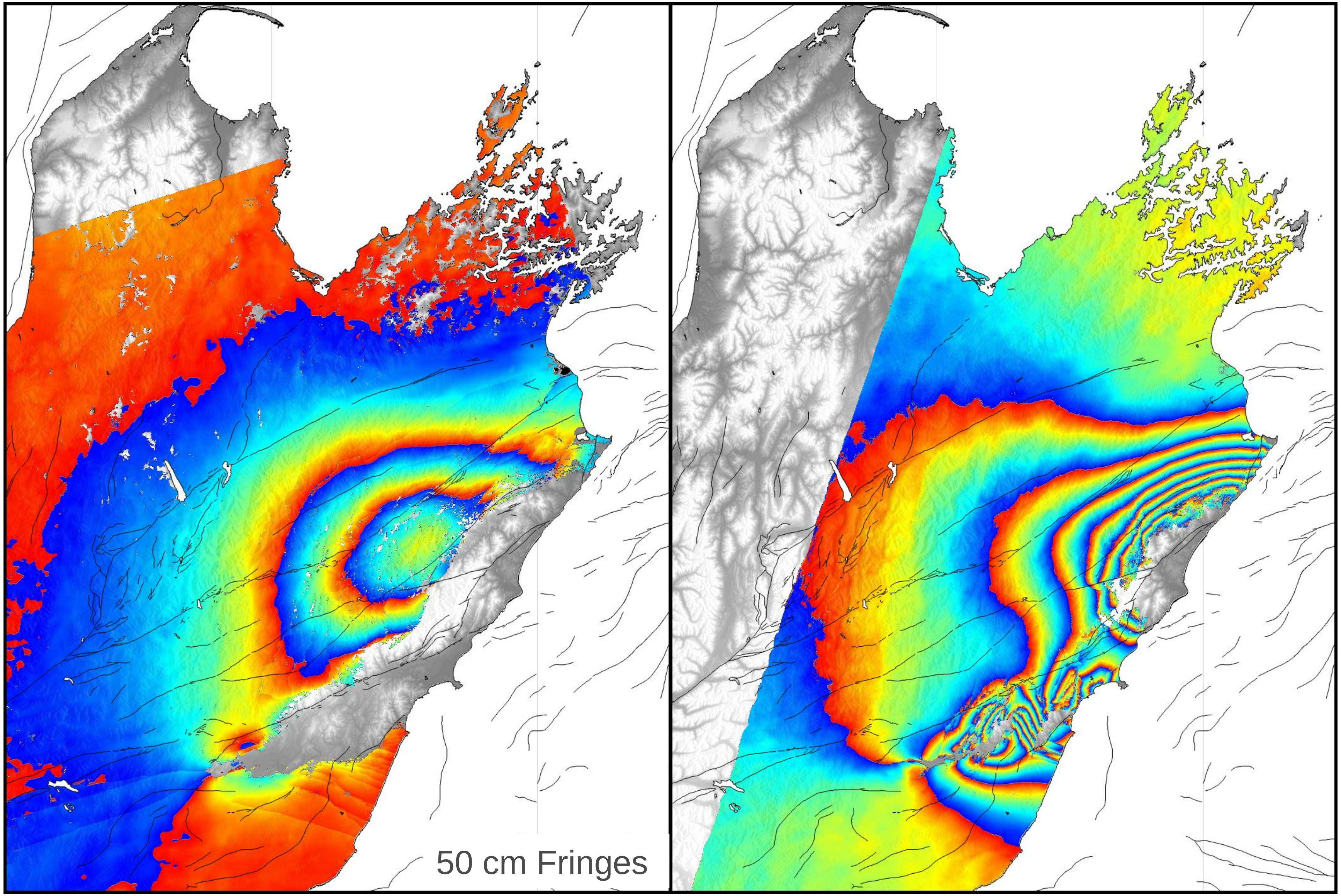


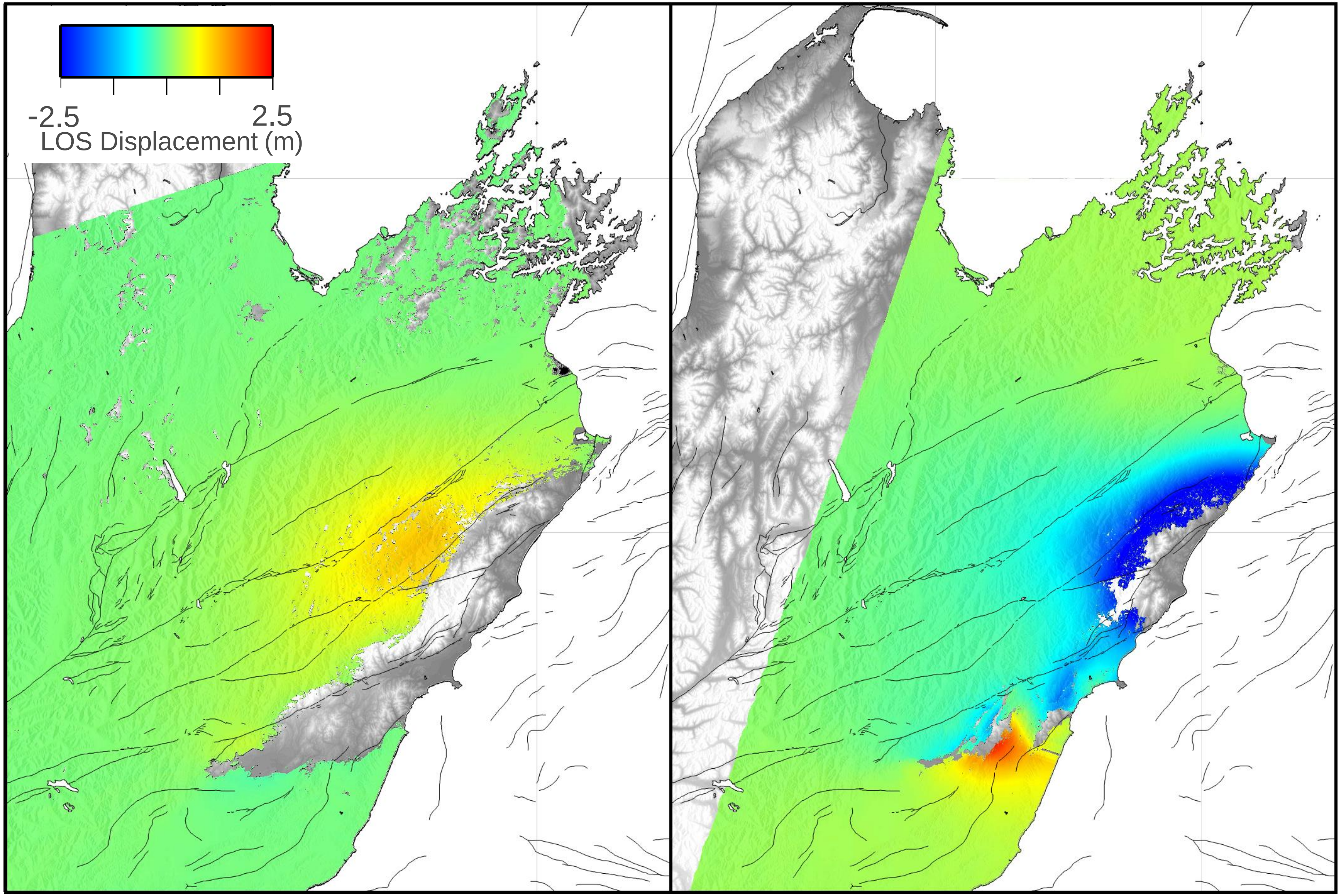
Mw 6.7 Lake Grassmere 2013

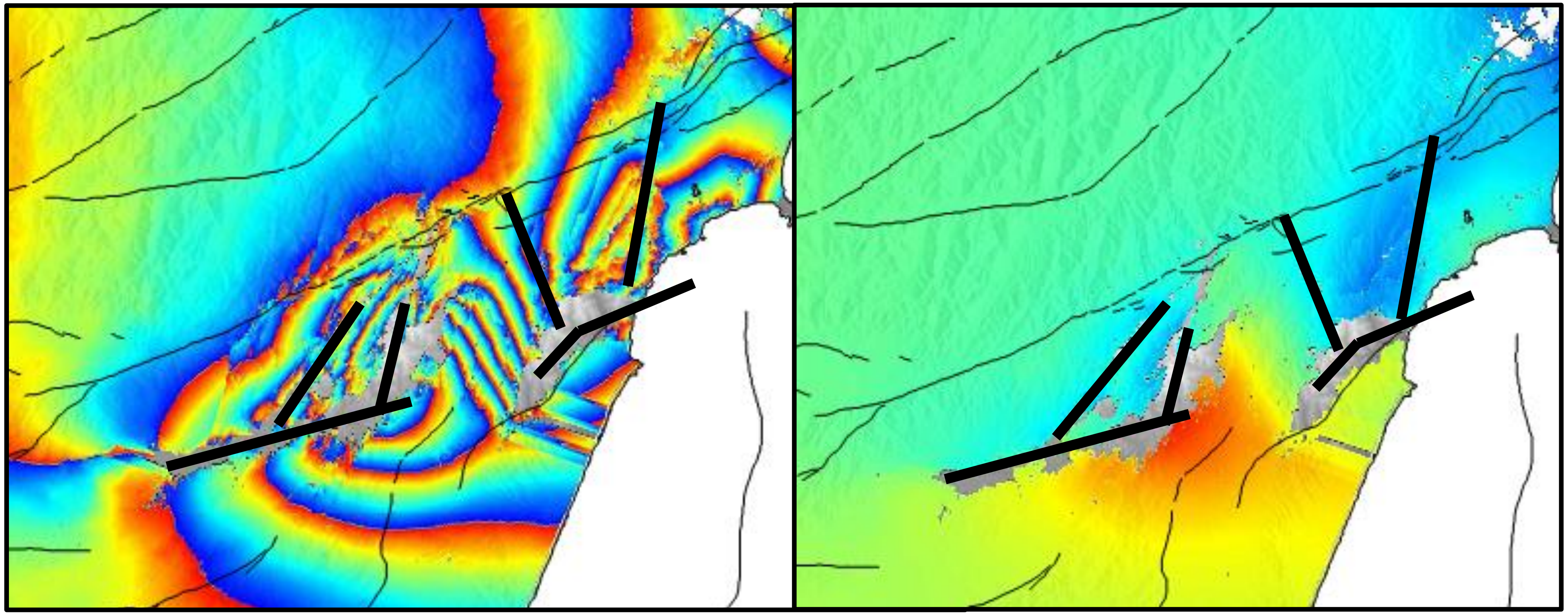
Mw 7.1 Darfield 2010

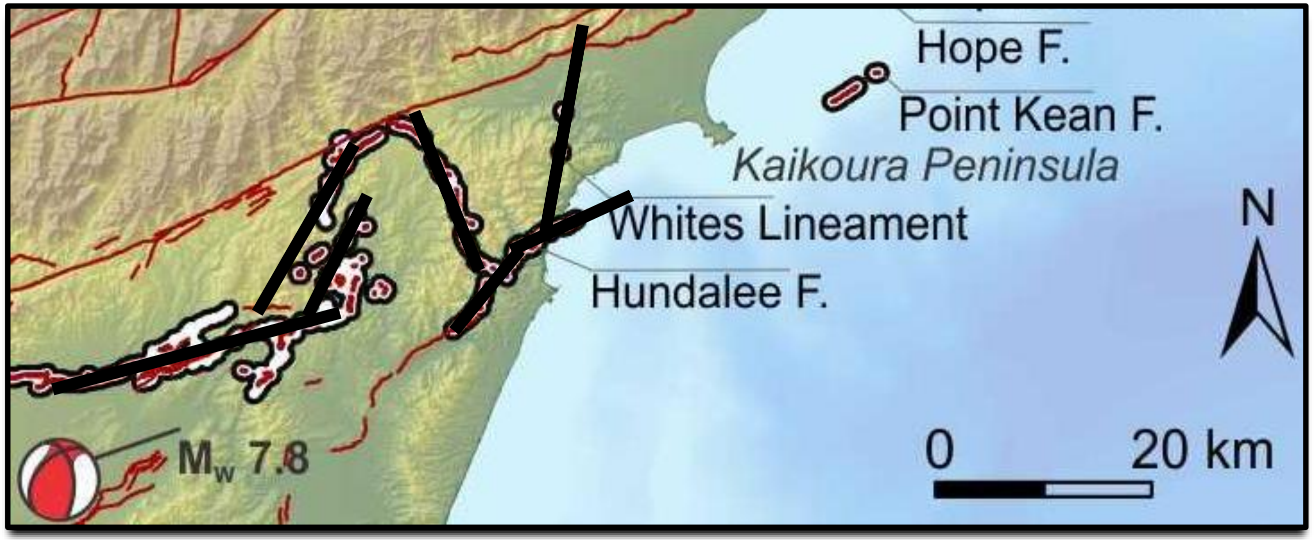
Mw 7.1 Darfield 2010




50 cm Fringes


-2.5
2.5
LOS Displacement (m)

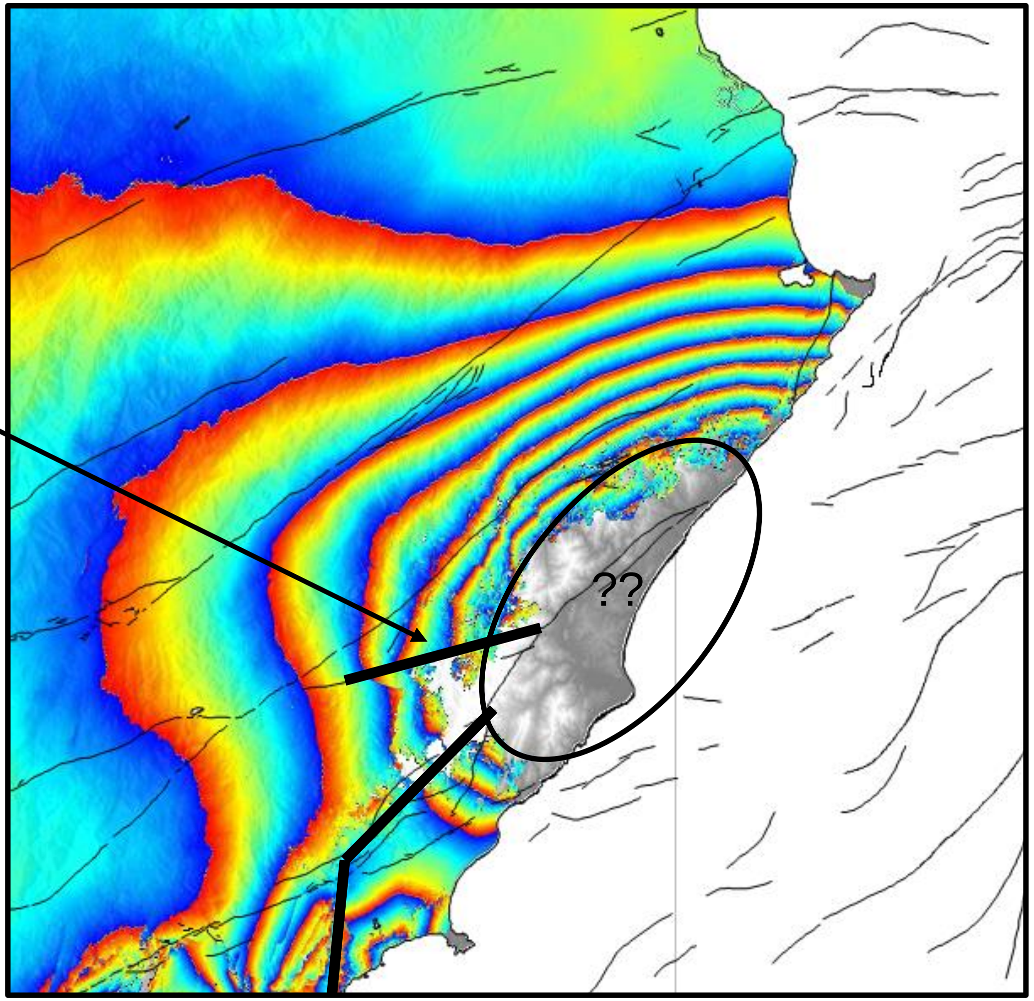


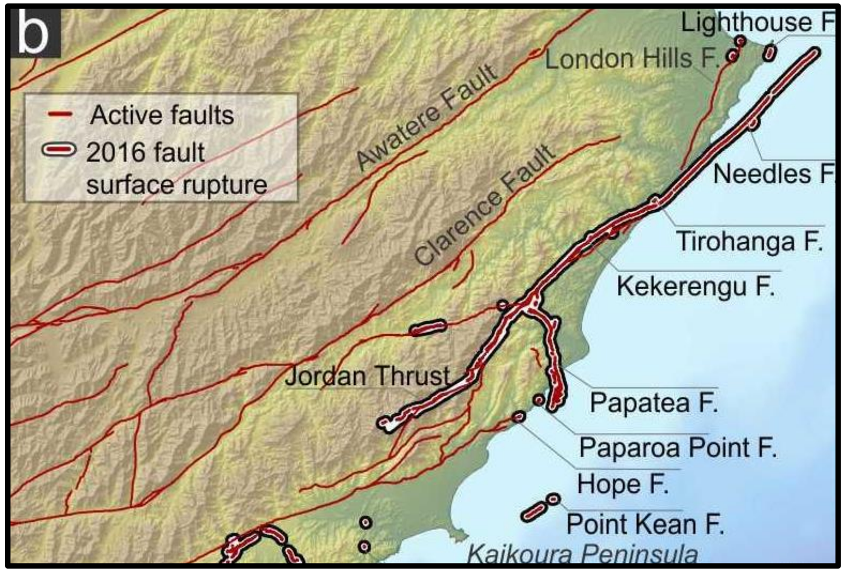


Fault ruptures can be directly traced in interferograms as sharp breaks in phase and zones of decorrelation

Clark et al; 2017 submitted

Offset in phase indicating rupture along Fidget fault

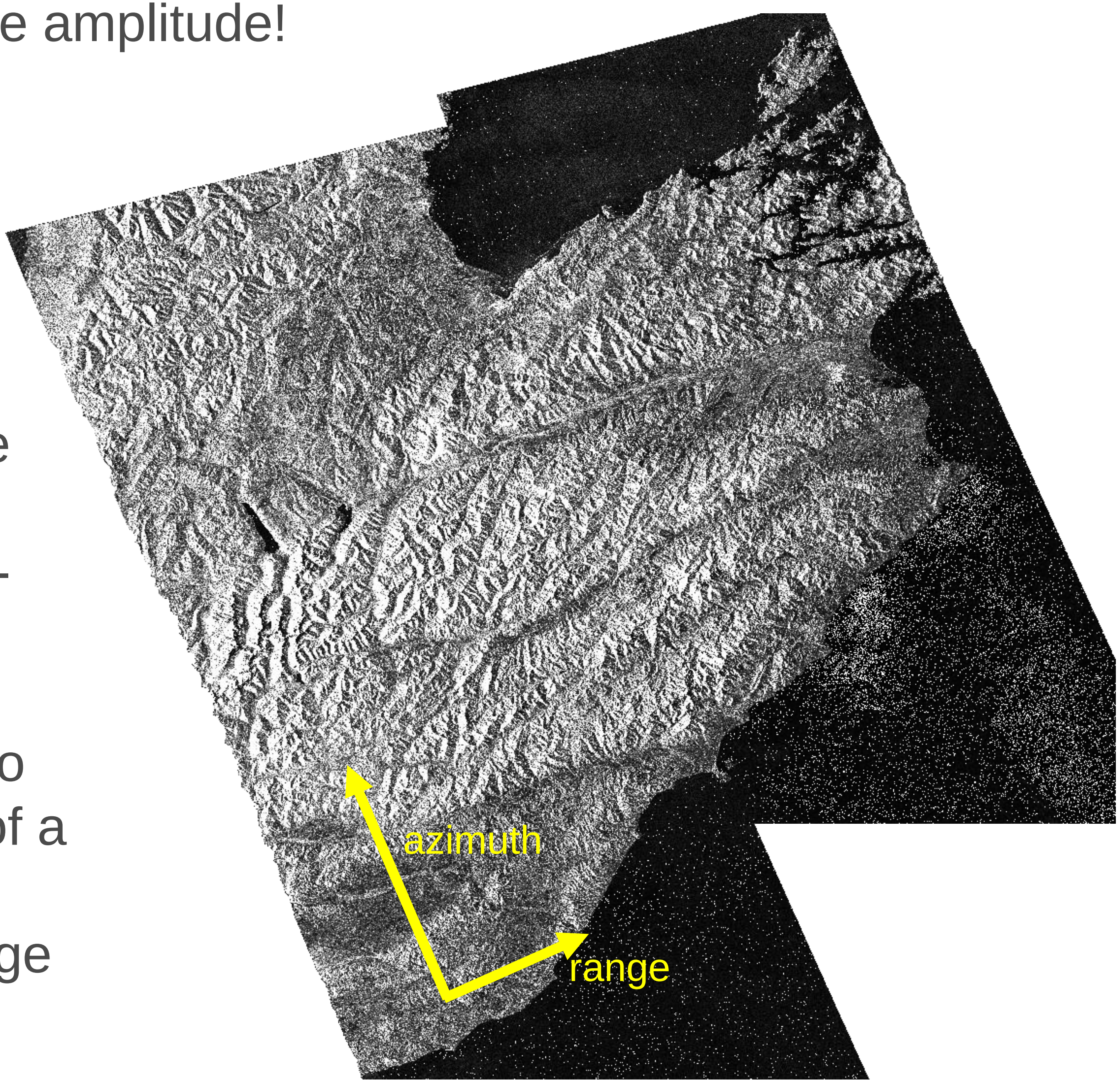




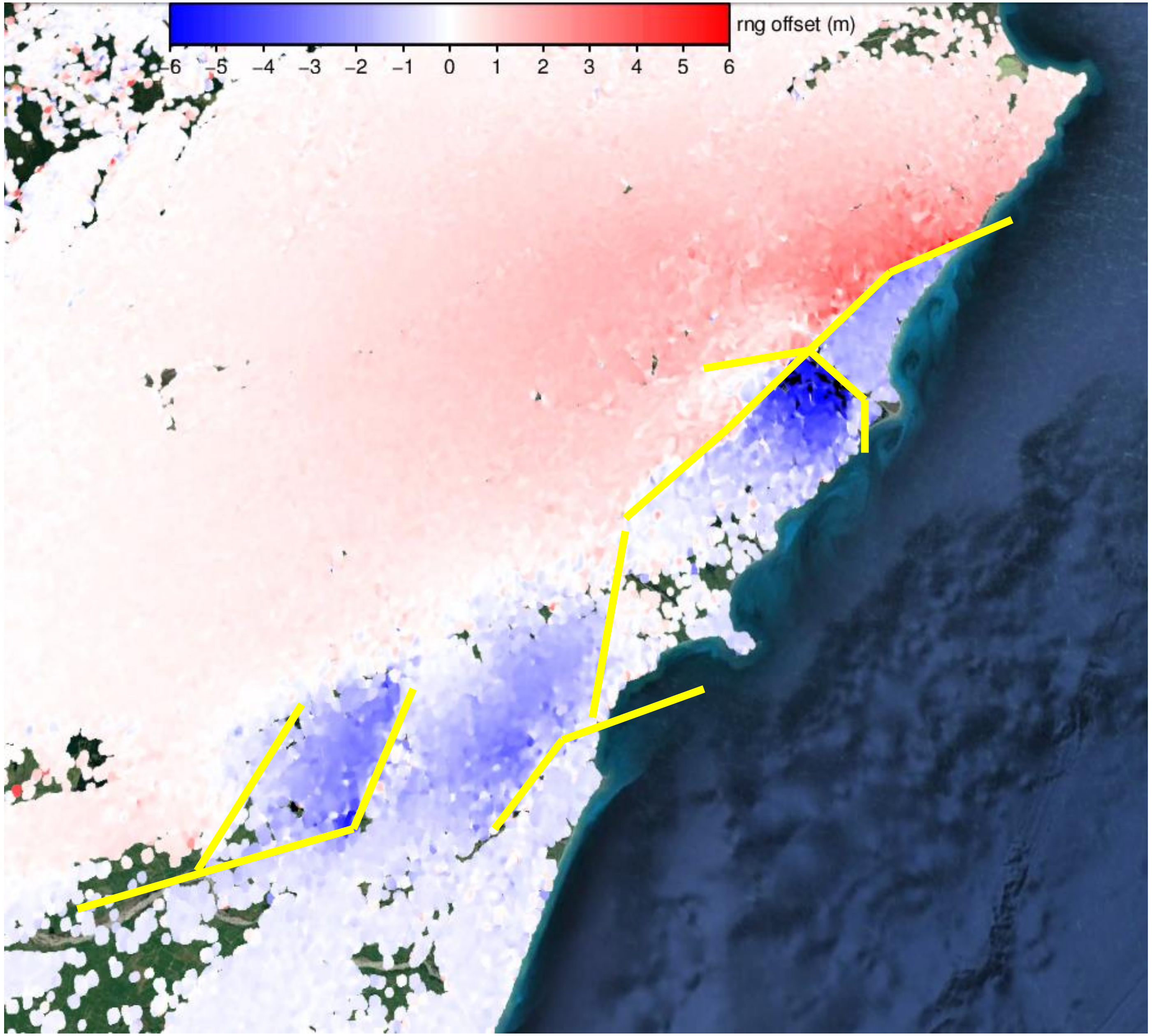
Ground damage and high phase gradients lead to de-correlation in the near field.

Now we can use the amplitude!

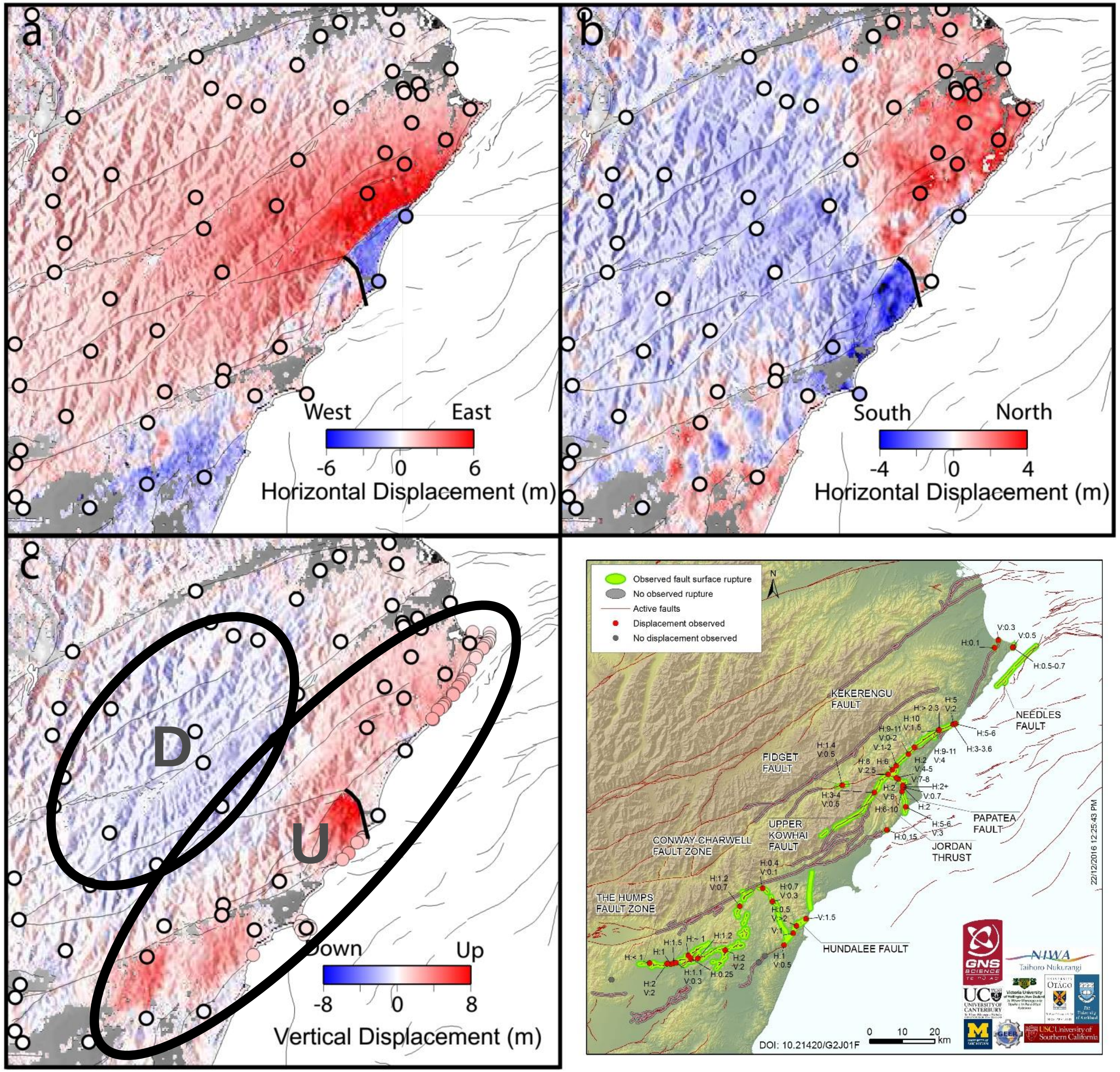
- To form the interferogram we have to align the images with sub-pixel accuracy.
- This provides two measurements of a pixels offset in azimuth and range



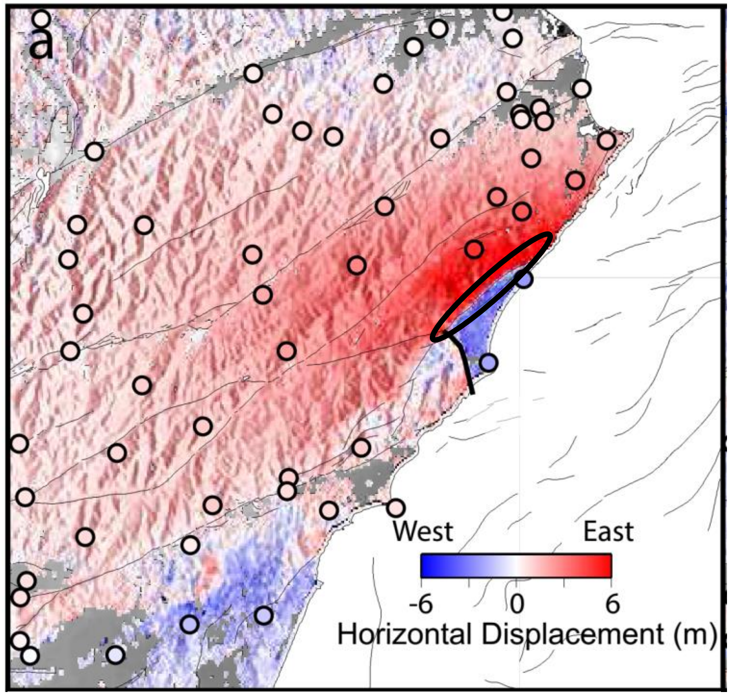
Azimuth offsets

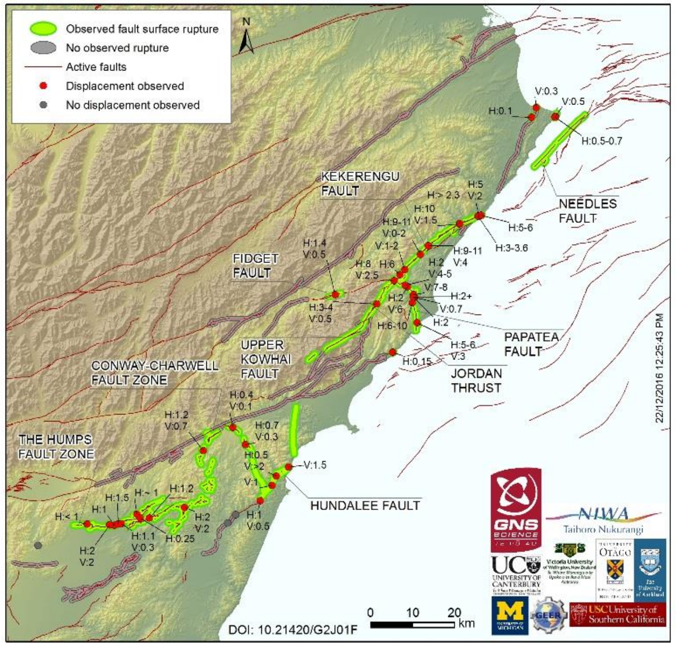


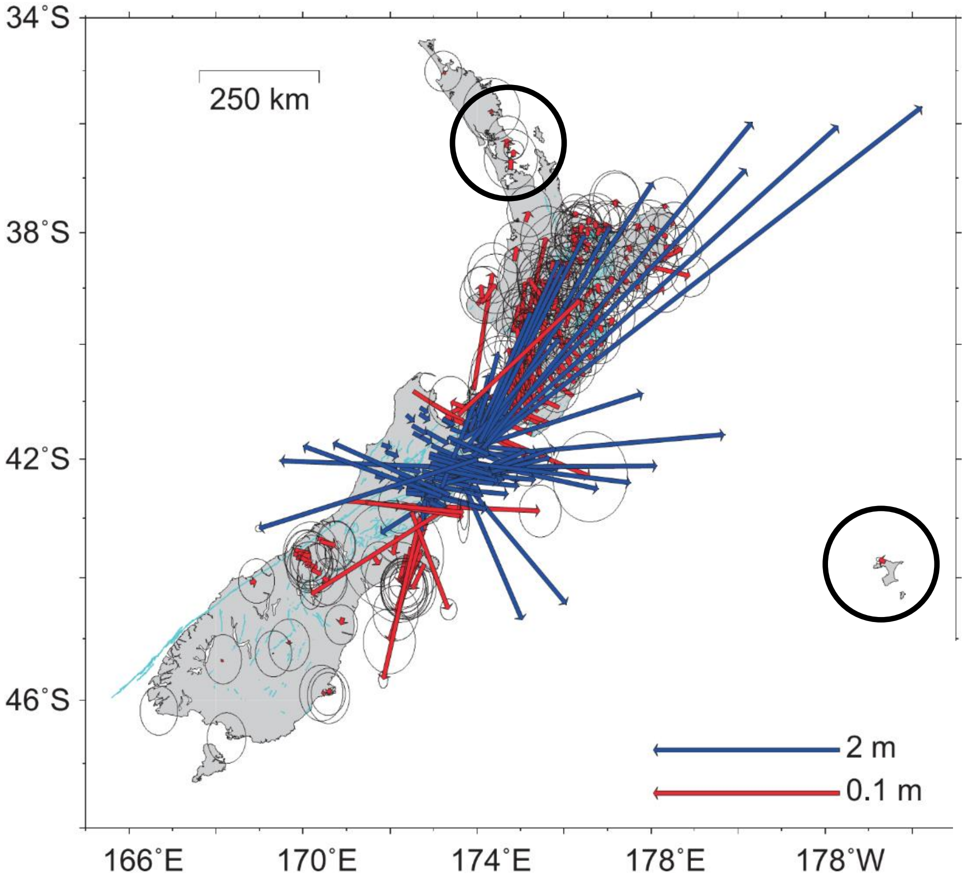
By using range and azimuth offsets from ascending a descending data we can derive the full 3D displacement field



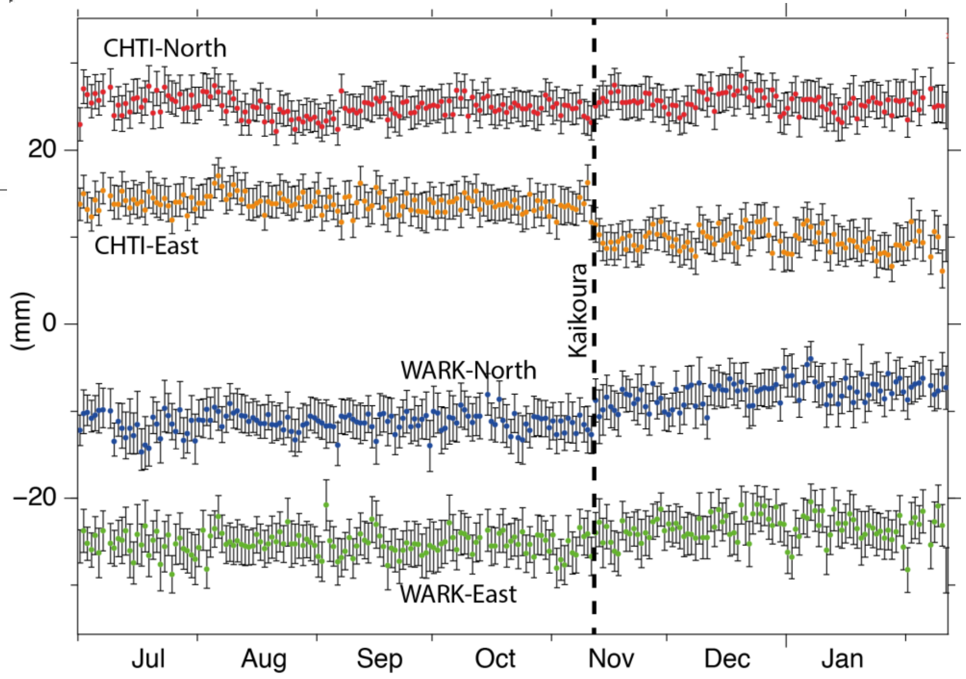
a
West
East
-6
0
6
Horizontal Displacement (m)
b
South
North
-4
0
4
Horizontal Displacement (m)
c
D
U
Down
Up
-8
0
8
Vertical Displacement (m)
Observed fault surface rupture
No observed rupture
Active faults
Displacement observed
No displacement observed
KEKERENGU FAULT
NEEDLES FAULT
FIDGET FAULT
PAPATEA FAULT
UPPER KOWHAI FAULT
CONWAY-CHARWELL FAULT ZONE
JORDAN THRUST
THE HUMPS FAULT ZONE
HUNDALEE FAULT
22/12/2016 12:25:43 PM
DOI: 10.21420/G2J01F


a
West
East
-6
0
6
Horizontal Displacement (m)

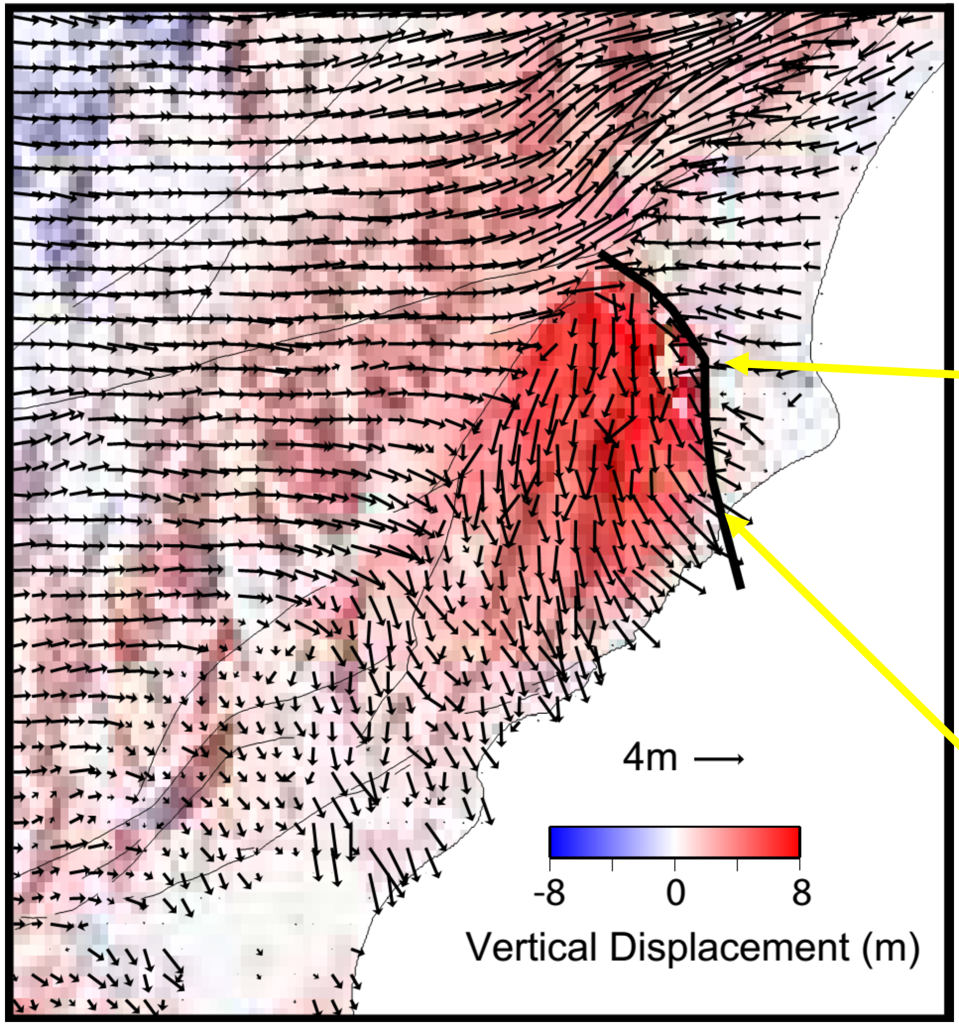

Observed fault surface rupture
No observed rupture
Active faults
Displacement observed
No displacement observed
N
KEKERENGU FAULT
NEEDLES FAULT
FIDGET FAULT
PAPATEA FAULT
UPPER KOWHAI FAULT
JORDAN THRUST
CONWAY-CHARWELL FAULT ZONE
THE HUMPS FAULT ZONE
HUNDALEE FAULT
V:0.3
V:0.5
H:0.1
H:0.5-0.7
H:5-6
H:3-3.6
H:9-11
V:4
H:2+
V:0.7
H:5-6
V:3
H:0.15
H:1.2
V:0.7
H:0.4
V:0.1
H:0.7
V:0.3
V:1.5
H:1
V:0.5
H:0.25
22/12/2016 12:25:43 PM
0 10 20 km
DOI: 10.21420/G2J01F
GNS SCIENCE
NIWA
Taihoro Nukurangi
UC UNIVERSITY OF CANTERBURY
OTAGO
USC University of Southern California



- Maximum horizontal displacements of 6 m in inland Kaikoura.
- Widespread uplift of up along much of the earthquake rupture.



Not only local area effected, sites on Chatham Islands and Auckland show displacements of a few millimeters


4m
-8
0
8
Vertical Displacement (m)

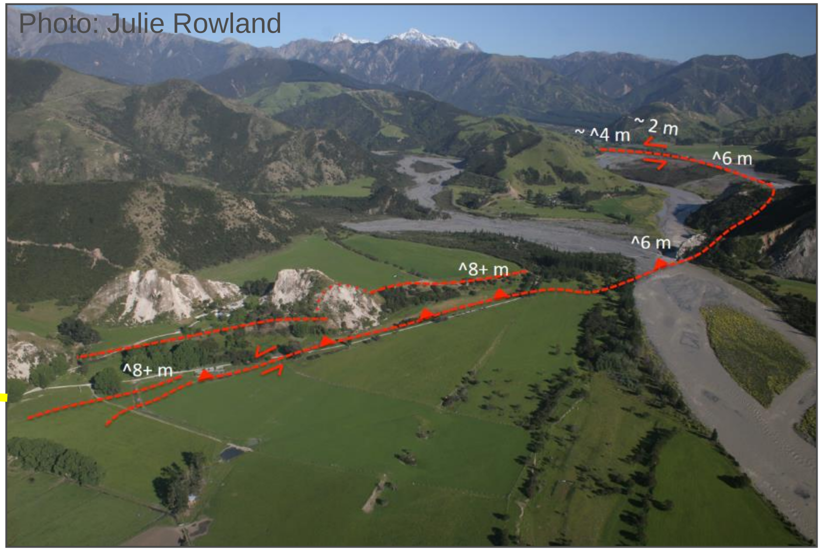


Photo: Julie Rowland
~ ^4 m
~ 2 m
^6 m
^6 m
^8+ m
^8+ m

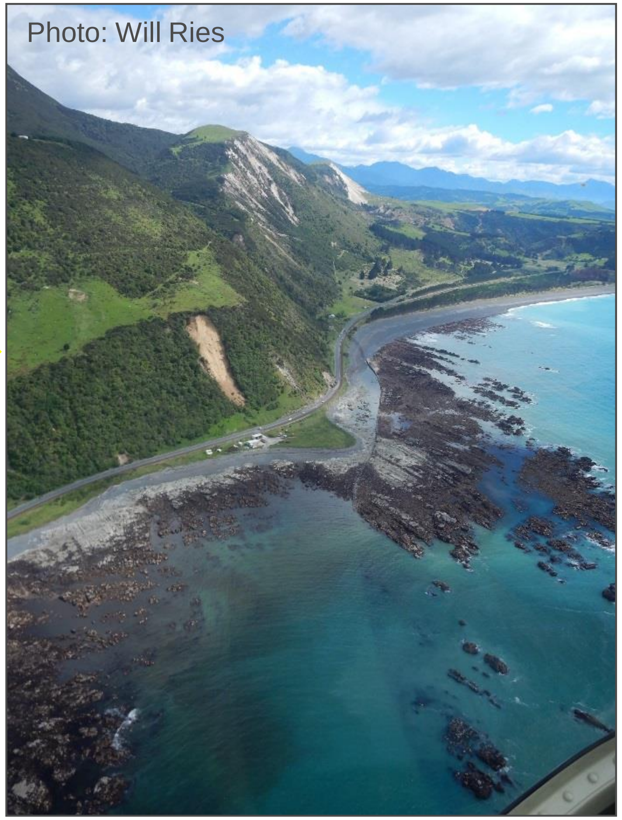
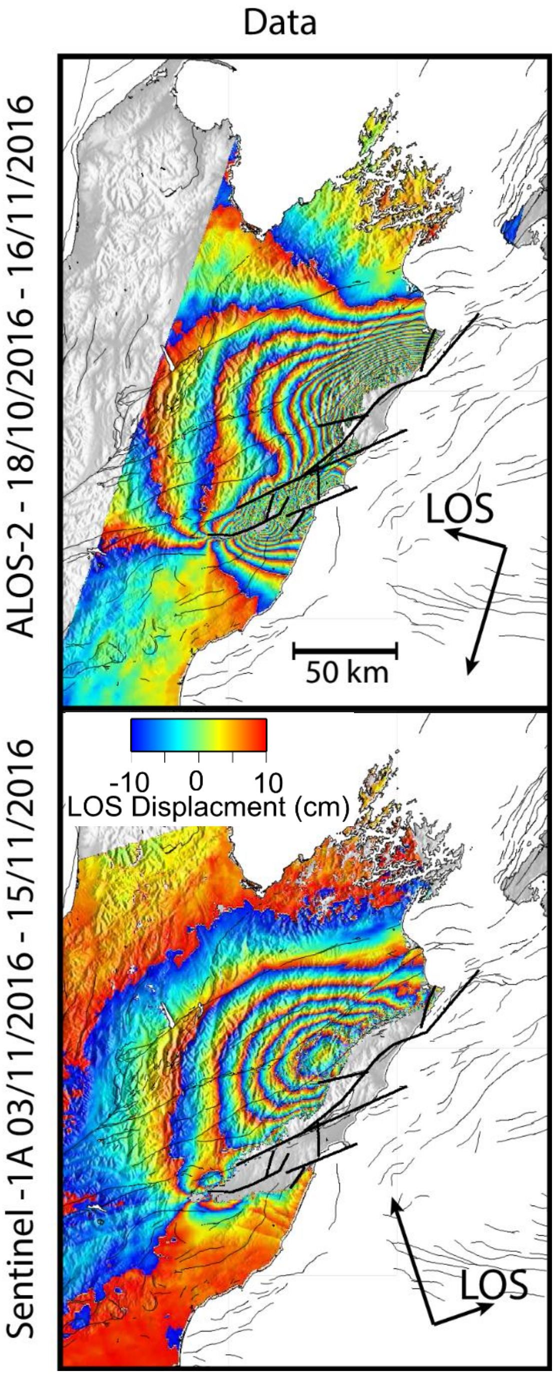
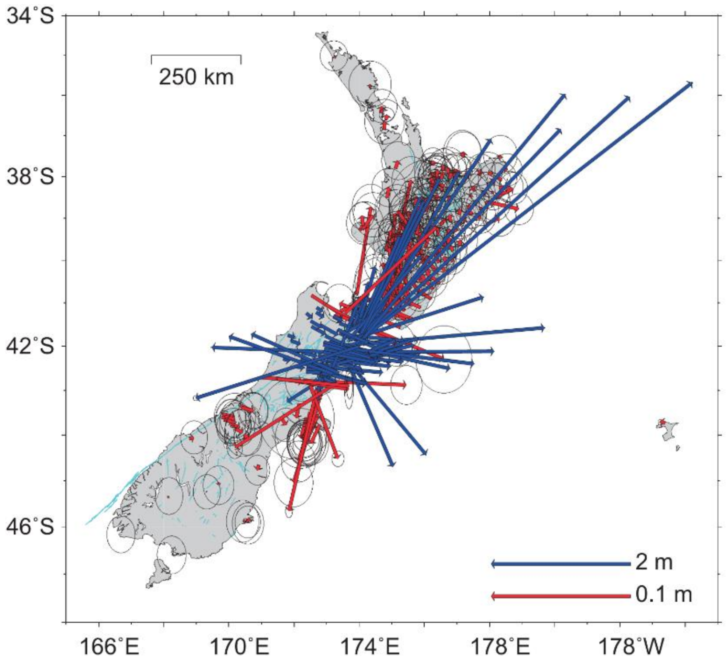


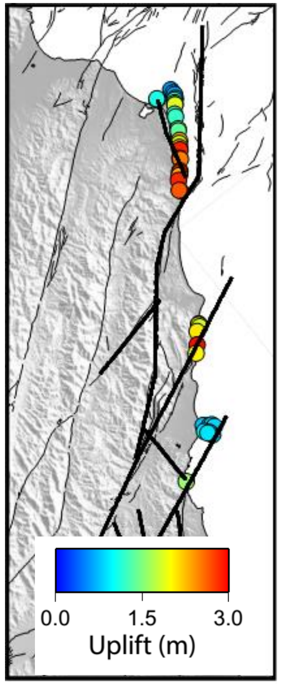
Photo: Will Ries

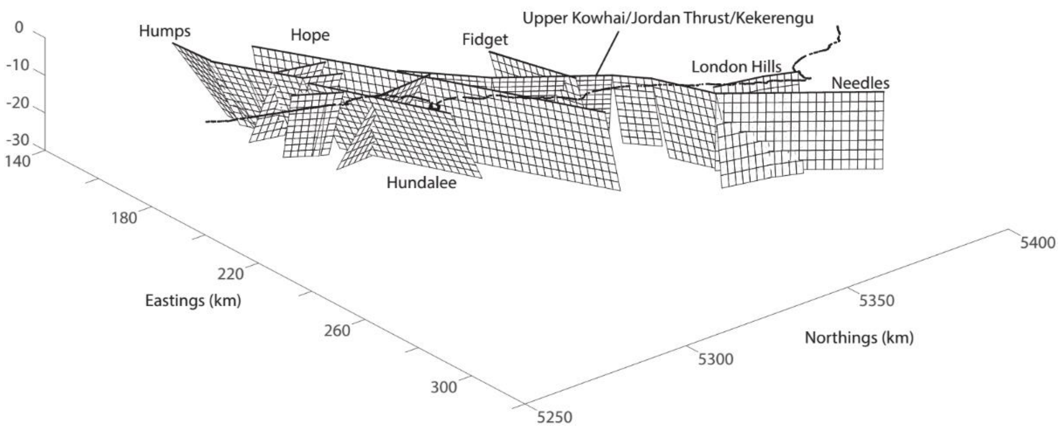


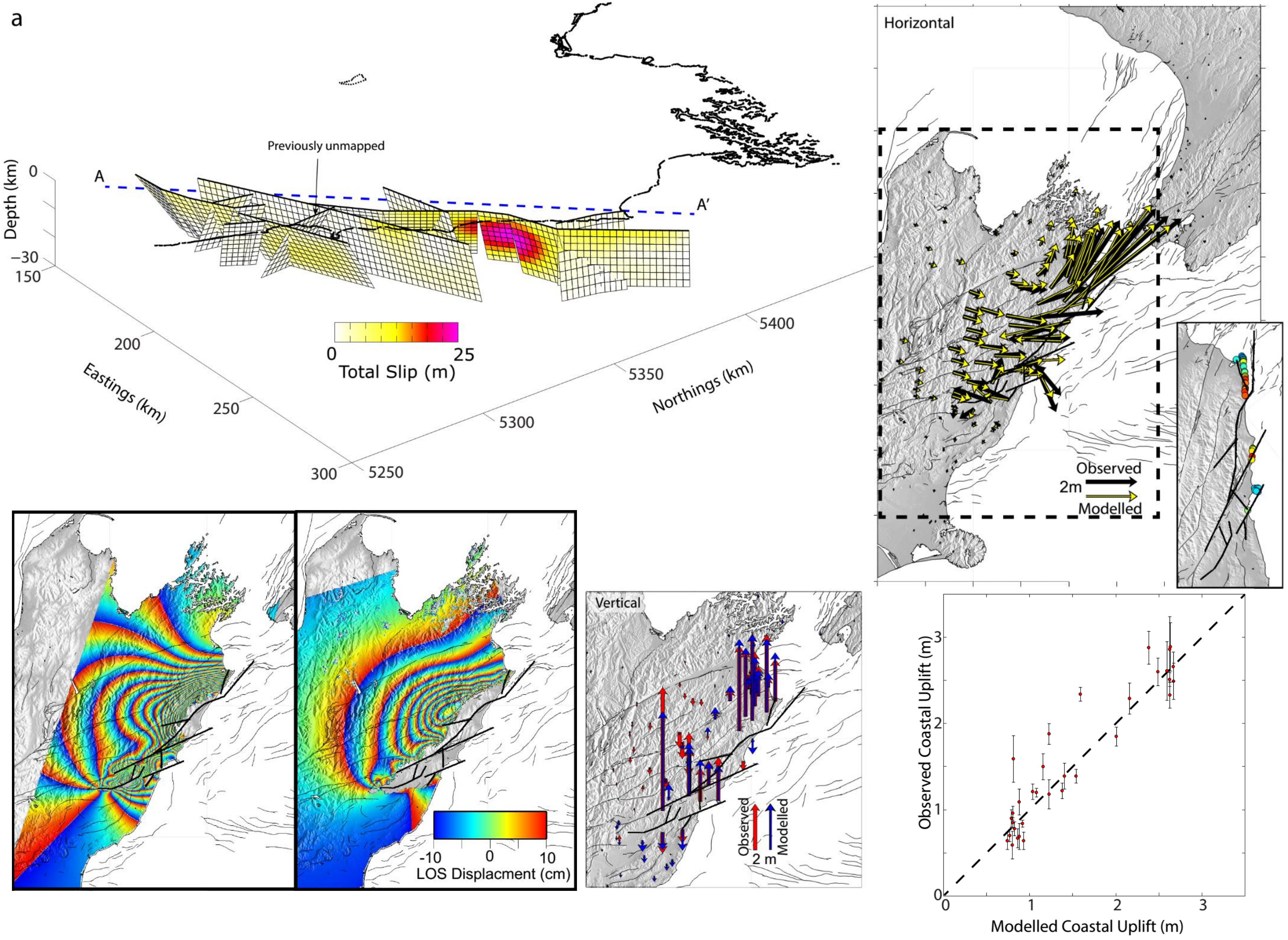


Based on offsets in radar data and field observations we build a fault model encompassing all the main structures.

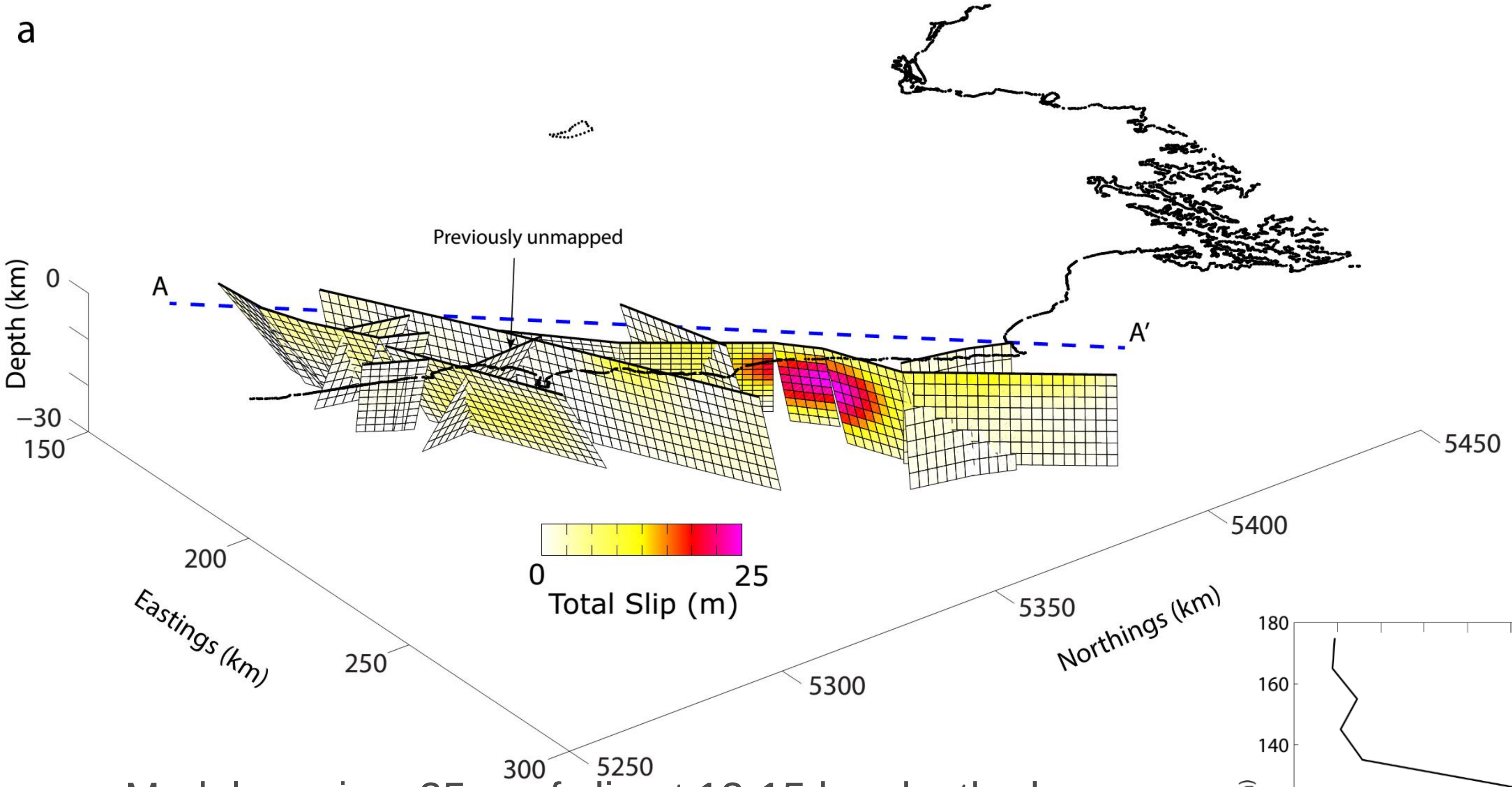
Split the model into 2x3 km sub-faults and solve for the best fit slip distribution.

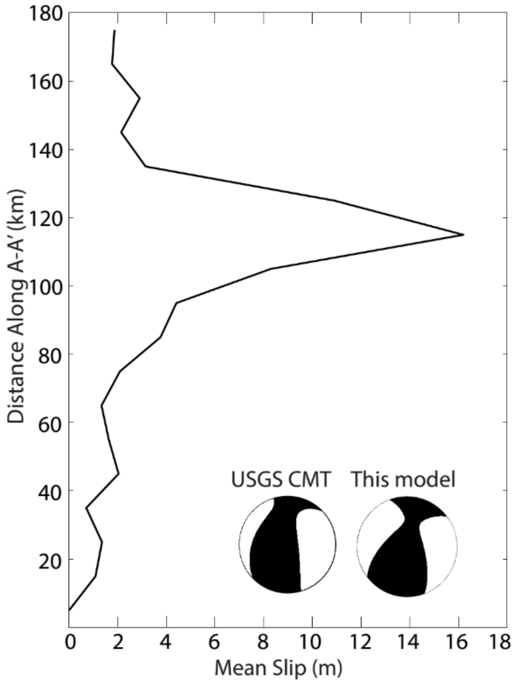






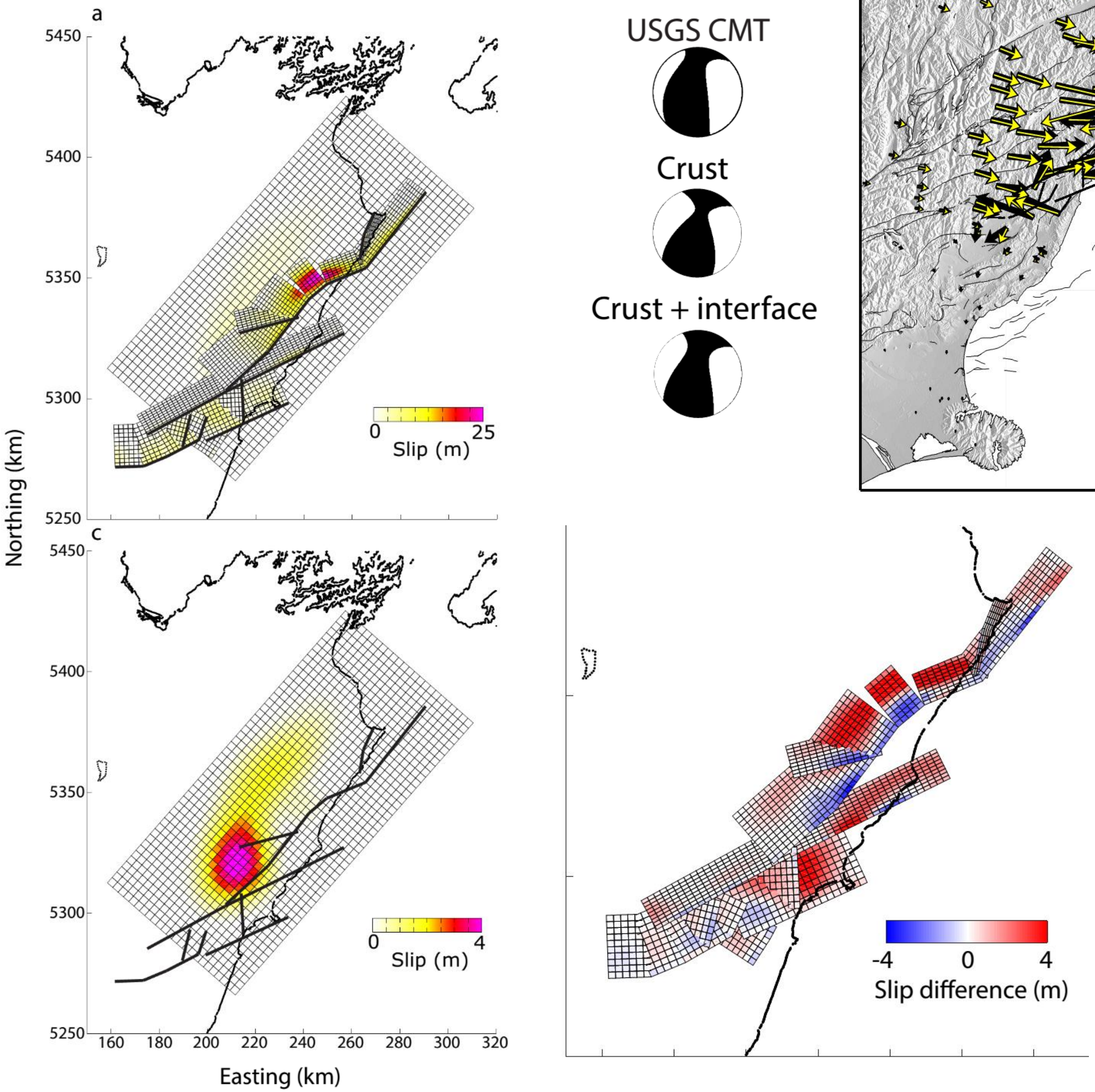
a
Previously unmapped
Depth (km)
0
−30
A
A′
150
200
250
300
Eastings (km)
5250
5300
5350
5400
Northings (km)
0
25
Total Slip (m)
Horizontal
Observed
2m
Modelled
-10
0
10
LOS Displacment (cm)
Vertical
Observed
Modelled
2 m
Observed Coastal Uplift (m)
Modelled Coastal Uplift (m)
0
1
2
3

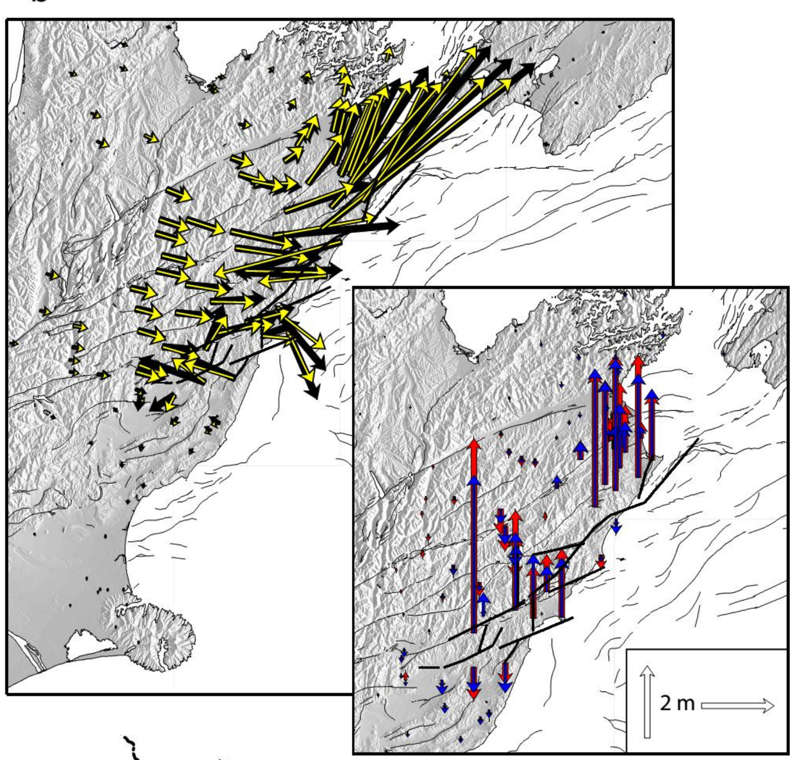




- Model requires 25 m of slip at 12-15 km depth along the deeper part of the Kekerengu fault.
- Predicted slip is consistent with field observations of surface rupture
- Although lower, slip of ~10 m is predicted at depth along the Humps and Hundalee segments in the south

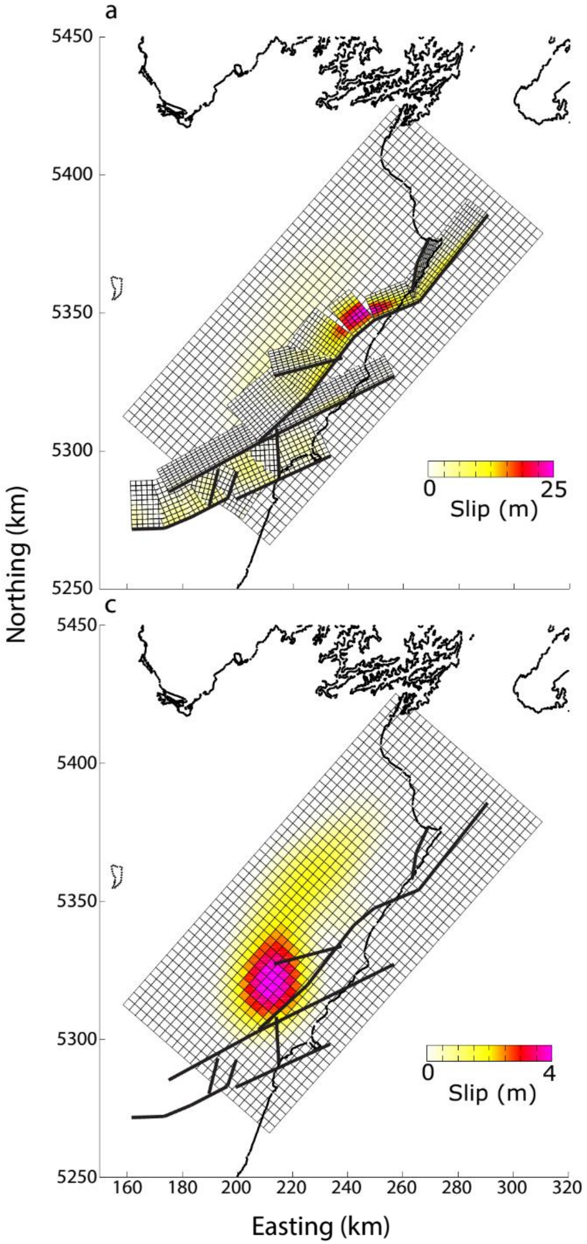
Was there slip on the southern Hikurangi?

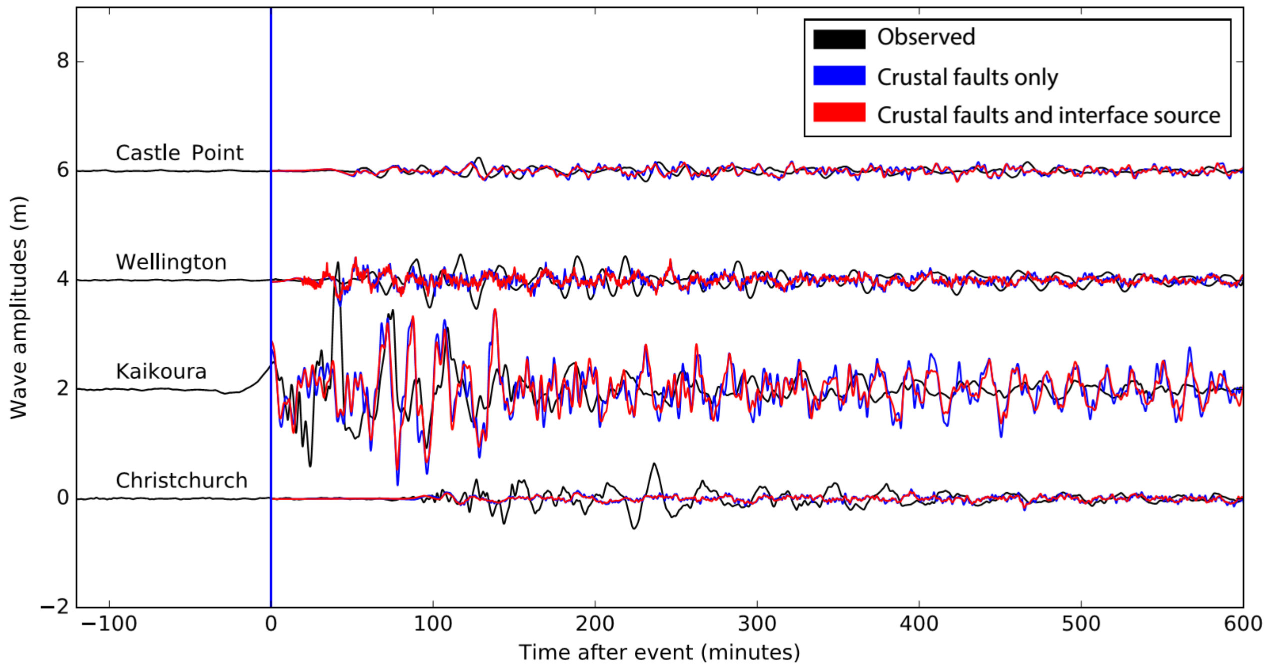




- With slip on the subduction interface, the focal mechanism becomes closer to the one derived from USGS W-phase inversion.
- Adding the subduction interface does not change the total misfit (<1%)
- Contribution of the interface o the overall moment is relatively minor (~15%)

Was there slip on the southern Hikurangi?





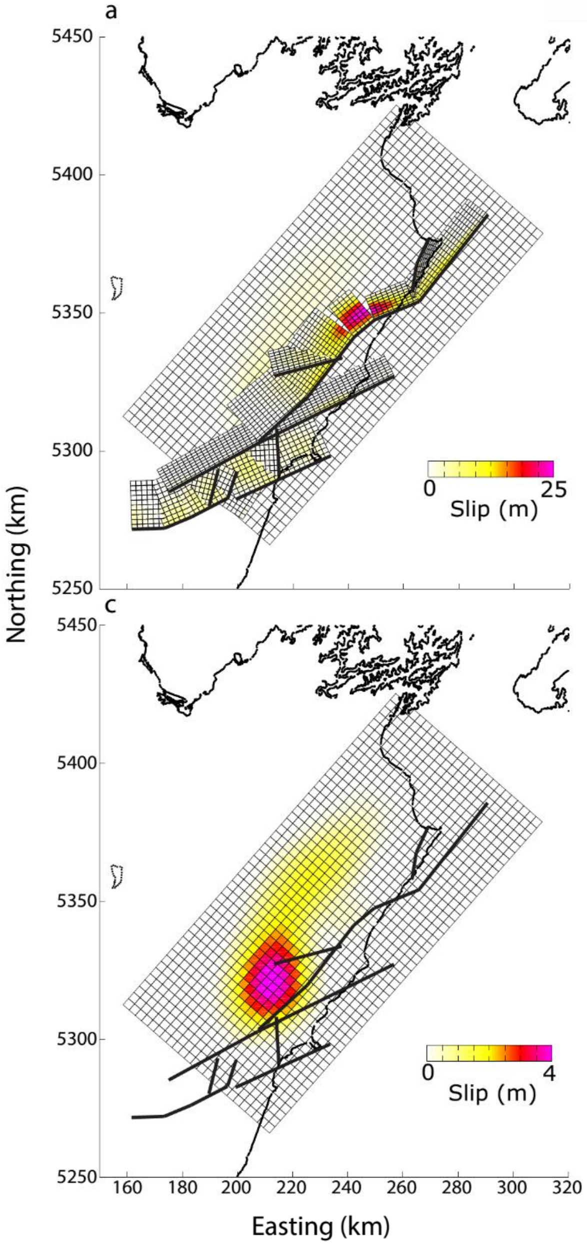
Can we fit the tsunami better??

Not really!

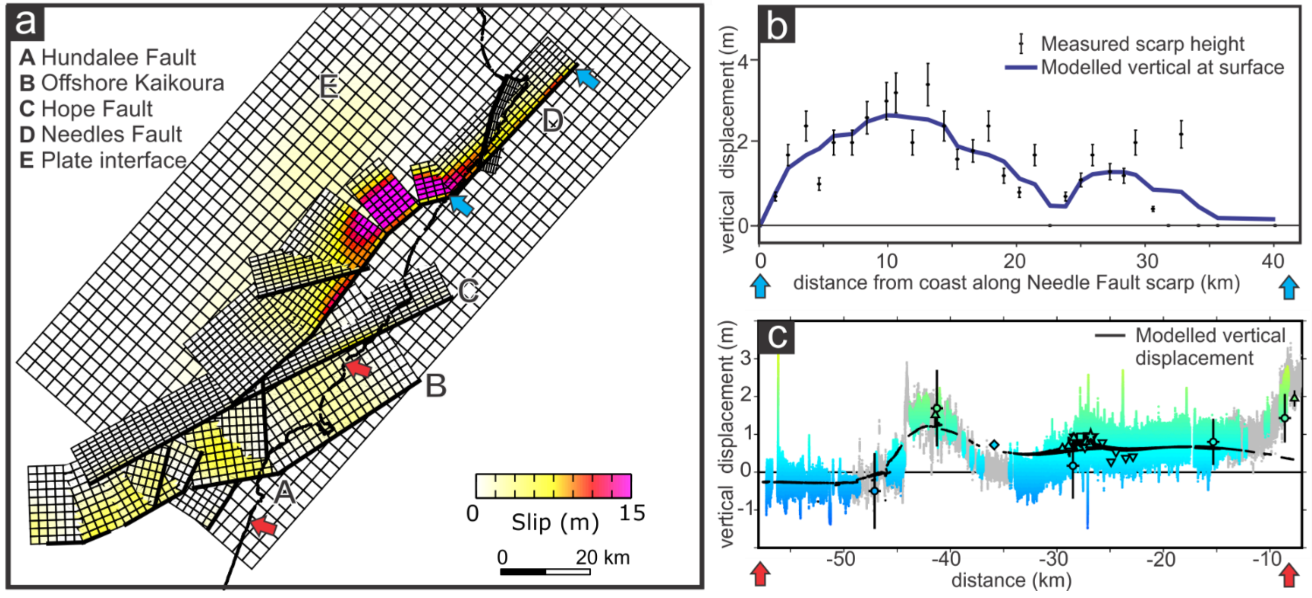
Still missing something??

Probably!

Was there slip on the southern Hikurangi?



Clark et al submitted

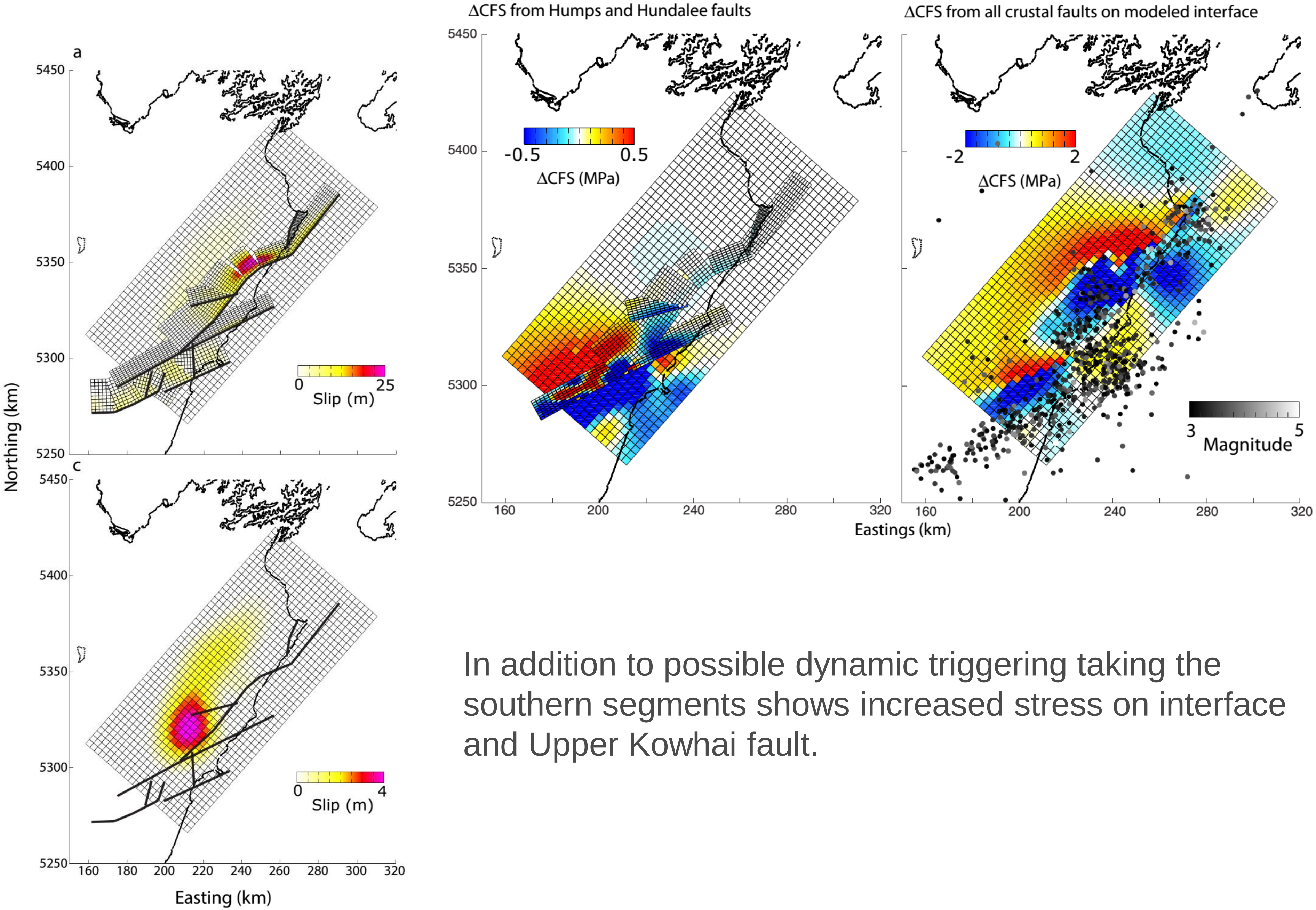


One option – crustal fault offshore.

To get broad uplift we require shallow dip ~ 30°

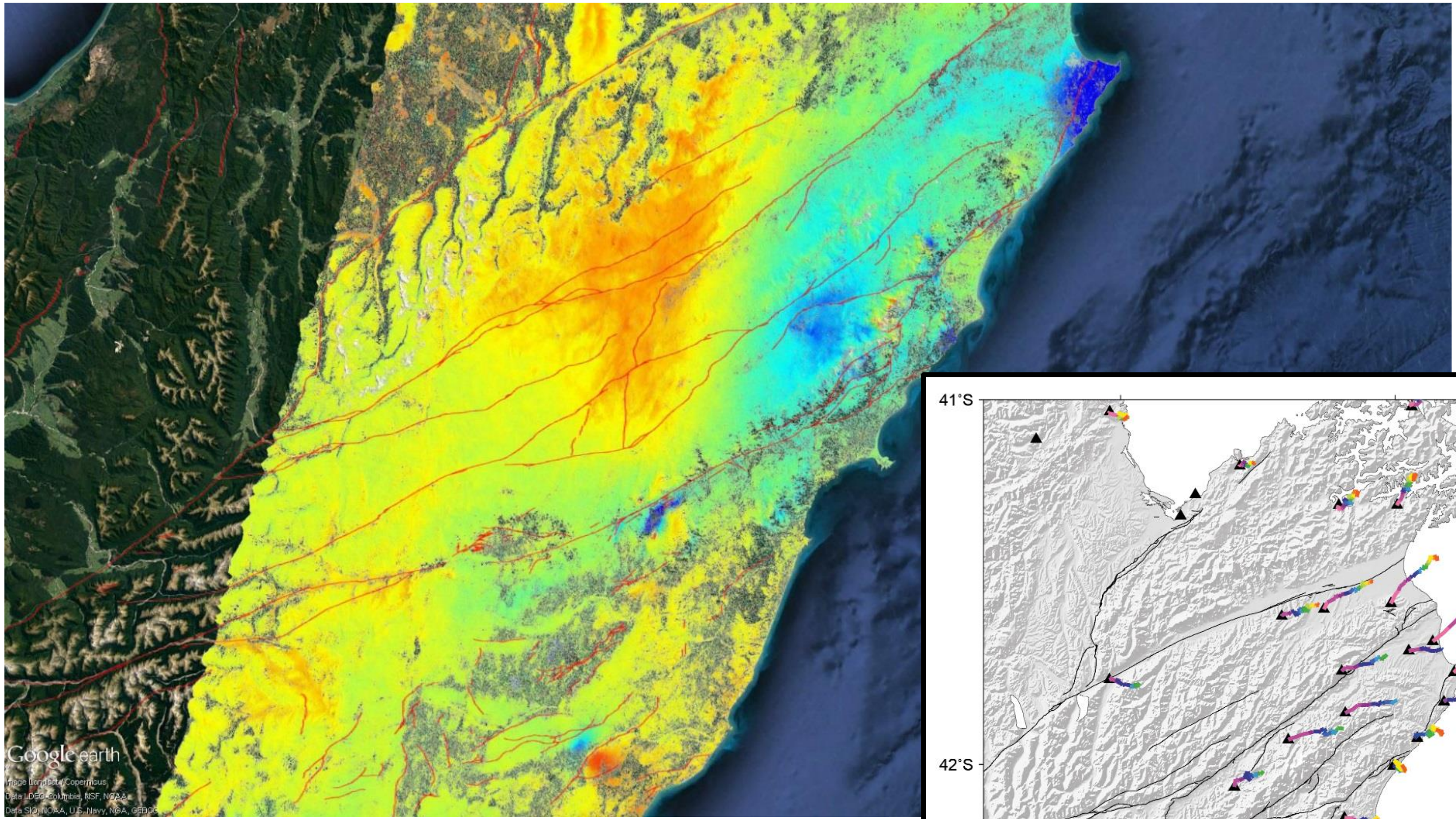
Not well constrained but removes some slip from interface.

Stressing from south to north

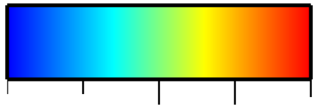


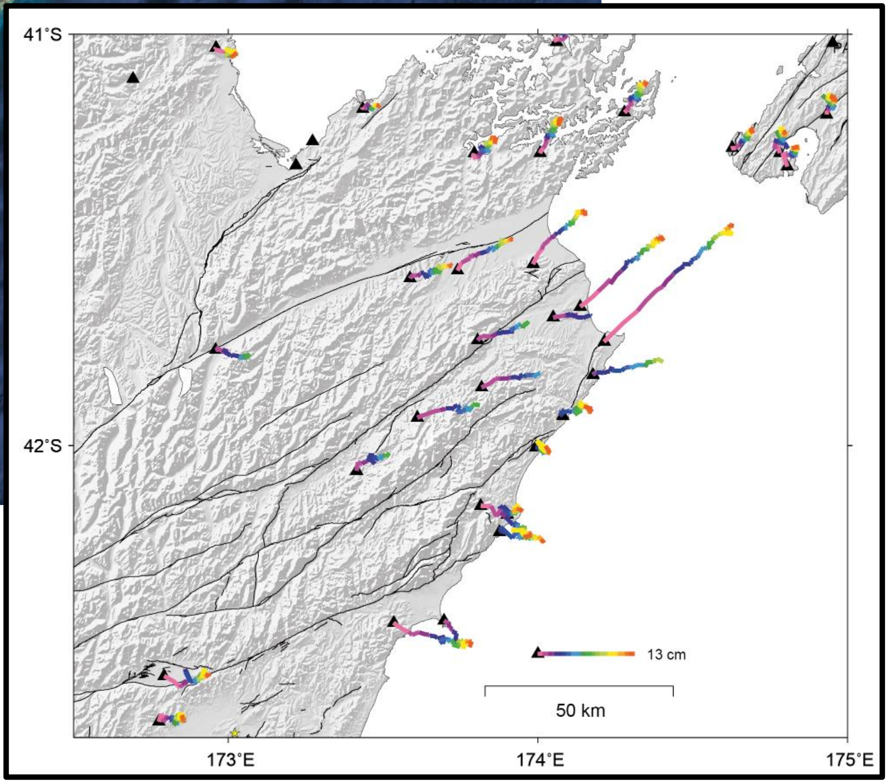
In addition to possible dynamic triggering taking the southern segments shows increased stress on interface and Upper Kowhai fault.

Post-seismic deformation

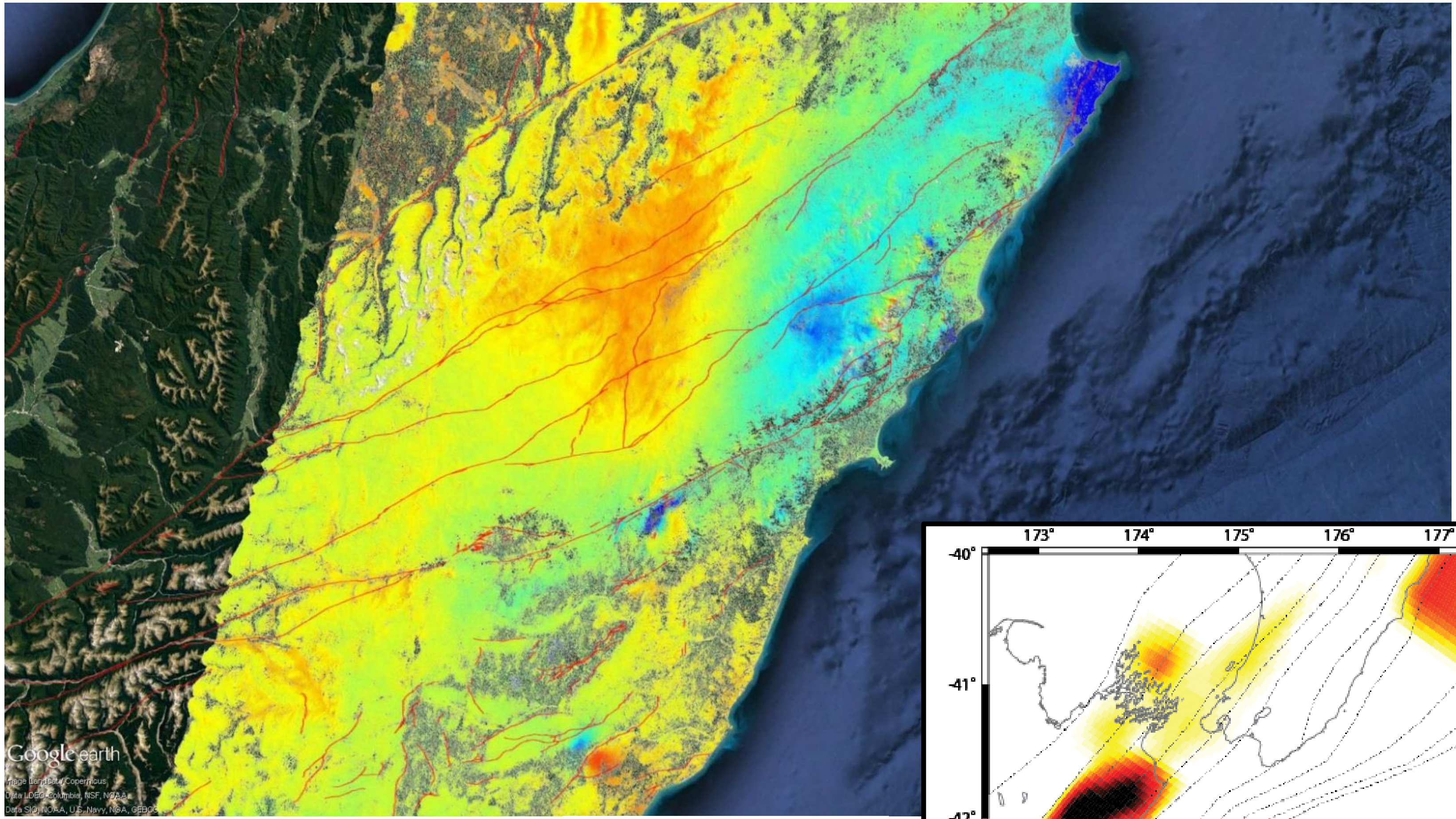


1 month post seismic interferogram

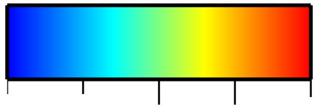


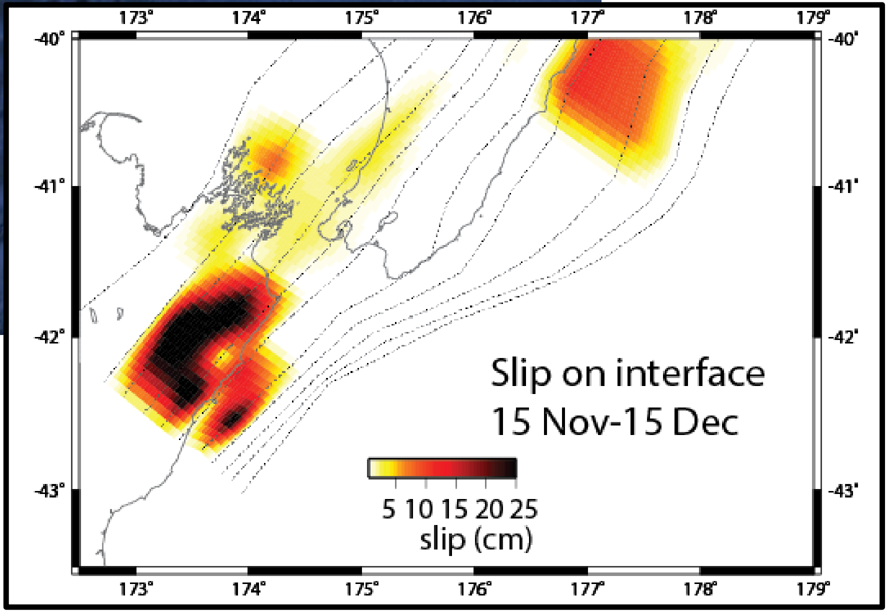


Postseismic deformation

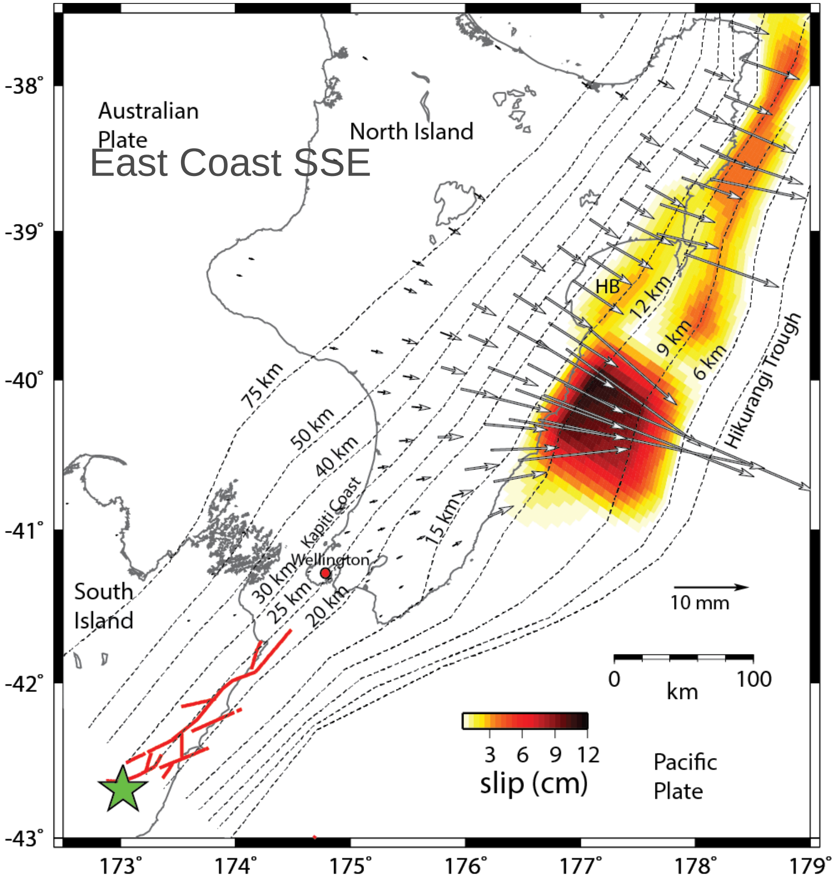


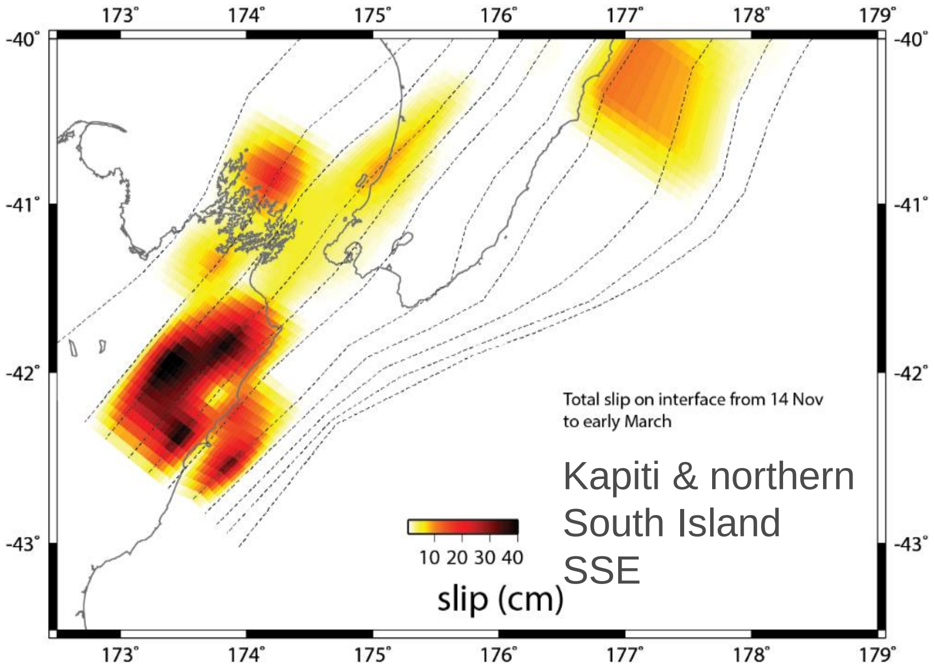
1 month post seismic interferogram





Current work on SSEs triggered by the Kaikoura M 7.8

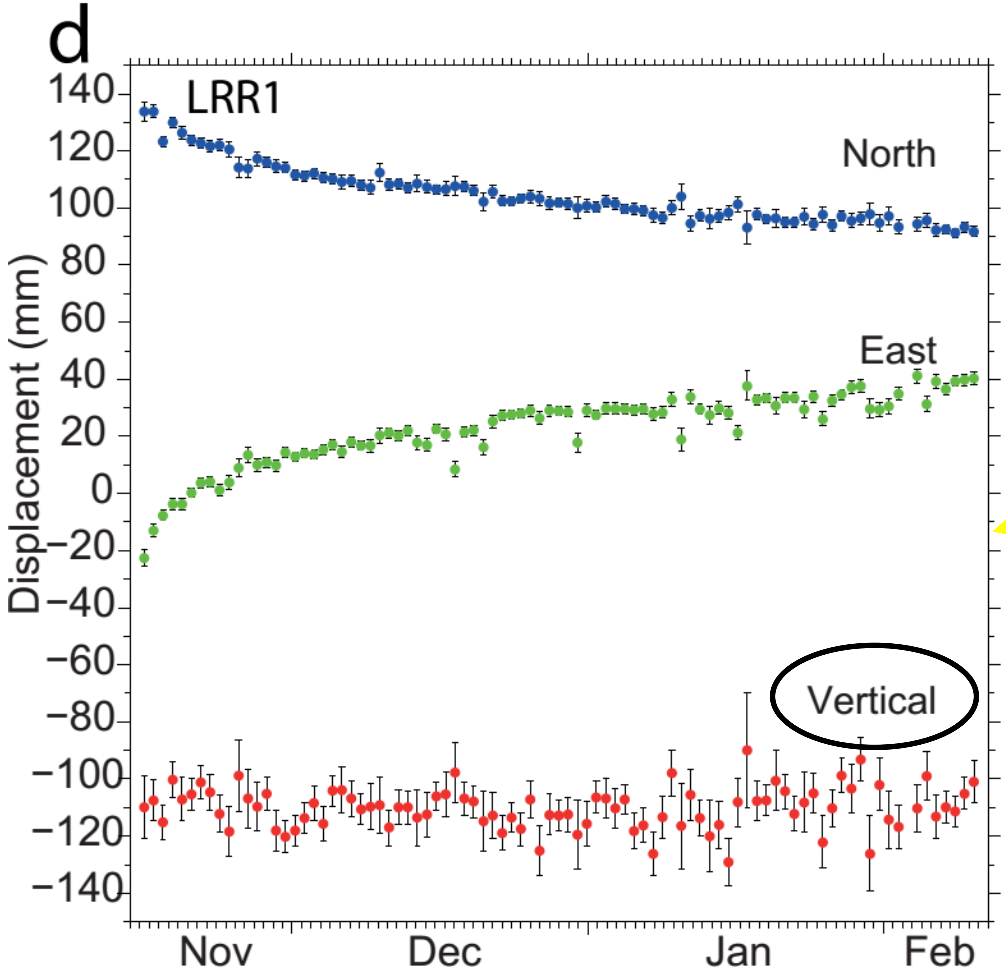


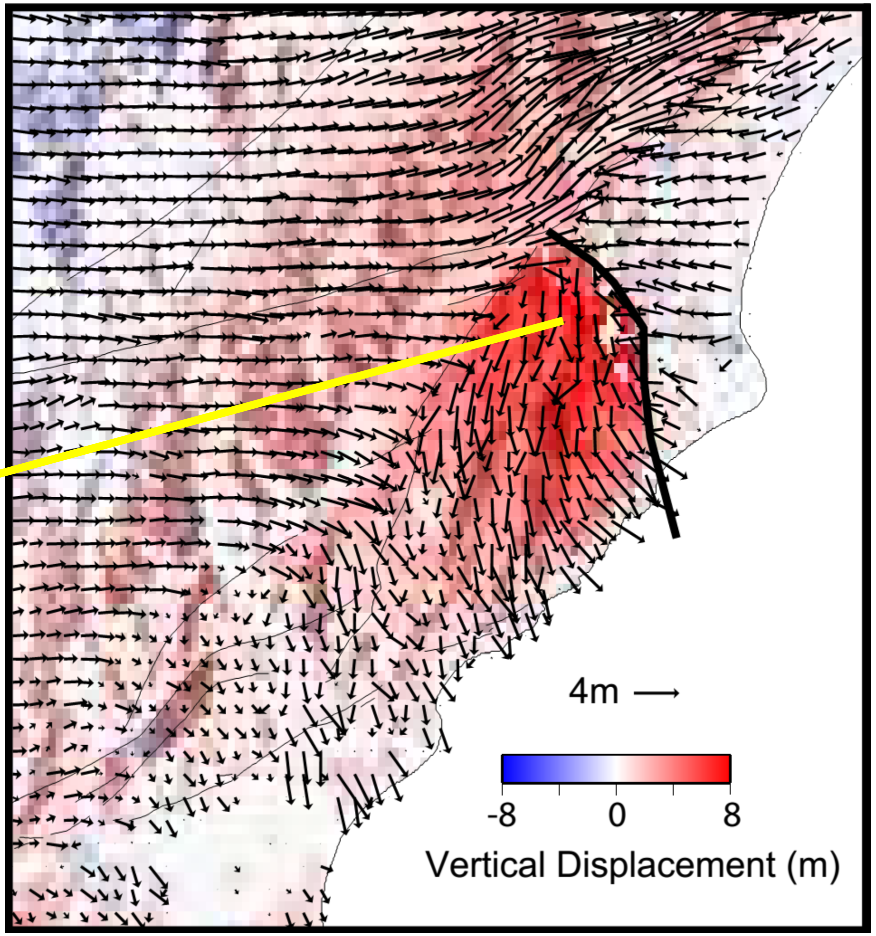


East coast SSE lasted 1-2 weeks

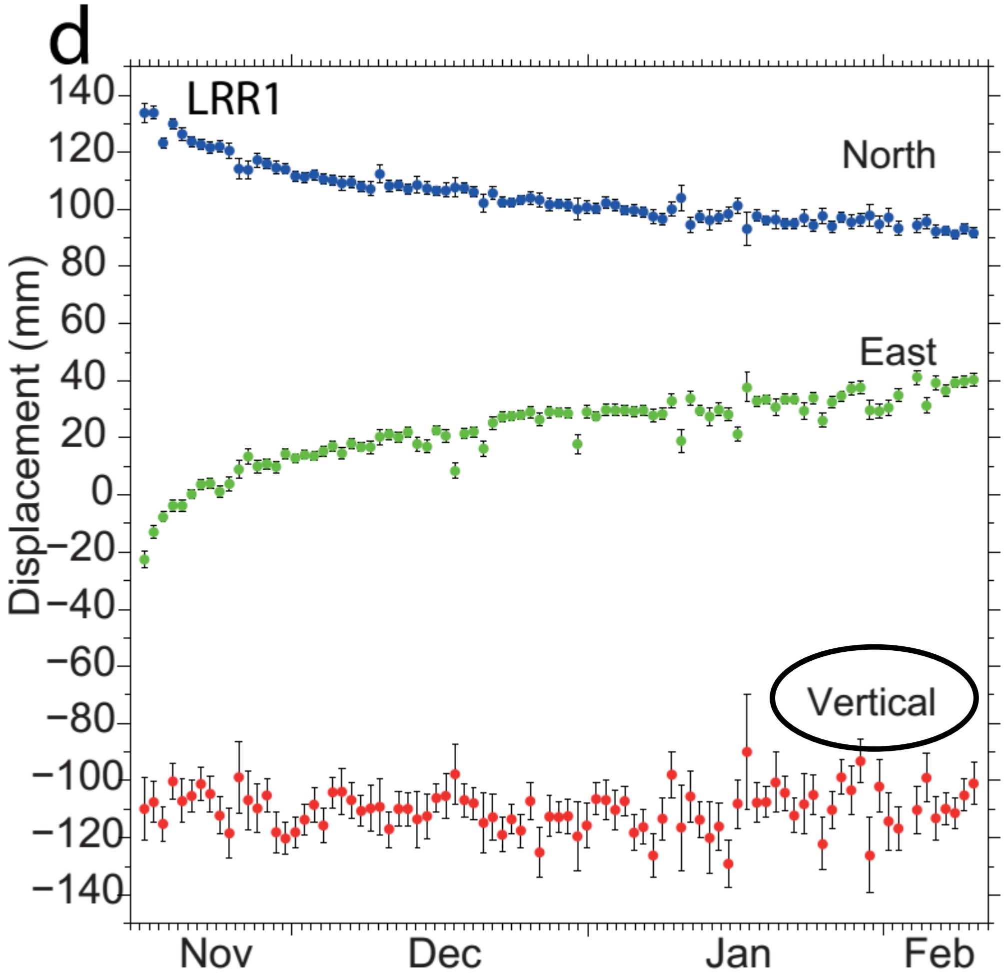
Southern Hikurangi (Kapiti, Cook Strait, Marlborough) SSEs/afterslip still ongoing

What's the Papatea block doing now???

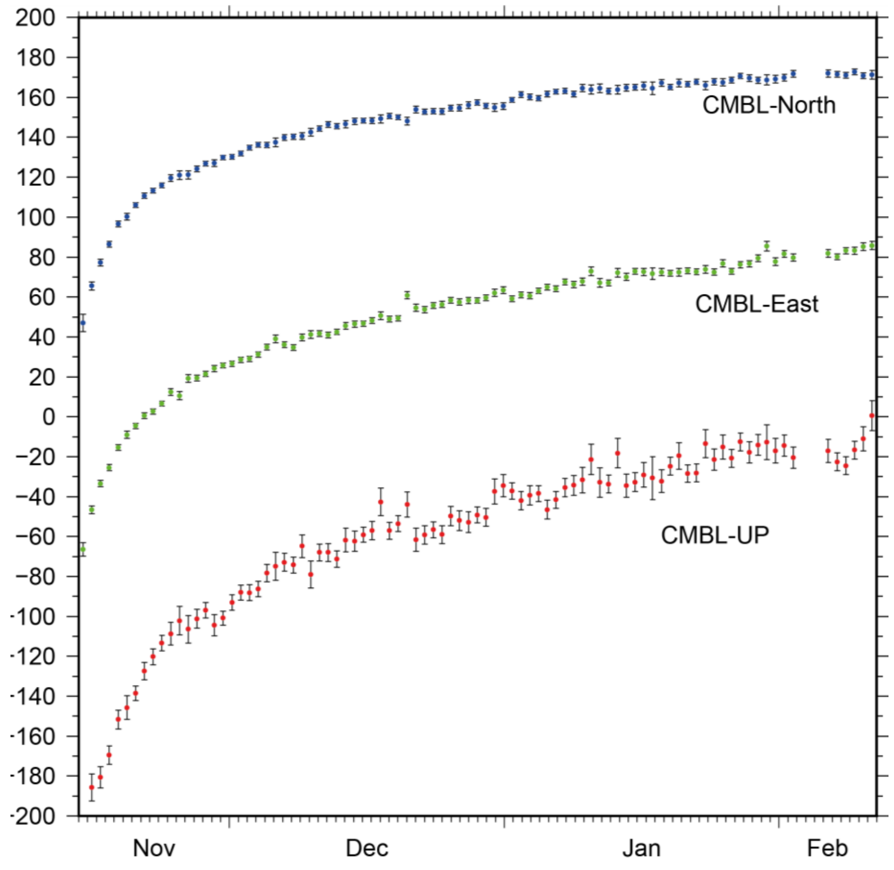




What's the Papatea block doing now???

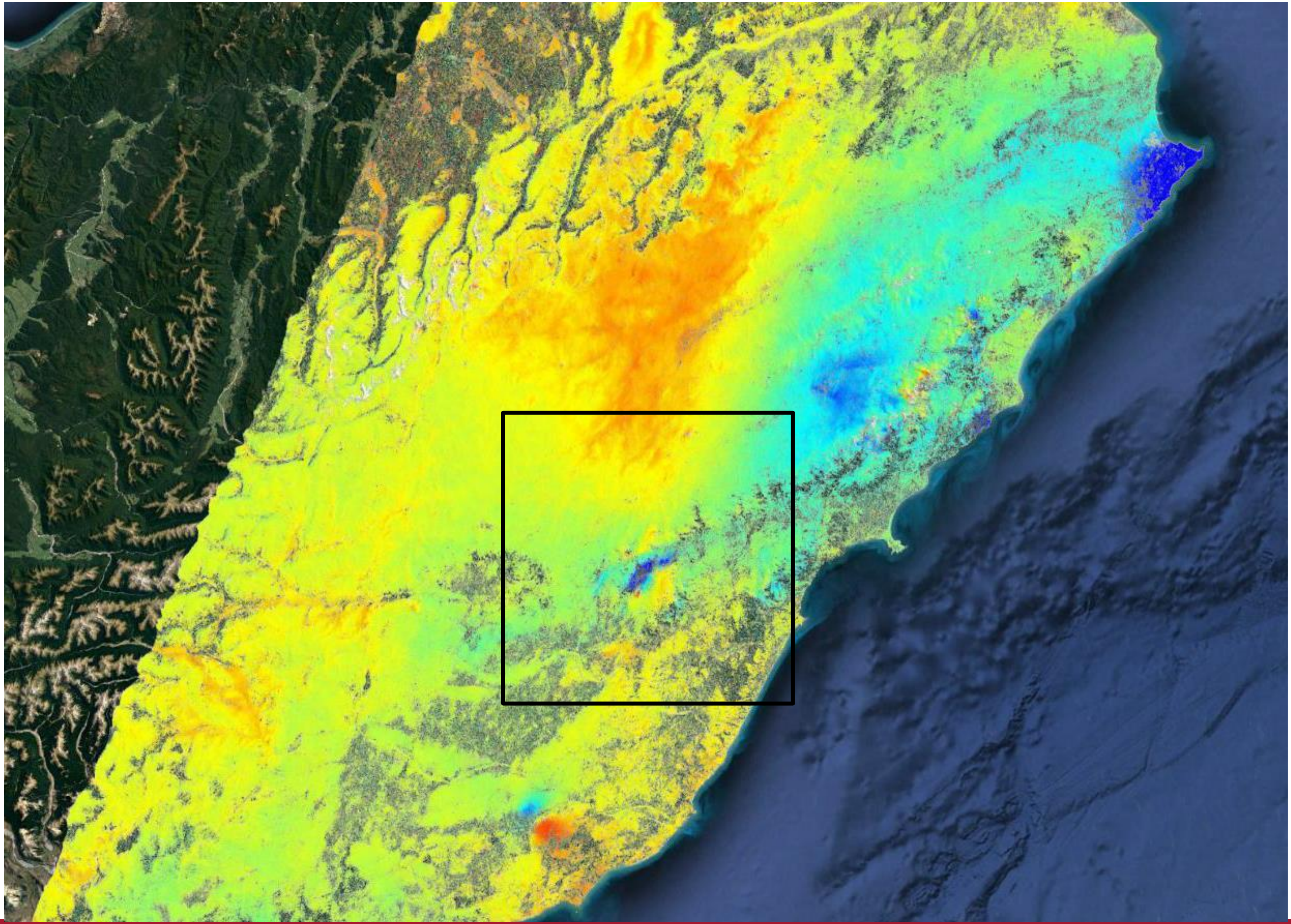


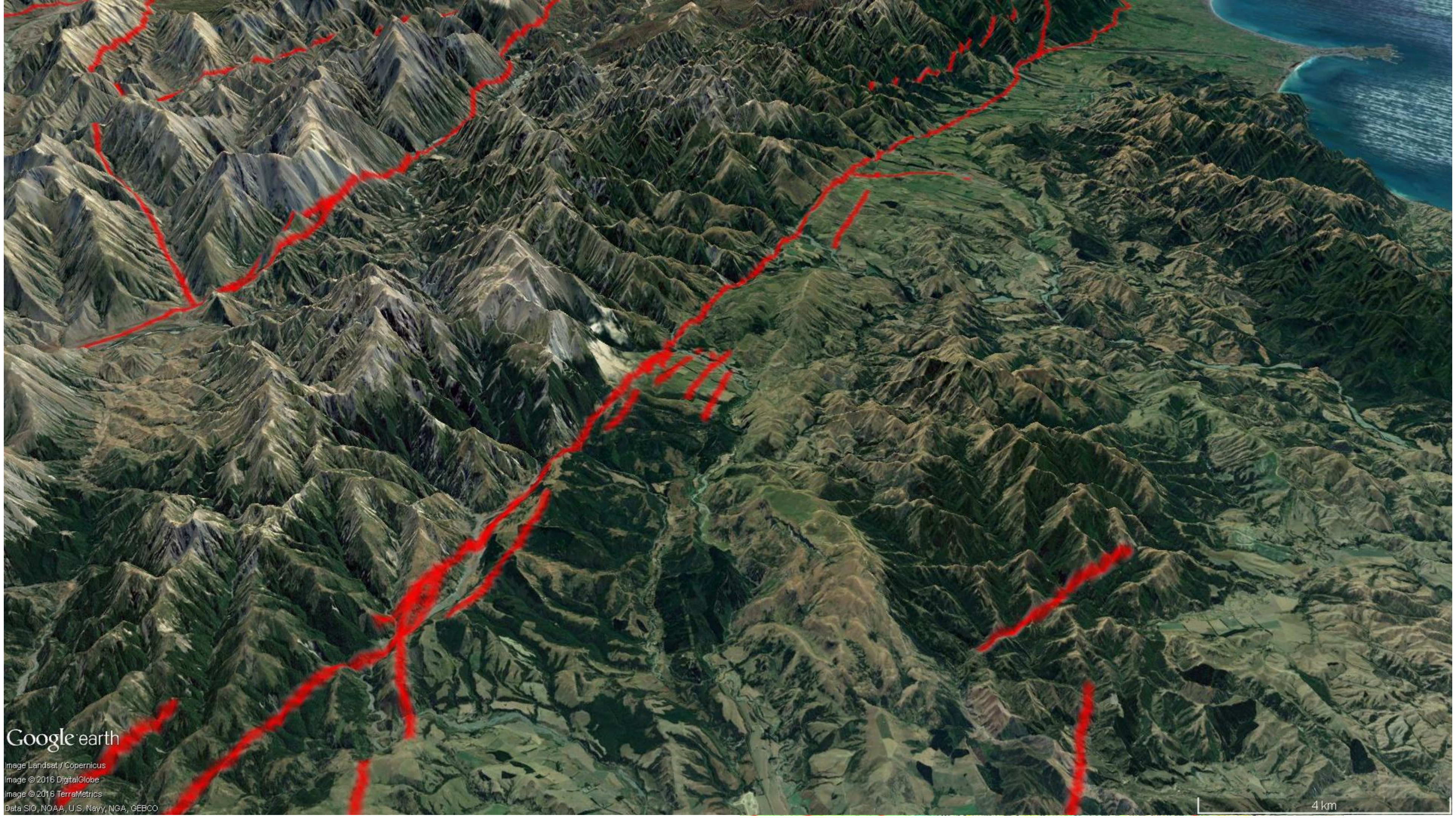
Coseismic – 8 m up

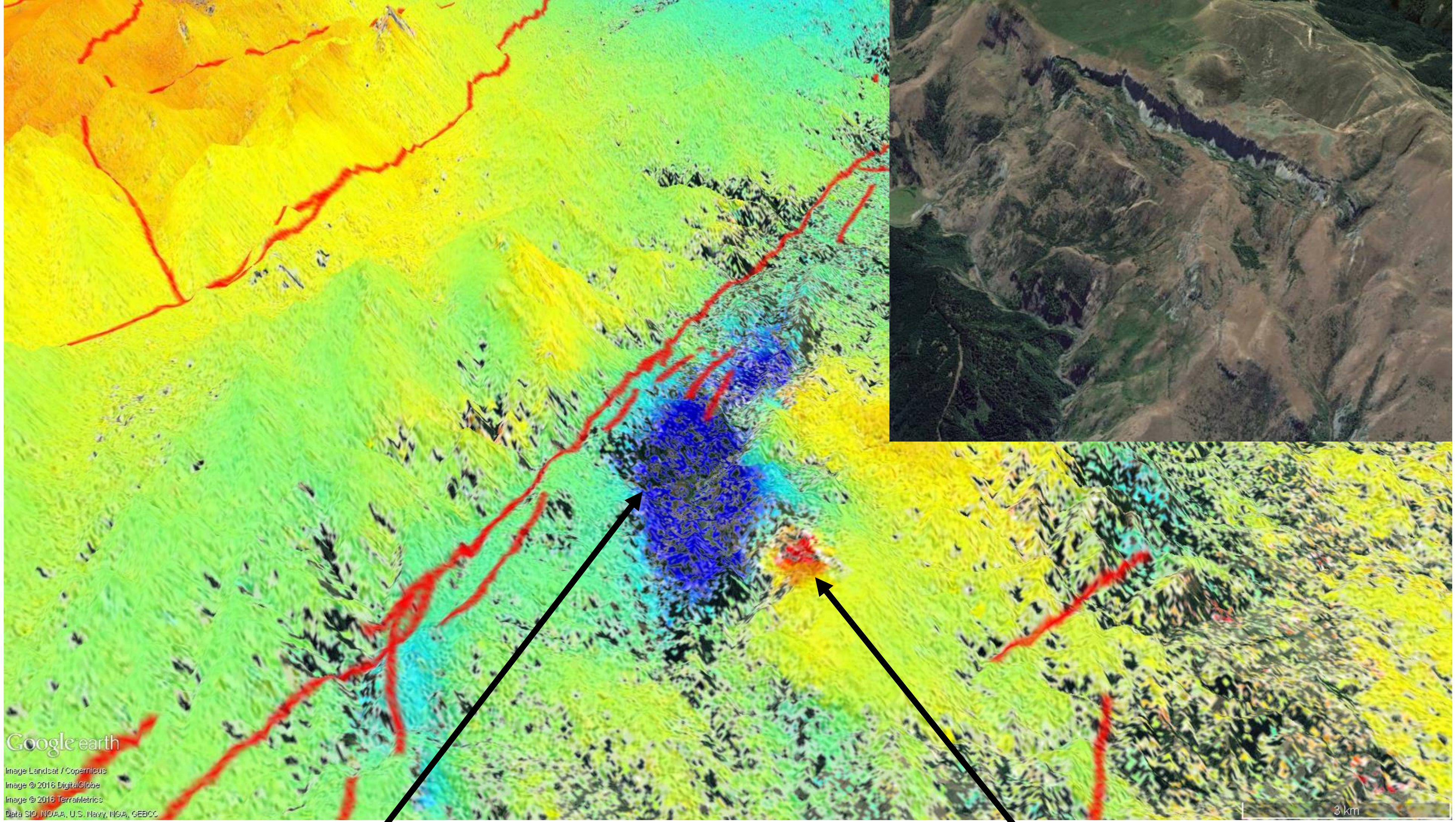


Coseismic – 2 m up

Postseismic deformation

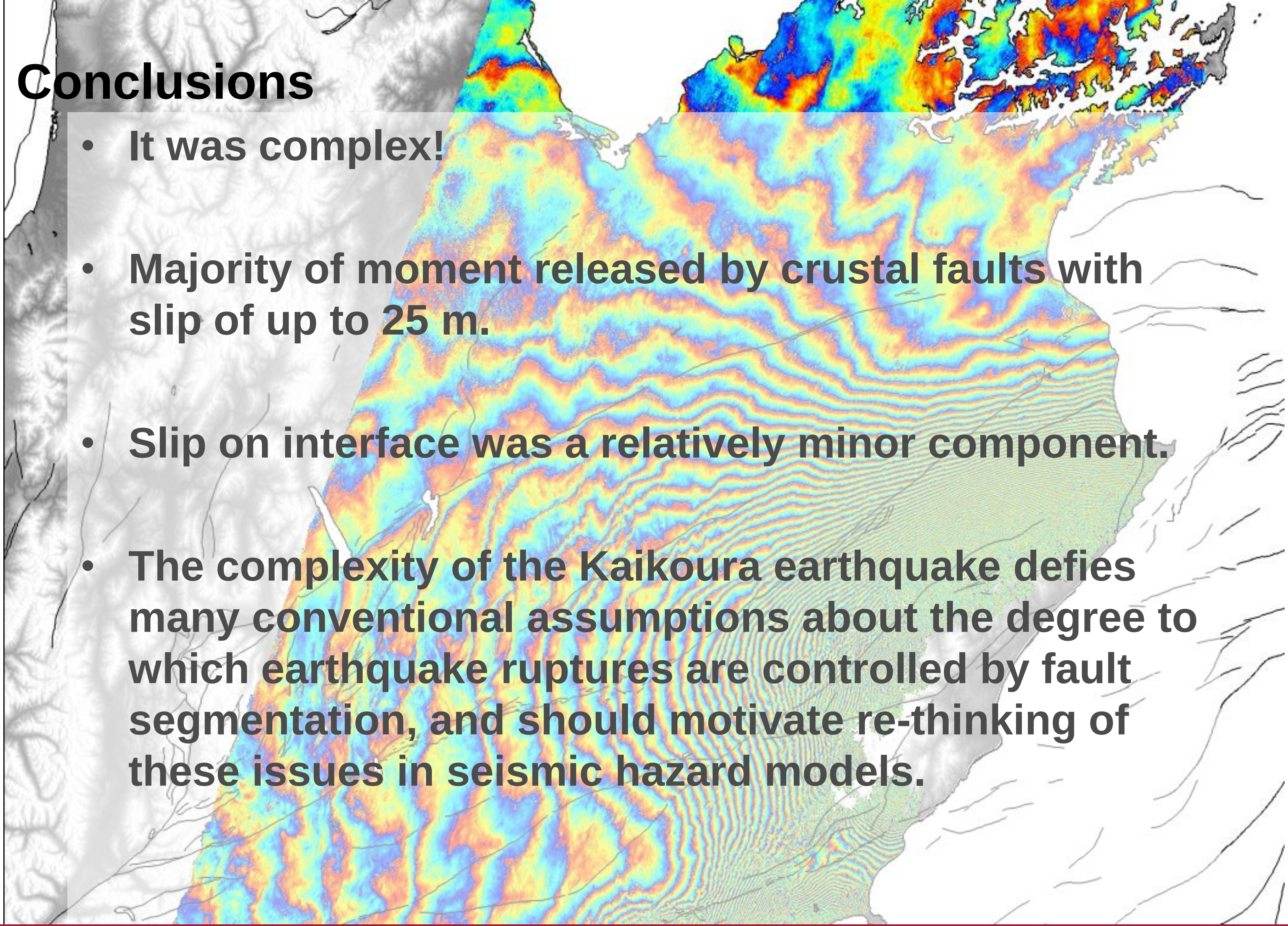



Google earth
Image Landsat / Copernicus
Image © 2016 DigitalGlobe
Image © 2016 TerraMetrics
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
4 km



~10 cm of range decrease mostly in the valley floor.

~5 cm of range increase suggesting downslope motion of landslide.



Conclusions

- It was complex!
- Majority of moment released by crustal faults with slip of up to 25 m.
- Slip on interface was a relatively minor component.
- The complexity of the Kaikoura earthquake defies many conventional assumptions about the degree to which earthquake ruptures are controlled by fault segmentation, and should motivate re-thinking of these issues in seismic hazard models.

Thanks!

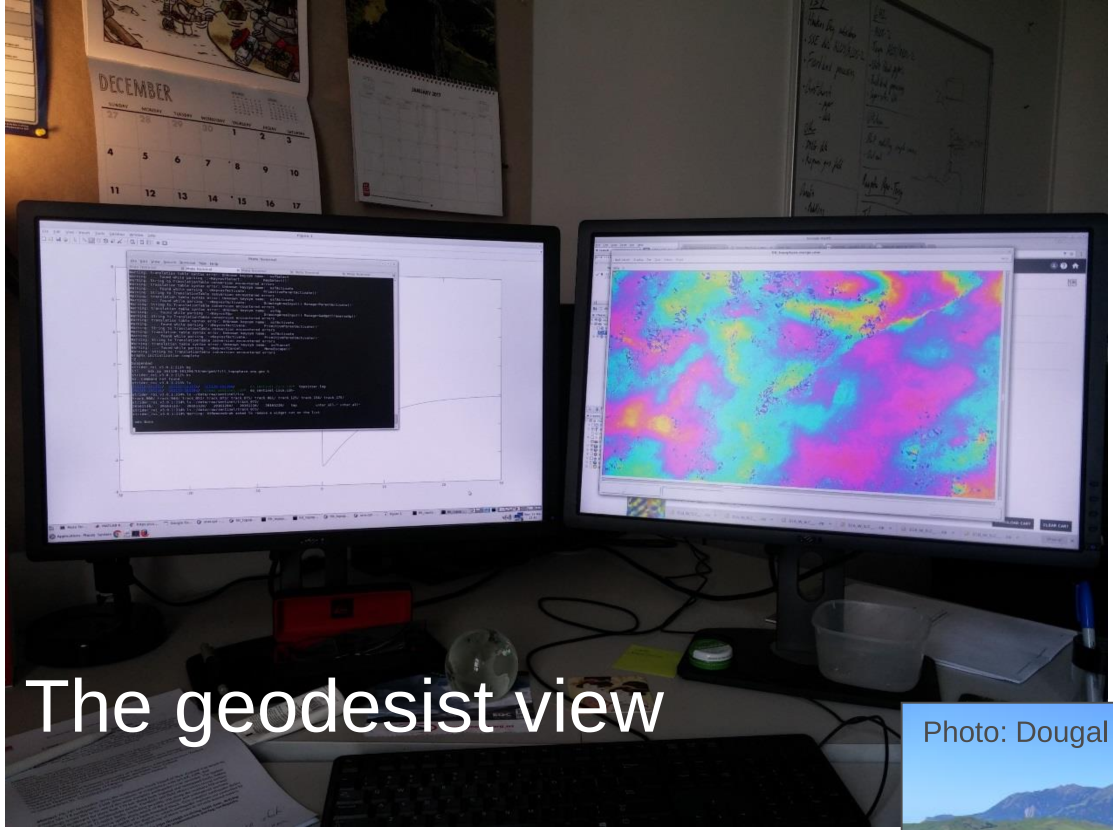


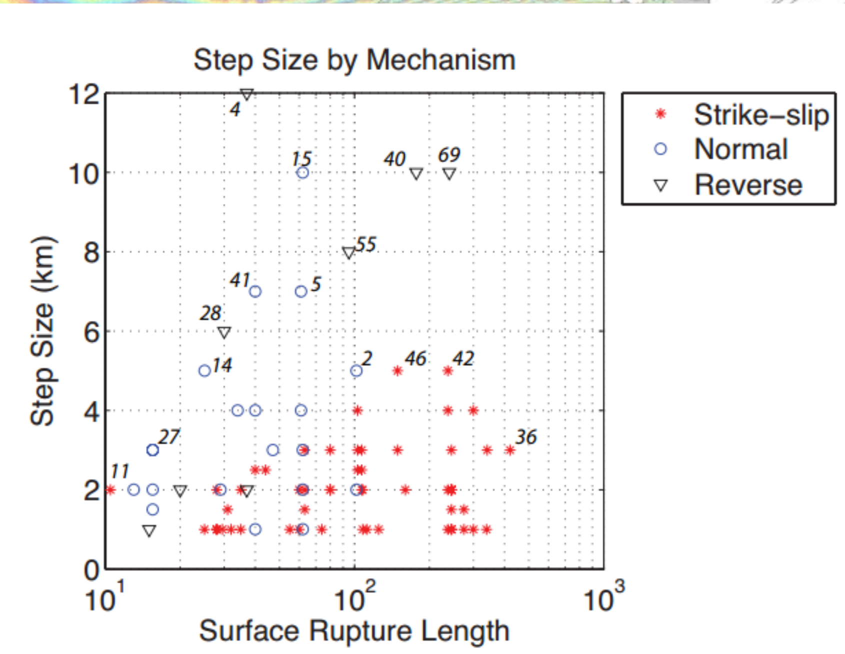
Photo: Dougal Townsend

Implications:

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

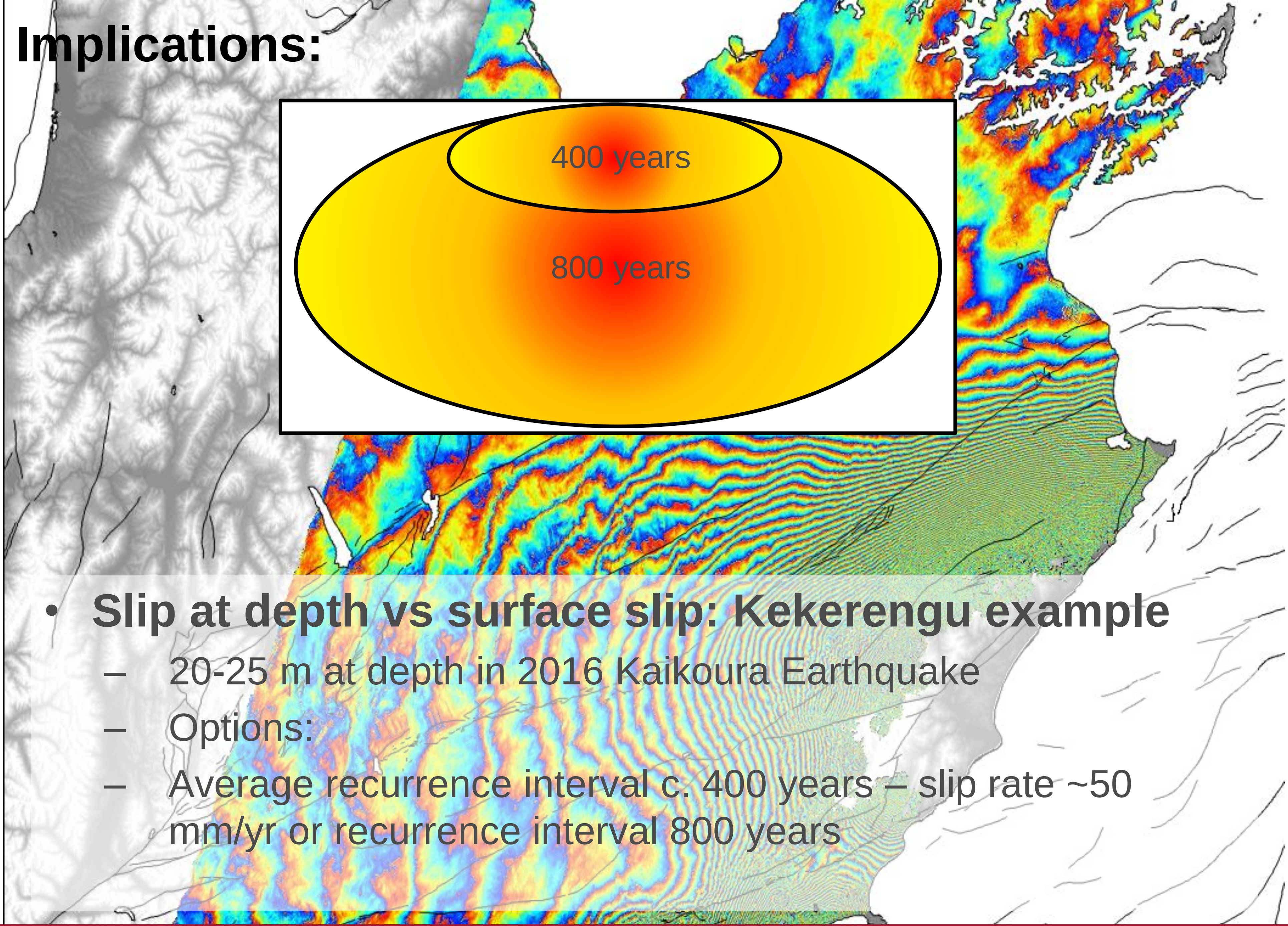
- We predict slip down to 25 km – at least 10 km more than allowed in most models.

- 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