Postseismic deformation following the 2016 Kaikoura earthquake *(18/754)*
Sigrún Hreinsdóttir, GNS Science

Research team
Laura Wallace, Neville Palmer, GNS Science
Paul Denys, University of Otago, School of Surveying

Key words
GNSS, earthquake, postseismic, deformation, Kaikoura

Summary
The M7.8 Kaikōura earthquake, took place in the northeastern South Island of New Zealand on 14 November 2016. It ruptured within a complex tectonic region, where the subduction along the Hikurangi margin to the north transitions to strike-slip and collision along the Alpine Fault in the south. The earthquake ruptured over 170 km with significant slip along at least 12 major crustal faults and possibly portions of the subduction plate interface beneath the region. In the first few days following the earthquake new continuous and semi continuous GNSS stations were installed to monitor postseismic response of the region. In addition a network of over 100 geodetic markers were measured in the Top of the South Island (TOPS) in the first few weeks to months after the earthquake, both in the near field of the earthquake rupture and far field. In 2018 the entire TOPS GNSS network was re measures to capture the first 15 months of postseismic response of the region. Postseismic deformation following the Kaikōura earthquake shows a large-scale northeast-directed movement with the most rapid deformation observed in the region of Cape Campbell (northeast tip of South Island), coinciding with a large cluster of aftershocks, decaying with time. The overall pattern of deformation is consistent with rapidly decaying slip on a low-angle source at depth, inferred to be the subduction interface beneath the Marlborough region, as well as significant afterslip on crustal faults that ruptured during the earthquake, in particular the Jordan Thrust/Kekerengu and the Needles fault. Majority of the afterslip relating to the subduction interface appears to have ceased by the middle of 2018 with a total moment release equal to a Mw7.4 event. Sites close to the fault rupture still have significant movement suggesting ongoing afterslip on crustal faults.

Introduction
On 14 November 2016 local time a major earthquake took place in the northeastern South Island of New Zealand. The M7.8 Kaikoura earthquake was the largest earthquake to hit New Zealand since the M7.8 Dusky Sound earthquake in 2009 and is one of the most complex crustal earthquakes ever recorded. The earthquake ruptured over 170 km with significant slip along at least 12 major faults (Hamling et al., 2017). In addition the earthquake possibly ruptured portions of the southern Hikurangi subduction plate interface beneath the northern South Island (Hamling et al., 2017; Duputel et al., 2017; Bai et al., 2017).

The earthquake ruptured within a complex tectonic region of the northern South Island, which occupies the transition from subduction at the Hikurangi subduction zone (North Island) to strike-slip and collision along the Alpine Fault in the central South Island. More than 75% of the relative plate motion in the northern South Island is accommodated by strike-slip in the Marlborough fault system, as well as a complex zone of strike-slip and transpression beginning in northern Canterbury and continuing northward (Van Dissen and Yeats 1991; Barnes, 1996; Cowan et al., 1996). This transition

from subduction to strike slip is largely a consequence of (a) the orientation of plate motion relative to the strike of the main plate boundary faults, and (b) a southward increase in thickness of the Pacific Plate, which transitions from the Hikurangi Plateau to the Chatham Rise.

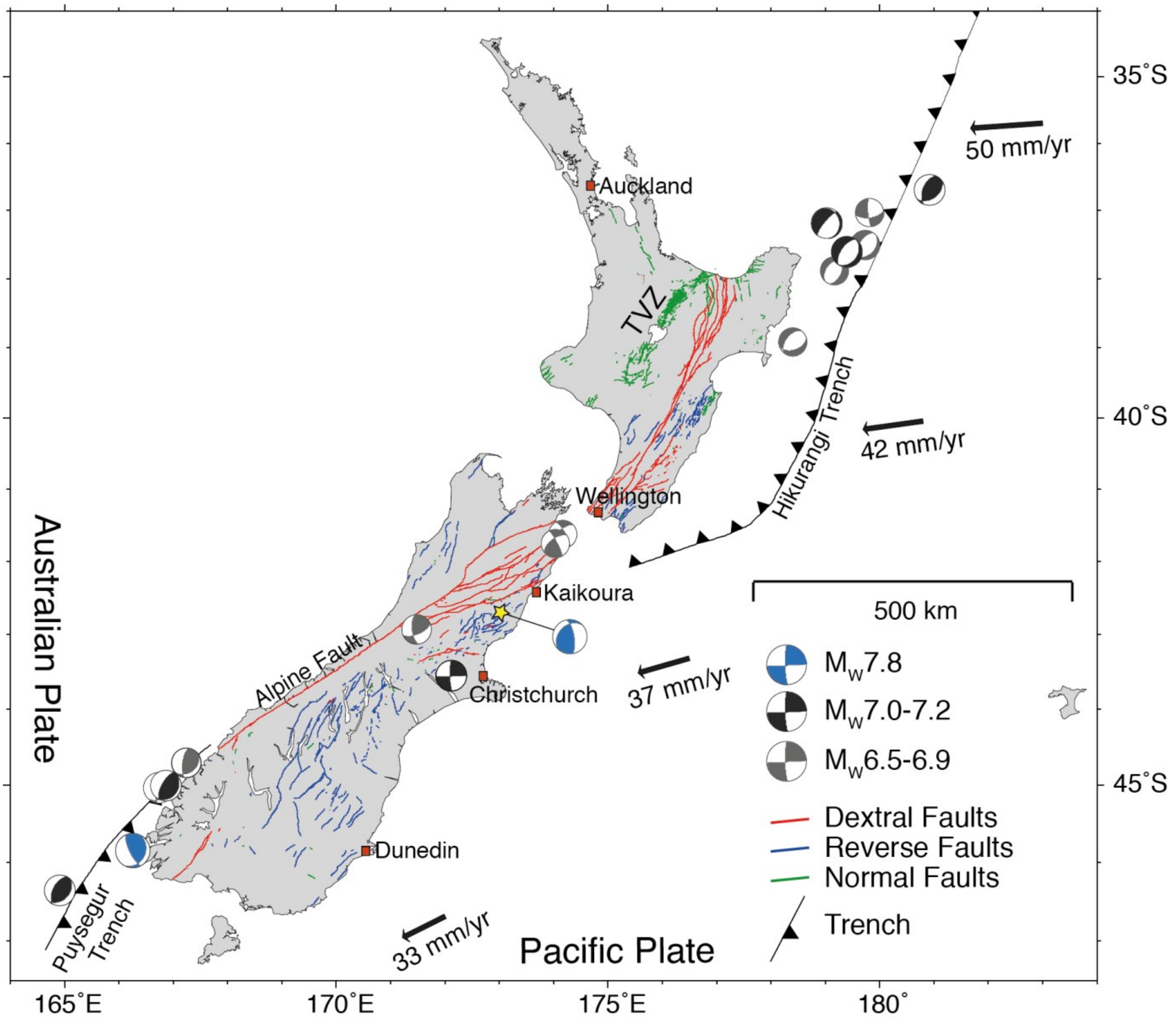

Figure 1. The Kaikoura earthquake (yellow star) initiated in the North Canterbury region and ruptured northeast along multiple crustal faults. Focal mechanism from the CMT catalogue spanning 1990 to 2017 (Ekström et al., 2012; Dziewonski et al., 1981), faults from the NZ fault database (Langridge et al., 2016).

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Since 1994 regular GNSS measurements have been conducted in the Top of the South Island (TOPS) to evaluate the interseismic velocity field for the region to study the kinematics of the transition from subduction to strike-slip (Beavan et al., 2016). Previous studies have suggested that the subduction plate boundary beneath the northern South Island is permanently locked (e.g., that it no longer accommodates plate motion; Reyners et al., 1998). However, elastic block modelling of the GNSS velocities and active fault slip rates suggest that the Hikurangi subduction interface may indeed play a role in the accommodation of plate motion beneath the northern South Island (Wallace et al., 2012). The network was last measured in 2012 in collaboration between GNS Science, OUSD and Land Information New Zealand (LINZ). In addition, parts of the network have been measured in response to nearby earthquakes (2010 Darfield, 2013 Lake Grassmere and 2013 Cook Strait) (Beavan et al., 2010, Hamling et al., 2014).

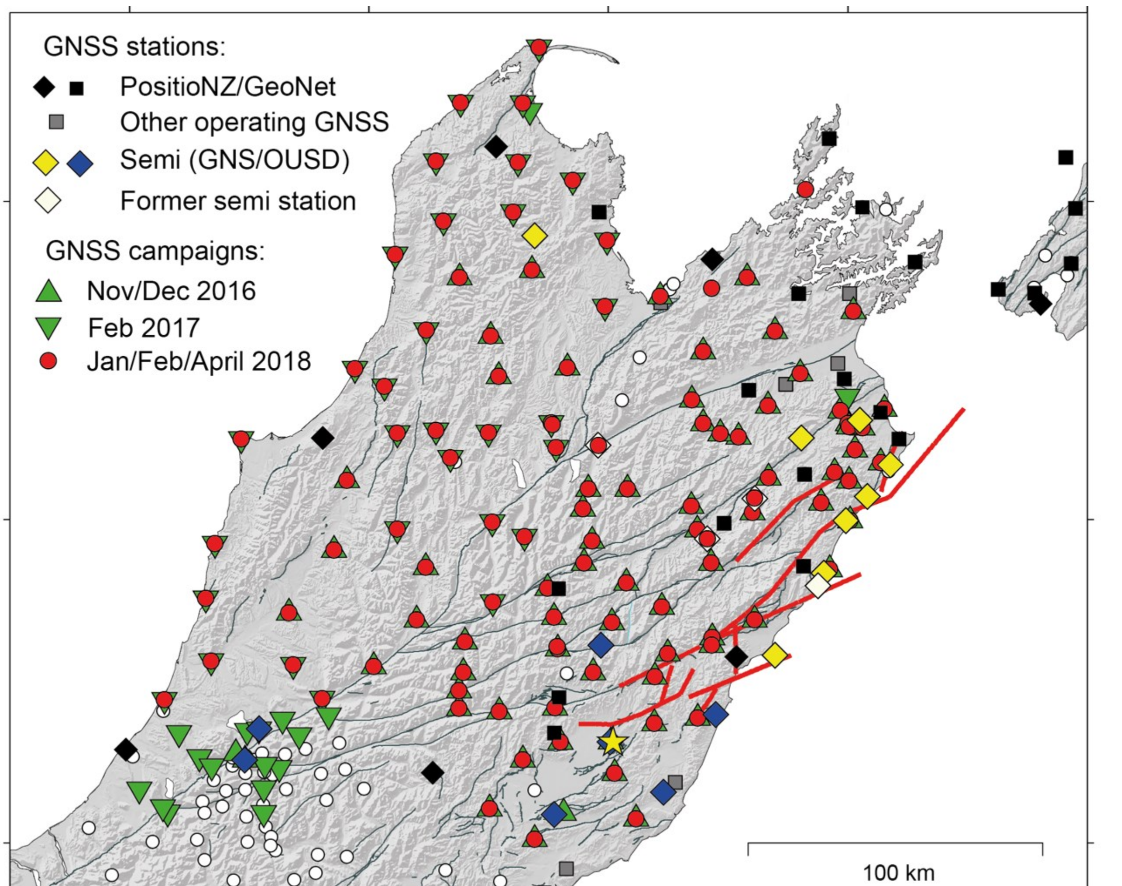

Figure 2. GNSS measurement following the Kaikoura earthquake (yellow star). Red circles show geodetic markers, measured during the TOPS2018 campaign, and yellow and blue diamonds show semi continuous GNSS stations, operated during the projected by GNS Science and OUSD respectively. Previous post Kaikoura measurements are shown with green triangles and white diamonds (semi continuous stations no longer in operation). Black and grey squares/diamonds show GNSS stations operating in the area. White circles show other sites in the area with no post Kaikoura measurements. Red thick lines show Kaikoura earthquake fault rupture model by Hamling et al. (2017).

Following the Kaikoura earthquake about 80 geodetic markers in the TOPS network, mostly located within 50 km of the fault ruptures, were measured as part of a rapid response to the earthquake in collaboration between GNS Science, OUSD and LINZ. The measurements were used along with continuous GNSS, InSAR and coastline uplift data to evaluate a coseismic slip model for the earthquake (Hamling et al., 2017; Clark et al., 2017). In addition, semi continuous GNSS stations were set up, augmenting the sparse PositioNZ/GeoNet network in the region (Figure 2), to capture postseismic deformation following the earthquake. In February 2017, three months after the earthquake, 50 additional campaign sites were measured with funding from the Natural Hazards Research Platform to complete the coseismic measurements of the TOPS GPS network and set the basis for future post seismic deformation studies.

With funding from EQC the whole TOPS network was remeasured in early 2018 to evaluate the first 15 months of postseismic response of the region (red circles, Figure 2) and set the basis for evaluation of long term post seismic response. In addition the funding allowed us to continue to operate and download data from selected semi continuous GNSS stations in the region (yellow diamonds, Figure 2).

Objectives

The primary goal of the project was to remeasure the whole TOPS geodetic network to evaluate in more detail the first 15 month of postseismic deformation following the 2016 Kaikoura earthquake and operate semi continuous GNSS stations. The measurements allow us better understand the spatial pattern and temporal decay of the different postseismic processes affecting the region. The GNSS data combined with InSAR data are being used to constrain models of the underlying crustal and mantle processes and to evaluate stress transfer on active faults in the region and the subduction interface.

Postseismic deformation from an event of this magnitude (Mw 7.8) will affect the region for years with afterslip on crustal faults, viscoelastic response of the mantle and possibly slip on the underlying subduction interface. Afterslip that takes place on faults that ruptured during the earthquake usually dominates near field motions for weeks to months. However, viscoelastic response of the lower crust and upper mantle will dominate in longer term (years) and affect wider region. The measurements of the whole network 15 months after the earthquake allows us to study afterslip on faults that ruptured during the earthquake as well as give us an important benchmark for future studies of long term viscoelastic processes which might be affecting the region.

Conclusions and key findings

The Kaikoura earthquake ruptured within a complex tectonic region of the northern South Island, where we see transition from subduction at the Hikurangi subduction zone (North Island) to strike-slip and collision along the Alpine Fault in the central South Island (Wallace et al., 2012). A majority of the coseismic deformation can be explained by rupture of upper crustal faults in Canterbury fault zone and the Marlborough fault system with the largest moment release taking place on the Jordan thrust/Kekerengu dextral strike-slip segment.

The GNSS measurements following the earthquake show variable postseismic deformation in the region, with the most rapid movement at sites in the Cape Campbell region, moving toward northeast and up (Figure 3, 4), coinciding with a large cluster of aftershocks. Sites along the east coast have a more east-southeast movement toward the coast, but sites in the epicentral region show relatively minor postseismic response. (Figure 4, 5). There is significant postseismic deformation over 100 km from the fault rupture, with sites on the west coast moving a few cm toward the southeast, toward the Kaikoura region, and sites in the North Island moving northeast, away from the Kaikoura region. The earthquake also triggered slow slip events along the east coast of the North Island and Kapiti region (Wallace et al., 2017, 2018).

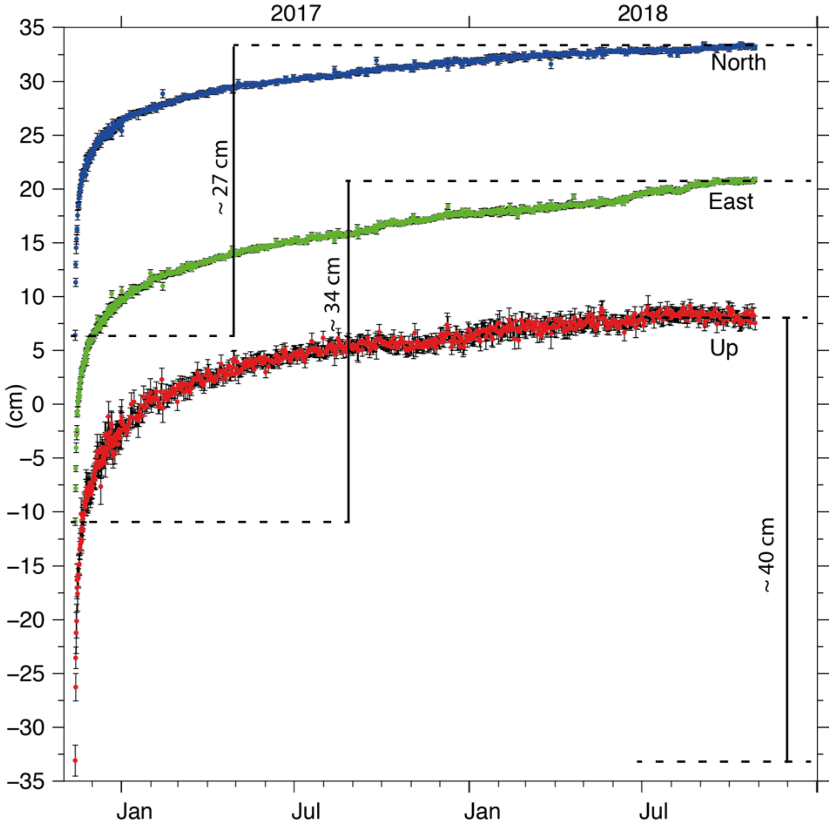

Figure 3. Postseismic deformation at Cape Campbell (CMBL), the fastest moving GNSS station in the region following the Kaikoura earthquake. The postseismic movement was most rapid in the first few hours and days after the earthquake but then decays off, with very low (near background) rates observed after middle of 2018. The first datapoint for each component (North-blue, East-green, Up-red) shows reference location evaluated from data spanning the first few hours after the earthquake (12:00-16:00 UTC, the earthquake took place at 11:02 on 13 November UTC time). Other data points show average location every 8 hours for 2016 and every 24 hours for 2017-8. Background (interseismic) deformation has been subtracted from the measurements.

Modelling of the first few months of postseismic deformation estimated from GNSS and InSAR measurements (Wallace et al., 2018), revealed up to 0.5 m of afterslip on the subduction interface beneath the Kaikoura region following the earthquake as well as slip on crustal faults that ruptured during the earthquake, in particular the Jordan Thrust/Kekerengu, the Needles fault and a fault offshore Kaikoura (from Clark et al., 2017). The estimated total moment release on the plate interface below the Kaikoura region was equivalent to about Mw 7.4 earthquake by January 2018. In addition, the data show that a large slow slip event was triggered beneath the southern North Island, in the Kapiti region, equivalent to about Mw 7.1.

The GNSS data collected in 2018 show that the postseismic deformation following the Kaikoura earthquake is decaying rapidly with time (Figure 3, 5). The data show continued postseismic movement of GNSS sites until the middle of 2018 when sites in the southern North Island appear to go back to background deformation and sites in the South Island change direction, mostly toward the east coast but sites in the epicentral region now moving southwest and sites in the Cape Campbell region moving more easterly. Preliminary modelling of the data suggests that this marks the end of the Kapiti slow slip event and afterslip on the subduction interface, with the plate interface locking up again (Figure 6, Hreinsdóttir et al., 2018). The pattern of deformation in the South Island after middle of 2018 (Figure 5) suggests that afterslip on the offshore Kaikoura and the Needles fault could still be ongoing at decaying rate but further modelling is required to explore viscoelastic processes that could be acting in the region.

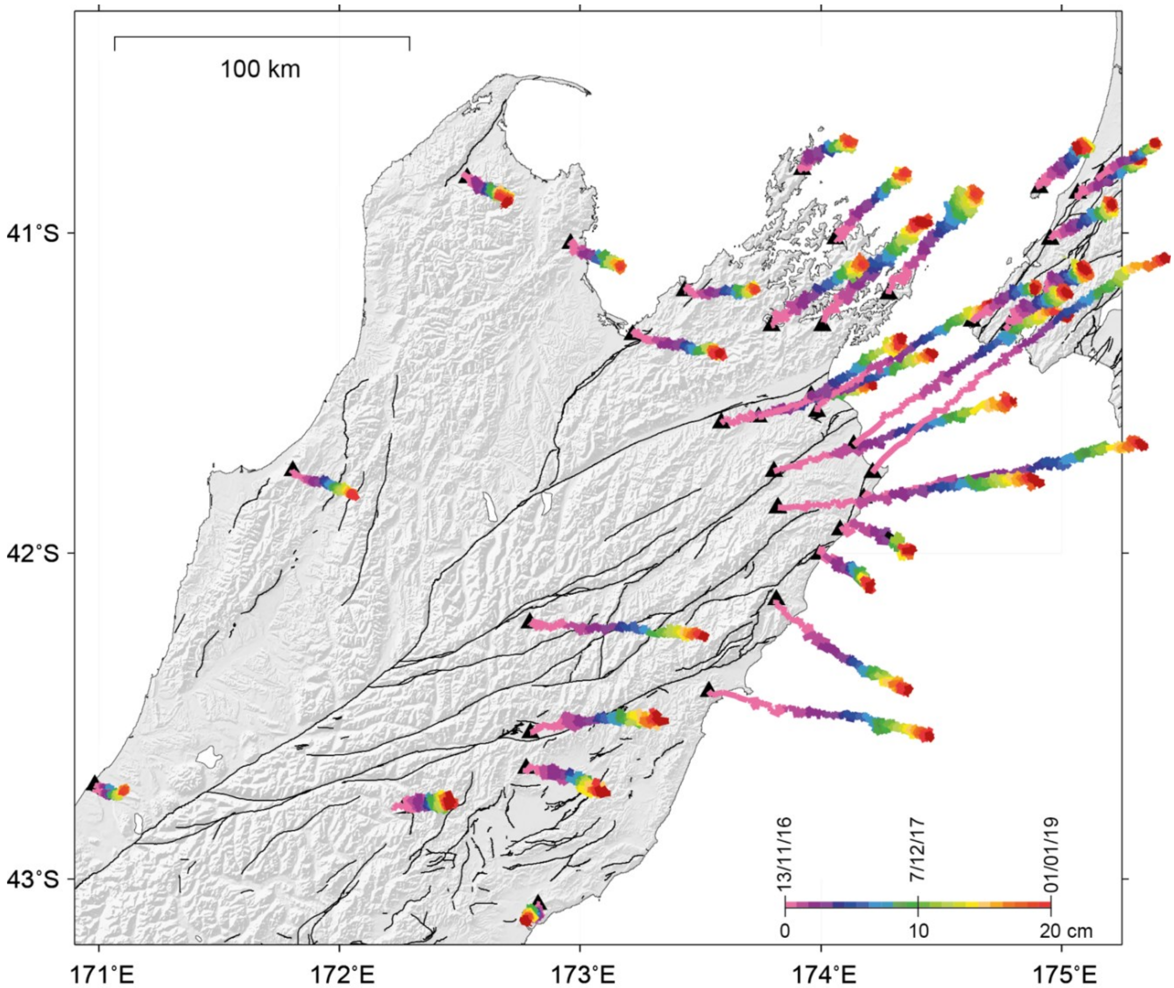

Figure 4. Postseismic movement of continuous and selected semi continuous stations in the Top of the South Island. The figure shows daily (average over 24h) estimates of how much the sites have moved (length) with time (color), see scale in bottom right corner. Background (interseismic) velocities evaluated from data collected prior to the Kaikoura earthquake have been subtracted from the measurements.

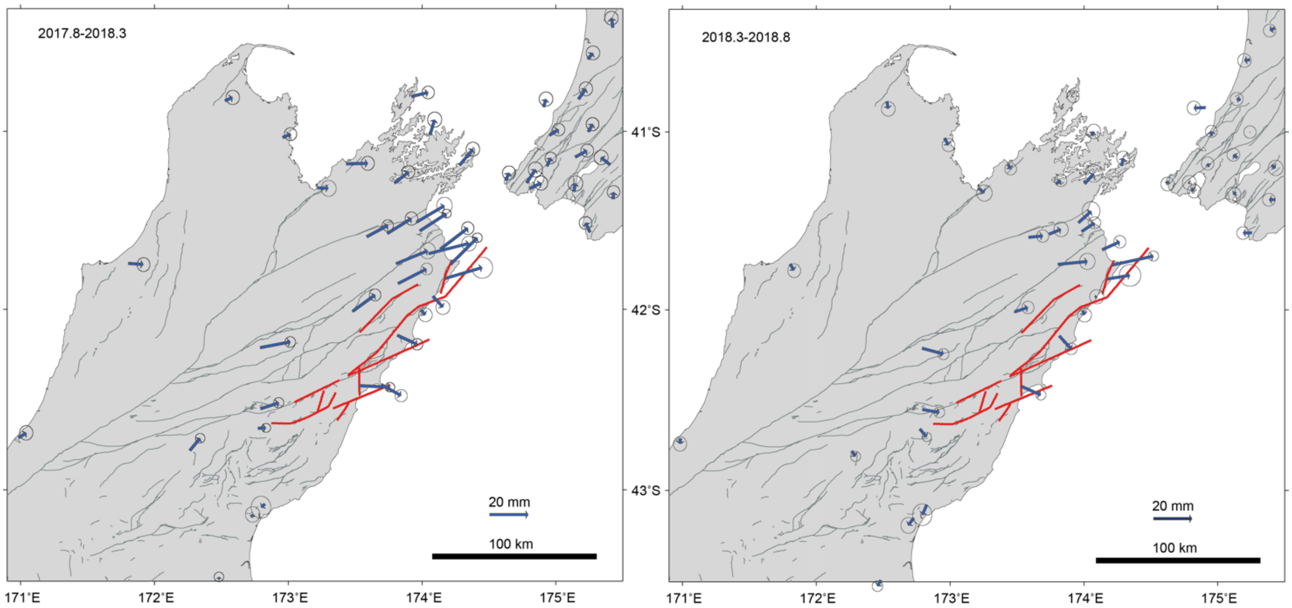

Figure 5. Average postseismic movement of sites from November 2017-April 2018 (left) and April-November 2018 (right). Background (interseismic) velocities evaluated from data collected prior to the Kaikoura earthquake have been subtracted from the measurements. Red thick lines show Kaikoura earthquake fault rupture model by Hamling et al. (2017).

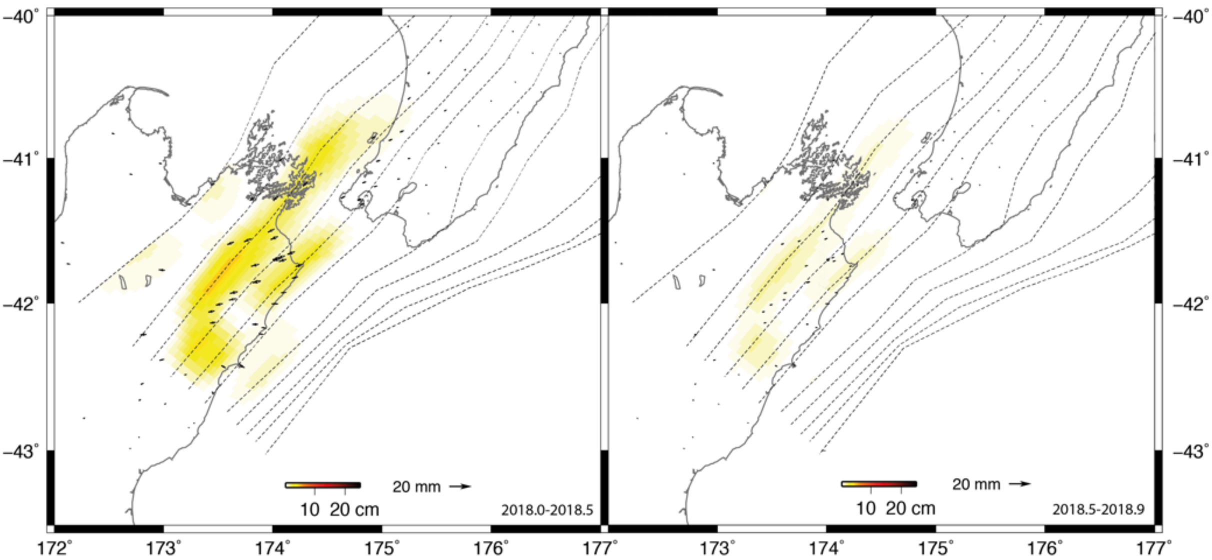

Figure 6. Preliminary model showing slip on the plate interface from January-July 2018 (left), July to November 2018 (right). Very little slip is resolved on the plate interface from July 2018.

In Figure 7 we show comparison between interseismic deformation estimated from data spanning 1998-2016, prior to the Kaikoura earthquake, and post Kaikoura deformation estimated from data spanning January 2017 to April 2018. Figure 7 differs from previous figures in that we do not correct the postseismic data for the pre earthquake (interseismic) deformation, but rather show how the region was deforming before and after the Kaikoura earthquake.

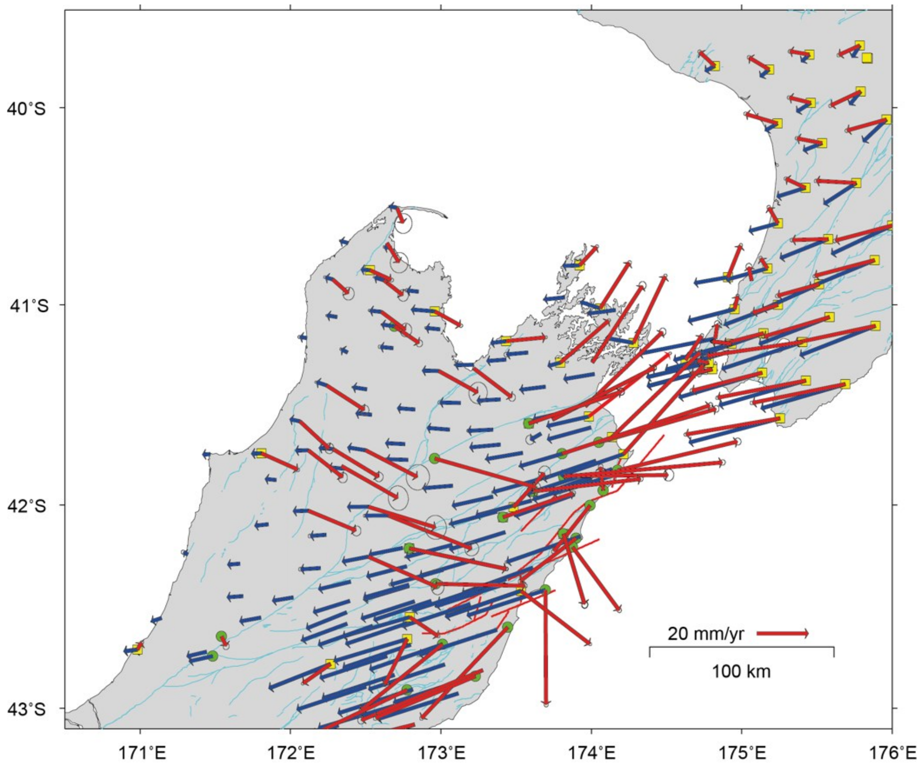

Figure 7. Comparison between pre and post Kaikoura deformation shown in Australian fixed reference frame. Blue) interseismic deformation prior to the Kaikoura earthquake, estimated from campaign and GNSS data spanning 1998-2016, Red) average velocity estimated from January 2017 to April 2018. Yellow squares indicate continuous GeoNet/PositioNZ GNSS stations and green circles show semi continuous GPS stations installed following the earthquake.

Impact

The data collected during this project has allowed us to evaluate afterslip on faults that ruptured during the earthquake as well as the plate interface. We will continue to refine models and explore possible effects of mantle relaxation on the longer-term postseismic deformation. The postseismic deformation influences seismic hazard on other faults in central New Zealand both in the short and long term, loading some faults and unloading others. Better understanding of the postseismic processes will lead to enhanced assessment and modelling of New Zealand's geohazard risk. The measurements are also helping us understanding the role of the Hikurangi interface beneath the northern South Island which is currently not fully understood and directly impacts how large earthquakes we could expect on the Hikurangi interface.

Future work

Preliminary modelling of the GNSS data collected in early 2018 suggest that majority of the signal we observe is dominated by slip on the plate interface beneath the region and afterslip on crustal faults that ruptured during the earthquake. The slip on the plate interface seems to have decayed rapidly, lasting until the middle of 2018 but we still see significant movement of sites in the near field of the earthquake rupture, indicating continued afterslip on crustal faults. In the next few months we will explore models which include viscoelastic response to the lower crust and upper mantle. In addition we will evaluate stress transfer on active faults in the region and what it means in terms of seismic hazard.

The TOPS GNSS network will be remeasured in 2020 as part of a regular SSIF funded monitoring of deformation in New Zealand. Selected semi continuous stations will be operated until at least 2020. The data will be used to evaluate viscoelastic response of the region to the Kaikoura earthquake.

Acknowledgements

We acknowledge all the people that participated in the TOPS2018 fieldwork campaign and made sure high quality GNSS data were collected. LINZ contributed two people team to help with the measurements for the duration of the campaign. A summer intern at GNS Science, Cyril Journeau (MS student at ENS France), also participated in the fieldwork. Along with the campaign GNSS data we use GNSS data available from GeoNet/PositioNZ stations in the region. In addition continuous GNSS data from Allterra and Global Survey were made available to the project as well as data from local and global IGS stations. The GNS Science core TSZ project co funded scientist and technician time (Dr Hreinsdóttir, Mr Palmer) to work on this project. Laura Wallace's time spent on modeling the data was co-funded by a Marsden fund grant awarded to Bill Fry, as well as a U.S. National Science Foundation grant to investigate slow slip on the Hikurangi subduction zone.

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Outputs and Dissemination

2018 AGU Fall Meeting (talk)
Presentation title: **Deformation Following the 2016 Mw 7.8 Kaikōura Earthquake, New Zealand**
Presentation number: G21A-01
Authors: S Hreinsdottir, I J Hamling, L M Wallace, P H Denys, S M Ellis, N Palmer, E D'Anastasio, P Gentle, C Pearson and P Upton
Date of presentation:11 December 2018
https://agu.confex.com/agu/fm18/meetingapp.cgi/Paper/454513

University of Iceland, Institute of Earth Sciences (Lunchtime talk)

Presentation title: **Crustal deformation during and following the 2016 M7.8 Kaikoura earthquake, what we have learned so far**
Authors: S Hreinsdottir, I J Hamling, L M Wallace, S M Ellis, P H Denys, N Palmer, E D'Anastasio, P Upton, and C Pearson.
Location:
Date of presentation: 5 December 2018

ITP Wellington (talk)
Presentation title: **Kaikoura: How technology uncovered a tale of subduction, rifts and transformation**
Authors: S Hreinsdottir, I J Hamling, L M Wallace, S M Ellis, P H Denys, N Palmer, E D'Anastasio, P Upton, and C Pearson.
Date of presentation: 29 November 2018
https://itp.nz/events/wellington/1814-Kaikoura_How_technology_uncovered_a_tale_of_subduction_rifts_and_transformation_

GNS Science and University of Wellington Workshop: Kaikoura earthquake research and identifying gaps in knowledge (talk)
Presentation title: **Deformation Following the 2016 Mw 7.8 Kaikōura Earthquake, New Zealand**
Authors: S Hreinsdottir, L M Wallace, I J Hamling, P H Denys, S M Ellis , N Palmer, E D'Anastasio, P Gentle, P Upton, C Pearson, P Upton
Date of presentation: 29 January 2019

GNS Science Report
Author: R. J. A. Hart, N. G. Palmer
Report title: Field report on GNSS surveys of the Top of the South Island Network in 2018 (TOPS2018)
Report Number: GNS Science Report 2019/20
ISBN: 978-1-98-856941-3
DOI: 10.21420/P0CY-D396

List of key end users

The data collected and models published will be provided to LINZ to allow for updates to the regional deformation model to determine precise positions of the PositioNZ GNSS data in the New Zealand Geodetic Datum 2000.

This work will impact the National Seismic Hazard model.