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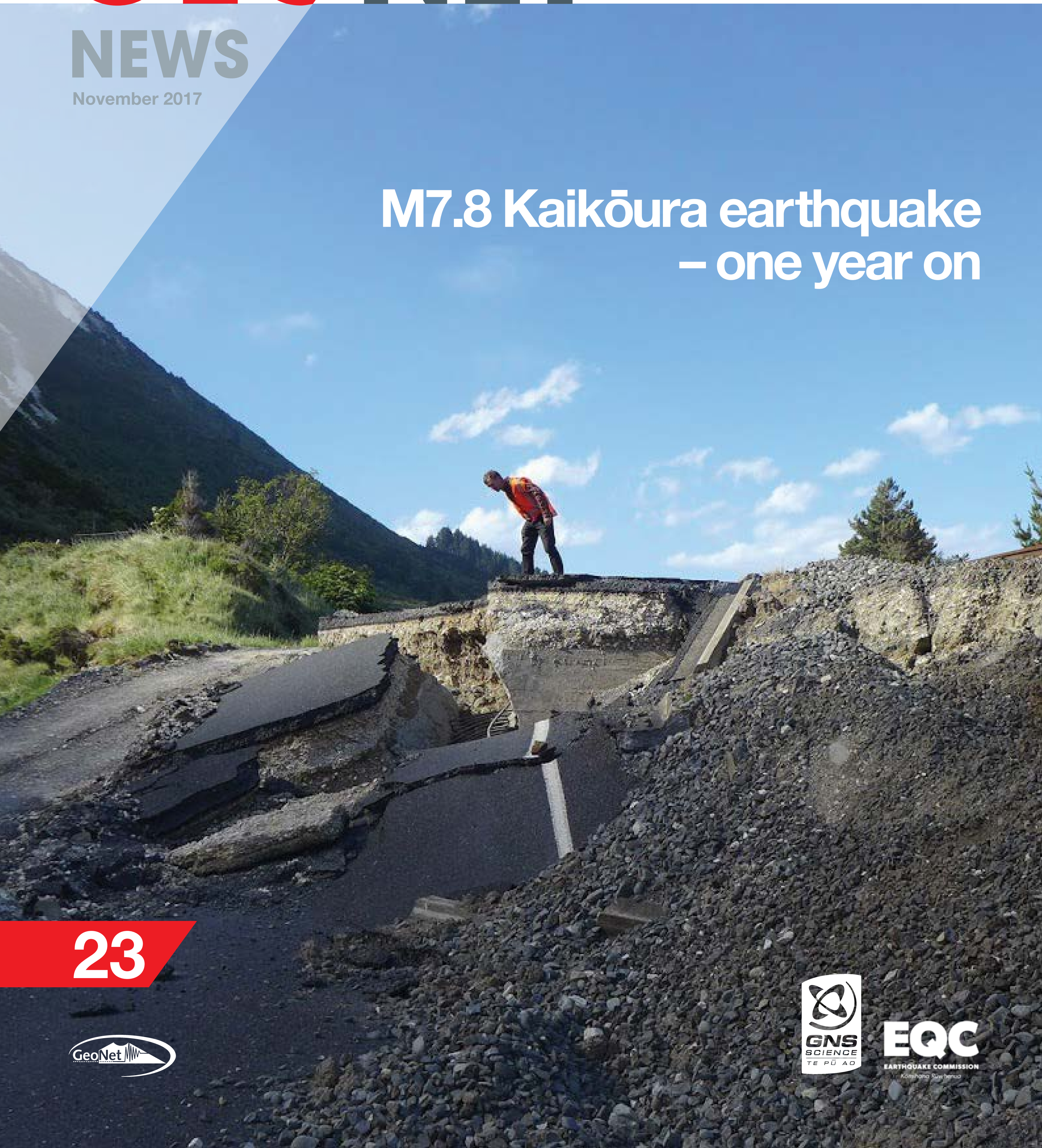
November 2017



M7.8 Kaikōura earthquake – one year on

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GeoNet

GNS SCIENCE TE PŪ AO

EQC EARTHQUAKE COMMISSION

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Kōmihana Rūwhenua

Reflections from the front line

AUTHOR: ANNA KAISER

Duty Officer Anna Kaiser.

Fortunately, as a duty officer it's not every day, or even every decade, that you are shaken awake by a M7.8 earthquake in the middle of the night, but we always know it could happen. On November 14th, the shaking that woke me up was only moderate, with nothing in the house broken or even displaced. However, the long duration of shaking was unmistakably that of a large and potentially damaging earthquake. It was clear there would be an extremely busy night ahead for the GeoNet response team.

The first job of the duty officer is to assess the earthquake parameters and review the automatic solution generated by our earthquake location software. As I started work on the earthquake, I could still feel the ground shifting as the surface waves rolled through and around the Wellington basin. The automatic parameters of the solution I picked up indicated a 45km-deep M<7 earthquake in North Canterbury. A review of the location confirmed that the earthquake initiated at <20km depth and the epicentre was indeed located inland in North Canterbury, south of the Hope Fault. A review of the magnitude was complicated by the sheer size of the earthquake and the fact that seismic stations more distant from the rupture were not able to be included in the initial working solution at that time using the procedure we had in place. In smaller earthquakes (M<6.5), this is of less consequence, but in the largest earthquakes, broadband stations even 100 or 200km away from the epicentre can be clipped under very strong shaking and therefore return unrealistically low magnitude estimates. Hence, the initial magnitude on the GeoNet website was considered a lower-bound estimate, with the possibility that the earthquake was significantly larger (although the full size of this huge M7.8 event was not at all clear). This information was all communicated quickly to the Ministry of Civil Defence and Emergency Management duty officer.

As with any large event, the main shock is followed by a flurry of aftershock activity and the possibility of large 'ghost quakes' generated around the country by our automatic location system, which generate a barrage of automatic alert pages that the duty officers need to sort out. Understanding where aftershocks are happening (and alerting authorities if they are potentially damaging) is crucial to gain a better picture of the area affected. The initial aftershocks occurred clustered around the epicentre. Duty officers Lara Bland and Agnes Mazot then jumped on board to help with the large task of reviewing and confirming the ongoing aftershock activity.

At the same time, an alert from the Pacific Tsunami Warning Center (PTWC) was issued with the earthquake estimated at M7.4 and slightly closer to the coast, but no tsunami threat was expected. This provided confirmation that the earthquake was larger in size than initially posted and raised some questions about the tsunami potential. This prompted a quick discussion with the GeoNet Director; we still considered a tsunami unlikely based on the inland location of the earthquake and the information available at the time. However, a short time later I reviewed and confirmed a M6.2 aftershock very close to the coastal town of Kaikōura (which raised initial concern as it indicated that the seismic activity involved a wider area) and then in rapid succession we were alerted by tsunami modeller William Power to a drawdown of >1m observed on the Kaikōura tide gauge indicating a potentially significant tsunami was imminent on the Kaikōura coast. The change in situation was communicated as quickly as possible to the MCDEM duty officer, unfortunately arriving at the same time that the initial 'Tsunami No Threat' messages were being released. This was followed 13 mins later by a message from the PTWC with an updated M7.9 magnitude and revised tsunami warning. The full extent of the size and impact of this earthquake was only now becoming clear and this was by far the most challenging aspect of the response. The media enquiries were also now starting to flood in and the latest information needed to be urgently communicated to the public.

The wider GeoNet response was also kicking into gear as our dedicated team came on board. Caroline Holden stepped in to chair the Tsunami Experts Panel; Bill Fry went down to the National Crisis Management Centre in the Beehive as the GNS Science liaison; Sara McBride continued to co-ordinate the comms response; I was first port-of-call for media enquiries; John Ristau acted as media backup when my line was busy; Jérôme Salichon was doing an in-depth review of the earthquake parameters to update the website; and many many others were busy aiding with other aspects of the response effort. From my side, much of the rest of the night was spent responding to the media while doing my best to keep abreast of the latest earthquake information. It was becoming clear this was a complex earthquake involving several different faults. It was also an event where there were fatalities and many people severely affected, which is extremely sobering for all involved, as we do the best we can to provide the latest information to the public.

The incoming duty officer; John Ristau took over the duty responsibilities at 9am (after also being up all night helping with the response), and it was time for me to focus on specific aspects of the earthquake science. Sometimes it is only when you arrive back home at the end of the day that you have time to fully reflect on the events and feel the exhaustion and intensity of the long response effort.

This was one of the most challenging events to respond to as a duty team, as it involved so many complex aspects and intense media interest. A local-source tsunami was generated and a globally unprecedented number of fault ruptures were recorded in a single earthquake. Looking forward from the Kaikōura earthquake, I'm excited to see new tools already up and running in our toolbox which will be invaluable in allowing us to more quickly and accurately assess an earthquake. As a seismologist, I am excited by the strong ground motion data visualisation tool (that was just not quite ready for the Kaikōura earthquake!) that lets us see immediately what amplitude of ground shaking was recorded at all our strong motion stations just minutes after the earthquake (www.geonet.org.nz/strong). As part of the Enhanced Geohazard Monitoring effort, a new tool is also being developed to aid in rapid assessment of local-source tsunami, which will help us meet new expectations about providing very rapid initial tsunami advice. There is much work to be done ahead as we work to improve our tools and procedures, always looking to be the best prepared we can be for the next big event.

GeoNet is a non-profit project operated by the Institute of Geological & Nuclear Sciences Limited (GNS Science) with core funding from the Earthquake Commission. It involves GNS Science building and operating a modern geological hazards monitoring system for New Zealand.

The GeoNet project started in 2001. It provides real-time monitoring and data collection for rapid response to and research into earthquakes, volcanic eruptions, tsunami and landslides. Data collected by GeoNet are available free of charge. Visit www.geonet.org.nz for more information.

The Kaikōura earthquake

15,840
felt reports

21
identified faults

Kekerengu Fault. (Photo Julian Thomson)

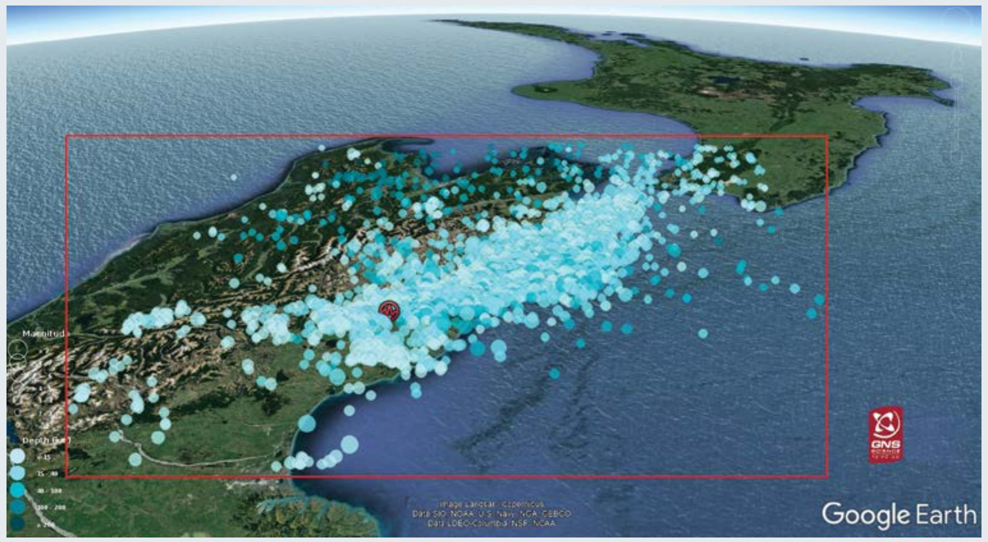
10,000+
landslides

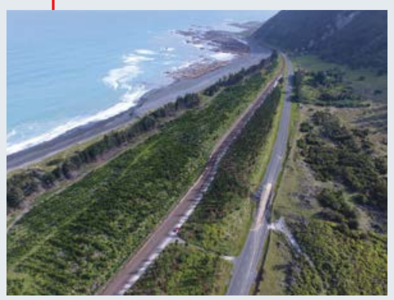
The Papatea Fault scarp. (Photo Julian Thomson)

3g+
peak ground acceleration (PGA) recorded at Waiau

M7.8
severe shaking

19,000+
total aftershocks to date
M4 = 506
M5 = 58
M6 = 3
M7 = 1





Papatea Fault crossing SH1 and heading out to sea. (Photo Julian Thomson)

Seismology in action: Mapping the quake from space and on the ground

AUTHORS: BEN PAYNE, KATE CLARK, IAN HAMLING

As the most complex earthquake ever recorded on instruments, investigating the Kaikōura quake has revealed ground-breaking scientific knowledge about how fault systems work during high magnitude events.

Geodesy and geological observations have provided a very detailed picture of the M7.8 Kaikōura earthquake, from different scientific vantage points. The addition of a time element from the GeoNet seismic network allowed us to capture a valuable data set for scientists to work with and understand the complex network of faults that unfolded along the east coast of the South Island.

A SNAPSHOT FROM SPACE – WATCHING THE EARTHQUAKE UNFOLD WITH GEODESY

'Geodesy' is all about keeping track of the Earth's shape, so 'geodetic data' are often the locations of a point on the Earth's surface recorded over time. For GeoNet these points are GNSS sensors, 'flying-saucer' antennae located at our monitoring stations, which record the position of satellites orbiting the Earth up to 10 times every second. By locating themselves relative to the satellites, the GNSS sensors record a continuous stream of how New Zealand is moving.

GeoNet's network (of geodetic, short and long motion sensors) had limited coverage in the North Canterbury and Marlborough regions at the time of the quake. Within three days of the main shock, however, our tech teams had deployed several temporary monitoring sites, such as one at Seddon, which allowed us to capture the post-seismic deformation with fantastic clarity! (see the back page)

These geodetic data have provided detailed insight into the tectonic movement and deformation that occurred during the Kaikōura main shock and in the following aftershocks. For the last year, leading scientists here at home in New Zealand, and abroad, have been delving into GeoNet's data to develop various, multiple-source 'slip models', which have provided ground-breaking science explaining land movement with the shock.

By way of overview, these multiple-source modelling techniques suggest the earthquake ruptured (more or less continuously) more than 20 fault segments from south to north and went on for more than 90 seconds.

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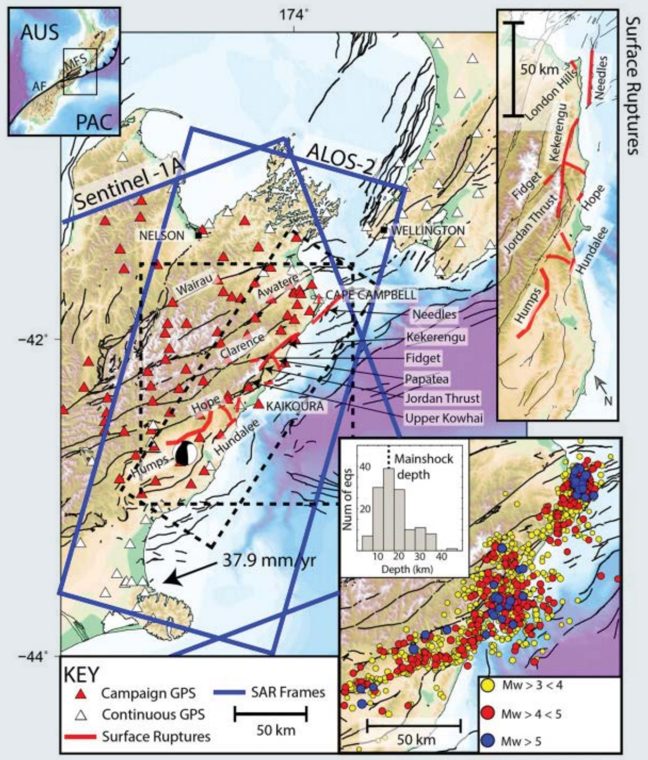


Fig 1: Colour shaded relief of central New Zealand. The main figure shows the location of the continuous (white triangles) and campaign (red triangles) GPS sites. Heavy blue lines indicate the frame boundaries for the Sentinel-1a and ALOS-2 InSAR frames used in the study and red lines show the location of surface rupturing. The lower case labels denote some of the major crustal faults running through the MFS and the upper case labels show the towns/cities of Kaikōura, Wellington and Nelson and the Cape Campbell region. The dashed black boxes indicate the regions shown by the two sub-figures. The vector shows the relative plate motion between the Pacific (PAC) and Australian (AUS) Plates as indicated in the top left. The beach ball gives the W-phase moment tensor generated by the USGS at the epicentral location. Bottom right: Distribution of relocated aftershocks over magnitude 3 occurring in the first 2 weeks. Earthquakes are colour coded by magnitude. The histogram shows the depth distribution of M4.5 and above. Top right: Map showing the regions with observed surface ruptures (red lines).

The dominant energy release actually occurred in the northern part of the rupture area, roughly 60km south of Wellington, about 60-70 seconds after rupture initiation.

A few facts and figures show why people across the region found the 14 November 2016 quake traumatic, with GPS data recording land displacements with more than 6m of sideways (lateral) motion near Cape Campbell (Figs 1 and 2) and uplift of up to 2m at the northern end of the Seward Kaikōura mountain range (Fig 2). Widespread uplift also occurred near Kaikōura with areas of subsidence found inland of the Clarence Fault and to the south of the Humps and Hundalee Faults in North Canterbury (Figs 1 and 2). Two sites, located to the south of the Kekerengu Fault, show the westward motion of at least 2m.

This post-quake data capture and seismological studies provide detailed insight into the crustal structure beneath central New Zealand. Geodetic modelling is a powerful tool because it provides understanding of the 'fault slip' (lateral and vertical movement) that occurred along the fault margin at various depths below the surface.

2

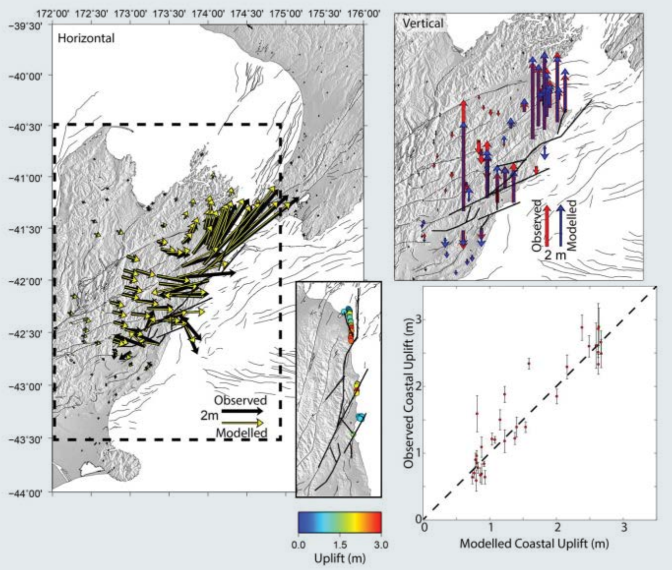


Fig 2: Observed (black) and modelled (yellow) horizontal displacements at continuous and campaign GPS sites assuming only crustal faulting. The black dashed line indicates the region shown in the top right image. Observed and modelled vertical displacements are shown as red and blue arrows respectively. Coastal uplift observations are indicated by the coloured circles and a comparison between the observed and modelled uplift is shown in the bottom right. The dashed line shows a correlation of R = 1.

SURFACE CHANGE – A GEOLOGICAL PERSPECTIVE

The extensive coastal uplift and the ripped up, folded landscapes that occurred suddenly with the M7.8 Kaikōura earthquake are images that stick in many of our minds, and surface ruptures and rifts tell of the immense forces at play.

Over the past year, scientists like GNS Science's Kate Clark have been producing world leading research into coastal uplift and crustal rupture by investigating surface changes, with techniques like ground differencing LiDAR (Light Detection and Ranging) imagery. LiDAR is a remote sensing survey method that measures the elevation of the ground surface by illuminating the target landscape with pulsed laser light, and measuring the reflected pulses with a sensor. Differences in laser return times and wavelengths can then be used to make digital 3-D representations and amazing imagery that can show surface change at a broad level.

It was fortuitous really, but a ~90km long strip of the Kaikōura coastline had been surveyed by Environment Canterbury with airborne LiDAR in July 2012, which provided a useful benchmark of LiDAR coverage. Within a matter of hours following the earthquake Kate and a team of other experts were on the ground in Kaikōura, and between the 19th and 21st of November 2016, the same 90km strip of Kaikōura coastline was surveyed with LiDAR. This is where the 'ground differencing' part comes into play. The extensive LiDAR coverage from both before and after the Kaikōura earthquake has enabled unparalleled research on the coastal uplift, providing an accurate, high resolution assessment of topographical changes and uplift. Some of these changes are shown in Figure 3.

3

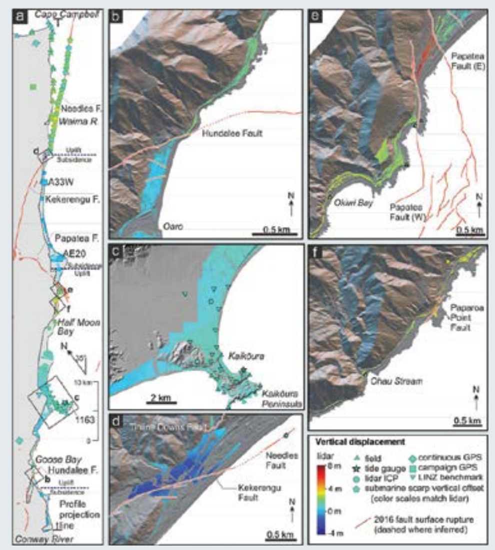


Fig 3: Maps of coastal vertical displacement occurring in the 2016 Kaikōura earthquake. (a) Coastline impacted by Kaikōura earthquake, dashed black line shows the extent of overlapping pre- and post-earthquake LiDAR coverage, within which the the colour shaded areas represent the 0-5 degree slopes over which we measured 2012-2016 vertical displacement. The dark blue dashed lines delineate the hinge points between uplift and subsidence. (b)-(f) Detailed maps of areas of interest, particularly around fault surface ruptures.

Using imagery to map landscape changes

AUTHOR: BEN PAYNE, GARTH ARCHIBALD, CHRIS MASSEY, SALLY DELLOW

In the first few days after the Kaikōura earthquake, photographs, satellite and radar-based imagery, such as InSAR, helped us to identify where the ground was displaced by landslides, active faults and crustal shift at a landscape scale (see pages 6-7 for some up-close perspective on what's been done).

At a more localised scale, drones and a terrestrial laser scanner have been used by our landslide team to build a detailed understanding of landslide processes and develop 3-D models of the landslide dams that formed during the Kaikōura quake. Our GeoNet landslide scientists have so far mapped more than 11,000 landslides from the M7.8 Kaikōura earthquake from North Canterbury through to Marlborough.

The location of the slips caused by the Kaikōura quake are shown in Fig 1. Interestingly, landslides are clustered around the areas of fault rupture, not around the earthquake epicentre (which is what we would normally expect to see). In fact, many of the largest landslides occurred right at the places where faults ruptured to the ground surface.

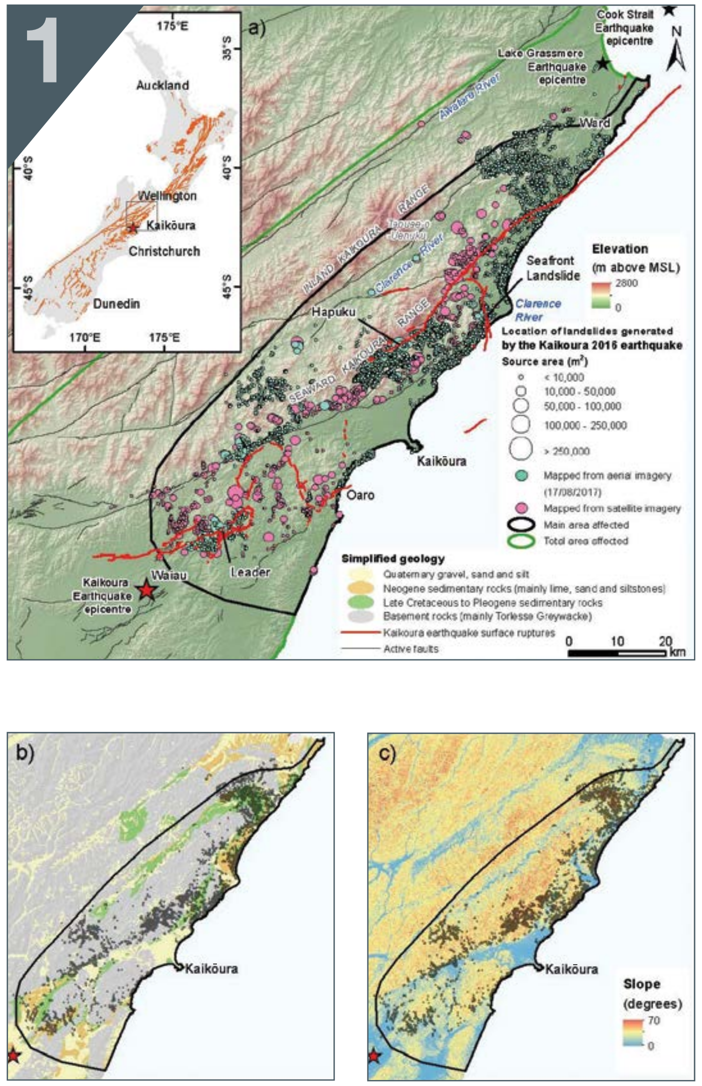


Fig 1: Mapped landslides as of August 2017. Inset map shows the area of New Zealand affected by coseismic landslides triggered by the M7.8 2016 Kaikōura earthquake. The main map shows the mapped (more than 11,000 landslides) coseismic landslide source areas and their size (area) triggered by the earthquake, superimposed on the 8m by 8m digital elevation model for New Zealand, classified by elevation in metres above sea level.

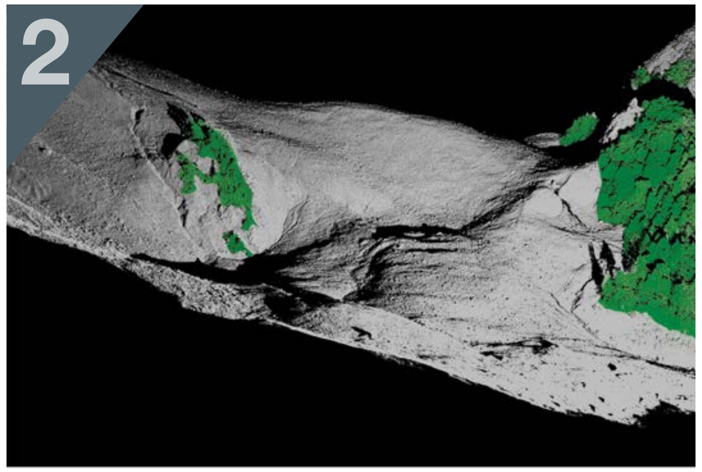
Conway landslide dam. (Photo GNS Science)

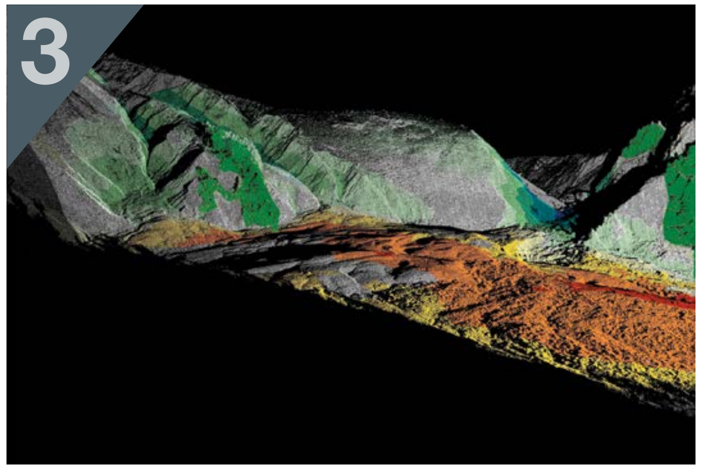
THE CURRENT STATUS OF THE MANY LANDSLIDE DAMS

Massive amounts of material slumped and blocked river valleys, creating landslide dams.

More than 200 significant landslide dams were created by the main shock and aftershocks that followed, and they have been a fascinating outcome of the earthquake for scientific study, illustrating how much energy is released by high magnitude events and how dramatically a region's landscape can change in such a short time!

3-D modelling of some of the landslide dams over the past year has allowed our scientists to understand how the dams have changed such as with the development of overflow channels, erosion and seepage points prior to failure. Many of the significant landslide dams have now breached. All the five dams our scientists have been studying due to the downstream risk they pose to infrastructure have now failed and the impounded water either totally or partially released. Our scientists via detailed ground surveys have captured the before and after failure models of the dams and the effects their failure have had downstream, therefore allowing them to calibrate their models, which can now be used to forecast the potential impacts of other dam breaches. This is shown in Figs 2 and 3.

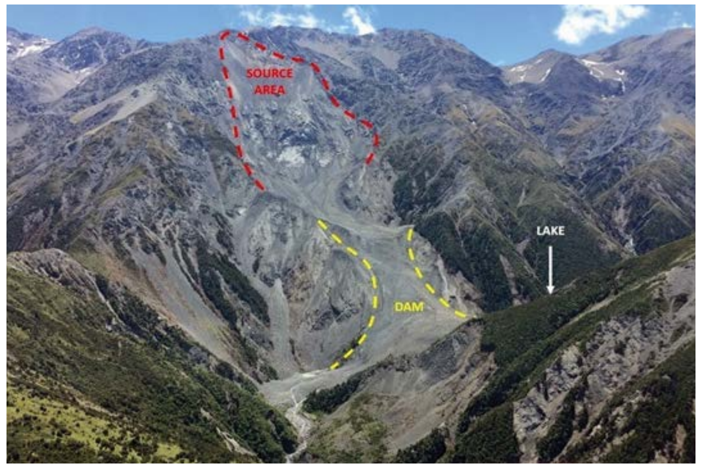




Figs 2 & 3: The images show the coloured point clouds from ground-based LiDAR surveys carried out of the Hapuku landslide dam by GNS Science. The left-hand image shows a model of the dam as it was in December 2016. The right-hand image shows a model of the dam in October 2017, after it had overtopped and breached. Note the breach geometry on the right of the right-hand image.

The approximate volume of dam material eroded is about 1 million cubic metres. Much of the dam is still present, but water continues to flow out of the lake along the breach channel. The orange and red colours in the right hand-image represent material deposition (aggradation) and the blues and greens represent material erosion.

Dam breaches can be dangerous, with the potential for flash floods to flow rapidly down river valleys, but we now understand more about the processes driving them and are better able to monitor and predict future changes. This helps us to reduce risk to people and assets over time, and the GeoNet landslide team is continuing to work closely with councils and the NZ Transport Agency to assess and manage the risk from landslide dams to downstream communities and infrastructure.



Hapuku landslide dam: about 20 million cubic metres of rock travelled 2.7km to the valley floor. (Photo GNS Science)

Hapuku landslide dam. (Photo Environment Canterbury)

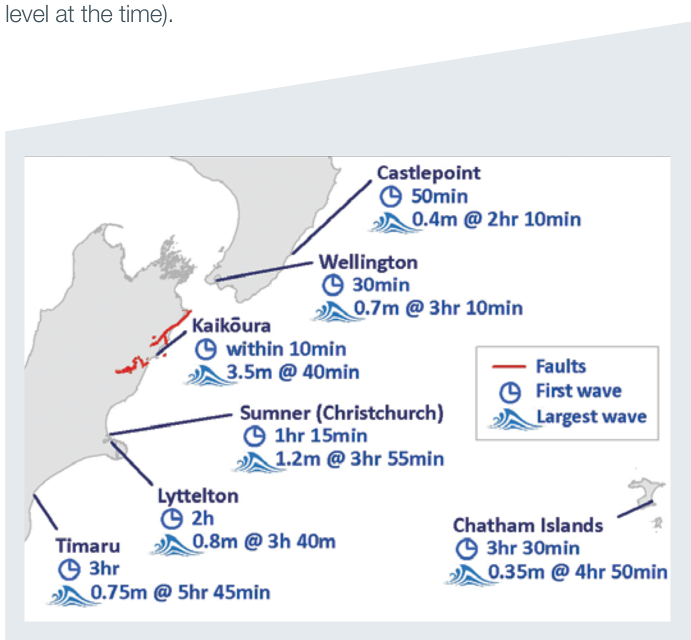
The Kaikōura tsunami

AUTHORS: HELEN JACK, WILLIAM POWER, EMILY LANE (NIWA)

The tsunami was the biggest local-source tsunami in New Zealand since 1947 (and by local-source we mean a tsunami created close to our shore rather than a distant-source tsunami created on the other side of the Pacific Ocean, for example).

It was unusual in that it was generated from an earthquake that started on land and crossed the coastline offshore – that's pretty rare. It was also unusual because of the number of offshore faults that moved. This unique combination meant that the tsunami behaved a little differently from your more standard tsunami generated from only one fault.

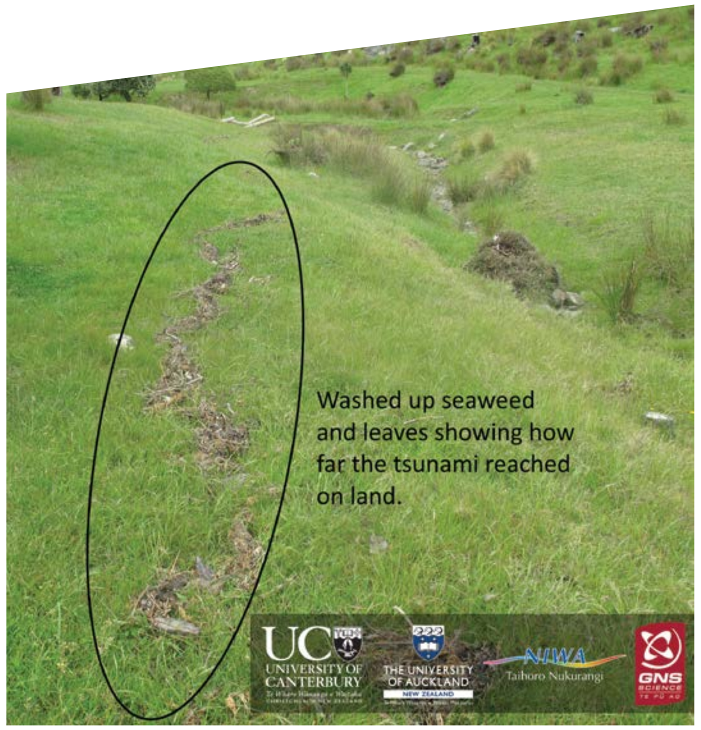
The map below shows where water level gauges recorded the tsunami. The clock icon is how long after the earthquake that the first tsunami waves arrived, and the wave icon is the maximum tsunami wave recorded and the time after the earthquake that it was recorded. The maximum wave in this case is measured from peak to trough (that is, the largest change in water level from the top of a wave to the bottom, rather than the largest height above normal sea level at the time).



Kaikōura tsunami travel time map. From GeoNet tsunami gauges and Lyttelton Port Company and PrimePort Timaru tide gauges.

As you can see the first waves reached the Kaikōura coast within 10 minutes of the earthquake – a good reminder of why you need to move away from the coast quickly if you feel a long or strong earthquake. Ten minutes may not be long enough for our seismologists to confirm a tsunami has been generated, and for Civil Defence to issue an official warning to everyone – natural warnings are the best warnings.

You may have read that the tsunami was 7 metres high near Kaikōura. This sounds huge, but it's not quite the 7 metre wall of water at the coast that it sounds like. This figure referred to the 6.9 metre 'run up' measured in Goose Bay, just south of Kaikōura. The tsunami wave height in the sea was probably around 3-4 metres above the normal sea level at the time when it reached Goose Bay, but the beach there is very steep and the wave pushed up against it, leaving debris up to 6.9 metres above sea level. The tsunami also pushed at least 150 metres up the Ote Makura Stream in Goose Bay and over 200 metres up Te Moto Moto stream in Oaro.



Evidence of how far the tsunami reached on land.

Seaweed left high and dry by the tsunami at Oaro.
(Photo D N King)

On the whole, the damage along the Kaikōura coast from the tsunami was less than we might have expected because the tsunami arrived at mid to low tide, much of the Kaikōura coastline was uplifted during the earthquake, and the beaches along the coastline here are steep. Otherwise the damage could have been much worse.

The other unusual aspect about the tsunami was that the worst damage happened 150km away from where the tsunami started. The tsunami waves would have been almost unnoticeable as they silently travelled south through the open waters off the North Canterbury coast. But once they got to Banks Peninsula (whose narrow bays and harbours have been described in the past, by someone who shall remain nameless, as 'a collection of funnels waiting to receive tsunamis') 1.5 hours after the earthquake, north-facing Little Pigeon Bay sat at just the right angle for the waves to flow straight into it, and it was just the right shape for the waves to start bouncing around inside the bay. This particular mix of circumstances created tsunami surges at the head of the bay that were bigger and more forceful than those seen in other northern Banks Peninsula bays.

The differing impacts from the Kaikōura tsunami along the eastern South Island and southern North Island coasts show us again what tricky little beasts tsunami are. Scientists work really hard to understand tsunami behaviour so that they can provide better information to people both before and during a tsunami. Because this event was so complex, scientists are still working on a model to explain how the fault movements during the earthquake caused the flooding and impacts seen on land.

A very important, but not unusual, aspect of the tsunami was that in most places (apart from very close to where the tsunami started) the highest tsunami waves arrived a couple of hours after the first wave. While an official warning can't replace the natural warning of the earthquake itself (remember – long OR strong earthquake, get gone!), our seismologists will still work closely with the Ministry of Civil Defence and Emergency Management (who issue tsunami warnings) to advise people of a possible local-source tsunami, even if the first waves may have already arrived. This is because (a) it confirms to those coastal residents that did evacuate when they felt the long or strong earthquake that it was a good idea, and that they should stay away for the time being and (b) the largest tsunami waves may still be on their way, so for people who haven't already evacuated, it's still a good idea.

Earthquake forecasting

AUTHORS: MATT GERSTENBERGER, ANNEMARIE CHRISTOPHERSEN AND DAVID RHOADES

Earthquake forecasts have become a standard part of the GeoNet response to major earthquakes since the 2010/11 Canterbury earthquakes. The earthquake forecasts provide the probability of an earthquake happening in a certain area over a defined period of time. They are mainly based on the occurrence of earthquake clustering in time and space. The Kaikōura earthquake inspired the refinement of these forecasts and their use in a range of practical applications.

Our forecasts are based on research into time-dependent earthquake occurrence, including international testing of forecast models over more than a decade. We distinguish two types of earthquake clustering: decay of aftershocks following a major earthquake, and increase in seismicity prior to a major earthquake. We combine variants of these two types of models with models of the long-term average rate of seismicity to derive the earthquake forecast.

The earthquake forecast probabilities are useful for engineers, infrastructure managers, private companies, Civil Defence, government planning, and insurance organisations, including EQC. The Kaikōura forecasts have been used in hazard and risk applications and have influenced legislation on retrofitting unreinforced masonry buildings, helping us to be more resilient to earthquakes in the future.

More details on the methods can be found here: www.gns.cri.nz/EQforecastInfo

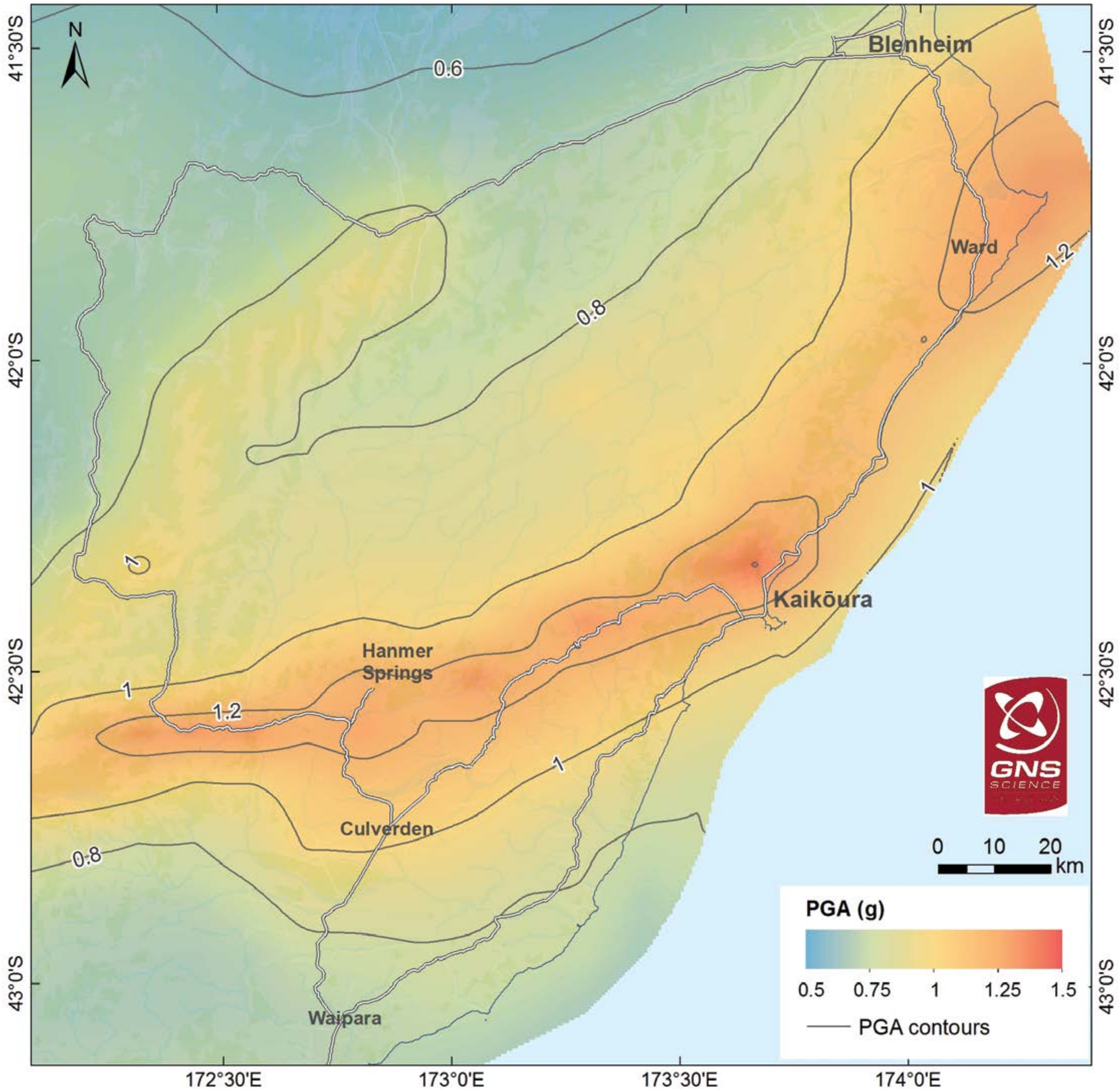
THE KAIKŌURA HAZARD MODEL

We have developed a Kaikōura earthquake hazard model (see image on the right) for a 100-year time period, to inform building and infrastructure repairs and rebuilds in the area affected by the Kaikōura earthquake. Earthquake hazard models are a combination of earthquake rates, fault information and ground motion models. For the Kaikōura hazard model, the earthquake rates are a combination of different types of models, similar to the forecast published by GeoNet. The fault information is based on the New Zealand active fault database and includes information on the time since the last rupture on the fault, if known. Special consideration was given to how to model a possible Hikurangi subduction zone earthquake. We have used multiple ground motion models to capture the uncertainty in the process. This figure is an example of a hazard map that is used for recovery planning in North Canterbury. It shows the ground motion in PGA (peak ground acceleration) that has a 1 in 1000 chance of being exceeded per year for shallow soil (Class C). Compared to the 2010 National Seismic Hazard Model the hazard increased everywhere on the map, with the highest increase of 60% in PGA near Culverden and Ward.

Slow slip

The increased slow slip on the North Island subduction interface after the Kaikōura earthquake (see page 14) has initiated a new line of research into combining information on slow slip into earthquake forecasts. In December 2016 a group of scientists with expertise in physical and statistical modelling of earthquake occurrence estimated the impact of the slow slip on the probability of future large earthquakes (M7.8+) happening in central New Zealand. This estimate was included in the forecast scenario published on the GeoNet website.

On the anniversary of the Kaikōura earthquake we are holding an international workshop to review research already undertaken, propose future research on combining slow slip into earthquake forecasts and re-estimate the probability of future large earthquakes in the region.



The following people contributed to the development of the Kaikōura hazard model: Gerstenberger, M., Rhoades D., Litchfield, N., Kaiser, A., Holden, C., Fry, B., Van Dissen, R., McVerry, G., Goded., T, Stirling. M., Christophersen, A., Wallace, L., Bannister, S., Reyners, M., Langridge, R., Nicol, A., Little, T., Hamling, I., Barnes, P., Kaneko, Y., Barrell, D., Abbott, E., Pettinga, J., and Lukovic, B.

The latest earthquake forecasts are available online: www.geonet.org.nz/earthquake/forecast/kaikoura.

The forecasts include tables of the number of earthquakes expected during future time periods (currently three months and one year) for different magnitude ranges. They also includes maps of the probability of earthquake shaking and possible scenarios of how the earthquake sequence might develop.

Understanding the relationship between earthquakes and slow slip events

AUTHORS: EMILY LAMBIE, LAURA WALLACE

In the weeks and months following last November's earthquake GeoNet's continuously operating GPS network (Global Positioning System) detected widespread slow slip that was triggered off the North Island's east coast, beneath the Kapiti Coast region, and beneath the northeastern South Island. This is the largest episode of slow slip observed to date in New Zealand, and the first time that scientists have observed simultaneous slow slip in all three areas.

Slow slip events (also referred to as silent earthquakes) involve the intermittent slow movement (over days to months) along fault lines where two tectonic plates meet. They are similar to earthquakes, however earthquakes occur over a matter of seconds. We commonly observe slow slip events on the Hikurangi subduction zone, which is New Zealand's most active plate boundary, where the Pacific Plate dives or "subducts" beneath the North Island.

Laura Wallace of GNS Science tells us "the slow slip event following the Kaikōura earthquake is the largest and most widespread episode of slow slip observed in New Zealand to date, and is probably the clearest example worldwide of long distance, large-scale slow slip triggering".

The slow slip event off the east coast occurred at less than 15km below the surface (or seabed) spanning an area of more than 15,000 sq km offshore from the Hawke's Bay and Gisborne regions, and lasted less than 10 days. In contrast the slow slip beneath Kapiti and the northern South Island is occurring at more than 25km depth, and continues today. We expect the Kapiti slow slip to continue for at least a few more months, based on its past behaviour.

Yoshihiro Kaneko, explained "the slow slip offshore from the east coast was triggered by stress changes in the Earth's crust caused by passing seismic waves from the Kaikōura quake, which was ~600km away from the triggered slow slip." Kaneko showed that the passing seismic waves were amplified offshore Gisborne due to the presence of a compliant sedimentary wedge offshore, which may have caused the slow slip event triggering. The Kapiti slow slip is much closer to the Kaikōura earthquake rupture, and is probably due to longer-lasting changes in stress induced by the earthquake (rather than stresses induced by passing seismic waves).

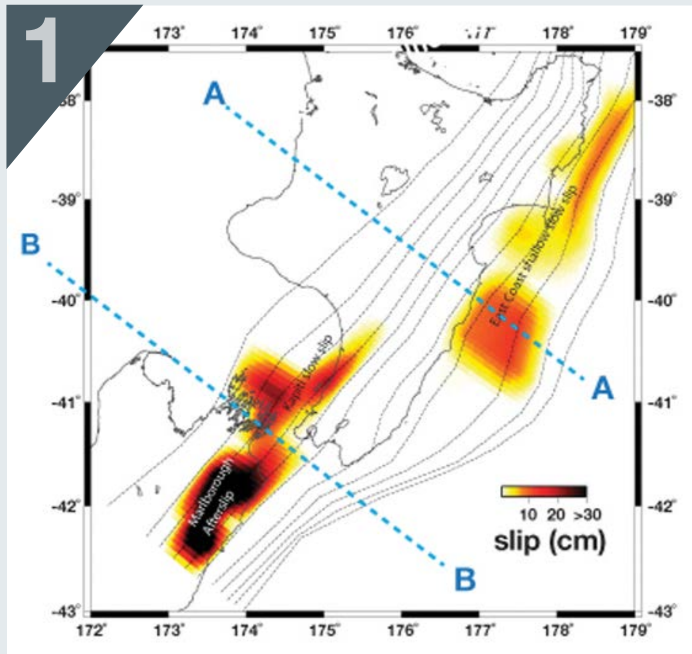


Fig 1: Amount of movement in centimetres on the subduction zone during the slow slip event triggered by the Kaikōura earthquake.

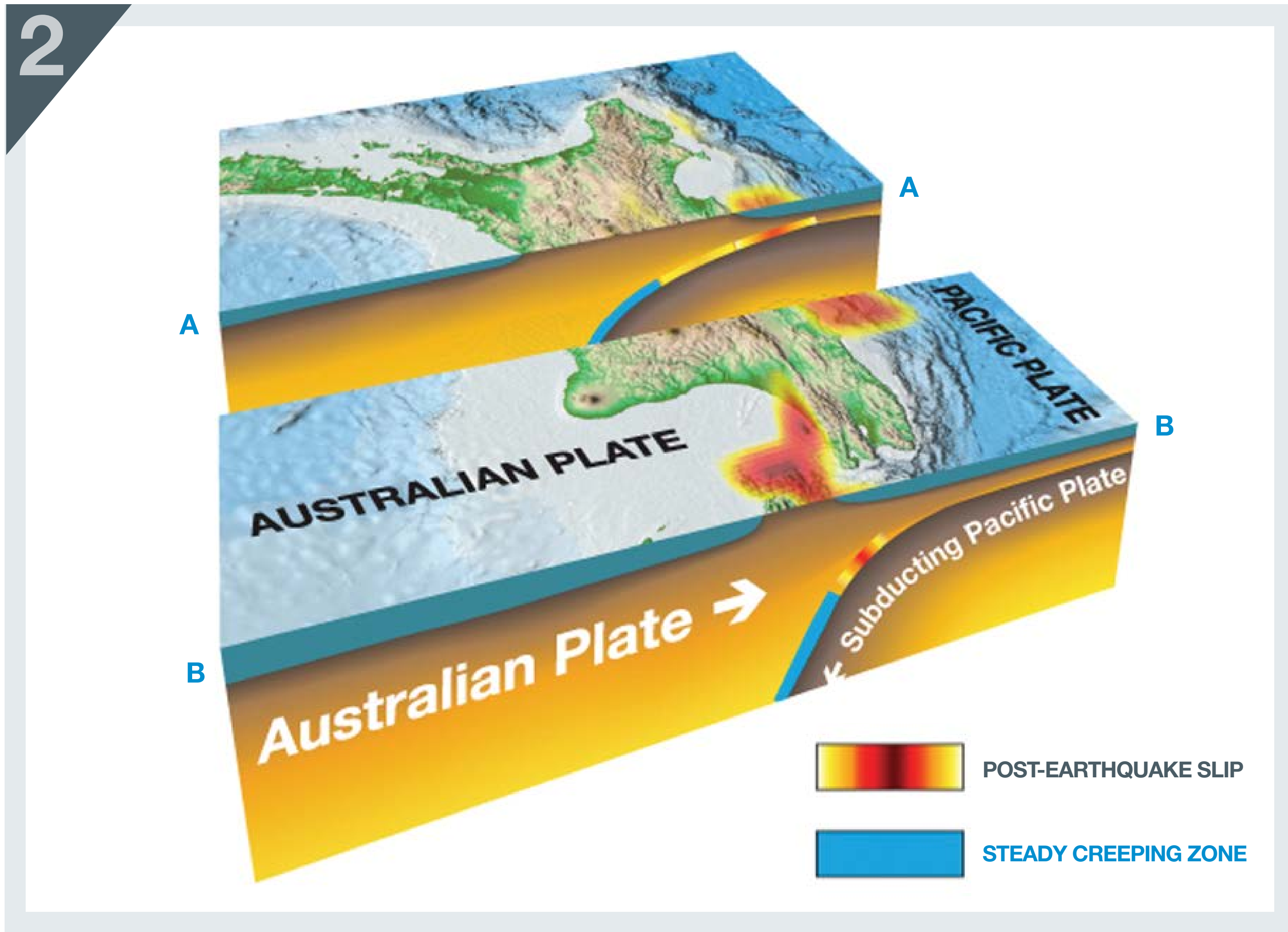


Fig 2: Cross-section of the slow-slip zones shown in Fig 1, at the boundary between the Australian and Pacific Plates. Slow slips in the south (Kapiti and Manawatu) happen at greater depth than those in the north (Hawke's Bay and Gisborne.)

The east coast slow slip event released energy equivalent to a M7.1 earthquake during the two weeks following the Kaikōura earthquake, while the Kapiti slow slip event has released energy equivalent to a M7.0 earthquake over the last year. The east coast slow slip event started offshore from Gisborne and migrated south towards Porangahau during the last half of November.

Our scientists have modelled GeoNet's cGPS displacements across the network to determine the slip on the subduction zone during the slow slip event triggered by the Kaikōura earthquake (see Fig 1).

Slow slip events are a relatively newly discovered form of fault slip behaviour at subduction zones and GeoNet's continuous GPS sites are the primary way to detect them. Since 2002 we have observed more than 30 distinct slow slip events at our cGPS sites in the North Island and significantly transformed our understanding of how plate boundary faults work.

The slip that we observe on the subduction plate boundary beneath the northern South Island during the last year is the first time that slip on that part of the subduction zone has been observed. However, instead of calling this "slow slip" our scientists are calling it "afterslip" due to its proximity to the faults that ruptured during the Kaikōura earthquake. This "afterslip" phenomena is commonly observed on the portions of faults close to earthquake ruptures.

When they were discovered, our data revealed that different parts of New Zealand's subduction zone behave differently. Some areas beneath the lower North Island are completely locked together and probably only move with an earthquake. In other areas, such as the Gisborne and Hawke's Bay regions, the plates mostly move past each other during slow slip events.

In New Zealand, we often observe at least one or two slow slip events each year. These are commonly accompanied by earthquake swarms – a swarm of earthquakes is a sequence of nearby earthquakes striking in a short period of time. These earthquakes are likely to be in response to the stress changes in the Earth's crust caused by the slow slip.

Substantial research efforts are underway by our scientists and internationally to better understand why slow slip events happen in some parts of New Zealand, while in other parts of the Hikurangi subduction zone the plates lock together and slip in earthquakes. This will help to resolve the relationships between earthquakes and slow slip. Once our scientists can better understand the influence of slow slip events on earthquake rates, we can greatly improve our shorter-term earthquake forecasts and provide important insights to where great subduction earthquakes are most likely. See page 12 to read about how slow slip is informing earthquake forecast research.

NETWORK ADDITIONS

In the weeks following the Kaikōura event our technicians were busy installing new instruments in the region to help us better locate the many aftershocks, and see how the land was behaving/moving. This included adding both temporary and new permanent stations to our national network.

NEW SITES

GNSS with strong motion

GLOK	GLOS	Glen Orkney
LOOK	LOKS	Mt Lookout
SEDD	SDNS	Seddon
WRAU	WRAS	Wairau Valley

GNSS with weak and strong motion

CLRR	CRSZ	Clarence River Middle Hill

NEW TEMPORARY SITES

Temporary GNSS with strong motion

TEN2	TENS	Lake Tennyson (will be made permanent)
MUL1	SM1F	Muller Station
GDS1	SM2F	Gladstone Station
LOK1	SM3F	Glen Orkney (temporary station)

ADDITIONS TO EXISTING SITES

Strong motion added to regional seismic and sites upgraded

TUWZ		Tuamarina
BSWZ		Blackbirch Station
CMBL	CMWZ	Cape Campbell

Temporary weak motion added to strong motion

KEKS		Kekerengu

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