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Natural Hazards Research Platform

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Active Submarine Faulting and Earthquake Potential: North Canterbury and Marlborough

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Active Submarine Faulting and Earthquake Potential: North Canterbury and Marlborough

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Key message for the media:

- Active faults beneath Pegasus Bay are thought to provide insights into the faulting hidden beneath the North Canterbury coastal hills and plains, and activated in the 2010-2011 Canterbury earthquake sequence.
- New mapping and analysis shows that active faulting in North Canterbury involves widespread reactivation of pre-existing faults under the present day tectonic environment. The nature of faulting has relevance to seismic hazard assessment.
- Low geological fault slip rates are consistent with long earthquake recurrence intervals on individual faults.
- Tectonic deformation and faulting of the eastern Marlborough continental margin between Cook Strait and Kaikoura includes a network of major high slip-rate plate boundary faults which are thought to be associated with relatively larger and more frequent earthquakes than in North Canterbury.
- New mapping and analysis reveals many new details of the major offshore Marlborough faults, including their location, activity, and spatial relationship to the 2013 Cook Strait earthquake sequence.

Abstract:

The continental margin of northeastern South Island straddles an important part of the Pacific-Australian plate boundary zone through central New Zealand, and includes many active faults representing earthquake hazards. In this project marine seismic reflection, multibeam bathymetry, and sediment sample data are used to undertake mapping and analysis on active faulting in two geographic regions, **Pegasus Bay, North Canterbury**, and e**astern Marlborough – Southern Cook Strait.** The project involved a collaborative team from six organisations from New Zealand, United Kingdom, Turkey, and USA.

The work in North Canterbury aimed to improve understanding of the Canterbury earthquakes and the possible role of inherited crustal structure in controlling the location and style of active faulting. Marine seismic reflection data are analysed to produce new maps of regional faults and undertake retro-deformation of geological sections, thus providing new insights into the geometry and kinematics of ongoing tectonic deformation. We demonstrate that many of the reverse and possibly strike-slip active faults in this region reactivate and overprint older fault structure. Analysis of fault growth allowed us to constrain fault rates, identify the onset of active deformation, and evaluate the evolutionary sequence of compressional reactivation of inherited faults thought to be representative of structures hidden beneath the Canterbury Plains and involved in the 2010-2011 Canterbury

earthquake sequence. Characterisation of earthquake source parameters associated with hidden, low rate faults capable of producing moderate to large magnitude earthquakes may improve the current national seismic hazard model (NSHM).

The work in eastern Marlborough and southern Cook Strait aimed to advance understanding of the location, structural style, and segmentation of major (high slip-rate) plate boundary faults in an area where earthquakes are expected to be larger and more frequent compared to North Canterbury. Marine seismic reflection, multibeam bathymetry, and sediment sample data are used to produce detailed new maps of the active faults, and where possible to improve estimates of lateral slip rates. Of particular significance is the many detailed improvements to knowledge of the major active strike-slip faults between the continental shelf between Kaikoura and Cook Strait, and of major thrust faults beneath the slope associated with the southern reaches of the Hikurangi subduction zone. New data on active submarine faulting is discussed in the context of the NSHM and the 2013 Cook Strait earthquake sequence.

Keywords: Active faulting, seismic stratigraphy, seismic reflection, structural restoration, compressional inversion, slip rate, seismic hazard, North Canterbury, Marlborough, New Zealand

Introduction:

The 2010-2011 Canterbury earthquake sequence commenced with the Sept. 4th 2010 M_w 7.1 Darfield earthquake, and was remarkable in its geological complexity and evolution of aftershocks. Over 1.5 years, these earthquakes ruptured up to ten previously unrecognised faults hidden beneath the Canterbury plains, with major aftershocks generally migrating to the east, and ultimately advancing offshore into Pegasus Bay in late 2011. Less than three years after the commencement of the Canterbury sequence, the 2013 Cook Strait earthquake sequence developed within the northeastern part of the Marlborough Fault System, and similarly ruptured previously unrecognised faults. This sequence commenced with earthquakes beneath southern Cook Strait and propagated to the SW beneath northeastern Marlborough. The Canterbury and Marlborough earthquakes collectively highlight the importance of (1) hidden faults as earthquake sources near urban regions, (2) complex stress interactions that may trigger other structures in a fault network to rupture and prolong an earthquake sequence, and (3) understanding of fault behaviour and earthquake hazard in all parts of Pacific-Australian plate boundary zone, including regions with varied geological strain rates, fault dimensions, and background seismicity levels.

Many active faults don't reach the land surface or seafloor and remain hidden, some beneath growing fold structures. Such faults, particularly those capable of moderate earthquake magnitude, and associated with low vertical slip rates and long recurrence intervals, may be under-recognised in the landscape as specific fault sources for seismic hazard studies. In general the surface appearance of an active fault, whether beneath land or ocean, is a complex function of the fault geometry and its kinematic behaviour, rate of propagation of the fault tip, vertical and dextral slip rate, and sedimentation rate. The marine environment is an excellent setting to evaluate active faulting, because sediments are typically widely deposited over propagating fault tips, thus recording the growth and activity of the geological structures. One of the important benefits of marine seismic reflection profiles is that the data may be extensive providing quality imaging of fault geometry, and allow analysis of fault growth, rate and evolution.

The overarching aim of this project has been to develop improved understanding of earthquake hazards and plate boundary faulting through the generation of new knowledge of tectonic deformation of the continental margin of northeastern South Island. This project involved a collaborative team from six organisations from New Zealand, United Kingdom, Turkey, and USA, and used marine seismic reflection, multibeam bathymetry, and sediment sample data to undertake mapping and analysis on active faulting in two geographic regions, **Pegasus Bay, North Canterbury**, and **eastern Marlborough – Southern Cook Strait.**

Research Aim 1.

Active faulting beneath Pegasus Bay: Evaluating the geological context of the Canterbury earthquakes and the role of inherited crustal structure

By characterising active faulting in North Canterbury using marine seismic reflection data tied to boreholes and sediment samples we aimed to improve understanding of compressional and strike-slip faulting, the role of inherited crustal structure and tectonic inversion, and the geological framework of the Canterbury earthquake sequence. We aimed to capture our data in ArcGIS, to consider active faults as earthquake sources for improved seismic hazard assessment of the region, to provide advice to end users where necessary, and to develop a research paper.

Objective Achieved? Yes

Discussion

This task significantly advances preliminary work completed in a 2011 NHRP Short-term recovery project undertaken during the development of the Canterbury earthquake sequence. The work focussed on identification, mapping and analysis of late Quaternary faults beneath the central and northern parts of Pegasus Bay. We utilised an extensive data set of marine seismic reflection profiles of varying penetration and vertical resolution, including multichannel seismic (MCS), boomer and 3.5 kHz sub-bottom profiles, together with archived geological samples and coastal borehole logs. The MCS data included open-file oil industry sections collected and processed to migrated two-way-travel-time (TWTT) sections by Green Gate Pty in 2006 and 2007, together with low fold MCS data collected by NIWA in 2011 on survey KAH1105. Compared to subsurface seismic data available on land in North Canterbury, the marine data provide better spatial coverage and vertical resolution, making it possible to document the 3-dimensional architecture and progressive development of fault systems.

The interpretation and analysis of the MCS data were carried out using *Move* software (Midland Valley), and involved: (1) interpretation of stratigraphy and structure in each individual seismic section in the TWTT domain; (2) depth conversion of all sections (including the low-fold KAH1105 lines) using interval velocities determined from the industry dataset for each major regional stratigraphic unit; (3) correlation and mapping of major faults considering all available digital and non-digital seismic data (i.e., MCS, boomer and 3.5 kHz), (4) construction of best fit depth surfaces of two of the key marker horizons (top basement and top Kowai Formation, ~1.2 ± 0.4 Ma) using the ordinary Kriging method, and (5) structural modelling and section retro-deformation to investigate the timing and evolution of compressional reactivation of inherited normal faults. Analysis of fault growth allowed us to better constrain fault slip rates and total displacements. Furthermore, it allowed us to identify the onset of active deformation and an evolutionary sequence of reactivation of individual faults thought to be geometric and kinematic analogues of faults hidden beneath the Canterbury Plains and involved in the 2010-2011 Canterbury earthquake sequence.

Our results demonstrate that Late Cretaceous-Paleogene normal faults belonging to a regional extensional system are well developed throughout Pegasus Bay, and are likely to continue beneath the Canterbury Plains. Contemporary contraction is accommodated by reverse faults and folds that are exposed in coastal North Canterbury and extend up to 30

km offshore beneath Pegasus Bay, with possible strike-slip faults also present, and very weak deformation extending southwards to Banks Peninsula.

The largest reverse faults are commonly associated with asymmetric folds in the late Cenozoic sedimentary cover sequence. These faults typically dip SE, have lengths of 10-37 km and dominant NE-SW orientation, with sinuous, segmented traces that include the more easterly trends of the Late Cretaceous-Paleogene normal faults. The geometry and thickness of syn-rift sequences in the hanging wall of the reverse faults and the progressive restoration of the reverse fault slip and associated folding using trishear mechanisms indicate that the vast majority of the active reverse faults are inherited normal faults reactivated under compression. Retro-deformation of individual reverse faults, normal fault splays, and associated fault-propagation folds has been achieved using one to three successive restoration steps, with initial stages of trishear folding above a pinned or very slowly propagating fault tip followed by younger stages of rapid fault tip propagation across the Plio-Quaternary sedimentary sequence. These results indicate that differences in total amount of separation and amplitude of folding above fault tips observed for individual structures reflects different evolutionary stages of structural inversion and variable amounts of total reverse displacement. Although structural inheritance exerts a profound influence on the geometry and style of active faulting, the system also includes newly developed faults with NE orientation, which obliquely overprint the primary inherited fabric.

Tectonic inversion and overprinting largely commenced after 1.2 ± 0.4 Ma, with no obvious systematic spatial progression in the onset of inversion across the offshore fault and fold system. Reverse vertical displacements of c. 100-370 m are significantly less than the maximum Late Cretaceous-Paleogene normal displacements (1500 m), indicating that structural inversion at the south eastern exterior of plate boundary deformation is at an immature stage.

Many of the structural characteristics highlighted for the Pegasus Bay faulted basement (e.g., wide range of inherited fault orientation, interference of structural trends, active growth of blind faults with tips that are presently propagating across the uppermost cover sequence) can also be inferred from the complex sequence of seismic faulting documented for the mainshocks and aftershocks of the 2010-2011 Canterbury earthquake sequence, supporting previous suggestions that seismic rupture involved activity of a mixture of newly-formed and inherited faults favourably oriented in the contemporary stress field.

Quaternary reverse fault slip rates beneath Pegasus Bay range from about 0.1-0.5 mm/yr, with best estimates for the major structures typically of the order of 0.1-0.3 mm/yr. These rates are less than local uplift rates on land ranging from about 0.5-1.7 mm/yr, supporting a previous interpretation that there is a significant gradient in strain rate across the North Canterbury coast towards the offshore deformation front. Possible E-W to NW-SE oriented strike-slip faults have individual lengths of $\leq$ 10 km, and vertical separation rates of < 0.05 mm/yr. In the far south of the bay there is tentative evidence for Quaternary faulting at the eastern end of the February 22nd 2011 M_w 6.2 Christchurch Earthquake fault rupture. The very low rates of vertical displacement on these faults are consistent with long (~7 ka) earthquake recurrence intervals in this region previously inferred from paleoseismic rock-fall data from Banks Peninsula.

Thirteen potential earthquake sources in Pegasus Bay are identified and characterised, in light of the 22nd February 2011 M_w 6.2 Christchurch earthquake and deformation observed

and modelled on many other faults in this study. We confirm some existing sources in the current NSHM, modify the precise locations and lengths of some faults where required, and we identify some new sources. Our best estimates of fault parameters indicate potential earthquakes with magnitudes ranging from about M_w 6.2 to 7.1, with recurrence intervals ranging from about 3000 years to 20,000 years.

Outputs:

Barnes, P.M., Ghisetti, F.C., Gorman, A., Bull, J., Cagatay, N., Woelz, S., Mountjoy, J., Lamarche, G., Collins, J., and C. Castellazzi (2015). Active submarine faulting in North Canterbury and eastern Marlborough, South Island, New Zealand. NIWA Client report WLG2015-39, 73p.

Barnes, P.M., Ghisetti, F.C., Gorman, A., (Submission August 2015). New insights into the tectonic inversion of North Canterbury and the structural context of the 2010-2011 Canterbury earthquake sequence, New Zealand. *Geochem. Geophys. Geosyst.*

Barnes, P.M. 2014. Identifying active submarine faulting beneath Pegasus Bay in the aftermath of the Canterbury earthquakes: Geophysical imaging and 3-dimensional analysis. Keynote oral presentation at the Association of Local Government Information Management (ALGIM) 2014 GIS Symposium, 7-8th April, Auckland.

Barnes, P.M., Nodder, S., Gorman, A., Woelz, S., Orpin, A., Characterising active-fault earthquake sources beneath the coastal environments of Christchurch and Wellington cities, New Zealand, using seismic-reflection profiles and fault displacement analysis techniques. Invited oral paper, Marine Geohazards, 2014 AGU Fall Meeting, San Francisco, 15-19 December, 2014.

Barnes, P.M., A., G., Lamarche, G., Nodder, S., Stirling, M., Van Dissen, R., Litchfield, N., Berryman, K., Pondard, N., Mountjoy, J., Langridge, R., Clark, K., and Ghisetti, F., 2012, Active submarine faulting in seismic hazard assessment: the Canterbury earthquakes in the context of New Zealand tectonic deformation, and the role of the geoscience response. New Zealand Coastal Society Conference: November 2012, Auckland.

NIWA Media release, 15th November, 2012. How prepared are we for a major marine earthquake? (Followed by numerous subsequent articles on Stuff.Co, and national newspapers; several telephone interviews with newspaper journalists; and a Radio New Zealand Morning Report interview at Radio NZ, Auckland Studio, 16th Nov. 2012.

End users engaged:

In 2013 advice was provided to Dr Marion Gadsby, Environment Canterbury Regional Council (ECAN) on potential offshore tsunami hazard from fault rupture, and was used by ECAN for prioritising hazard assessment investigations.

Presentations were provided by invitation to a range of coastal science and engineering practitioners, as well as various central and local government participants at two national meetings; the NZ Coastal Society annual conference in Auckland 2012, and the Association of Local Government Information Management (ALGIM) 2014 GIS Symposium in Auckland in 2014. These presentations highlighted the Canterbury earthquake sequence in relation to offshore fault structure and the research programme, placing the events in the context of coastal hazards and the current NSHM.

In addition to end user engagements, new interpretations of submarine earthquake sources have been provided to seismic hazard modellers at GNS Science for consideration; final data transfer will take place following further discussions. In addition, two new research linkages closely related to this project developed during the course of this study and remain ongoing. These include (1) contribution of offshore fault data and horizon depth surfaces from this project to the development of a geology-based 3D seismic velocity model of Canterbury being led by the University of Canterbury (UoC) [funded by Royal Society of New Zealand Marsden Fund (Fast-Start) 2014-2016 (Bradley -PI) and Royal Society of New Zealand Rutherford Discovery Fellowship (RDF) 2013-2018 (Bradley PI)], and (2) initiation of a new research initiative with Penn State University (USA) and UoC to develop and model onshore to offshore geological sections across the North Canterbury coast.

Research Aim 2.

Active fault structure, segmentation and earthquakes in the eastern Marlborough Fault System

The initial aim of this task was to advance understanding of fault interactions and validate if and how static stress changes trigger earthquake sequences on major plate boundary faults in eastern Marlborough. This challenging objective would require development of new submarine paleoseismic records from high-resolution seismic reflection data and modelling of Coulomb stress changes associated with past earthquakes. Whilst we contributed to the advancement of new paleoseimic data from the Vernon Fault in northeastern Marlborough – southern Cook Strait, it became apparent during the course of the project that developing new paleoseismic records from the major faults off the eastern Marlborough coast would not be deliverable with present seismic reflection data. Following consultation with seismologists at GNS Science, we renegotiated the objectives of this contracted task with NHRP management, foregoing the modelling of stress interactions and focussing on improving details of the location, structural style, segmentation, and slip rates of the eastern Marlborough strike-slip and thrust faults, including mapping of the faulted post-last glacial (<20 ka) sedimentary cover sequence on the shelf. These data would underpin future modelling of seismic hazard and plate boundary kinematics, and potentially improve understanding of future earthquakes. We aimed to capture our new fault mapping in ArcGIS, and consider active faults as earthquake sources for potential improvements of seismic hazard assessment of the region.

Objective Achieved? Yes

Discussion

In this task, we used extensive marine seismic reflection profiles of varying penetration and vertical resolution, including MCS, boomer and 3.5 kHz sub-bottom profiles, together with multibeam bathymetry data, to produce new detailed maps of active fault and fold structures beneath the eastern Marlborough margin.

The project required processing of two sets of high-resolution seismic reflection data. These included (1) boomer seismic sections recorded by NIWA on R.V. *Tangaroa* Survey TAN0807, targeted at the area of convergence between the Needles, Boo Boo and Nicholson Bank

(southern Wairarapa) faults, and (2) 3.5 kHz data acquired by Woods Hole Oceanographic Institution (WHOI) on R.V. *Thompson* survey TN229, targeted at the immediate offshore section of the Hope and Kaikoura faults south of the Clarence River mouth. We mapped in ArcGIS fault traces visible in 10 m-gridded multibeam data from the continental shelf and 25 m-gridded data from the continental slope. These data from the shelf, were integrated with the various digital and non-digital seismic data. We processed, identified, and radiocarbon dated seafloor samples collected to constrain dextral slip rate on the Boo Boo Fault, and we also measured dextral displacements on the Hope and Needles faults.

The major advances from this work are:

(1) Revised mapping of the offshore Hope, Kaikoura, Chancet, Campbell Bank, Needles, Boo Boo, Tako, and southern Nicholson Bank faults beneath the eastern Marlborough - southern Cook Strait continental shelf, and major thrust faults and folds beneath the Marlborough and southern Cook Strait continental slope.

(2) New estimates of dextral slip rate on the western (Campbell Bank) section of the Boo Boo Fault using radiocarbon dated seafloor samples from displaced submarine ridges on Campbell Bank, and a tentative dextral slip rate of a similar feature on the offshore Hope Fault. A dextral displacement is also documented on the Needles Fault but is not dated.

(3) Mapping of the distribution and thickness of the faulted post-glacial < 20 ka) sedimentary cover sequence on the eastern Marlborough and southern Cook Strait shelf.

We confirm that beneath southern Cook Strait and eastern Marlborough, the offshore Marlborough Fault System comprises three primary groups of active faults: These include (1) primarily strike-slip faults with major sections aligned similarly to the Pacific-Australian plate motion vector, including the Hope, Chancet, Boo Boo, and Southern Nicholson Bank faults, (2) a NNE-SSW striking set of oblique slip (strike-slip and reverse) faults, including the Needles and Campbell Bank faults, and (3) a regional set of predominantly NW-dipping thrust faults and associated anticlinal folds beneath the eastern Marlborough and southern Cook Strait continental slope, including the Kekerengu Bank and Upper Slope faults, representing the southern part of the Hikurangi subduction thrust-imbricate wedge.

One result of particular note is that the seaward segment of the Hope Fault is characterised by bifurcation and a possible releasing step-over incorporating the Kaikoura Fault south of the Clarence River mouth, and a transpressional section east and NE of the Clarence River characterised by numerous left-stepping (restraining) strike-slip fault traces and complex folds and thrust faults. A 25-30 m dextral offset of a seafloor ridge on one trace of the Hope Fault, that is undated but inferred to be about 13 ka, indicates a possible dextral slip rate of 2.1 ± 0.3 mm/yr. This estimate is in general agreement with previous assumptions of < 4 mm/yr.

The Chancet and Needles faults converge towards the high slip-rate Kekerengu Fault. The Chancet Fault is purely strike-slip and connects with or continues directly as the Campbell Bank Fault. The Needles Fault structure varies from oblique slip contractional in the south, to strike-slip and extension in the north. The Needles and Boo Boo faults are demonstrated to converge and locally connect in a complex strike-slip extensional system NE of Cape Campbell. A new dextral slip rate of 8.3 ± 1.2 mm/yr is established on the western part of

the Boo Boo Fault. The Nicholson Bank Fault in southern Cook Strait appears to continue SW and branch beneath the NE Marlborough shelf. This fault is mapped to the edge of the 2013 Cook Strait earthquake sequence.

We compared new our data with the earthquake fault sources in the current NSHM, and concluded that the current model is acceptable at a first order, although other rupture scenarios are possible. We also explored the spatial relationships between the newly mapped offshore faults and the 2013 Cook Strait earthquake sequence.

Although not planned as a specific task in this study, Barnes also contributed to the development and publication of neotectonic and paleoseismic work undertaken on the Vernon Fault. This structure extends offshore into southern Cook Strait east of Blenheim, and forms the northern boundary of the crustal block in which the 2013 Cook Strait earthquake sequence occurred. This paper developed from a jointly supervised student thesis project by Tim Bartholomew (VUW) in 2011, and relates closely to the tasks and initial objective themes outlined in this project.

Outputs:

The results of our work in this research aim are presented in part 2 of the following report listed also under Canterbury outputs:

Barnes, P.M., Ghisetti, F.C., Gorman, A., Bull, J., Cagatay, N., Woelz, S., Mountjoy, J., Lamarche, G., Colins, J., and C. Castellazzi (2015). Active submarine faulting in North Canterbury and eastern Marlborough, South Island, New Zealand. NIWA Client report WLG2015-39, 73p.

Bartholomew, T.D., Little, T.A., Clark, K., Van Dissen, R.; Barnes, P.M., (2014). Kinematics and paleoseismology of the active Vernon Fault, Marlborough Fault System, New Zealand: Implications for contractional fault bend deformation, earthquake triggering, and the record of Hikurangi subduction earthquakes. *Tectonics* 33: 1201-1218. 10.1002/2014TC003543.

Barnes, P. New work on active faulting in coastal Marlborough and relationships to the 2013 Cook Strait earthquakes. NIWA Seminar Series, 15th May, 2015.

End users engaged:

In the early stages of the 2013 Cook Strait earthquake sequence advice was provided to the NHRP management on active submarine faulting in Cook Strait.

In 2015 further advice was provided to Dr Marion Gadsby, ECAN, on the new results of our work on the offshore Hope Fault. ECAN have a strong interest in seismic hazard of the Kaikoura region, and have recently been prioritising their hazard assessment needs. Discussion centred round the possibility of generating future cofunding to advance studies of the slip rate on the offshore section of the Hope Fault.

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