NATURAL HAZARDS
RESEARCH PLATFORM

Contest 2015

Characterisation of active faulting earthquake sources in eastern Marlborough, South Island

Leader: Philip Barnes
Organisation: NIWA
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Characterisation of active faulting earthquake sources in eastern Marlborough, South Island.

Subcontract reference: 2015-NIW-03-NHRP

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Report peer review by Alan Grey (NIWA)

Key messages for media:

- New coastal and marine mapping reveals unprecedented geological and geomorphic details of major active faults in eastern Marlborough, including their location, geological structure, and earthquake potential.
- Two of the three faults that were the focus of this study (Hope and Needles faults) are among New Zealand's fastest slipping crustal faults.
- The Hope Fault, extending along the Mt Fyfe range-front north of Kaikoura and offshore NE for 70 km, is characteristic of *transpressional* faults, which accommodate both transform (side-ways slip) and convergent plate boundary deformation. High fault slip rates west of Mt Fyfe inland compared to low fault slip rates offshore indicated by offsets of seafloor features are consistent with slip transfer from the Hope Fault northward onto the Jordan Thrust Fault beneath the Seaward Kaikoura Ranges.
- The 14 November 2016 M_w 7.8 Kaikoura Earthquake activated many faults in coastal Marlborough, including the Needles Fault, the northernmost element of the > 90 km long composite Kowhai-Jordan-Kekerengu-Needles fault rupture. New marine data collected over the Needles Fault before and after the earthquake reveal a remarkably linear, 35 km long, previously unrecognised seafloor trace that displaced the seabed vertically by up to 3.5 m during the earthquake.
- The new knowledge of fault structure in coastal Marlborough gained in this project has contributed to revisions of the active fault earthquake source component of the National Seismic Hazard Model. This work with GNS Science and others, contributed to the North Canterbury Transport Infrastructure Recovery initiative, as well as informing stakeholders of seismic hazard information.

Abstract:

Northeastern Marlborough straddles part of the Pacific-Australian plate boundary zone through central New Zealand, and includes many active faults representing earthquake hazards to central New Zealand. In this project, new marine multibeam bathymetry and seismic reflection data, together with coastal field mapping and LiDAR interpretations, have been used to advance our knowledge of several major faults. These include the Mt Fyfe and Seaward sections of the Hope Fault in the southern region, and the offshore Needles, Chancet and western Boo Boo faults in the northern region. We show that the Mt Fyfe and Seaward sections of the Hope Fault, as well as the Needles Fault, are characteristic of right-lateral transpressional fault systems in which strike-slip and contractional components of deformation are partitioned across distributed arrays of surface faulting and folding. The Chancet and Boo Boo faults are more characteristic of right-lateral strike-slip faults. We confirm there is a significant slip reduction along the Hope Fault, where slip is transferred northward to the Jordan Thrust beneath the Seaward Kaikoura Ranges, and that most of the Kekerengu Fault slip appears to be routed offshore through the Needles Fault zone. Revised interpretations of eastern Marlborough earthquake sources in the NSHM consider a range of earthquake rupture segmentation and a number of potential rupture scenarios. The 14 November 2016 M_w7.8 Kaikoura Earthquake

faulting straddled the Hope Fault and included the Needles Fault into the northern part of the earthquake rupture zone. This included about 35 km of linear strike-slip surface rupture on the Needles Fault with vertical displacement of up to 3.5 m, and about 1 km of surface rupture on an associated oblique thrust fault to the SE.

Keywords: Active faulting, fault structure, seismic hazard, earthquake, marine, Marlborough Fault System, New Zealand

Introduction / Background:

The coast and 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 to central New Zealand. Present deficiencies in understanding of fault structure and slip rate result in uncertainties in our current National Seismic Hazard Model (NSHM) and in kinematic models of plate boundary deformation. This project aimed to improve earthquake source characterisation of major high-slip rate faults, by increasing knowledge of their structure, tectonic geomorphology, slip rate and earthquake potential.

Marine multibeam bathymetry and seismic reflection data, together with coastal field mapping and LiDAR interpretations, have been used to advance previous mapping and analysis of active faulting associated with the eastern Marlborough Fault System (Fig. 1). The major fault targets included the on-land coastal and offshore sections of the Hope Fault in the southern region, and the offshore Needles, Chancet and western Boo Boo faults in the northern region. The latter carry slip offshore from the on-land Kekerengu Fault. Collectively, this system of high slip rate faults transfer plate boundary deformation from the Alpine Fault beneath the Southern Alps to the Hikurangi subduction zone off NE New Zealand. The project involved collaboration between two principal investigators based at NIWA and University of Canterbury, supported by data acquired collaboratively in earlier work involving National Oceanographic Centre (UK), Istanbul Technical University (Turkey), and Woods Hole Oceanographic Institution (USA).

The project aimed to improve earthquake and tsunami hazard assessment through inclusion of new information on active faulting into revisions of the National Seismic Hazard Model (NSHM). We focused on the structure of the plate boundary, including the structural and geomorphic segmentation of the major faults. This work would enable a reconsideration of potential earthquake sources, and would underpin future kinematic modelling of zones that transition from continental collision to subduction.

During the course of this project, the 14 November 2016 M_w7.8 Kaikoura Earthquake struck the eastern Marlborough region, straddling the Hope Fault and incorporating the Needles Fault into the northern part of the earthquake rupture zone. This event had a profound impact on the project, leading to new post-earthquake fault data sets being acquired, that enabled comparisons of pre- and post-earthquake data. The event led to inevitable reprioritization of our efforts related to the two research aims of the project, and new collaborative opportunities as we engaged with many other researchers responding to the earthquake. We prioritized our efforts into Research Aim 1.2, contributing to new and additional analyses to understand this earthquake, both in terms of the co-seismic surface ruptures and their tectonic framework. As a result, we contributed to several publications on fault structure and co-seismic surface rupture that not were not in our original research plans in Research Aim 1.2, and we are still working towards the publication of results generated by our study of the Hope Fault in Research Aim 1.1.

Our aim was to inform the public and other stakeholders of active faulting in the eastern Marlborough region. From this, regional territorial authorities would be better informed of seismic hazards in their respective jurisdiction, and would therefore be empowered to make better planning decisions involving natural hazards.

Title—Impact Statement 1:
Characterisation of active faulting earthquake sources in eastern Marlborough, South Island

❖ Research Aim 1.1

Title: Active geological structure and slip rate of the Seaward Section of the Hope Fault, eastern Marlborough.

Budget: $100,000

Research Aim achieved? Yes

Research aim: Advance understanding of transpressional plate boundary faults, and contribute to improved New Zealand seismic hazard assessment, by identifying the structure and Late Quaternary slip rate of the Seaward Section of the Hope Fault, eastern Marlborough. We will characterise the structural segmentation and strain partitioning, constrain the possible dextral slip rate, and document the associated tectonic geomorphology, using marine seismic reflection profiles, multibeam bathymetry data, and adjacent onshore field data. We will liaise closely with other US and NZ research teams developing paleoseismic data from the Hope Fault onland, and contribute to improved assessment of the earthquake potential of the fault. We will inform and provide data to relevant regional councils, including ECAN and GWRC, and publish our results in peer reviewed scientific forums.

Discussion

This research aim focussed on advancing understanding of the Late Quaternary surface traces and slip rate of the Seaward Section of the Hope Fault from Mt Fyfe to more than 70 km offshore (Figs 1 and 2). We aimed to characterise the structural segmentation and strain partitioning under a regional transpressive tectonic setting, document the associated tectonic geomorphology, and constrain the dextral slip rate using new and existing marine and field data.

To advance understanding of the offshore Hope Fault structure and slip rates, we successfully completed a high-resolution multibeam bathymetry survey targeted at specific fault traces off the eastern Marlborough coast (Lead: Philip Barnes). The survey IKA1610 was undertaken between 5-7 April 2016 on NIWA's coastal survey launch *Ikatere,* and involved mobilisation of a Kongsberg EM2040 multibeam echosounder (MBES). Both Canterbury Regional Council and Marlborough District Council were consulted during the planning and permitting of the survey. Four survey areas ranging in length from about 5-10 km and width about 1 km were selected based on fault mapping undertaken with lower resolution data as part of previous research. The survey targeted seafloor traces of the fault exposed on the outer shelf, where geomorphology would offer potential piercing points for identifying dextral displacements. The MBES survey resulted in digital elevation surfaces processed to 2 m grid resolution, which were loaded into an ArcGIS for mapping. Figure 2 shows a revised interpretation of the structure of the Hope Fault, derived from the new MBES data combined with an extensive volume of subsurface seismic reflection profiles of various penetration and vertical resolution.

Figure 3 illustrates some of the major left-stepping surface traces along the northern (Te Rapa) section of the fault, with coloured areas highlighting the locations of the MBES *Ikatere* IKA1610 survey. Examples of the spectacular tectonic geomorphology are presented in Figures 4 and 5. These data revealed multiple overlapping seabed traces, more complex than previously recognised. Numerous sites with right-lateral displacements of stratigraphic bedding and sedimentary bedforms of post-glacial age, were recognised and are typically < 20-30 m. The results appear to be consistent with transpressional faulting, in which right-lateral motion is accommodated on left-stepping strike-slip faults, and contraction is accommodated by thrust faulting, folding and uplift. The dextral offsets appear to be consistent with previous estimates for a low slip rate on the offshore section of the fault (<5 mm/yr).

Structural and geomorphic data from previously completed student theses at the University of Canterbury, along the Mt Fyfe range front and coastal section of the Hope Fault were captured in ArcGIS (Lead: Jarg Pettinga) (Fig. 2). These interpretations were revised using coastal LiDAR data and high-resolution geo-referenced orthophotos (Fig. 6). We discovered that the previously mapped and published fault trace along the foot of the Mt Fyffe range was simplistic. Our work has highlighted a much more complex array of faulting, with the Mt Fyffe range-front segment from the Kahutara River in the SW to the Hapuku River in NE being characterized by a wide and distributed zone of deformation. There is a wider pattern of strain partitioning associated with the development of a contractional fault wedge, and a number of oblique dextral strike slip fault splays are recognised to the inland side of the fault wedge in the lower parts of the mountain "escarpment". Previous attempts to determine representative slip rates from this section of the fault have likely been compromised by the lack of documentation of the full extent of the fault zone, with distributed slip across a wider zone leading to under-estimation of the representative slip rates here. To the Northeast of the Hapuku River, and beyond the intersection with the Jordan Thrust that underlies Mt Fyfe, the Hope fault continues as a series of anastomosing splays to Half Moon Bay, where it passes offshore (Fig. 6).

Collectively our study of the Mt Fyfe, coastal and offshore sections of the Hope Fault has revealed a highly complex transpressional fault zone with slip rate apparently reducing significantly across the intersection with the Jordan Thrust fault. Our findings were presented at scientific conferences and workshops, and are being prepared for publication at the time of this report. From improved understanding of the fault structure, we were able to interpret major structural and geomorphic segment boundaries on the fault (red dots on Fig. 2). This enabled an improved interpretation of earthquake rupture potential. We revised earthquake source characteristics in collaboration with Nicola Litchfield and Russ Van Dissen at GNS Science, and incorporated them into revisions of the fault source model in the NSHM as part of the North Canterbury Transport Infrastructure Recovery (NCTIR) project led by GNS.

List of outputs

Barnes, P.M., Pettinga, J., Bull, J., Gerring, P., Collins, J. (2016). The Mt Fyfe and Seaward sections of the Hope Fault, eastern Marlborough, South Island. Geosciences 2016. The 2016 Geosciences Society Annual Conference, 28 November – 1 December 2016, Lake Wanaka Centre, Wanaka.

Barnes, P.M., Pettinga, J., Bull, J., Cagatay, N., Collins, J., Gerring, P., Kane, T. (2016). Characterising active faulting in eastern Marlborough, South Island. Natural Hazards Research Platform Research Workshop, GNS Science, August 18th 2016.

Barnes, P.M., Pettinga, J., Bull, J., Cagatay, N., Collins, J., Gerring, P., Woelz, S. (paper in prep.). The transpressive Mt Fyffe and Seaward Segments of the Hope Fault, Marlborough Fault System, New Zealand. *Geosphere*.

End-users

Work on updating fault sources in the National Seismic Hazard Model was undertaken with GNS Science and University of Canterbury collaborators as part of the North Canterbury Transport Infrastructure Recovery (NCTIR) project led by GNS. Faulting and earthquake source data have been provided in ArcGIS formats to GNS, NCTIR, and ECAN.

❖ Research Aim 1.2

Title: Active geological structure and slip rate distribution of a linked fault network between Kekerengu and Cape Palliser, northeastern Marlborough and southern Cook Strait.

Budget: $100,000

Research Aim achieved? Yes

Research Aim: Characterise a linked submarine crustal fault network in northeastern Marlborough and southern Cook Strait, east of the 2013 Cook Strait earthquake sequence, to underpin improved models of transform - to - subduction plate boundary faulting and seismic hazard in central New Zealand. In particular, we will document the structure, sense of displacement, and where possible the Late Quaternary slip rates of the Needles, Chancet, Campbell Bank, and Boo Boo faults using marine seismic reflection profiles, multibeam bathymetry data, and dated seafloor samples. These data together with slip rate estimated on the Hope Fault in Research Aim 1.1, and on the Kekerengu Fault in close liaison with other researchers, will place constraints on the slip budget distributed across the entire coastal network of crustal faults. We will provide data to relevant regional councils, update earthquake source parameters for the NSHM if required, and publish our results in peer reviewed scientific forums.

Discussion

On *Ikatere* survey IKA1610, we acquired new EM2040 MBES data processed to a tide-corrected 2 m grid resolution DEM over the eastern, outer shelf part of the Chancet Fault (Target 5, Fig. 7) and the northern part of the Needles Fault east of Cape Campbell (Target 6). Figure 8 (inset map) illustrates an example of the data over the Needles Fault, where the structure is a knife-edge lineament on the seafloor, associated with bathymetric ridges. We confirmed a previously identified dextral offset of a bathymetric high, but were unable to identify its age for constraining the dextral slip rate. Data over the Chancet Fault however, revealed dextral offsets of bedding and sedimentary bedforms of post-glacial age, of not more than 30-40 m, indicating a likely slip rate of not more than 3 mm/yr.

Figure 8 (main map) shows the extent of multibeam bathymetric and sub-bottom profile data collected on RV *Tangaroa* voyage Tan1613 in response to the 14 November 2016 M_w7.8 Kaikoura Earthquake, and later on *Ikatere* coastal bathymetric survey IKA1701. Neither of these surveys were funded from this project, but the data were a critical component of our fault mapping and analysis undertaken in the project. These surveys covered both the Chancet and Needles faults, enabling revised mapping of each, including the intersection of the Needles and Boo Boo faults.

The data revealed an extremely linear trace of the Needles Fault extending from offshore of the Kekerengu Fault to the previously (pre-earthquake) well-studied sections of the fault east of Cape Campbell (Fig. 9). This trace had not been recognized before the earthquake, only because no surveys had been undertaken in shallow water close enough to the coast. We mapped the trace is detail, observing a vertical seafloor scarp of up to 3.4 m, that we were able to demonstrate as having formed during the Kaikoura Earthquake. We identified the likely NE extent of coseismic rupture from comparison of pre-and post-earthquake survey data (e.g., Fig. 10 B), and we produced a high-resolution dataset of vertical coseismic displacement along the fault. Interpretation and mapping of the grid of sub-bottom TOPAS profiles acquired on Tan1613, combined with archived seismic data, confirmed and revised an array of distributed faulting across the intersection of the Needles and Boo Boo faults (e.g., Figs. 9 and 10). We found no evidence of rupture of these structures in the Kaikoura Earthquake.

The grid of sub-bottom TOPAS profiles acquired on Tan1613, combined with archived seismic data, also enabled revised mapping of an array of oblique thrust faults east (offshore) of the main trace of the Needles Fault. These structures had been recognized as being part of the Needles Fault zone from previous work prior to the Kaikoura Earthquake, and help to

accommodate the convergent deformation across the Needles Fault system. We identified that a short section (~1 km) of one of these thrust faults had surface displacement during the earthquake (Fig. 9).

Results of the new mapping were provided to GNS in ArcGIS format as part of the wider Kaikoura Earthquake geoscience response effort. These maps have been used in public presentations, scientific and technical workshops, and several publications. In collaboration with Nicola Litchfield and Russ Van Dissen at GNS Science, we revised earthquake source characteristics of the NE Marlborough faults and incorporated them into revisions of the fault source model in the NSHM as part of the North Canterbury Transport Infrastructure Recovery (NCTIR) project led by GNS.

List of outputs

Kearse, J., Little, T.A., Van Dissen , R.J., Barnes, P.M., Langridge , R., Mountjoy, J.J., Ries , W., Villamor, P., Clark , K., Benson, A., Lamarche, G., Hill, M., Hemphill-Haley, M., (Submitted 6*th* *Oct.* 2017). Surface Fault Rupture and Slip Distribution of the Kekerengu, Needles, Jordan, Upper Kowhai and Manakau Faults During the M_w 7.8 2016 Kaikōura Earthquake, New Zealand. *Bulletin of the Seismological Society of America*.

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M.W. Stirling, N.J. Litchfield, P. Villamor, R.J. Van Dissen, A. Nicol, J. Pettinga, P. Barnes, R.M. Langridge, T. Little, D.J.A. Barrell, J. Mountjoy, W.F. Ries, J. Rowland, C. Fenton, I. Hamling, C. Asher, A. Barrier, A. Benson, A. Bischoff, J. Borella, R. Carne, U.A. Cochran, M. Cockroft, S.C. Cox, F. Fenton, C. Gasston, C. Grimshaw, D. Hale, B. Hall, K. Hao, A. Hatem, M. Hemphill-Haley, D.W. Heron, J. Howarth, Z. Juniper, T. Kane, J. Kearse, N. Khakavi, G. Lamarche, S. Lawson, B. Lukovic, C. Madugo, I. Manousakis, S. McColl, D. Noble, K. Pedley, K. Sauer, T. Stahl, D.T. Strong, D.B. Townsend, V. Toy, M. Villeneuve, A. Wandres, J. Williams, S. Woelz, and R. Zinke (2017). The Mw 7.8 2016 Kaikōura earthquake: Surface fault rupture, and seismic hazard context. *Bulletin of the New Zealand Society for Earthquake Engineering, 50*: 73-84.

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Media Release, 22nd November 2016, Scientists detect huge fault rupture offshore from Kaikoura. https://www.niwa.co.nz/news/scientists-detect-huge-fault-rupture-offshore-from-kaikoura

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Mountjoy, J. and Barnes, P. (2017). The marine survey response to the Mw 7.8 14th November 2016 Kaikōura Earthquake. Wellington Branch, Geoscience Society of NZ, 27th July 2017, Victoria University Pipitea Campus, Rutherford House, Wellington.

Van Dissen, R.J., Little, T., Benson, A., Bischoff, A., Hatem, A., Barrier, A., Nicol, A., Wandres, A., Lukovic, B., Hall, B., Gasston, C., Asher, C., Grimshaw, C., Madugo, C., Fenton, C., Hale, D., Barrell, DJA., Heron, DW., Strong, DT., Townsend, DB., Noble, D., Howarth, JD., Pettinga, J., Kearse, J., Williams, J., Manousakis, J., Borella, J., Mountjoy, J., Rowland, J., Clark, KJ., Pedley, K., Sauer, K., Berryman, KR., Hemphill-Haley, M., Stirling, MW., Villeneuve, M., Cockroft, M., Khajavi, N., Litchfield, NJ., Barnes, P., Villamor, P., Carne, R., Langridge, RM., Zinke, R., McColl, S., Cox, SC., Lawson, S., Stahl, T., Cochran, UA., Toy, V., Ries, WF., Juniper, Z, (2017). Surface fault rupture during the November 2016 Mw 7.8 Kaikoura earthquake, and paleoseismology of the Kekerengu Fault - one of the country's fastest slipping onland active faults. 10th International Workshop on Statistical Seismology (StatSei10) in Wellington, New Zealand, in February 2017. Wellington, 20-24 February, 2017.

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List of end-users

Work on updating fault sources in the National Seismic Hazard Model was undertaken with GNS Science and University of Canterbury collaborators as part of the North Canterbury Transport Infrastructure Recovery (NCTIR) project led by GNS. Faulting and earthquake source data have been provided in ArcGIS formats to GNS, NCTIR, and ECAN.

Conclusions & Recommendations:

The Hope, Chancet, Needles and western Boo Boo faults are important structural elements of the Eastern Marlborough Fault System. New data and interpretations reveal complexity in the distribution of surface deformation associated with these faults. The Mt Fyfe and Seaward sections of the Hope Fault, as well as the Needles Fault, are characteristic of right-lateral transpressional fault systems in which strike-slip and contractional components of deformation are partitioned across distributed arrays of surface faulting and folding. The Chancet and Boo Boo faults are characteristic of right-lateral strike-slip faults.

The 14 November 2016 M_w7.8 Kaikoura Earthquake faulting straddled the Hope Fault and included the Needles Fault into the northern part of the earthquake rupture zone. This included about 35 km of linear strike-slip surface rupture on the Needles Fault with vertical displacement of up to 3.5 m, and about 1 km of surface rupture on an associated oblique thrust fault to the SE.

Revised interpretations of eastern Marlborough earthquake sources in the NSHM consider a range of earthquake rupture segmentation and a number of potential rupture scenarios.

We consider there is still much to learn of the fault structure, slip rate distribution, paleoseismic record, and earthquake potential of the eastern Marlborough faults, which include high-slip rate components of the plate boundary that are likely to generate relatively frequent large magnitudes earthquakes. We recommend this system of faults remain a high priority research target if we are to fully understand the role of the Kaikoura Earthquake in long-term deformation, the history and potential of the system to generate past and future earthquakes, and the wider kinematics of plate boundary deformation in New Zealand.

Acknowledgements:

We appreciate the positive collaborations and co-operation with a large number of New Zealand Geoscientists that developed or continued from previous work, during the course of this project. We thank the entire crew and science team on *Ikatere* surveys IKA1610 and IKA1701, and on *Tangaroa* survey Tan1613, which provided new data used this project. In particular, we thank Joshu Mountjoy, Peter Gerring, Tim Kane, John Mitchell, and Susi Woelz for assistance with data acquisition and processing. Other programmes contributed co-funding towards this science including NIWA SSIF Core programme *Marine Physical Processes and Resources* (COPR1702-1802), and MBIE Endeavour programme *Hikurangi subduction earthquakes and slip behaviour* (Contract C05X1605, subcontract ref: GNS-MBIE00054).

Dr Philip Barnes
NIWA Principal Scientist – Marine Geology

Professor Jarg Pettinga
University of Canterbury

Figures:

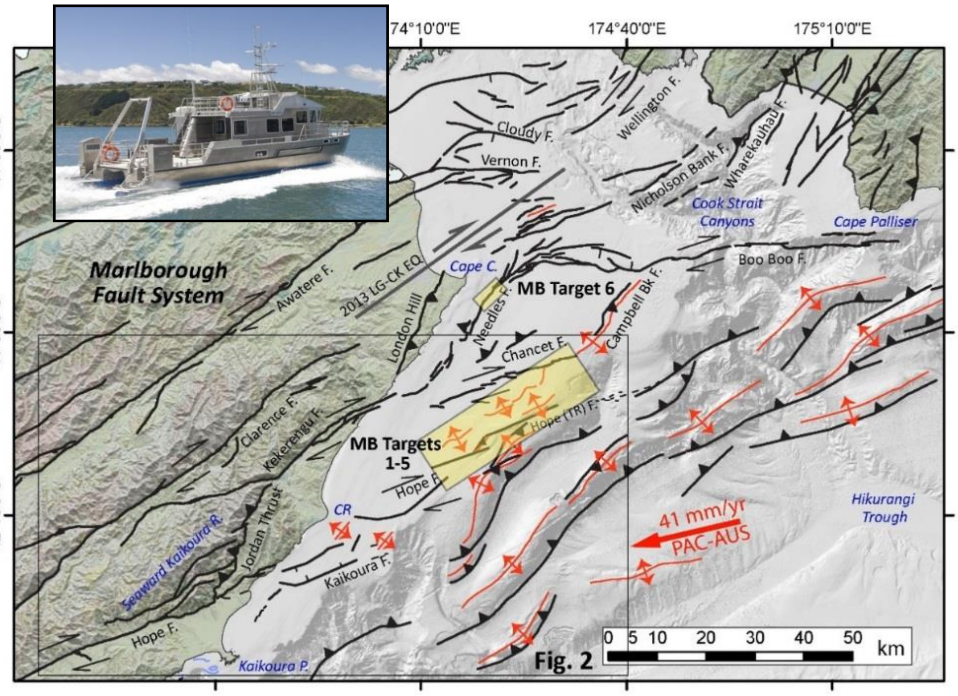

Figure 1. Regional map of major tectonically active faults. Yellow boxes show the general areas that were targeted for mapping on Survey IKA1610. Inset shows survey vessel *Ikatere*.

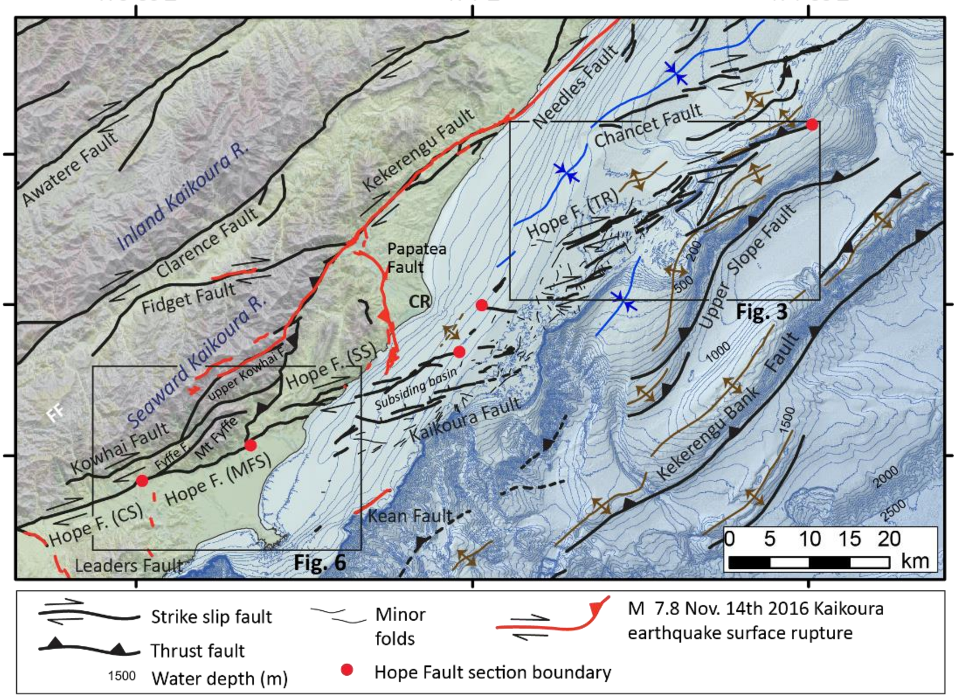

Figure 2. Map showing coastal faults in eastern Marlborough, the Mw7.8 Kaikoura Earthquake ruptures, and the locations of Figs. 3 and 6.

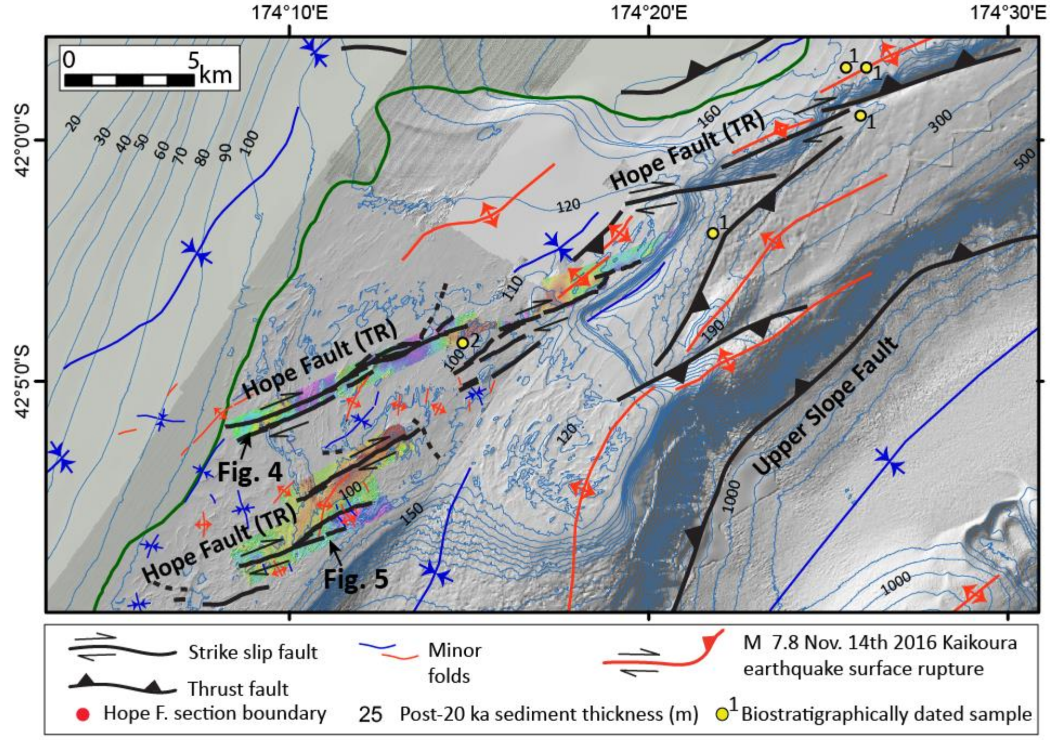

Figure 3. Seafloor traces mapped as part of this project along the northeastern section of the Hope Fault on the outer continental shelf. Coloured areas of seafloor highlight some of the areas that were surveyed by our *Ikatere* survey IKA1610. Bathymetric contours (m) are shown at 50 m intervals on the continental slope beyond 200 m, and 10 m intervals on the shelf. Note the smooth bathymetric surface at depths shallower than about 100 m reflecting the occurrence of post-last glacial (<20 ka) sediment cover on the middle shelf. See Figs. 4 and 5 for examples of the new multibeam data and interpretations.

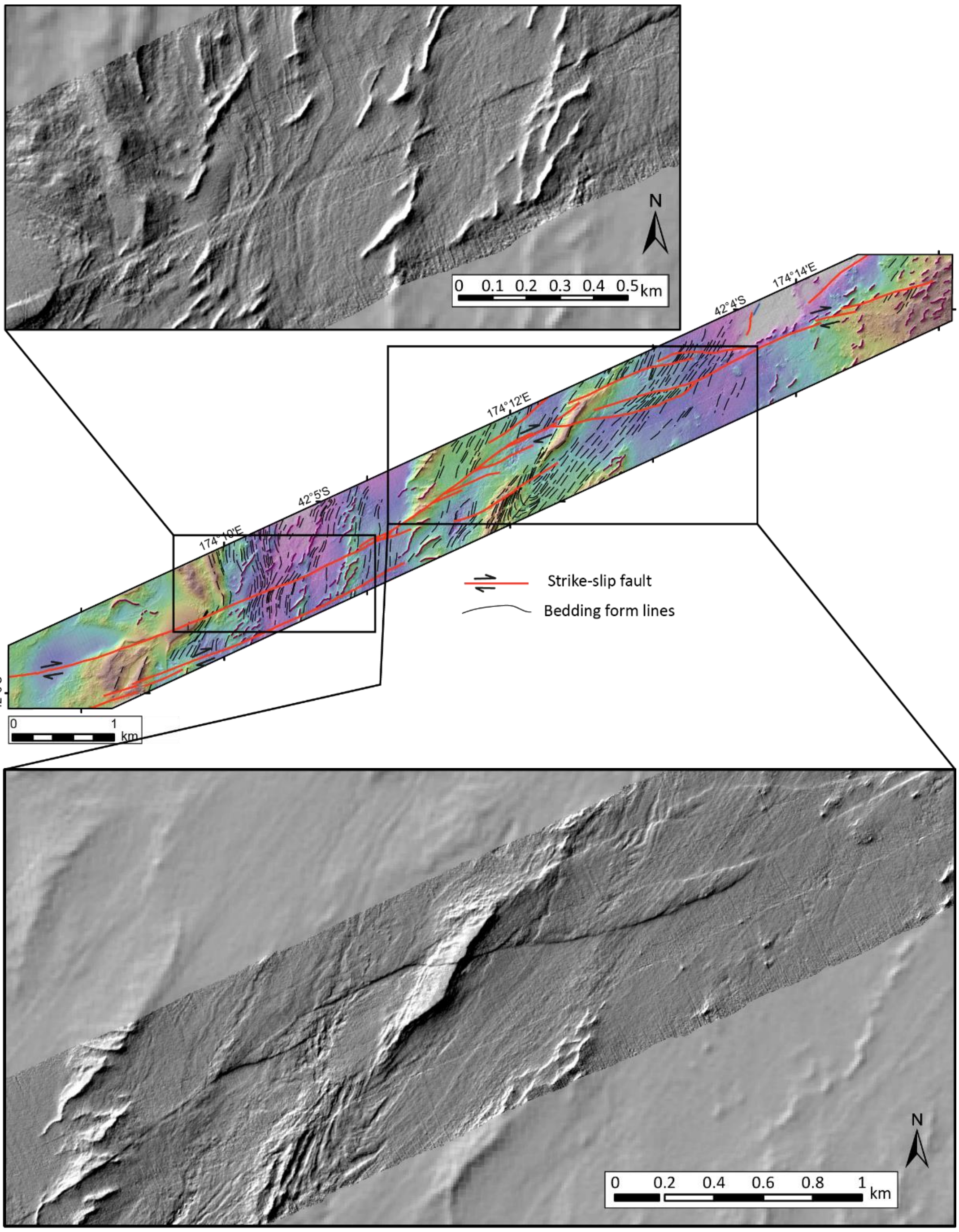

Figure 4. Example of new EM2040 multibeam bathymetric data from area 3 processed to 2m grid resolution showing clear surface traces of the Hope Fault and numerous geomorphic features suitable for analysing dextral displacements. Background bathymetry grid is 30 kHz data from LINZ, gridded to 10 m DEM.

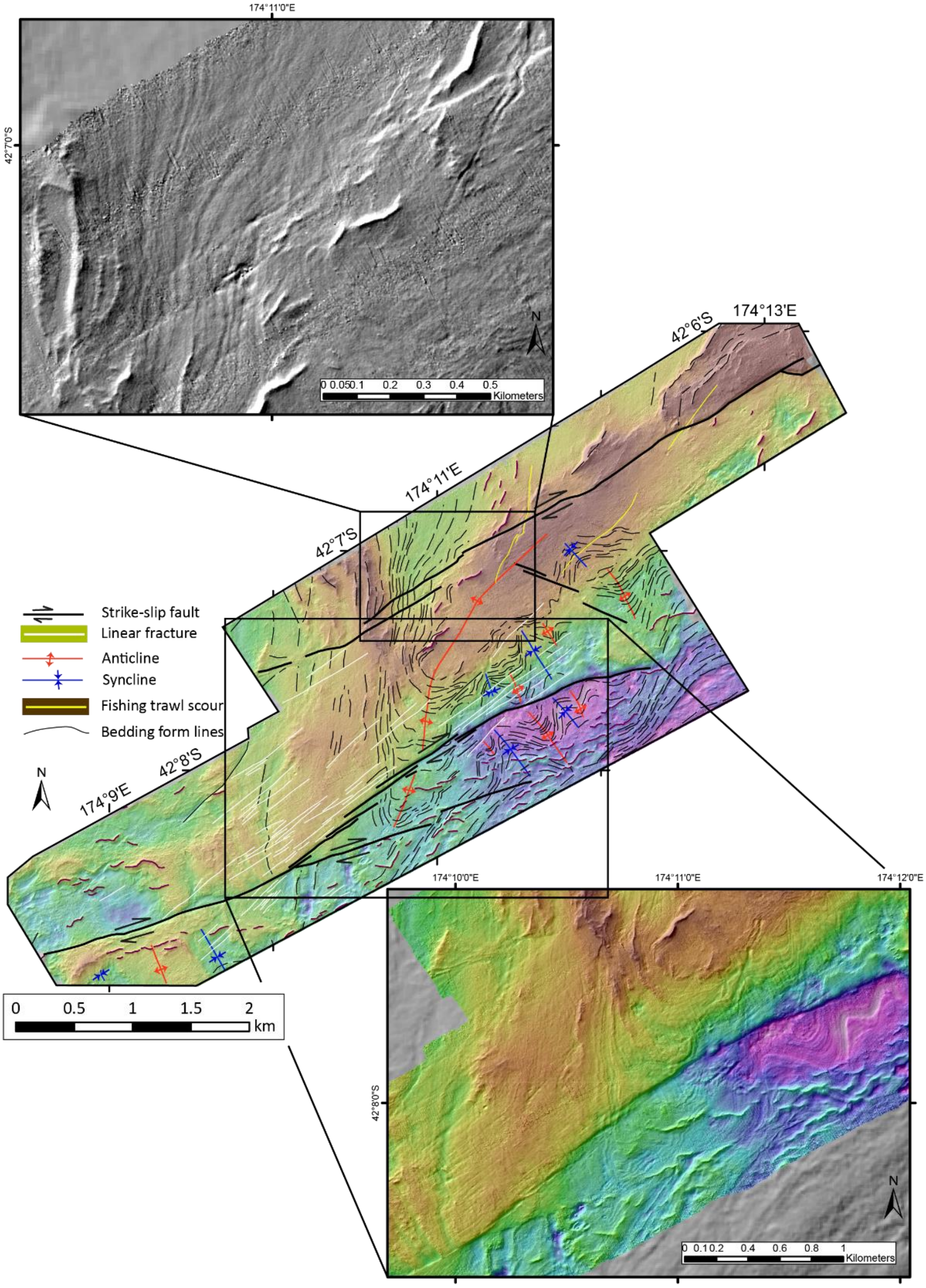

Figure 5. Example of new EM2040 multibeam bathymetric data from areas 1 and 2, processed to 2m grid resolution showing clear linear surface traces of the Hope Fault and numerous geomorphic features suitable for analysing dextral displacements. Background bathymetry grid is 30 kHz data from LINZ, gridded to 10 m DEM.

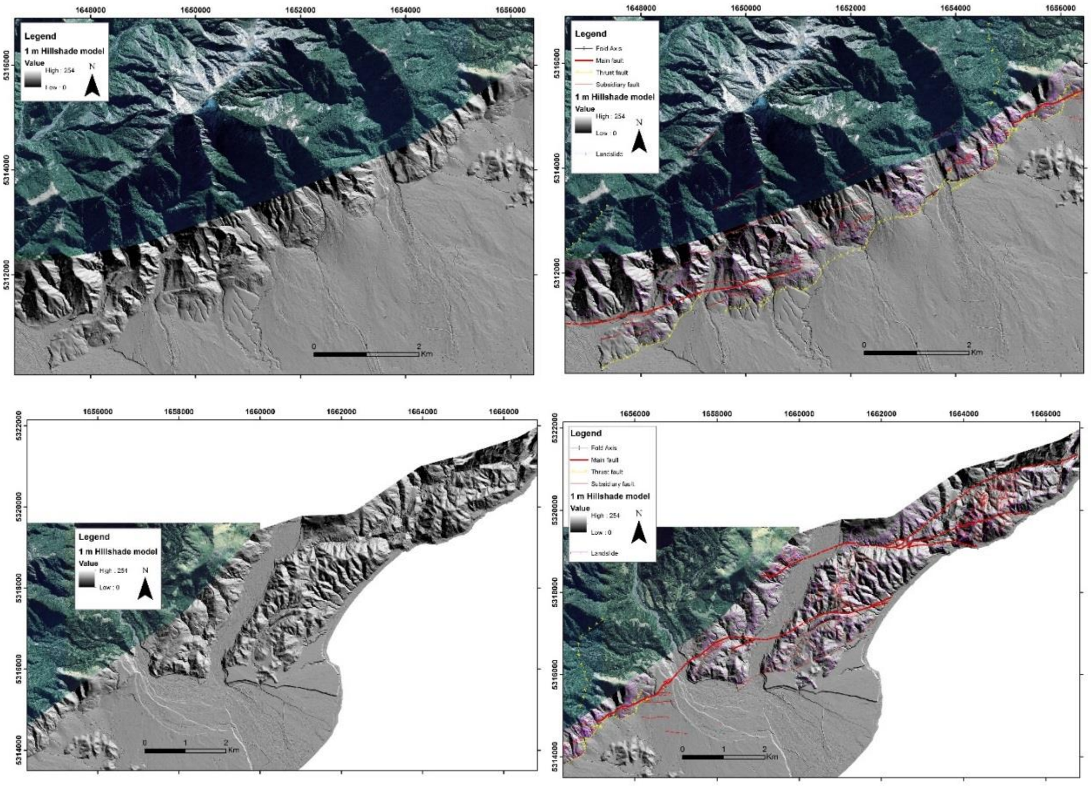

Figure 6. Mapping of the Hope Fault undertaken in this project by Jarg Pettinga. Mt Fyfe range front (upper two panels; left uninterpreted, right interpreted), coastal sections (lower two panels; left uninterpreted, right interpreted). Map base compiled from LiDAR imagery and Kiwimap aerial photos.

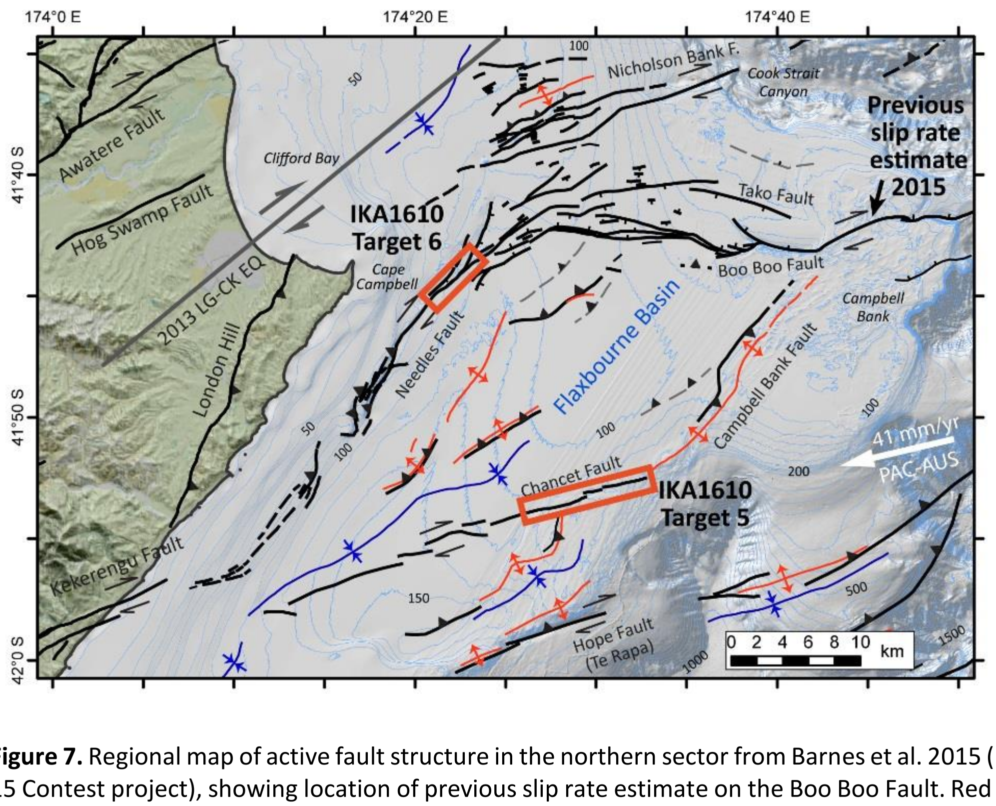

Figure 7. Regional map of active fault structure in the northern sector from Barnes et al. 2015 (NHRP 2012-15 Contest project), showing location of previous slip rate estimate on the Boo Boo Fault. Red boxes show locations of new IKA1610 EM2040 multibeam survey areas 5 (Chancet Fault) and 6 (Needles Fault) undertaken in this project.

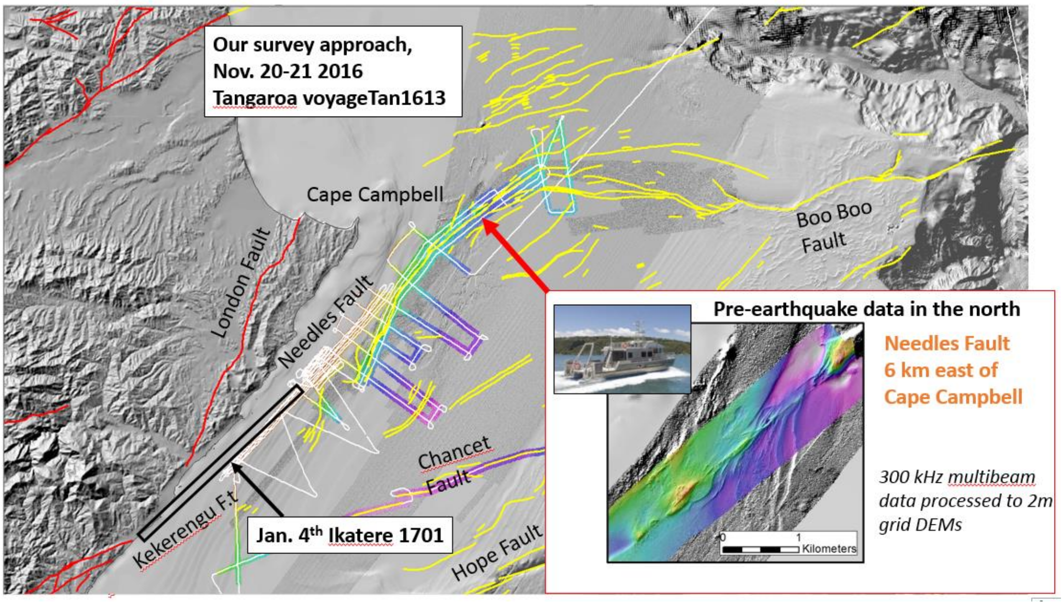

Figure 8. Map of active faulting in coastal Marlborough (red onshore, yellow offshore), showing survey data coverage collected by *Tangaroa* on survey Tan1613 immediately following the M_w7.8 Kaikoura Earthquake (thin white lines are sub-bottom profiles, coloured seafloor is new EM302 multibeam bathymetric data processed to 2m grid resolution). The thin black rectangle refers to the area of the southern Needles Fault surveyed by Ikatere on survey IKA1701, January 2017, by NIWA). The inset map shows the area in colour that was mapped by *Ikatere* (Photo) at 2 m grid resolution *before* the earthquake during our survey IKA1601 in April 2016. Analyses of the data collected before and after the earthquake helped us to evaluate the NE extent of seafloor rupture on the Needles Fault during the earthquake (details provided in Kearse et al., submitted).

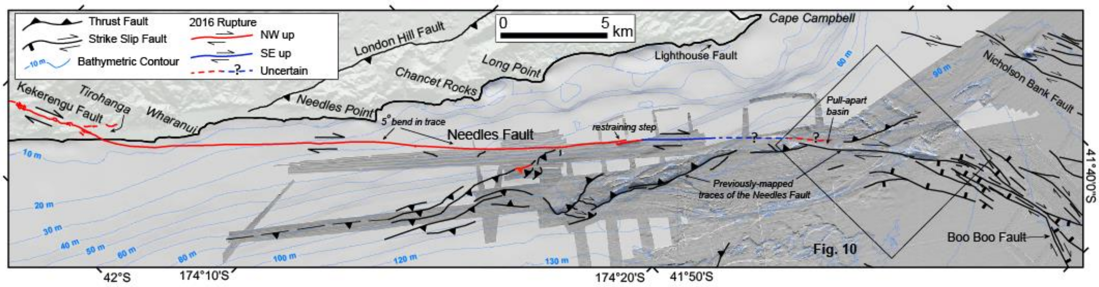

Figure 9. Mapping undertaken in this project showing the extent of offshore surface rupture on the Needles Fault during the M_w7.8 Kaikoura Earthquake (red lines), along with offshore active fault structures that did not break in this earthquake (Black lines) (from Kearse et al., submitted).

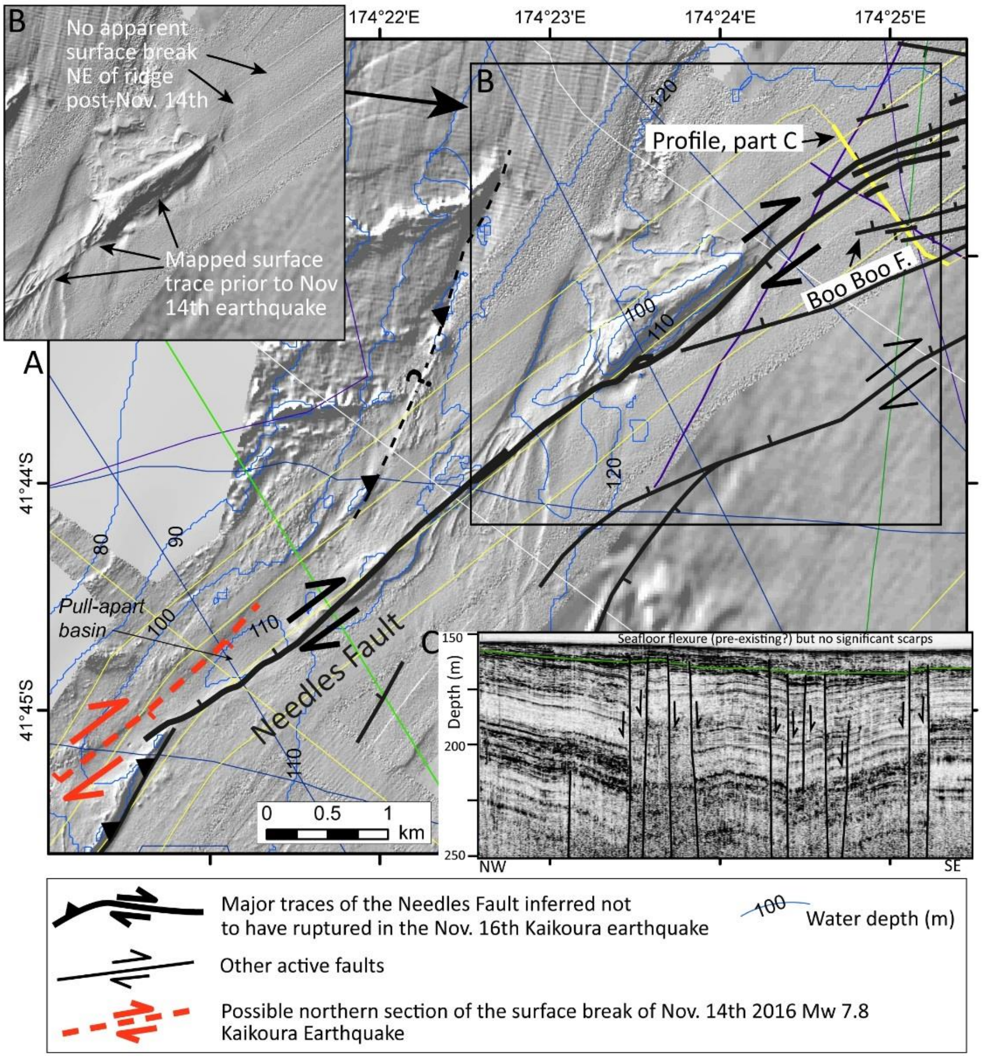

Figure 10. A. Details of the NE section of the Needles Fault east of Cape Campbell showing the inferred extent of offshore surface rupture during the M_w7.8 Kaikoura Earthquake (red dashed line), along with offshore active fault structures mapped in this project that did not break in this earthquake (Black lines). B. Inset map shows largely undisturbed sediment cover over the Needles and Boo Boo faults NE of a prominent seafloor ridge. C. Example of TOPAS sub-bottom profile collected on *Tangaroa* Tan1613 and used to map the intersection of the Needles and Boo Boo faults. (Data presented in Kearse et al., submitted).