NATURAL HAZARDS RESEARCH PLATFORM

Contest 2015

Title: *"Slip Rate and Paleoseismicity of the Kekerengu Fault: An anchor point for deformation rates and seismic hazard through central New Zealand"*

Leader: Timothy A. Little
Organisation: Victoria University of Wellington
Total funding (GST ex): $182,778

Title: *Slip Rate and Paleoseismicity of the Kekerengu Fault: An anchor point for deformation rates and seismic hazard through central New Zealand*

Programme Leader: Timothy A. Little
Affiliation: Victoria University of Wellington

Co-P.I.: Russ Van Dissen (GNS Science)

A.I.: Kevin Norton (VUW)

Has this report been peer reviewed? Provide name and affiliation.
Part of it: the paper by Little et al. was published in 2018 in the Bulletin of Seismological Society of America, which is a peer-reviewed international journal.

Table of Contents:

Key Message for Media: ***[****Why are these findings important? Plain language; 5 sentences.****]***
Prior to this study, little scientific data existed about the rate of activity and earthquake hazard posed by the active Kekerengu Fault near the Marlborough coast in northeastern South Island. Our study was designed to test the hypothesis that this fault carries most of the Pacific-Australia plate motion through central New Zealand, and is a major source of seismic hazard for NE South Island and adjacent regions straddling Cook Strait—something that had previously been encoded in the NZ National Seismic Hazard Model. Serendipitously, the Mw 7.8 Kaikōura Earthquake took place on November 14, 2016, rupturing the entire 26 km length of the onshore Kekerengu fault, which slipped horizontally by up to ~12 m—thus providing strong affirmation of our thesis. In this project, we further reinforced the hypothesis by: 1) documenting that 4 large surface rupturing earthquakes have taken place on the Kekerengu Fault since 1200 years ago, making it one of the most seismogenically active faults in New Zealand; and 2) that the long-term average rate of slip on the fault is 20-26 mm/yr (20-26 kilometres per million years), a rate that is second only to the Alpine-Hope fault system.

Abstract:
This project focuses on the Kekerengu Fault, and tests the hypothesis that the chief locus of plate boundary deformation in northern South Island steps northeastward from the eastern Hope Fault to follow the Jordan Thrust and Kekerengu Fault before extending offshore into Cook Strait. To test models of plate motion and seismic hazard through central New Zealand, we excavated three trenches across the Kekerengu fault. Two of these were later dextrally displaced ~9 m in the M_w 7.8 2016 Kaikōura earthquake. On the basis of 13 radiocarbon samples, we document paleoearthquakes at 249-108, 528-356, and 1249-903, cal yrs. B.P. Including the 2016 rupture, the youngest 3 events indicate a mean recurrence interval (RI)

for the Kekerengu fault of 376 ± 32 yrs (± 1σ = one standard deviation). This RI is within error of that of the Hope fault; moreover, using a 9 ± 4.5 m Single Event Displacement for the Kekerengu fault, this RI implies a dextral slip-rate of 24 ± 12 mm/yr (1σ), which overlaps with the late Quaternary slip rate of the Hope fault. Our data supports the hypothesis—one encoded into the New Zealand National Seismic Hazard Model, and indicated by the up to ~12 m of slip taking place on the Kekerengu Fault in the 2016 earthquake—that slip on the Hope fault is transferred predominantly northward onto the Jordan-Kekerengu-Needles fault to reach within 60 km of Wellington, rather than extending ENE along the offshore Hope fault. The last three paleoearthquakes on the Kekerengu fault were closely spaced in time or coeval with earthquakes on the Hope fault suggesting possible stress triggering. It is possible that this correspondence may reflect the previous occurrence of complex, multi-fault earthquakes that—like the 2016 earthquake—involved mutual surface rupturing of these two faults, and perhaps also of the subduction interface below them. Two Holocene earthquakes on the Kekerengu fault have been closely followed by others on the Wairarapa fault, most recently in 1855, suggesting possible static stress loading across Cook Strait. The latter two faults straddle a ~30 km width of Cook Strait. Since AD 1855 they have combined to rupture >200 km in central New Zealand with unusually large surface displacements.

To further test models of plate motion and seismic hazard through central New Zealand, we analyzed Optically Stimulated Luminescence (OSL) samples and cosmogenic nuclide exposure age profiles of two key aggradational fluvial terraces that have been displaced dextrally and vertically by the Kekerengu Fault. These are the older Kulnine Terrace, and the younger Winterholme Terrace (of probable post Last Glacial Maximum age). The Kekerengu Fault truncates a prominent riser (ancient river bank) that was cut downward by Glencoe Stream and that separates the Kulnine and Winterholme terraces from one another. The horizontal distance between the riser and its source, Glencoe Stream, is ~600±50 m. The OSL data indicate that the riser was cut at ~25-30 ka (where "ka" denotes 1000 years before present) during the peak of Kulnine degradation, and prior to the onset of extensive Winterholme aggradation. Because subsequent Winterholme aggradation may have caused some further trimming of the riser, this measured distance provides a maximum estimate of lateral offset. These data imply a maximum dextral slip rate of ~18-26 mm/yr. The Kekerengu Fault also truncates, and dextrally displaces, a beheaded channel that lies on the Kulnine surface by ~850 ±150 m. This terrace was abandoned at 27-34 ka yielding a slip rate of ~20-37 mm/yr. Taken together, the above two dated offsets provide a combined dextral slip rate of 20-26 mm/yr, making the Kekerengu Fault the second or third fastest on-land fault in New Zealand (behind the Alpine-Hope fault system), and demonstrating that most slip on the Hope Fault is transferred northeastward via the Jordan Thrust onto the Kekerengu Fault.

Keywords: Seismic Hazard, Kekerengu Fault, Slip-rate, Recurrence interval, Paleoseismology, Fluvial Terraces, Hope Fault, Wairarapa Fault

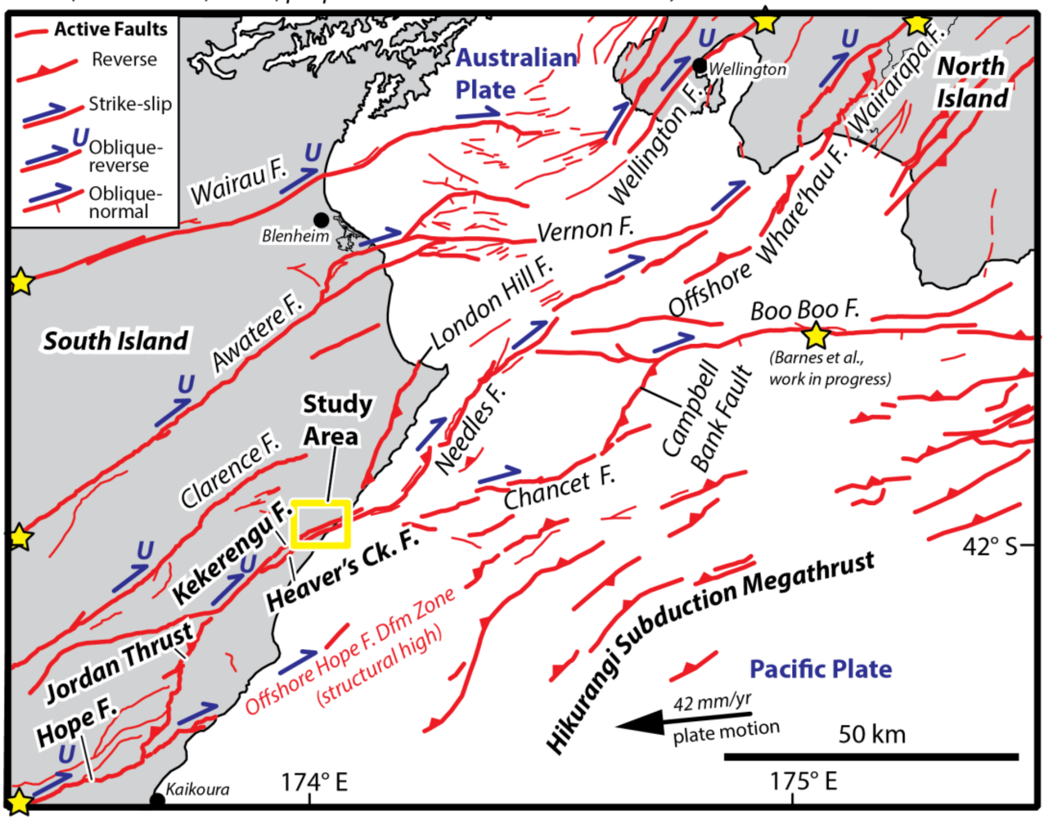
Introduction / Background:

This project focuses on the Kekerengu Fault, and tests the hypothesis that the chief locus of plate boundary deformation in northern South Island steps northeastward from the eastern Hope Fault to follow the Jordan Thrust and Kekerengu Fault before extending offshore into Cook Strait. Prior to this study, remarkably little scientific data existed about the activity and earthquake hazard of the active Kekerengu Fault along the Marlborough coast in northeastern South Island (Fig. 1, below). We proposed to study this fault in detail near the coast near Kekerengu township—near where the fault heads out to sea towards Cook Strait. Detailed information at the site would provide an "anchor point" with which to gauge the

activity and importance of this fault in accommodating plate motion through central New Zealand and in generating seismic hazard on both sides of Cook Strait. On the basis of a tectonic model that remained unconfirmed using modern neotectonic research (Van Dissen and Yates, 1991), the New Zealand National Seismic Hazard Model (Stirling et al., 2012) encodes a scenario that most plate motion from the Hope Fault is routed northeastward on the Jordan-Kekerengu-Needles Fault system rather than eastward onto the Hope Fault deformation zone immediately eastward and offshore of the Hope Fault near Kaikōura. If true, this model places a major active fault to within 50 km of Wellington City. But is it true?

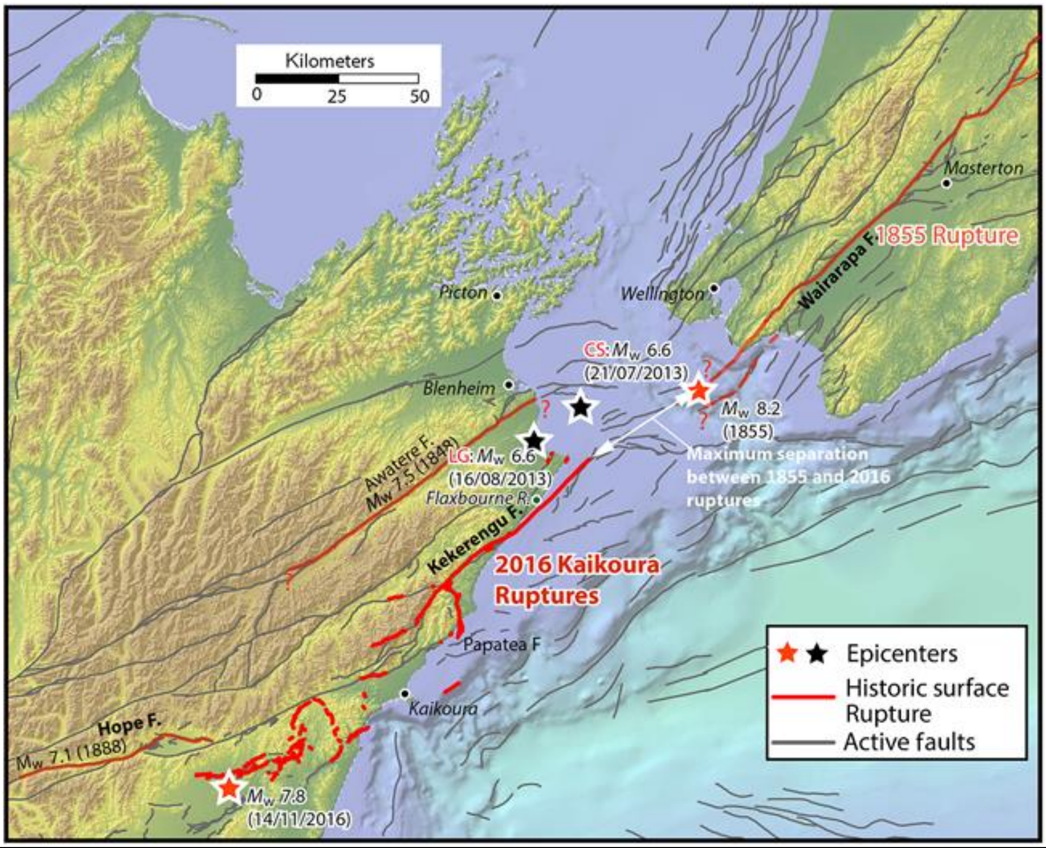
In order to evaluate the pace of activity on the Kekerengu fault, we pursued two main objectives in this project: 1) to document the chronology and tempo (Recurrence Interval, RI) of large surface rupturing earthquakes on the fault in the Holocene by means of paleoseismic trenching combined with radiocarbon dating, and OSL dating; and 2) to document the Late Quaternary (geologically young, <2.6 Myrs old) slip rate on the fault by measuring the horizontal offset of displaced river terraces across the fault using LiDAR imagery and orthophotography and by determining the age of those terraces using two radiometric dating methods: a, Optically Stimulated Luminescence (OSL) dating; and b, Cosmogenic Nuclide surface exposure dating. Knowing the results of these two objectives would improve our understanding of how active plate boundary deformation is distributed through central New Zealand, and of the seismic hazard it poses.

Figure 1. *Active fault map of central New Zealand in the Cook Strait region (simplified from Pondard and Barnes, 2010; Litchfield et al., 2014), showing location of the Kekerengu Fault and the proposed study area in the Pacific-Australia plate boundary zone (plate motion vector from Wallace et al., 2007). Yellow stars denote the approximate location of where slip-rates on the major faults through central New Zealand are geologically well constrained (= "anchor points"). Note the strategic importance of adding the coastal Kekerengu Fault as a new anchor point. References for these are: Ninis et al. 2013 for Wellington Fault; Carne et al. 2011, Van Dissen et al., 2013 for Wairarapa Fault; and Mason et al., 2006 for Awatere Fault. Other current projects are targeting the Wairau and Hope Faults (Dolan et al., N.S.F. funded project) and the Boo Boo Fault (Barnes et al., NIWA, proposal PROP-42835-HAZNAT-NIW).*



Serendipitously, the Mw 7.8 Kaikōura Earthquake took place at a mid point during the tenure of our project on November 14, 2016, rupturing the entire 26 km length of the onshore Kekerengu fault (Fig. 2), as well as the offshore Needles fault to the NE and the Jordan-Upper Kowhai-Manakau faults to the SW (a total onshore + offshore distance of 84 km, Kearse et al., in press; Litchfield et al., in review). The Kekerengu fault slipped horizontally by up to ~12 m, and had an average dextral slip magnitude of ~5.5 m (Kearse et al., in press). The ~12 m maximum strike slip placed it among the top 5 largest earthquake so far documented globally. This earthquake thus provided strong independent affirmation of the thesis on which this NHRP project was based.

Figure. 2. *Map showing location of surface rupturing during the 2016 Mw 7.8 Kaikōura earthquake (heavy red lines in the South Island, including on the onshore-offshore Jordan-Kekerengu-Needles fault system), and other selected historic ruptures (thin red lines, including the Awatere Fault, South Island, in 1848; and the Wairarapa fault, North Island, in 1855). Also shown are the epicentres (from Hamling et al., 2014) of the Mw 6.6 Lake Grassmere (LG) and Cook Strait (CS) earthquakes of 2013. Figure is taken from Little et al. (2018).*



This section must be completed.
Insert additional Impact Statements & Research Aims as needed.

Title - Impact Statement 1

❖ **1 Research Aim**

Title: Determining Kekerengu Fault Paleoseismic History

Budget: $120,633
Research Aim achieved? Yes

Overview: In January of 2016, we excavated, logged, and sampled three paleoseismic trenches across the Kekerengu Fault and logged and sampled a natural outcrop of the Heaver's Creek fault splay. Twenty-five radiocarbon samples and one OSL sample were collected from these trenches and the exposure. Of these radiocarbon samples, 14 were submitted for analysis to the Rafter Radiocarbon Laboratory. The OSL sample was analyzed at Victoria University of Wellington. Ten months later, during the Kaikoura earthquake, the Kekerengu Fault displaced two of these trenches dextrally (horizontally) by ~ 9 m. After the earthquake, using a combination of direct field observations, GPS surveying, and analysis of LiDAR topographic models, Little, Van Dissen, and M. Sc. student, Jesse Kearse, mapped the 2016 rupture fault traces on the Kekerengu fault (Litchfield et al., 2017), including in the near-coastal area where our fault trenches were located (Little et al., 2018). In addition, they documented the coseismic displacement of hundreds of natural and cultural features,

evaluating the coseismic slip distribution on the Kekerengu fault system during the 2016 earthquake (Kearse et al., in press).

Primary output of Research Aim 1:

The data and results of Research Aim 1 for this NHRP project were published in the Bulletin of the Seismological Society of America in an article entitled, *"Kekerengu fault, New Zealand: timing and size of Late Holocene surface ruptures"* (Little et al., 2018). We reproduce this article as Appendix 1 of this report, and include the Electronic Supplements to this paper as Appendices, 2, 3, and 4.

Below are the main conclusions of the paper:

The Kekerengu fault has ruptured at least four times during the past ~1200 years. At 95% confidence, these included:

E0, Last event: 16 November, AD 2016 (-67 cal. yrs B.P.)
E1, Penultimate event: 249-108 cal. yrs B.P.
E2, Third oldest event: 528-356 cal. yrs. B.P.
E3, Fourth oldest event: 1249-903 cal. yrs. B.P.
E4, Fifth oldest event, uncertain age: either 1726-1093 or >1605 cal. yrs. B.P.

Based on the last 4 events (including the 2016 earthquake) we estimate a mean late Holocene recurrence interval of 322-438 years (95% confidence range) or 376 ± 32 yrs (mean ±1σ). The timings of the youngest three paleoearthquakes on the Kekerengu fault are within error of the youngest three paleoearthquakes (not including the 1888 Amuri earthquake) on the Hurunui section of the Hope fault (Khajavi et al., 2016). This apparent matching suggests either that closely spaced earthquakes took place on the Hope and Kekerengu faults, perhaps as a result of static stress triggering, or that coeval rupturing occurred on the two faults during complex, multi-fault earthquakes. The available historic and paleoseismic data, albeit sparse, suggests possible stress triggering between the Kekerengu and Wairarapa faults, which both rupture deeply into the crust. During the past ~1000 yrs, two large earthquakes on the Kekerengu fault have been closely followed by others on the Wairarapa fault. The last two earthquakes on these faults ruptured >200 km of plate boundary on either side of Cook Strait. Both the Wairarapa fault in 1855 and the Kekerengu Fault in 2016 slipped with unusually large dextral displacements (maximum of 12-18 m and with unusually high displacement-to-length ratios). The dextral-reverse faults may rupture deeply, reaching most of the way down to—or even co-rupturing—the subduction interface (Darby and Beanland, 1992; Rodgers and Little, 2006; Hamling et al., 2017; Clark et al., 2017).

The data in this paper support the model of slip from the Hope fault being transferred predominantly northeastward onto to Jordan-Kekerengu-Needles fault system, rather than extending ENE along the offshore Hope fault. In particular, the Hope and Kekerengu faults have similarly short mean earthquake recurrence intervals. Moreover, if it is a representative Single Event Displacement (SED), then ~9.1 m of dextral slip on the eastern Kekerengu fault during the November 2016 earthquake in combination with a Covariance (CoV) for the SED of 0.5 and the above recurrence interval, implies a dextral slip-rate of 24 ± 12 mm/yr, which is within error of the late Quaternary slip rate of the Hope fault. Independent of the Hope fault, the sinistral-reverse Papatea fault also contributes slip into the Kekerengu fault system. The northward routing of plate boundary deformation onto the Kekerengu-Needles fault system into Cook Strait, and to within 60 km of Wellington, supports the current National Seismic Hazard Model for New Zealand (Stirling et al., 2012), which encodes the Kekerengu-Needles fault system as a principal earthquake source on the southern margin of Cook Strait.

Secondary outputs completed as a part of Research Aim 1:

1. The References Section of this report (below) lists all abstracts and papers relating to this NHRP project.

2. As resolved in the original NHRP proposal, both the NZ Active Faults Database and NZ Seismic Hazard Model were updated to accommodate all the findings of this objective (also the implications of the 2016 Kaikoura earthquake rupture).

3. Little presented the results of this Research Aim at two conferences, including, Little et al. (2016—talk at NHRP Workshop, Avalon); Little et al. (2016—NZ GeoSciences Conference, Wanaka); and Little et al. (2017—talk to the Meeting on Paleoseismology, Active Tectonics and Archeoseismology—PATA, held in Blenheim). The latter international conference also published a corresponding, 4-page long, peer-reviewed conference paper on our presentation.

4. Little and Van Dissen delivered many public lectures on the topic of the paleoseismic history and seismic hazard of the Kekerengu Fault (many more than the 2-3 lectures that we committed to giving in the NHRP proposal) and on its role in the 2016 Earthquake.

<u>Lectures to a scientific audience include:</u>

1. Wellington Branch of the New Zealand Geosciences Society (by Little) on 9 February, 2017 and
2. Australia-New Zealand Geomorphology Group (by Van Dissen) on 9 February, 2017.
3. International StatSei Conference (by Van Dissen) on 24 February, 2017.
4. GeoSciences Society of New Zealand Conference (by Little) in November, 2016.
5. International Conference, 8th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA) in November, 2017 (by Little).

<u>Public outreach lectures include:</u>

1. Inner City Association of Wellington (by Van Dissen) on 21 March, 2017.
2. Wairarapa Science Society (in Masterton, by Little) on 4 May, 2017.
3. Keynote address at BOINZ (Building Officials Institute of New Zealand) annual conference and expo (in Auckland, by Van Dissen) on 8 May, 2017 with >200 in attendance.
4. Tararua Tramping Club (by Little) on 9 May.
5. Kekerengu Valley-Clarence Township Community (in Kekerengu by Little & Van Dissen) on 10 May, 2017, sponsored by “Top of the South” Community Trust.
6. Ward Township-Seddon Community (in Ward, by Van Dissen & Little) on 11 May, 2017, sponsored by “Top of the South” Community Trust.
7. Hutt Valley War Memorial Library, a talk in the “Planning for our Future: The Science We Need to Know” information series (in Lower Hutt, by Van Dissen) on 15 June, 2017.

These outreach talks to lay audiences have highlighted the findings of our NHRP research project, focusing on the Kekerengu Fault, and have pointed out the relevance of the earthquake ruptures, coastal uplift, and damage to public understanding of earthquake hazard.

<u>Other outreach projects</u>

To capitalize on the high level of public interest following the Kaikōura earthquake, both PI's contributed to video clips distributed on the EQC and GNS websites, one of which went viral on Reddit in the US:

https://youtu.be/JVttCngC-ko.

Van Dissen was featured largely in an article on the Kaikoura earthquake in *NZ Geographic* (Jan-Feb., 2017). Much of this article is devoted to the Kekerengu Fault and features our NHRP-funded project results.

list of future outputs:

- All milestones related to this objective are complete and no future outputs are planned.

list of end-users:

New Zealand Seismic Hazard Model
New Zealand Active Faults Database
GeoSciences Society of New Zealand
Wellington City Council
Wellington Region Emergency Management Office (WREMO)
Marlborough Civil Defense Emergency Management (CDEM)
The Earthquake Commission
Top of the South Community Trust.

❖ 2 Research Aim

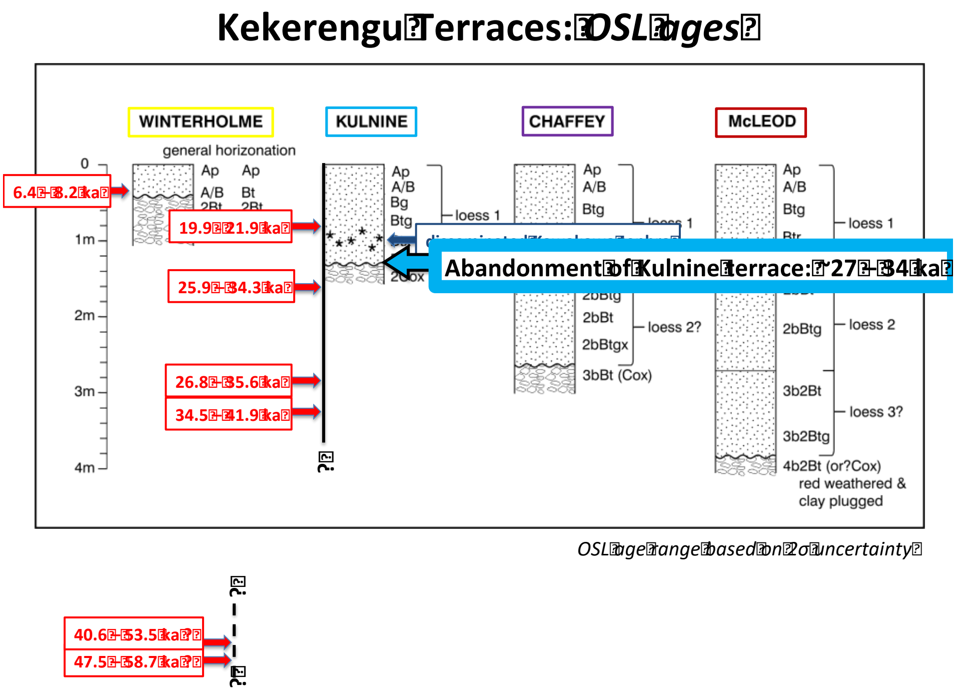
Title: Determining the Late Quaternary Slip Rate of the Kekerengu Fault

Budget: $62,145

Research Aim achieved? No (final written output still in preparation)

Overview: In January and February 2016 Van Dissen, Norton, Little, and VUW Summer Scholars J. Kearse and J. Whattam, excavated, logged and sampled three sample pits on the key fluvial terraces for evaluating the Late Quaternary slip rate of the Kekerengu fault, and collected 12 OSL samples in these pits and from natural outcrops of the terrace sequences. Of these, 9 were submitted to the OSL laboratory at VUW. In conjunction with identification of the Oruanui (~26.5 ka) tephra in the coverbed of the Kulnine Terrace, these OSL ages provided tight constraints on the timing of fluvial aggradation and degradation. The team also collected 16 sand and gravel samples from the three terrace sample pits for ^{10}Be cosmogenic nuclide dating analysis that were processed at VUW, and analyzed using AMS at Rafter laboratory. The ^{10}Be cosmogenic nuclide isotopic results of the terrace pit samples were modeled by Norton (Norton et al., 2017, AGU abstract) and support the OSL results. These data sets were used to date the two key fluvial terraces cut by the Kekerengu Fault (the Kulnine and Winterholme terraces). In particular, the OSL ages (Fig. 3) constrain the timing of abandonment of the Kulnine Terrace, and the start of downcutting of the fault-displaced, Kulnine-Winterholme riser to the period 34-27 ka.

Figure 3. *Summary of the soil stratigraphy and OSL-based age control on aggradation and downcutting of four fluvial terraces near Kekerengu. The McLeod is the highest and oldest terrace, the Winterholme, the lowest and youngest. Red ages in boxes are 2σ errors for OSL ages.*



After the 2016 Kaikōura earthquake, LiDAR topographic data was flown in by NZTA near the coast and by GNS Science farther inland, and accompanying, high-resolution orthophotography was taken. These data were used measure the 600 ±50 dextral offset of Glencoe Stream that accrued after the main phase of riser down-cutting between the Kulnine and Winterholme Terrace that formed the incisional riser between these two terraces (Fig. 4). This slip is a maximum estimate because the riser may have been trimmed laterally during the Winterholme aggradation.

Figure 4. *Oblique aerial photograph (Lloyd Homer, GNS Science), showing the dextral offset of the Kulnine-Winterholme riser formed by incision of Glencoe Stream downstream of the Kekerengu fault.*

Prior to the Kulnine-Winterholme riser being down-cut, Glencoe Stream incised a shallow channel on the Kulnine Terrace. The channel is now beheaded and has been offset by ~850 ±150 m (Figure 5).

Figure 5. *Oblique aerial photograph (Lloyd Homer, GNS Science), showing the dextral offset of the beheaded channel on the Kulnine Terrace (formed by Glencoe Stream).*

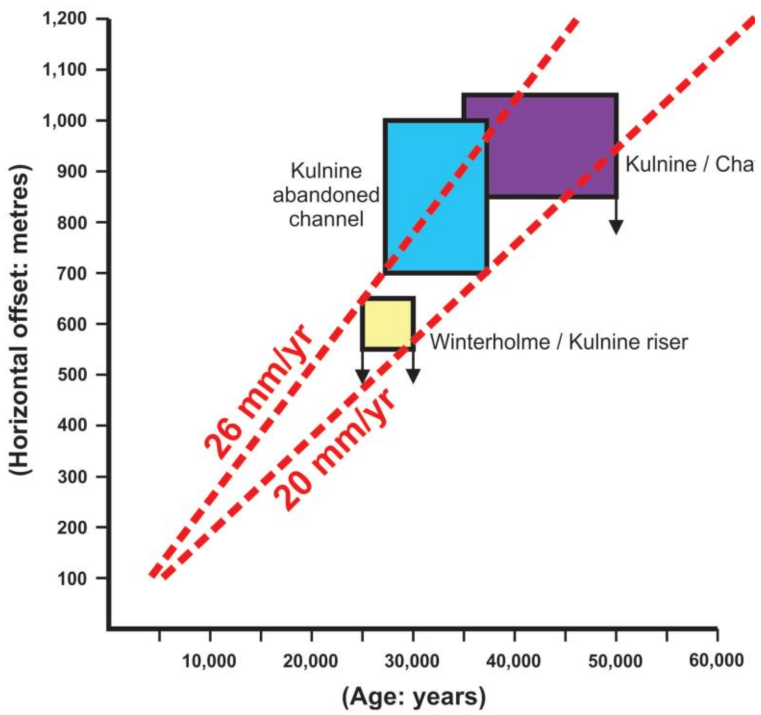
Primary output of Research Aim 2:

The above findings indicate that since ~25-34 ka, the Kekerengu Fault has experienced a dextral-slip rate of ~20-26 mm/yr (Fig. 6), making it the second or third fastest on-land fault

in New Zealand (behind the Alpine-Hope faults), and demonstrating that most slip on the Hope Fault is transferred northeastward via the Jordan Thrust onto the Kekerengu Fault in accordance with scenarios currently embedded in the New Zealand Seismic Hazard Model (Stirling et al., 2012). Post-Kaikoura earthquake fieldwork has documented that the Kekerengu-Jordan Fault system slipped dextrally by up to 11.8 meters and vertically by up to 2.5 meters during the 2016 earthquake, with our NHRP trench sites (Research Aim 1) being dextrally displaced by ~9.1 m (Kearse et al., in press). This high coseismic slip magnitude, together with the outcome from Research Aim 1—that the Kekerengu fault at our near-coastal trench sites has a mean recurrence interval of 376 ± 32 yrs—reinforce the main conclusion of Research Aim 2 that the Late Quaternary slip rate of the Kekerengu Fault is very high (20-26 mm/yr).

The final written output of Research Aim 2, a peer-reviewed article in an international journal is in preparation at the time of writing of this report.

Figure 6. *Age (years B.P.) vs. dextral offset (metres) for fluvial terrace cut by the Kekerengu Fault near Kekerengu, showing range of possible slip-rates*.



Secondary outputs completed as a part of Research Aim 2:

1. The References Section of this report (below) lists all abstracts and papers relating to this NHRP project.

2. As resolved in the original NHRP proposal, both the NZ Active Faults Database and NZ Seismic Hazard Model were both updated to accommodate all the findings of this objective.

3. Van Dissen delivered several conference presentations addressing the Late Quaternary slip-rate of the Kekerengu Fault, the 2016 earthquake ruptures on the fault, and its seismic hazard. These include:

Van Dissen et al. (2016—talk at NZ GeoSciences Conference, Wanaka); in Van Dissen

et al. (2017—invited talk at European Geosciences Union (EGU) General Assembly, in Vienna, Austria); and in Van Dissen et al. (2017—talk to the International Meeting on Paleoseismology, Active Tectonics and Archeoseismology—PATA, held in Blenheim).

4. Public talks by Van Dissen and Little. For a list of our scientific and outreach talks please refer back to the previous section listing the secondary outputs for Research Aim 1 (each of the talks included material relating to both Research Aim 1 and Research Aim 2 of this NHRP project, and thus the list is not repeated here).

list of future outputs:

The final output of Research Aim 2, a peer-reviewed article in an international journal is in preparation at the time of writing of this report. All other Milestones relating to this Research Objective have been achieved.

list of end-users:

New Zealand Seismic Hazard Model
New Zealand Active Faults Database
GeoSciences Society of New Zealand
Wellington City Council
Wellington Region Emergency Management Office (WREMO)
Marlborough Civil Defense Emergency Management (CDEM)
The Earthquake Commission
Top of the South Community Trust.

Conclusions & Recommendations:

This project has demonstrated the importance of the Kekerengu fault in accommodating Pacific-Australia Plate motion through central New Zealand and the seismic hazard it poses on both sides of Cook Strait—inferences that were reinforced by the key role played by the Kekerengu fault in the November 2016, Mw 7.8 Kaikōura Earthquake.

One of the conclusions of Research Aim 1 was that there may have been static stress triggering across Cook Strait between the Kekerengu fault and the Wairarapa Fault; and between the Kekerengu fault and the Hope Fault; and that the latter two faults (and possibly the subduction interface) may have previously ruptured together in complex, multifault earthquakes. We believe that this would be a topic worthy of future multidisciplinary research.

Acknowledgements:

We thank the Natural Hazards Research Platform for its support. Further support was provided by the 2015 Victoria University of Wellington, Student Summer Scholarship Scheme, grants 122 and 166. An anonymous reviewer and Vasso Mouslopoulou provided constructive reviews that improved the Bulletin of the Seismological Society of America (BSSA) paper. Jack Whattam contributed to the fieldwork. Andrew Rees helped us with the OxCal modeling. Jennifer Dahl (Rafter Radiocarbon Laboratory) supervised our selection and preparation of organic material for radiocarbon analysis. Matt Hill and Salmon Ashraf (GNS Science) provided the DSM used the BSSA paper. We gratefully acknowledge helpful conversations with Phil Barnes, Matt Hill, Nicola Litchfield, Kate Clark, Rob Langridge, Will Ries, Pilar Villamor, and Julie Rowland. We would like to thank Sandy and Anna Chaffey for providing accommodation during the fieldwork; and Tim, James, and Kaye Moore (East Lane

Station), and Richard and Sank McFarlan and Tom Bell (Tirohanga Station) for granting us permission to excavate on their land and to use their access roads. The hospitality and helpfulness of these and many other landowners in the Kekerengu District, even after their properties had been damaged in the Kaikoura earthquake, was a marvel. Finally, John and Richard Fissenden (of Fissenden Brothers Ltd, Kaikoura) excavated the trenches with great patience and skill.

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