

## Always finding faults: New Zealand 2016

Kevin W. Hall<sup>1</sup>, Helen Isaac<sup>1</sup>, Malcolm Bertram<sup>1</sup>, Kevin Bertram<sup>1</sup>, Don Lawton<sup>1</sup>, Alexis Constantinou<sup>2</sup>, Doug Schmitt<sup>3</sup>, Randy Kofman<sup>3</sup>, Jennifer Eccles<sup>4</sup>, Vera Lay<sup>5</sup>, Stefan Buske<sup>5</sup>, John Townend<sup>6</sup>, Martha Savage<sup>6</sup>, Andrew Gorman<sup>7</sup> and Richard Kellett<sup>8</sup>

<sup>1</sup>CREWES/University of Calgary, <sup>2</sup>Schlumberger, <sup>3</sup>University of Alberta, <sup>4</sup>University of Auckland, <sup>5</sup>Technical University Bergakademie Freiberg, <sup>6</sup>Victoria University of Wellington, <sup>7</sup>University of Otago, <sup>8</sup>GNS Science

### Summary

CREWES participated in two collaborative seismic surveys that were conducted in New Zealand in early 2016. The target of interest in the Whataroa valley (South Island) is the Alpine Fault, which forms part of the boundary between the Australian and Pacific Plates in southern New Zealand, and has the potential to produce M8+ earthquakes. The Deep Fault Drilling Project (DFDP) drilled and instrumented borehole DFDP-2b prior to the seismic program.

The Hauraki Rift survey (North Island) crossed the northern Kerepehi fault, which has previously been inferred from gravity data. The Kerepehi fault is considered to be active, and is thought to have produced M6+ earthquakes in the past. The primary objective of both programs was to better define seismic velocities and geometries of faults that are known to be earthquake risks.

Initial processing of surface seismic data has provided relatively good images of sediments, the base of sediments and, we believe, the Alpine and Kerepehi faults.

### Introduction

CREWES participated in two collaborative seismic surveys that were conducted on the North and South Islands of New Zealand in early 2016 (Figure 1). The target of interest in the Whataroa valley is the Alpine Fault, which forms part of the boundary between the Australian and Pacific Plates in southern New Zealand. It delineates the steep western front of the Southern Alps over a distance of approximately 500 km. Slip on the fault is responsible for lifting up the Southern Alps and for offsetting rocks laterally by hundreds of kilometres. During the last two million years, the central portion of the Alpine Fault has slipped at an average rate of approximately 27 mm/yr horizontally and 10 mm/yr vertically. In the Whataroa Valley the surface trace is near the range front of the Southern Alps and the Alpine Fault dips ~45° to the SE beneath the mountains (GNS Science Public Wiki, 2016).

The Hauraki Rift survey was conducted along the top of a stop-bank (dike) over unconsolidated river and marine sediments within the rift, and consisted of a single 1C-2D crooked-line. This seismic line crosses the northern Kerepehi fault, which has previously been inferred from gravity data. The Kerepehi fault is considered to be active, and is thought to have produced M6+ earthquakes in the past.

This abstract presents preliminary processing and interpretation results for the 1C-2D surface seismic lines.

### Method

An IVI Envirovibe was used for both surveys, running sixteen second linear sweeps with a four second listen time for acquisition. The Whataroa valley survey used 10-200Hz sweeps for the zero-offset VSP, 10-60Hz and 10-150 Hz for the walkaway VSPs and 10-150 Hz for the surface seismic data. 10-100Hz sweeps were used for the Hauraki Rift survey. The 1C-2D surface seismic data were acquired with a 10 m source interval with a nominal 4 sweeps per vibe point, and with a 10 m receiver interval using single 10 Hz Inova SM-24 geophones.

## Whataroa Valley Survey

Previous seismic surveys are summarized by Townend et al., 2016. In general, they were able to provide deep (>1 km) and shallow (<500 m) information, but it has proved difficult to image the Alpine Fault in the target 500-1000 m depth range due to energy scattered from the steep valley sides. A clear image of the main Alpine Fault reflector with a dip angle of around 50° has been obtained in the depth range between 1-2 km by Lay et al. (2016). from the WhataDUSIE seismic reflection data acquired in 2011.

The Deep Fault Drilling Project (DFDP) aims to determine the ambient conditions in a continental fault zone late in its typical cycle of large (M~8) earthquakes. A borehole (DFDP-2b) was drilled in the Whataroa valley with intent to intersect the Alpine fault (Sutherland et al., 2015). The drillers encountered approximately 240 m of gravels, silts and diamictites before penetrating a metamorphic sequence of schist, proto-mylonite and mylonite. The borehole is near-vertical at the surface but deviates to become normal to the fault-plane. The borehole did not intersect the fault-plane due to anomalously high temperatures at bottom-hole. A casing failure during drilling caused the bottom of the borehole to fill with cement. However, the top half of the borehole remains open and can be well-logged. A six-strand fiber-optic cable was cemented into the borehole over the entire length of the well.

The 2016 seismic survey consisted of a number of zero-offset and walkaway VSP surveys in the DFDP-2b borehole using the permanent fiber as well as a clamped string of 4x3C geophones. In addition, 1C-2D, 1C-3D and 3C-3D and sparse-3D common source surveys were conducted on the surface using cable and nodal systems (geophones and seismometers). As previously reported, there is a good qualitative match between unprocessed vertical component borehole geophone data and distributed-acoustic-sensing (DAS) fiber-optic data (Constantinou et al., 2016).

We attempted to process the Whataroa line to achieve an interpretable migrated section. There is a lot of noise in the data and probably some sideswipe. Repeated sweeps for different VSP geophone tool levels and for 3D receiver patch moves allow up to 136 vertical fold for some vibs points. We applied standard processing, which included true amplitude recovery, air blast attenuation, radial filtering, and Gabor deconvolution. Refraction statics were calculated from the first break picks and applied using a final datum of 100 m with a replacement velocity of 2350 m/s. We stacked the line using crooked line binning. After stacking the data, we migrated the section using post-stack finite difference time migration. There is a lot of noise in the stacked section below 1.5 s so the data do not migrate well here. To interpret the data and tie it to borehole information, we converted the time migrated section to depth using velocities obtained from the VSP data (Schlumberger Internal Report) for the top 800 m and velocities from data processing below that depth. Figure 2 shows this depth-converted section with the location of the deviated borehole DFDP-2b and our interpretation. We interpreted the location of the Alpine Fault from the observed contrasting dips of reflections. The depth of the Alpine Fault matches well the depths documented in published work (Norris et al., 2012) for the Whataroa area. The deviated DFDP-2b borehole reached a depth of 893 m (724 m TVD) and terminated in mylonitic rocks which are inferred to be within 200–300 m of the principal slip zone (Townend et al., 2016). The location of our interpreted Alpine Fault fits this scenario.

## Hauraki Rift Survey

Geological and geophysical studies of the Hauraki Rift (Schofield, 1967; Hochstein and Nixon, 1979; Edbrooke, 2001; Haywood and Grenfell, 2010) show it to be part of an active continental rift structure which started to form after the collision of the Indian and the Pacific plates. It is a ~30 km wide onshore-offshore extensional structure located 30 km to the east of the Auckland and Hamilton metropolitan areas (Hochstein et al., 1986). Individual 20+ km long fault segments mapped to date are thought to produce >M6-7 events; each segment with a recurrence interval of 2500-9000 years (de Lange and Lowe, 1990; Chick et al, 2001; Persaud et al., 2016). This tectonic feature is deemed to represent the primary seismic risk to the Auckland and Waikato regions (Hull et al., 1995; Wright et al., 2009). It is over 220 km in length, extending from the Taupo Volcanic Zone (SSE) to potentially offshore Whangarei (NNW; Hochstein and Nixon, 1979; Hochstein et. al., 1986), and contains the known active Kerepehi Fault. The Kerepehi Fault is only well defined at the surface as far north as Ngatea (Persaud et al., 2016), although gravity modelling indicates continuity of the deeper structure to the north (Hochstein and Nixon, 1979).

Recent active fault mapping and analysis of tilting of geomorphic surfaces also suggests that the Kerepehi fault extends up to the coast under younger undeformed alluvial and coastal sediments (Persaud et al., 2016).

The southern part of the Hauraki Rift is filled with about 3 km of Quaternary and Neogene sediments and is bounded on the western side by Jurassic metagreywackes. In the near surface the thin water-saturated low velocity layer is underlain on each side of the Piako River by up to 500 m of Quaternary sediments having a velocity of 1520-1570 m/s. The velocities of the deeper Neogene rocks are 2200-3000 m/s, and the velocity of 3770 m/s measured in the central uplift is typical of shallow greywackes observed elsewhere in New Zealand. Refraction seismic data showed the average velocity of the basement rocks to be 3450 m/s (Hochstein and Nixon, 1979). The Kerehepi Fault, which dips at 70-80° to the west, controls the major central basement uplift (Houghton and Cuthbertson, 1989). The 2016 seismic line investigates the lesser known northern Kerepehi Fault segment as modelled by Hochstein and Nixon (1979) and interpreted as active by Chick et al. (2001), allowing the northward trend of activity to be determined.

We processed the Hauraki line to attenuate noise and enhance signal. We applied true amplitude recovery, air blast attenuation, predictive deconvolution, and Gabor deconvolution. Surprisingly, given how flat the region is, source gathers show irregularities in the first breaks caused by lateral velocity changes and out-of-plane events. Refraction statics were calculated from the first break picks and applied using a final elevation datum of 37 m with a replacement velocity of 1000 m/s. The velocities mapped here agree with those of Hochstein and Nixon (1979), who calculated velocities of 500-800 m/s for the low velocity layer, and 1520-1570 m/s for the underlying Quaternary sediments. We stacked the line using crooked line binning and migrated the data using post-stack finite difference time migration, prestack Kirchhoff time migration and prestack Kirchhoff depth migration. To the west of the uplift on the right the prestack data appear faded out and the poststack data appear to be imaged better. The prestack depth migrated section has imaged the basement reflectors poorly. This could be due to the use of incorrect velocities, as the velocities were hard to establish. Figure 3 shows the post-stack finite-difference migrated seismic line (in time) with our interpretation of the major structural features annotated. The central basement ridge and Kerehepi Fault are seen clearly in the east. The top of the basement, although not well imaged, can be seen to dip from west to east. In the centre of the line are reflectors representing the Neogene sedimentary graben fill, which are tilted to the east and appear to be wedge shaped, with the thick end of the wedge to the east. This implies the sediments have been continuously deposited while the Kerepehi fault was active (growth fault).

## **Conclusions and Future Work**

Whataroa valley zero and multi-offset VSP geophone and fiber-optic data need be processed, matched to the surface seismic data, and interpreted. The 1C-3D and 3C-3D and sparse-3D data also need to be considered. We obtained fairly good images of the base of sediments and, we believe, of the Alpine Fault. Further processing to see if clearer images can be obtained should be conducted. Sections shown in this abstract should be interpreted in greater detail. The Hauraki Rift survey has produced decent images of structure within the Hauraki Rift, particularly of the base of sediments and of sediments deposited in the hanging wall of the Kerepehi fault. These data may also benefit from further processing, and certainly require a more detailed interpretation and integration with other geophysical data available in the area.

## **Acknowledgements**

DFDP-2 was principally funded by the International Continental Drilling Project, the Marsden Fund of the Royal Society of New Zealand, the Ministry of Business, Innovation, and Employment, GNS Science, Victoria University of Wellington and the University of Otago. This experiment was funded by the Earthquake Commission and Victoria University of Wellington, and grants held by the University of Calgary, University of Alberta and TU Freiberg. The authors would also like to thank Halliburton (SeisSpace) and Schlumberger (Vista) for the use of software donated to the University of Calgary. We also thank Rupert

Sutherland of the Victoria University of Wellington for comments and suggestions about figures contained in this abstract.

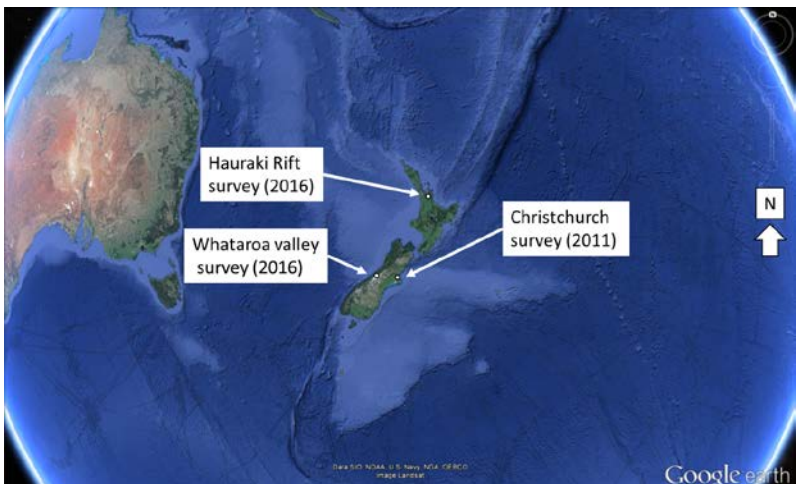


Figure 1. Location of New Zealand seismic surveys CREWES has participated in (Google Earth, 2016). Data: SIO, NOAA, U.S. Navy, NGA, GEBCO. Image: Landsat. The Christchurch survey is described by Lawton et al., 2012 and Lawton et al., 2013.

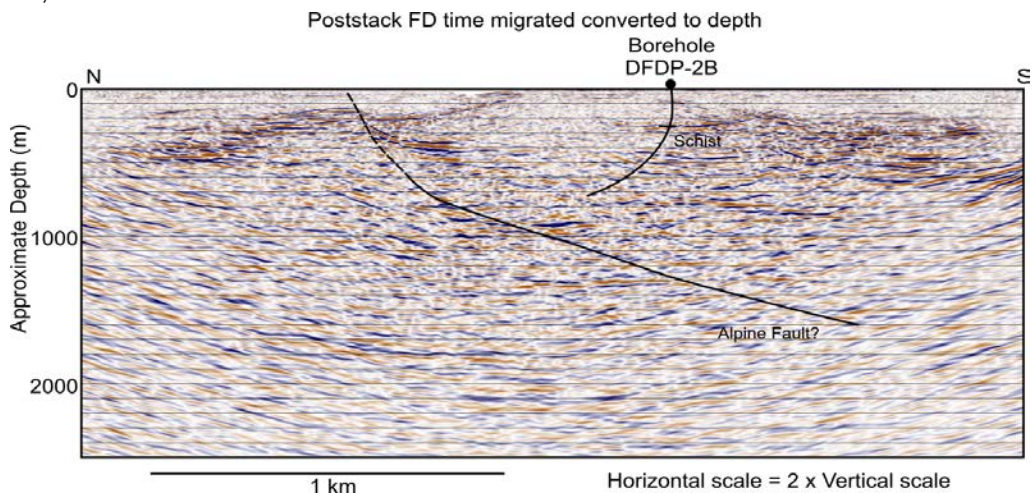


Figure 2. Top 2500 m of the depth-converted poststack time migrated section with the location of the DFDP-2B borehole and our interpretation of the Alpine Fault.

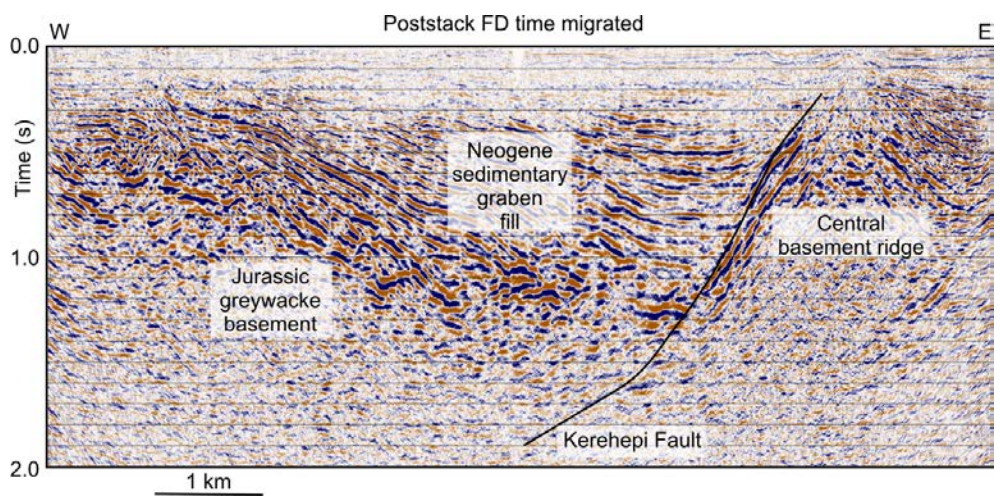


Figure 3. Interpretation of the Hauraki line with the main structural features annotated.



## References

- Chick, L.M., de Lange, W.P., and Healy, T.R., 2001, Potential tsunami hazard associated with the Kerepehi Fault, Firth of Thames, New Zealand: *Natural Hazards*, **24**, 309-318.
- Constantinou, A., Schmitt, D., Kofman, R., Kellett, R., Eccles, J., Lawton, D., Bertram, B., Hall, K., Townend, J., Savage, M., Buske, S., Lay, V., and Gorman, A., 2016, Comparison of fiber-optic sensor and borehole seismometer VSP surveys in a scientific borehole: DFDP-2b, Alpine Fault, New Zealand: SEG Internat. Expo. and 86th Ann. Mtg., Dallas, Soc. Expl. Geophys., Expanded Abstracts, 5608-5612.
- Edbrooke, S. W. 2001, Geology of the Auckland Area, 1:250,000 geological map 3, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand
- GNS Science Public Wiki: [https://wiki.gns.cri.nz/DFDP/DFDP-2\\_Whataroa\\_River/DFDP-2\\_FAQs](https://wiki.gns.cri.nz/DFDP/DFDP-2_Whataroa_River/DFDP-2_FAQs), accessed October 25, 2016.
- Google Earth, 2016, Google Earth version 7.1.7.2600 software downloaded and installed from <http://www.google.com/earth/index.html>, images accessed March 18, 2016.
- Haywood, B. W. and H. R. Grenfell, 2010, The Puketoka Formation and the age of the Hauraki Graben. Preconference field trip, Auckland: Geoscience Society of New Zealand Miscellaneous Publication 129B, 7pp.
- Hochstein, M. P. and I. M. Nixon, 1979, Geophysical study of the Hauraki Depression, North Island, New Zealand, *New Zealand Journal of Geology and Geophysics*, 22:1, 1-19, DOI: 10.1080/00288306.1979.10422550.
- Hochstein, M. P., Tearney, K., Rawson, S., Davey, F.J., Davidge, S., Henrys, S., and Backshall, D., 1986, Structure of the Hauraki Rift (New Zealand), *in* Recent crustal movements of the Pacific region, edited by Reilly, W.I., and Hurford, B.E.: *Bulletin - Royal Society of New Zealand*, **24**, 333-348.
- Houghton, B. F. and Cuthbertson, A.S., 1989, Kaimai, Geological Map of New Zealand 1:50000, T14BD, 35. Department of Scientific and Industrial Research, Wellington, New Zealand.
- Hull, A., Mansergh, G., Townsend, T. and Stagpoole, V., 1995, Earthquake hazards in the Auckland region. Prepared for the Auckland Regional Council. Auckland Regional Council Technical Publication 57.
- de Lange, P. J. and Lowe, D.J., 1990, History of vertical displacement of Kerepehi Fault at Kopouatai Bog, Hauraki Lowlands, New Zealand, since c. 10,700 years ago: *New Zealand Journal of Geology and Geophysics*, **33**, 277-283.
- Lawton, D.C., Bertram, M.B., Hall, K.W., Bertram, K.L., and Pettinga, J., 2012, Post-earthquake seismic reflection survey, Christchurch, New Zealand: SEG 82nd Ann. Mtg., Las Vegas, Soc. Expl. Geophys., Expanded Abstracts, 1-5.
- Lawton, D.C., Bertram, M.B., Hall, K.W., Bertram, K.L., and Pettinga, J., 2013, Imaging Unknown Faults in Christchurch, New Zealand, after a M6.2 Earthquake, 75th EAGE Conference & Exhibition incorporating SPE EUROPEC 2013 London, UK, 10-13 June 2013, 1-5.
- Lay, V., Buske S., Lukács, A., Gorman, A.R., Bannister, S., and Schmitt, D.R., 2016, Advanced seismic imaging techniques characterize the Alpine Fault at Whataroa (New Zealand): *Journal of Geophysical Research (Solid Earth)*, **121**, 8792-8812, DOI: 10.1002/2016JB013534.
- Norris, R. J., A. F. Cooper, V. Toy, S. Read and L. Easterbrook, 2012, Three-dimensional structure of the Alpine Fault in the region around the Waiangi-taona and Whataroa Rivers, University of Otago, Department of Geology,
- Persaud, M., Villamor, P., Berryman, K. R., Ries, W., Cousins, J. Litchfield, N. and Alloway, B. V., 2016, The Kerepehi Fault, Hauraki Rift, North Island, New Zealand: active fault characterisation and hazard: *New Zealand Journal of Geology and Geophysics*, **59**, 117-135.
- Schofield, J. C., 1967, Sheet 3 Auckland. Geological Map of New Zealand 1:250 000. New Zealand Department of Scientific and Industrial Research, Wellington.
- Sutherland R., Townend J., Toy, V., and the DFDP2 Team, 2015, DFDP-2 completion report. GNS Science Report SR2015/50
- Townend, J., Eccles, J., Kellett, R., Buske, S., Constantinou, A., Schmitt, D., Bertram, M., Hall, K., Savage, M., Gorman, A., Kofman, R., Benson, A., Lay, V., Gulley, A., McNab, A., Lindsay, D., Hopp, C., Mann, C., Bodenbun, S.B., Kleine, F., Lepine, P., Bowman, H., Broderick, N., Capova, L., Lawton, D., 2016, Seismic Experiment Acquisition Report: GNS Science Report, 2016/36.
- Wright, K., Baldi, M., Van Dissen, V., Salinger, J., Dellow, G., Page, M., Power, W., King, D., and Lindsay, J., 2009, Natural hazards and their impacts: Auckland region. Prepared for the Auckland Regional Council. Auckland Regional Council Technical Publication 2009/2010.