Active-source seismic imaging of the Alpine Fault at Whataroa
(EQC project 14/676)

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Alpine Fault; Deep Fault Drilling Project; DFDP-2B; vertical seismic profiling; heterodyne distributed vibration sensing (hDVS)

Overview
The aim of this study was to acquire a high-resolution geophysical image of the central Alpine Fault, capitalising on the large amount of scientific effort focussed on the Whataroa River valley as part of the Deep Fault Drilling Project (DFDP). In particular, this study made use of an improved acquisition geometry made possible by borehole sensors installed in the DFDP-2B borehole, as well as arrays of three-component surface sensors, and a large number of highly repeatable vibroseis shot-points on multiple profiles.

Objectives
The original objectives of this experiment were to:

1. Acquire vertical seismic profiling data in the DFDP-2 borehole using a combination of downhole and surface receivers and repeated mini-vibe shots;
2. Process the data to obtain high-resolution images of fault structure in the vicinity of the borehole and extending to the surface; and
3. Compare the images with previously acquired active source imaging results to characterize the shallow crustal structure of the Alpine Fault.

The data required to address all three objectives were collected in January 2016 (following a modification to the experiment design and schedule, described below) and are the subject of ongoing analysis.

Modifications to original experiment design and schedule
After funding was awarded, a number of events resulted in the schedule, budget and objectives of this experiment requiring revision. Drilling of the DFDP-2 borehole took place in August–December 2014. Technical problems in mid-December led to the hole being abandoned before the Alpine Fault had been penetrated but with a c. 892 m optical fibre installed behind casing in the borehole for ongoing temperature and seismic monitoring, including this active-source experiment. The borehole is cased, cemented, and accessible to 400 m depth.

The original survey design was based around deploying a vertical seismic array (VSP string) in a cased borehole. Subsequent revisions of the DFDP-2 technical plan required for other logistical reasons meant that deploying a VSP string would not be possible, and plans were made to rely solely on the optical fibre and one or more permanently installed seismometers (plus surface sensors). However, in light of the drilling ending at a shallower depth than planned, it was possible to deploy a VSP string to 400 m depth.

With EQC's approval in May 2015, the data acquisition schedule was lengthened beyond the original term of the funding, and arrangements were made to bring to New Zealand several otherwise unavailable pieces of equipment:

1. Distributed vibration sensing interrogator, being provided by Schlumberger (UK) under the terms of a confidentiality agreement signed by Schlumberger and GNS Science;

2. An IVI EnviroVibe vibroseis unit, from the University of Calgary, which has a 9000 kg peak load and a 600 channel, 10 Hz ARAM acquisition system;

3. A Sercel high temperature slimwave VSP string and winch from the University of Alberta, to be shipped with the vibroseis;

4. 160 three-component and 40 one-component surface sensors and recorders on loan from the Geophysical Instrument Pool Potsdam to TU Freiburg.

Additional funding of €100,000 (NZ$151,000) was awarded by the German Science Foundation to project member Stefan Buske to meet the costs associated with TU Freiberg's work on this project. This funding included €10,000 ($15,000) for the shipping/insurance costs associated with the 200 surface sensors, plus travel costs for five TU Freiberg staff and graduate students. An internal funding proposal was submitted by John Townend that provided additional funding of $31,000. Don Lawton (Calgary) obtained funds from a Canadian source to cover the costs of vibroseis operator Malcolm Bertram. Jennifer Eccles (Auckland) applied for EQC funding that enabled some cost-sharing associated with shipping the vibroseis units.

Finally, arrangements were made for Richard Kellett, a marine geologist/geophysicist with VSP processing and interpretation experience, to contribute to the experiment design and data analysis under the auspices of GNS Science's internal development fund.

These modifications did not affect the project's fundamental goal of imaging the Alpine Fault.

Data collection and analysis

The field campaign was conducted in January 2016 and consisted of six components addressing the objectives of this project and a separate project (led by Stefan Buske) funded by the German Science Foundation. The table below summarises each component and identifies the equipment used to acquire the seismic data.

Part	Main Component	Project Description	Primary Equipment
1	Zero-offset VSP	VSP with a single source point at the wellhead. VSP tool was raised at 1 m intervals.	Vibroseis, hDVS fibre, University of Alberta VSP string
2	Offset VSP	Multi-Azimuth Walk-away VSP. Shot lines radiated from the wellhead to the S, SE, NW, N, and NE. All of the lines were repeated to obtain data at several levels of the VSP string. Shot point spacing was 10 m within 500 m of the well head then 20 m at far offsets out to 1 km.	Vibroseis, hDVS fibre, University of Alberta VSP string
3	3D Velocity	3D velocity model experiment. 160 3-component	Vibroseis, GIPP Cubes, University of

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	Model	and 40 vertical-component Cubes were deployed in a coarse grid throughout the valley to record shots from the multi-azimuth lines, as well as to record passive source earthquake and continuous noise data. The data generated have a multitude of azimuths and offsets suitable for 3D tomography.	Calgary 2D reflection system, University of Auckland seismometers, VUW borehole seismometer array
4	2D Reflection Survey	Crooked-line seismic reflection profiling. Two lines were laid with a cabled system at 10 m geophone spacing. Shot spacing was 10 m with some reduction to 20 m at far-offsets.	Vibroseis, University of Calgary 2D reflection system
5	3D Reflection Survey	Cube imaging. 160 Cubes (3C) from GIPP were deployed in dense patches with lines parallel to the trend of the Alpine Fault. The patches covered the width of the valley using available flat land. The patches were moved progressively up-stream along the valley and the shot points were repeated to provide full coverage.	Vibroseis, GIPP Cubes
6	Monitoring	Passive recording of earthquakes and ambient noise using sensors deployed overnight.	hDVS fibre, University of Alberta VSP string, GIPP Cubes, University of Auckland seismometers, VUW borehole seismometer array

The data collected were documented and archived at GNS Science as outlined in the GNS Science Report (Townend et al., 2018). Full details of the acquisition parameters, field schedule, and preliminary data processing are also provided in that report. Of note is that the experiment involved 11 graduate students who gained valuable skills in geophysical field practice and seismic acquisition, as well as the extensive health and safety considerations required to conduct this kind of fieldwork safely.

Analysis

Following the completion of the field campaign in late January 2016, progress was made on analysing several components of the dataset that had been collected. A preliminary analysis of the zero-offset VSP data has been made by Doug Schmitt and Alexis Constantinou and described in a peer-reviewed conference abstract (Constantinou et al., 2016). That work involves analysis of both the conventional VSP string recordings and Schlumberger's hDVS recordings. The 2D multichannel dataset has been analysed by the University of Calgary and preliminary results presented by Hall et al., 2017.

Vera Lay and Stefan Buske have coordinated analysis of the 3D reflection survey dataset, and this work is being incorporated in graduate student research projects (yet to be completed) at TU Freiburg.

An MSc thesis has been completed at Victoria University of Wellington by Andy McNab under the supervision of Martha Savage and John Townend. That results of that study have are being prepared for publication in the *New Zealand Journal of Geology and Geophysics.*

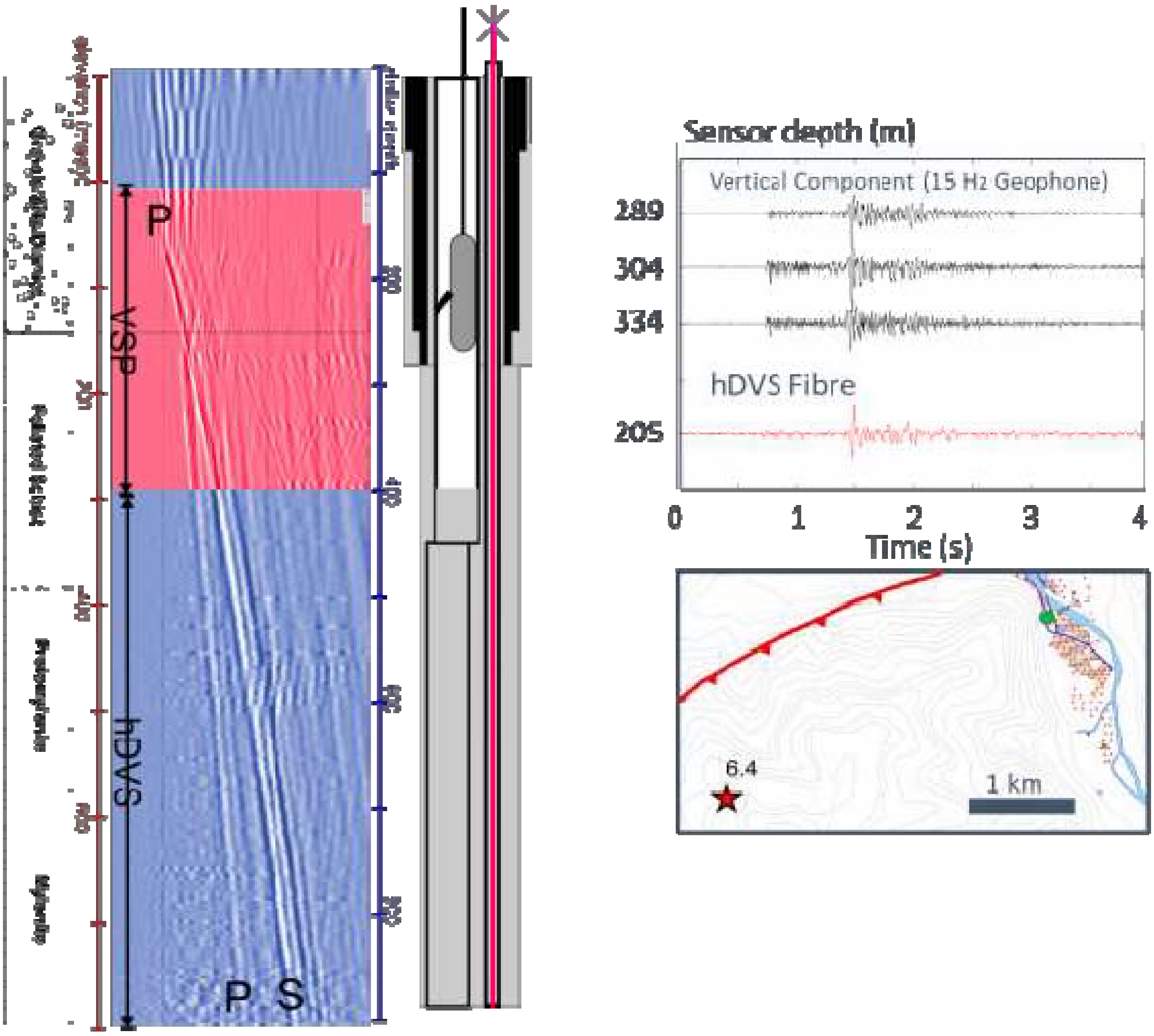
Finally, a preliminary analysis of the hDVS dataset has been conducted by Martha Savage, John Townend, and Alexis Constantinou, using both the ambient seismic field recordings and recordings of nearby earthquakes.

Additional work is planned on the dataset and it is expected that this will be prioritised and completed in 2019 once John Townend has stepped down from his current commitments as Head of the School of Geography, Environment and Earth Sciences at Victoria University of Wellington.

Conclusions and key findings

The project has yielded several preliminary results that are the subject of ongoing research:

1. First-arrival travel-time tomography has been applied to the VSP and surface-sensor recordings and improves upon the seismic velocity model obtained previously from 2D seismic profiling;
2. The three-component seismic data reveal glacial features in the near-surface (imaging separately in Andy McNab's MSc study) and some contamination from waves reflected from the steeply dipping valley flanks;
3. The optical fibre (hDVS) and conventional VSP data reveal transmitted and reflected P and S waves associated with the sediment/basement contact at 240 m depth;
4. The continuous hDVS and VSP recordings contain waves produced by nearby earthquakes, showing that optical measurements in DFDP-2B on a continuous basis can be used to obtain novel measurements that augment GeoNet's and local networks' observations.



(Left) Composite zero-offset VSP plot showing transmitted and reflected P and S waves recorded with the conventional VSP string (red) and the optical fibre (hDVS) system (blue). Also illustrated are the DFDP-2B borehole stratigraphy and borehole configuration. (Right) Conventional and optical recordings of a nearby earthquake; this recording was made overnight when the systems were left operating in continuous mode.

Future work

With the completion of the this project's field activities, the DFDP-2B borehole is available for the installation of permanent monitoring equipment. Discussions are underway with GeoNet to instrument the borehole with a downhole sensor and a short-period surface sensor, and to equip the DFDP-2 observatory with GeoNet's standard recording and telemetry equipment. This will provide a conventional seismological recording capability within ~1 km of the Alpine Fault trace (and 200–400 m of the fault at depth) that augments the optical fibre and optical monitoring equipment under development as part of a University of Auckland-led project funded by the Marsden Fund of the Royal Society Te Apārangi.

Links to publications/theses

Constantinou, A., Schmitt, D.R., Kofman, R., and 10 others (2016). Comparison of fiber-optic sensor and borehole seismometer VSP surveys in a scientific borehole: DFDP-2b, Alpine Fault, New Zealand. Society of Exploration Geophysicists, SEG Technical Program Expanded Abstracts 2016, p. 5608–5612.

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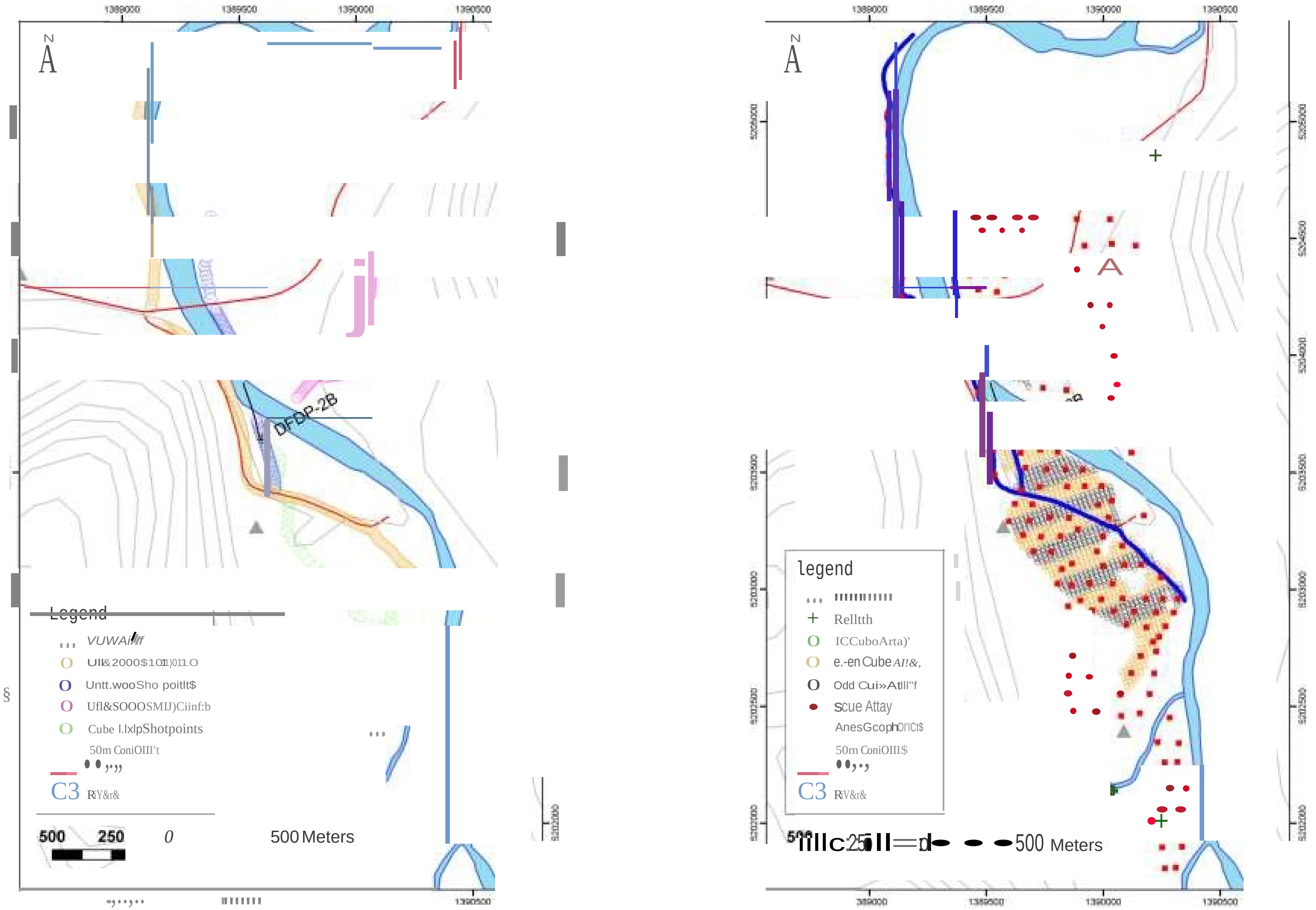
Lay, V., Bodenburg, S., Buske, S., and 10 others (2017). Imaging the Alpine Fault: preliminary results from a detailed 3D-VSP experiment at the DFDP-2 drill site in Whataroa, New Zealand. European Geophysical Union General Assembly Conference Abstracts, 19, p. 5121. http://adsabs.harvard.edu/abs/2017EGUGA..19.5121L.

McNab, A. (2017). Velocity structure of the Whataroa Valley using ambient noise tomography. Unpublished MSc thesis, Victoria University of Wellington, 114 p. http://researcharchive.vuw.ac.nz/handle/10063/6766.

Townend, J., Eccles, J., Kellett, R.L., and the DFDP Seismic Project Team (2018). Whataroa 2016 seismic experiment acquisition report. GNS Science report 2016/36. doi:10.21420/G2TK9T. [Summary details at http://doi.org/10.21420/G2TK9T; full 23 Mb file available electronically on request.]



Maps showing the final layout of seismic sources (left) and receivers (right).