Final Report to the Earthquake Commission on Project No. 08/546

Borehole seismometer monitoring of changing properties on Mt. Ruapehu Volcano

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June 2012

LAYMAN'S ABSTRACT

We installed borehole seismometers on Mt. Ruapehu volcano and examined seismic waveforms of earthquakes and explosions recorded on these and other GeoNet and portable seismometers. We developed and applied techniques to compare changes in seismic wave propagation on volcanoes to magma movements and to other techniques that measure stress changes on volcanoes. We determined baselines of seismic velocity values against which changes can be measured. We also found that on Ruapehu and other volcanoes, changes in anisotropy correlate to changes in stress indicators measured from other techniques such as GPS baseline lengths, focal mechanisms and the relative proportion of small versus large earthquakes (b-values).

Contents:

TECHNICAL ABSTRACT

On Mt. Ruapehu Volcano, previous studies suggested that changes in seismic anisotropy and attenuation occurred due to stress changes associated with magma emplacement. It was not clear, however, whether the changes would be large enough and close enough in time to predict future eruptions. A key to recognising subtle changes in geophysical properties is to determine background measurements during times of little change in the volcanic processes and to then use repeating seismic sources and a borehole seismometer.

We addressed three specific objectives:

1) To determine suitable repeating sources to use to measure changes in seismic properties over time, we installed a borehole seismometer, which was supplemented later by a second borehole seismometer funded by a Marsden grant. We also installed a 16-station portable network to complement the permanent GeoNet network around Mt. Ruapehu during the year 2008. We left a 5-station portable network running above a cluster of earthquakes in the Waiouru area so that we could use the highly correlated events among them as sources of repeating energy. Finally, we carried out a series of explosions in Lake Moawhango, which is near to Mt. Ruapehu and also to the Waiouru earthquake swarm, to provide a benchmark against which future changes in seismic properties can be measured.

2) We developed a set of automatic shear wave splitting computer programs to quickly measure anisotropy on Mt. Ruapehu and other volcanoes. The shear wave splitting parameters of fast polarisation give the orientation of the anisotropic medium, and the delay time is a product of the strength of the anisotropy and the length of the path in the anisotropic medium. Fast polarisations are expected to be parallel to the maximum principal stress direction if the anisotropy is caused by fluid-filled, stress-aligned cracks. Other possibilities are that faulting will cause minerals to align with the fault planes, or that polarisations will align with anisotropic minerals in rocks such as schists. We developed a code to perform a two-dimensional tomographic inversion for shear wave splitting delay time and spatial averages of fast directions. The codes were applied to the results of the portable deployment to serve as a benchmark against with other changes could be measured. We found that Mt. Ruapehu is more complicated than previously thought, with some regions being controlled by nearby faults and others by stress.

3) We compared the shear wave splitting measurements to areas where other types of stress indicators had been suggested to change, and we used the Coulomb 3.0 stress modelling code to try to determine if stress changes could explain all the phenomena. At Ruapehu changes in b-values for earthquakes in the Erua region occurred at the same time as changes in anisotropy for paths these earthquakes and permanent station FWVZ. At Mt. Asama volcano in Japan anisotropy changes correlated with changes in strain as measured by GPS baselines and at Souffriere Hills volcano in Montserrat, anisotropy changes correlated with changes in focal mechanisms. At both these latter volcanoes, calculated stress from inferred dykes could explain the general orientation of the anisotropy. At Okmok volcano in Alaska, changes in splitting were considered to be caused by changes in earthquake location; repeating multiplets yielded near constant splitting measurements, and stopped repeating after the eruption began.

A. Relation to other projects

This was the first of a series of two proposals funded by the Earthquake Commission and one by the Marsden Fund to use repeating seismic sources and borehole seismometers to monitor changes in seismic anisotropy and other seismic properties on Mt. Ruapehu Volcano. Project No. 08/546, which is the subject of this report, funded a single borehole installation at the Chateau observatory on the northwestern side of Ruapehu volcano. It funded us to keep a seismic network running to locate earthquakes near Waiouru, and provided some of the money needed to detonate explosions in Lake Moawhango. The earthquakes and explosions act as repeating sources to determine if seismic velocity has changed across the volcano, which could be related to magma movement. Martha Savage was also funded along with co-PIs Bill Fry and Art Jolly by a later EQC project, BI 10/603 “Time-varying seismic velocity in New Zealand’s volcanic regions: Comparisons between shear wave splitting and surface wave noise correlations”, to compare these measurements on past deployments.

Although this particular proposal was meant to last only two years, in 2010 we were funded by the Marsden Fund to install a second borehole seismometer and to carry out a three-year project studying Ruapehu and six other volcanoes around the world. The purpose of the Marsden project is to study magma movement and time varying stress and seismic properties. We requested and were granted an extension on this EQC project to allow us to wait to carry out the explosions until after both boreholes were in place.

Those boreholes are now both in place and in February and March of this year (2012) we carried out a first set of six explosions. The variations that we observe on these explosions will help to determine the variability on a single day, when conditions on the volcano were constant and the only changes were the small earth tidal effects, serving as a baseline to measure future explosions. Further explanation of the explosion study is presented in the following pages.

The Marsden Fund supported a second borehole, provided funds to keep the recorders operating, and helped to support the explosion sources. Additionally, Victoria University provided funds for a deployment in 2008 to record the static anisotropy field around the mountain.

B. Fulfilment of Objectives:

The objectives of this proposal as outlined in the full proposal were as follows:

On Mt. Ruapehu Volcano, previous studies have suggested that changes in seismic anisotropy and attenuation occurred due to stress changes associated with magma emplacement. It is not clear, however, whether the changes will be large enough and close enough in time to predict future eruptions. A key to recognising subtle changes in geophysical properties will be to use repeating seismic sources, and a borehole seismometer. The result will provide an understanding of the background stress changes around volcanoes between eruptions, and also the stress changes leading up to eruptions. These observations will thus provide the data that may eventually lead to prediction tools.

Three specific objectives and sub-objectives were proposed:

1) Determine suitable repeating sources that can be used to measure changes in seismic properties over time.

a) Install a borehole seismometer:
b) Carry out waveform cross-correlation to find repeating events.
c) Install a 3-station portable network over a set of repeating earthquakes in Waiouru
d) Use controlled sources in Lake Moawhango to provide a benchmark against which future small changes in seismic properties can be measured.

2) Determine stress indicators and their variation as a function of time. We planned to finish development of an automatic shear wave splitting program to quickly measure anisotropy on Mt. Ruapehu.

3) Modelling and comparison of changes in stress-related parameters.

We pointed out in the proposal that the requested grant money would mostly be used for the borehole seismometerand its installation, and that we would use cost-sharing from other programmes to help pay salaries.

We are happy to report that all the objectives have been met. The cost sharing eventuated with both the Marsden proposal, and a VUW PhD scholarship for student Jessica Johnson, and another scholarship for Adrian Shelley.

Addressing the objectives one by one, the following have been carried out.

1a) Borehole seismometer is installed (Shelley report)
1b) Waveform cross-correlation (Johnson PhD thesis, chapter 5) (see also Keats et al., 2011, discussed in more detail in the report for Project BI 10/603)
1c) Install 3-station portable network around Lake Moawhango (a 16-station network was installed in 2008 and 5 stations were left operating after the others were removed at the end of 2008; see the Shelley report; used also in Johnson thesis, chapters 4 and 5, which were also been published in JGR and JVGR, discussed in more detail in the report for Project BI 10/603.)
1d) Use controlled sources in Lake Moawhango (Shelley report).

2) Stress indicators: An early version of the method we developed for automatic determination of shear wave splitting was written in Andreas Wessel's PhD thesis and the final report for EQC Project 06/520. During this project we published a paper including further developments and used it to determine changes in anisotropy at

Asama volcano and to confirm previous changes measured at Mt. Ruapehu (Savage et al., 2010a; Savage et al., 2010b).

3) Modelling and comparison of changes in stress-related parameters: [Johnson PhD thesis, chapters 4 and 6, reprinted from Johnson et al., 2011 JGR and 2010 JGR respectively, included some modelling, but no strong changes were observed at Ruapehu. Savage et al., (2010a) carried out modelling to compare to changes in stress parameters at Mt. Asama volcano in Japan. Keats et al. (2011) found changes in b-values with changes in anisotropy for earthquakes in the Erua region (this is discussed more fully in the report for project BI10/603). Roman et al. (2010) found changes in anisotropy correlated with changes in earthquake focal mechanisms at Souffriere Hills volcano in Monserrat. Unglert et al. (2011) found changes in anisotropy correlated loosely with changes in ash eruptions at Aso volcano in Japan]

C. Publications relating directly to this project:

Refereed Journal Articles:

Johnson JH, Savage MK, Townend J, Distinguishing between Stress-induced and Structural Anisotropy at Mount Ruapehu Volcano, New Zealand, *J. Geophys. Res*., Vol. 116, B12303, 18 pp., doi: 10.1029/2011JB008308 2011. This was also chapter 4 of Jessica Johnson's PhD thesis and so is not included in this report to avoid duplication.

Johnson, JH, Prejean S, Savage MK, Townend J Anisotropy, repeating earthquakes, and seismicity associated with the 2008 eruption of Okmok volcano, Alaska, J. Geophys. Res., 115, B00B04, doi:10.1029/2009JB006991, 2010. This was also chapter 6 of Jessica Johnson's PhD thesis and so is not included in this report to avoid duplication.

Savage MK, Wessel A, Teanby NA, Hurst AW, Automatic measurement of shear wave splitting and applications to time varying anisotropy at Mount Ruapehu volcano, New Zealand, *J. Geophys. Res*., 115, B12321, doi:10.1029/2010JB007722, 2010a. (An early version of this method was written in Andreas Wessel's PhD thesis and the final report for EQC Project 06/520). The last submitted version of this article is included as an appendix; copyright issues preclude inclusion of the final article.

Savage MK, Ohminato T, Aoki Y, Tsuji H, Greve S, Stress magnitude and its temporal variation at Mt. Asama Volcano, Japan, from seismic anisotropy and GPS, *Earth and Planetary Science Letters*, vol. 290, Issues 3-4, doi: 10.1016/j.epsl.2009.12.037, pp. 403-414, 2010b. The last submitted version of this article is included as an appendix; copyright issues preclude inclusion of the final article.

PhD thesis:

Johnson, J. Discriminating between spatial and temporal variations in seismic anisotropy at active volcanoes, PhD Thesis, Victoria University of Wellington, 326 pp., submitted 5 May 2011 (now Postdoctoral Fellow at University of Hawaii, Hilo).

Publications discussed in the related project BI 10/603**:**

Johnson JH, Savage MK, Tracking volcanic and geothermal activity with shear wave splitting tomography, Journal of Volcanology and Geothermal Research, 223-224, 1-10, doi:10.1016/j.jvolgeores.2012.01.017, 2012. (An early version of this paper appears as chapter 5 of Johnson's PhD thesis).

Keats BS, Johnson JH, Savage MK, The Erua earthquake cluster and seismic anisotropy in the Ruapehu region, New Zealand, *Geophys. Res. Lett.*, Vol. 38, L16315, 6 pp., doi:10.1029/2011GL049014, 2011. (This paper appears as Appendix G in Jess Johnson's thesis).

Honours thesis:

Honours student project: Brook Keats: The Erua earthquake cluster and seismic anisotropy in the Ruapehu region, 2010, 60 pp. (presently Petroleum Geoscience Technician, Geological Resources Group, GNS Science.)

Publications project on other volcanoes that used the MFAST method developed in this project:

Unglert K, Savage MK, Fournier N, Ohkura, T and Abe Y, Shear-wave splitting, v_P/v_S and GPS during a time of enhanced activity at Aso caldera, Kyushu, *J. Geophys. Res.*, 116, B11203, doi:10.1029/2011JB008520.

Roman DC, Savage MK, Arnold R, Latchman JL, De Angelis S, Analysis and forward modeling of seismic anisotropy during the ongoing eruption of the Soufrière Hills Volcano, Montserrat, 1996–2007, *J. Geophys. Res*. 116, B03201, doi:10.1029/2010JB007667, 2011.

Postgraduate Diploma of Science in Geophysics project: Sofia Kufner: Temporal variation of seismic anisotropy at Okmok Volcano (Alaska) from analysis of regional earthquakes, 2010, 131 pp. (presently MSc student at University of Bremen, Germany)

Report on the Mount Ruapehu seismological survey at Lake Moawhango

Adrian Shelley

June 27, 2012

1 Report

This report concerns the EQC grant awarded to Professor Martha Savage to investigate time-varying hazard and risk assessment at Mt. Ruapehu. Recent studies made at Mt. Ruapehu and other volcanoes indicate a relationship between seismic anisotropy and attenuation and stress changes accompanying volcanic activity. This relationship could conceivably be used as part of the array of tools at our disposal to forecast volcanic eruptions and mitigate the associated risk to life and property. The objective of the EQC grant is to gather data to provide a deeper understanding of volcanic stress fields and their effect on anisotropy with the use of borehole seismometers and a repeating active seismic experiment.

At the time of writing, two borehole sensors, designations COVZ and WNVZ, have been installed and integrated into GeoNet (http://www.geonet.org.nz/), and the first of the seismic experiment at Lake Moawhango has been completed.

2 Lake Moawhango experiment

The initial stage of the active source experiment began on the 12^{th} of February, 2012. The experiment involved producing explosions at the bed of Lake Moawhango, an artificial lake situated roughly 20km South East of the summit of Mount Ruapehu in the Waiouru NZDF training area. The explosives were set with the collaboration of the New Zealand Defence Force and Creek Grange explosives. The experiment was well positioned with regards to borehole stations COVZ and WNVZ, as they lie both on the near and far side of Mount Ruapehu, potentially giving well recorded data that samples different portions of the volcanic stress field. In addition to the two borehole stations and the rest of GeoNet, there currently exists a temporary deployment of 5 short-period seismometers, designated as TADAR (Temporary Anisotropy Deployment at Ruapehu) situated around Waiouru to the South East of Mt. Ruapehu, further to which two short-period instruments were deployed just for the experiment in Kariori Forest (FDBT) and in National Park (NPFS), again to provide coverage on both the near and far side of the volcano.

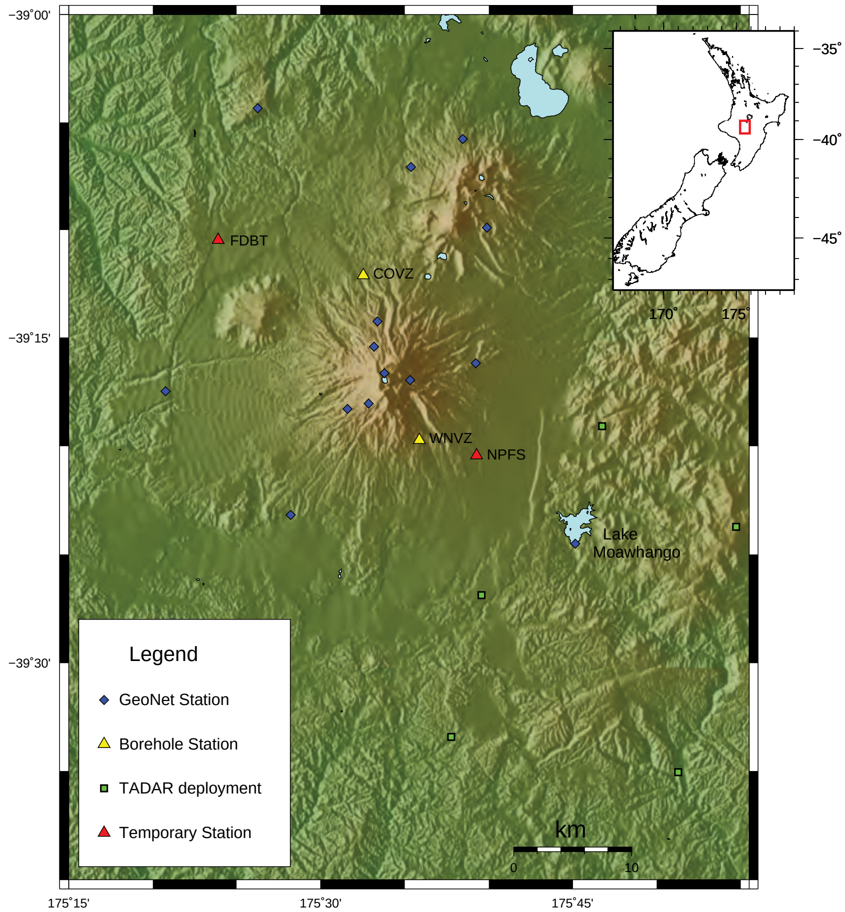


Figure 1: The area surrounding Mt. Ruapehu showing the locations of both borehole seismometers and the two temporary seismometers alongside the GeoNet stations and the TADAR deployment.

The experiment itself comprises producing repeated seismic sources over a timescale that encompasses changes in Mt. Ruapehu's volcanic stress. Initially, we set off several explosions over the course of the day, with further explosions being planned in the future in six month intervals. The initial explosions (of which six where planned) were timed to sample one period of the solid earth tide. Solid earth tidal loading typically contributes less than 0.1-1% of tectonic stress (De Fazio and Alba, 1973 [1],Métivier *et al.* 2009 [2]). However, lunar and solar tides have been attributed to observed variations in p wave velocity and attenuation, with amplitudes of 0.3% and 4% respectively (Yamamura *et al.*, 2003 [3]). Obtaining the records throughout the diurnal cycle provides the opportunity to see whether the experiment can resolve any changes in seismic velocity and attenuation due to the solid earth tide, and if so inform the decision over when during the tidal cycle to perform subsequent explosions. It also provides a set of measurements that will allow us to determine the uncertainties due to variations in location and source, by contrasting them with variations where location and source are constrained.

Figure 2: Gravity measurements and synthetic tide calculations over the course of the experiment showing the variation in gravitational acceleration.

In total, five explosions were set off during the initial stage of the experiment, each consisting of 100 kg of ammonium nitrate fuel oil (ANFO) at a depth of roughly 30m. Due to a technical failure, one scheduled barrel of ANFO failed to explode. This barrel was left on the lake bed until it was able to be safely detonated on the 7th of March, however the subsequent explosion was not recorded on the temporary stations or the on-site accelerometer that were initially used. The explosions were detonated to the following schedule (note that shot 6 did not have the same strict detonation procedure, so the timing may be subject to a larger margin of error):

Designation	Date	UTC Time	Location
Shot 1	2012/02/12	22:28:00	E1837632 N5636243
Shot 2	2012/02/13	03:14:00	E1837632 N5636243
Shot 3	2012/02/13	06:34:00	E1837632 N5636243
Shot 4	2012/02/13	13:04:00	E1837632 N5636253
Shot 5	2012/02/13	17:10:00	E1837632 N5636253
Shot 6	2012/03/07	23:56:33.15	Exact location unknown.

Energy from the explosions was far-reaching across the North Island, with a discernible signal reaching almost as far south as Wellington (see figure 3). Figure 4 shows a more detailed view of the offset moveout of the stations located around Ruapehu. Of the two temporary stations, NPFS was placed within the town of National Park, where much of the top surface layer is poorly consolidated fill on top of which the buildings are built. This combined with local traffic gave a very low signal to noise ratio at that station (see figure 5).

The signal that was produced showed the source was highly repeatable. Figure 6 shows the first 5 shots as recorded from GeoNet station MOVZ, which is the closest station to the source, being situated on the dam at Lake Moawhango. Shot 6, which occurred 23 days after the first shot, shows a noticeable decrease in acceleration amplitude across the stations that recorded it, as well as a marked change in waveform (see figure 6). Although it remains to be seen, the most likely reason for this is that the explosives were located at the bottom of the lake during this interval and will have been penetrated with moisture to some degree, reducing the efficacy of the explosives. Moreover, we are unable to say with any certainty what the location of shot 6 was, since the explosives almost certainly moved from the position they were lowered into the lake at. The shot recordings at the two borehole seismometers, WNVZ and COVZ are shown in figures 8 and 9.

In addition to the network of seismometers, we also placed an accelerometer < 50m from the shot explosion. Figure 7 shows the data recorded by the accelerometer for the first five shots. Here we see similar acceleration amplitudes and signal durations for each shot, however the waveform is less correlated than is evident in data from MOVZ and other seismometers. The accelerometer was situated on the lake shore near the area where the detonation charge was set. The detonation charge is a small electronically triggered explosion that provides the energy to detonate the submerged ANFO. This energy is transmitted through detonation cord, essentially a fuse consisting of a flexible plastic cord filled with pentaerythritol tetranitrate, which is itself an explosive (NB. the speed at which detonation chord detonates is relatively constant). These two sources, the detonation charge and chord, could affect the accelerometer record due to it's proximity. Closer examination of the detonation charge location will be made to investigate this.

Further data was recorded with three geophones configured in an array radial to the location of the explosions, spaced 100 m apart at a distance of 100 m. This data can be used to provide a constraint for the shot timings, a necessary component for accurate seismic velocity measurements.

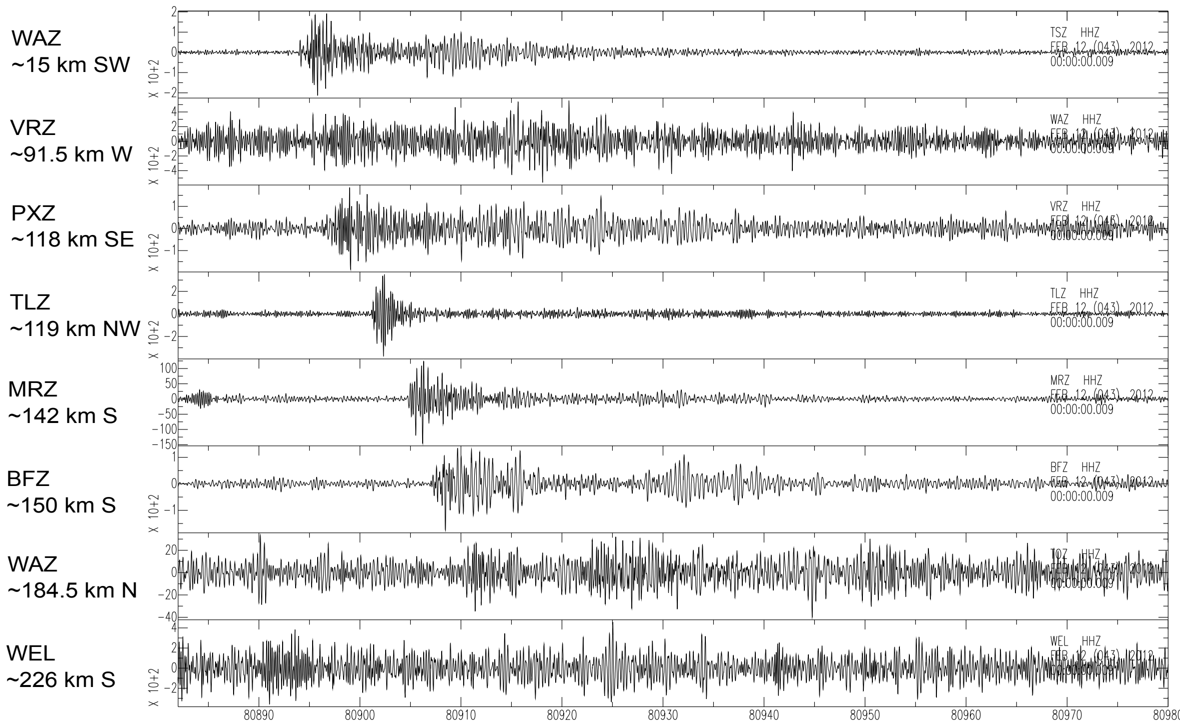


Figure 3: Seismographs showing vertical acceleration caused by shot 1 across GeoNet stations in the North Island (see ttp://www.geonet.org.nz/resources/network/netmap.html for detailed locations) and their approximate distances from Lake Moawhango. The time series have been put through a 2-10 Hz band pass filter. For reference, station WEL is located in Wellington City.

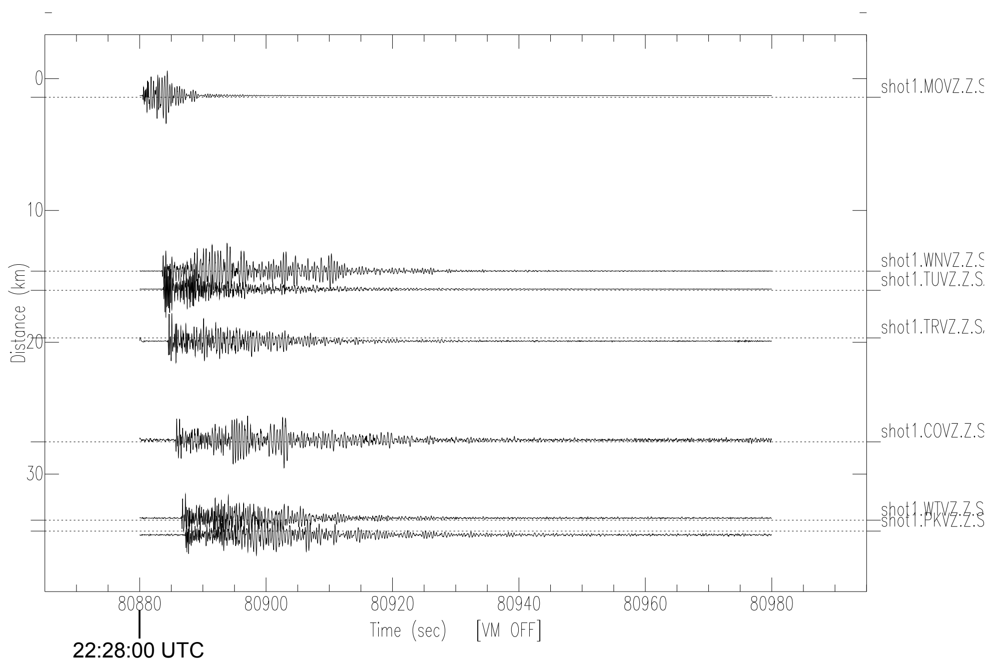


Figure 4: Seismographs showing vertical acceleration caused by shot 1 across GeoNet stations local to the Ruapehu vicinity, plotted relative to their distance to the Lake Moawhango blasts.

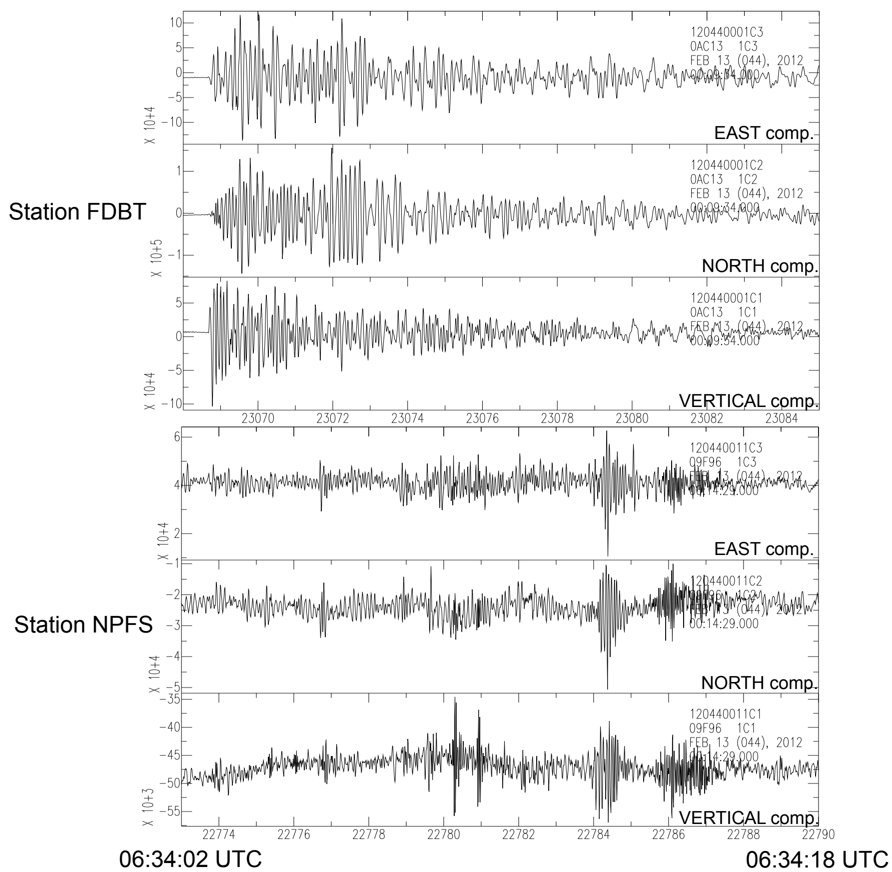


Figure 5: Shot 3 recorded on the two temporary stations FDBT and NPFS. The low SNR of station NPFS can be seen.

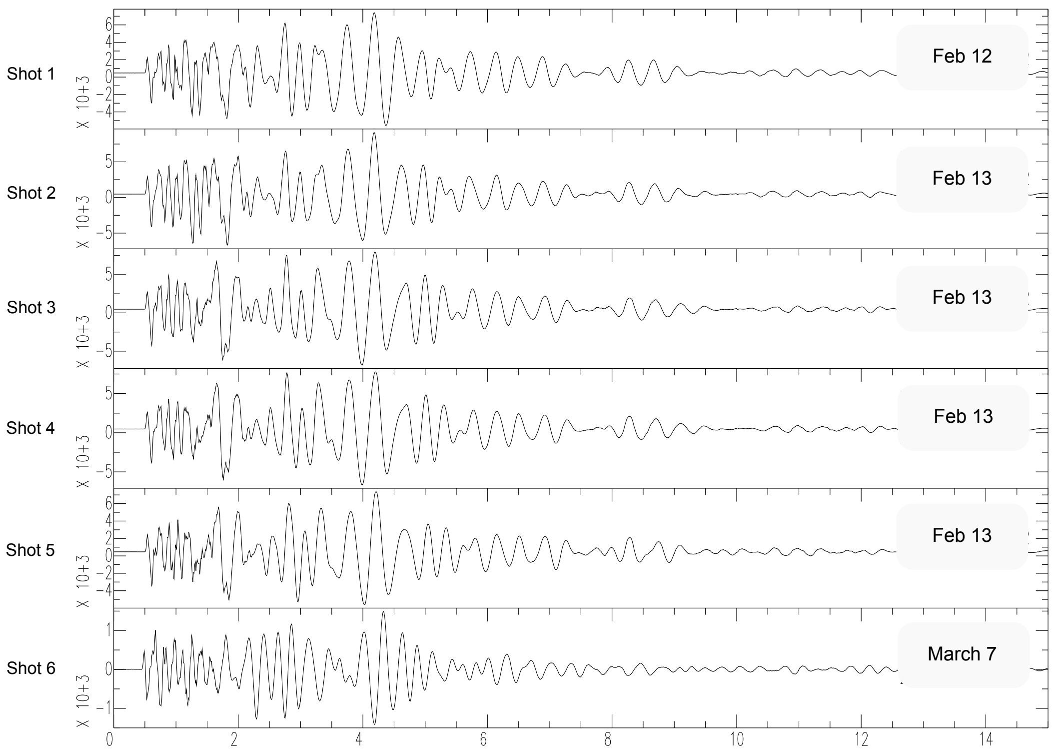


Figure 6: Vertical acceleration component seismograms from GeoNet station MOVZ showing all 6 shots. The first five shots where all taken within 24 hours of one another. Shot 6 was taken almost a month later. Amplitudes for shot 1-5 are consistent with one another, however the amplitudes reached in shot 6 are about 20% of the others. Dates are for shot timings in UTC.

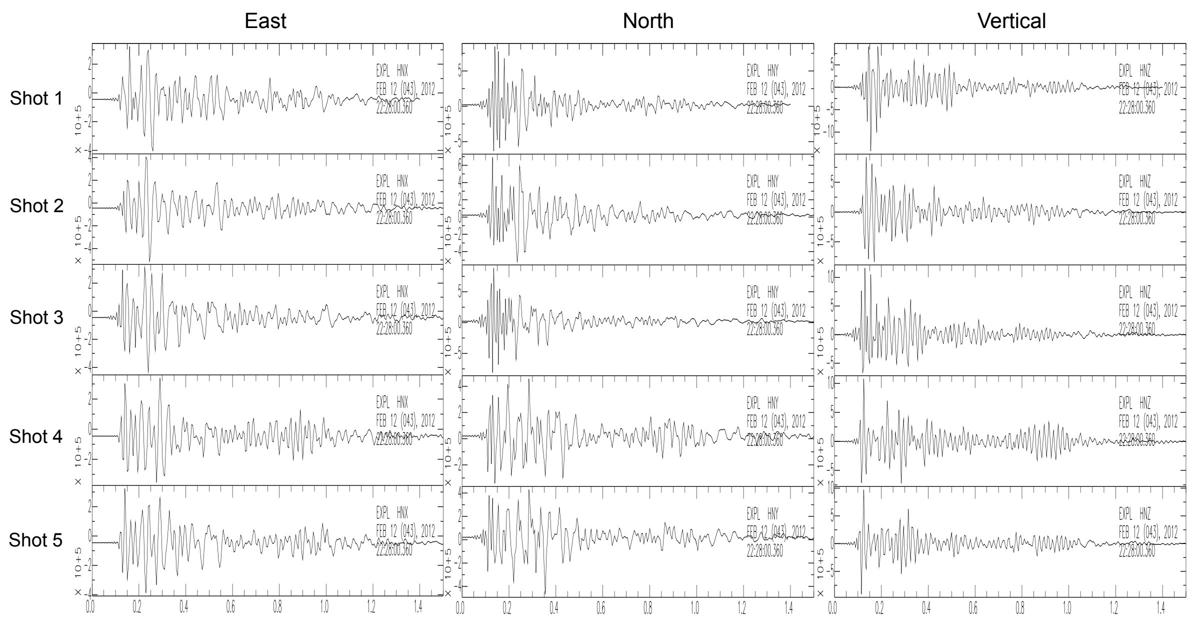


Figure 7: Strong motion acceleration records from the on-site accelerometer for the first 5 shots. The accelerometer was located close to the point at which the explosives were detonated. The waveforms show less correlation than can be seen on more distant seismometers, possibly due to the accelerometer's proximity to the detonation charges.

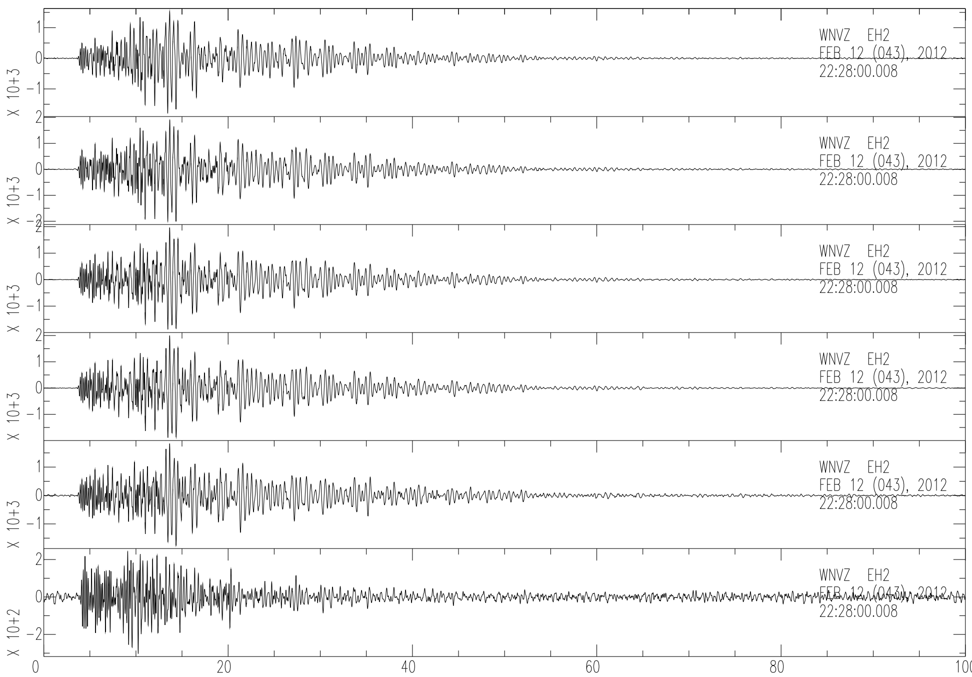


Figure 8: Vertical acceleration component seismograms from borehole station WNVZ showing all 6 shots, filtered with a band pass of 1-10Hz. Shots are ordered 1-6 from top to bottom, similarly to figure 6.

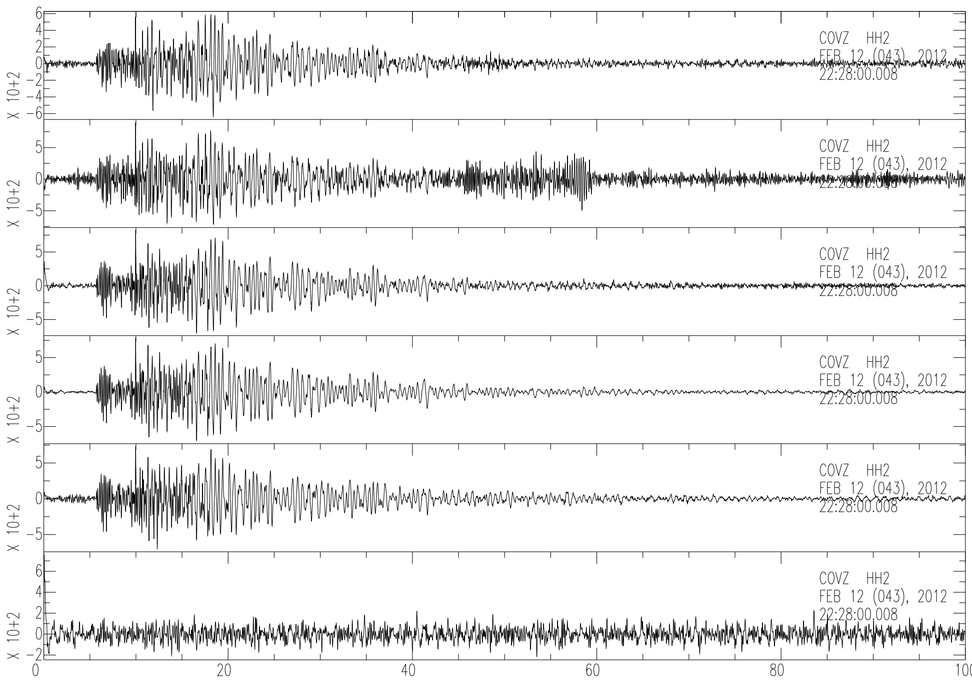
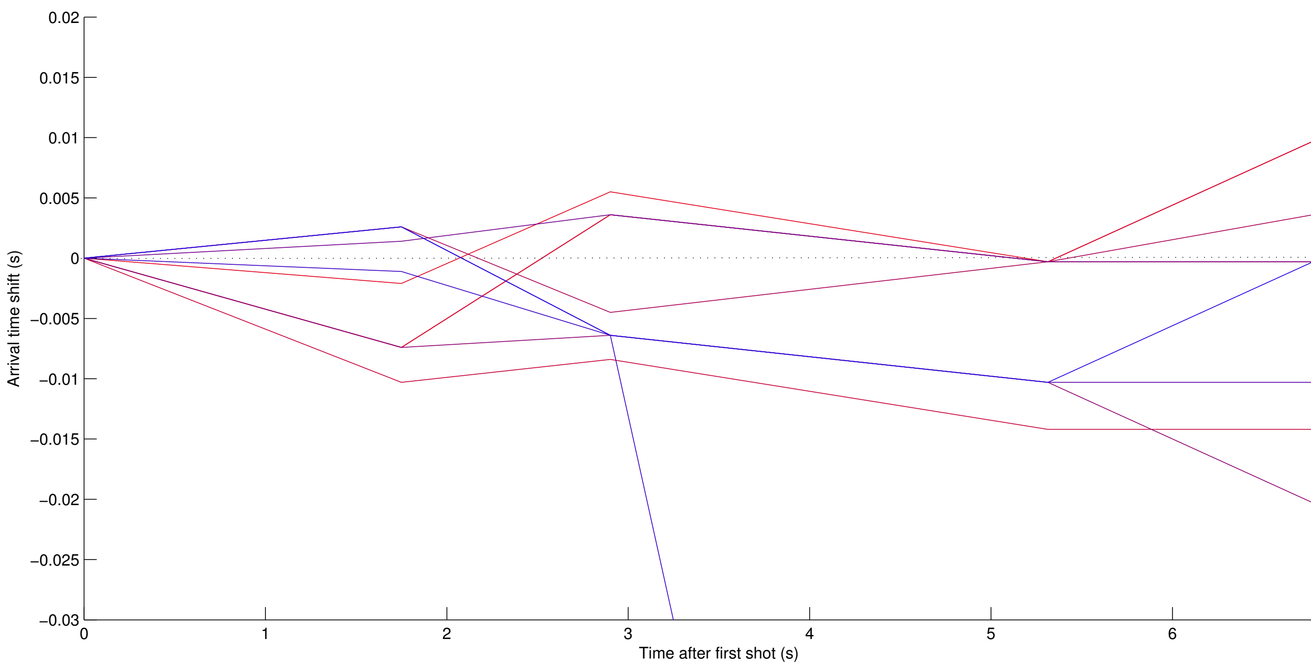


Figure 9: Similarly to the last figure, this shows vertical acceleration component seismograms from borehole station WNVZ showing each of the shots. Note that COVZ is further from the source than WNVZ, and the final shot has attenuated to below the level of noise at the station.


0.02
0.015
0.01
0.005
0
−0.005
−0.01
−0.015
−0.02
−0.025
−0.03
Arrival time shift (s)
0
1
2
3
4
5
6
Time after first shot (s)

3 Future Work

This experiment is continuing with the support of the Marsden fund. In it, we will do the following:

- Continuation of the experiment, with the next explosion scheduled for mid-late 2012.
- Finding accurate seismic velocities with the data collected so far.

4 Acknowledgements

Acknowledgement goes to the New Zealand Defence Force, Creek Grange explosives, Genesis Energy, who own the dam at Lake Moawhango, New Zealand Fish and Game, the Department of Conservation and the Horizons Council for providing permissions at the lake. Also acknowledged are Mark Henderson (GNS), Adrian Benson and Katrina Jacobs (Victoria University Wellington) for their help during the experiment.

References

[1] T. L. De Fazio and J. Alba. Solid earth tide and observed change in the in situ seismic velocity. *J. Geophys. Res.*, 1973.

[2] O. de Viron C. P. Conrad S. Renault M. Diament Métivier, L. and G. Patau. Evidence of earthquake triggering by the solid earth tides. *EPSL*, 2009.

[3] O. Sano H. Utada Y. Takei S. Nakao Yamamura, K. and Y. Fukao. Long-term observation of in situ seismic velocity and attenuation. *J. Geophys. Res.*, 2003.