

Project BIE 08/551
Geophysical characterisation of the Alpine Fault within the Haast Valley



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Technical Abstract

The subsurface orientation of the Alpine Fault is poorly constrained due to low seismicity, lack of direct geological observations, and the low resolution of past geophysical imaging experiments. This is particularly so in the southern section of the Alpine Fault, near Haast, where early work suggested that the fault may have a shallow dip. Two seismic lines were acquired in regions of relatively easy access along the Haast and Turnbull Rivers in late January 2009. The explosive data were recorded with a CMP spacing of 5 m and a nominal fold of 18. Far offsets as high as 720 m facilitated velocity analysis in the subsurface. A co-incident gravity survey was carried out to constrain the density properties and lithological contrasts interpreted in the seismic data. Interpretations of the resulting seismic sections identify the glacially-eroded base of the ancient valley and coastal plain that has now been filled with interbedded glacial till and fine-grained sediments. Offset of strata across the Alpine Fault is imaged and suggests that the Alpine Fault dips steeply to the southeast to depths of greater than 800 m, contrary to earlier suggestions that it would dip at a shallow angle. Uplift estimated from the offset of the eroded base of the valley across the fault on the Haast line corresponds to earlier published rates of 5.9 mm/a. Interpretations would be improved by networks of orthogonal seismic lines that could better constrain the 3D geometry of the ancient glacial valley in a location where dextral strike-slip motion the Alpine Fault, previously estimated at 23.1 ± 0.8 mm/a rapidly changes the downstream shape of the valley.

Abstract Suitable for Laypersons

The subsurface geometry of the Alpine Fault, the major boundary between the Pacific and Australian Plates on the South Island of New Zealand is enigmatic due to the scarce amount of information that we have from the subsurface. This is particularly so in the southern section of the Alpine Fault, near Haast, where we know the fault is capable of very large earthquakes – but have never seen one happen. Geological and geophysical techniques can be used to improve our knowledge of such a fault and how it will rupture in the future. Two seismic lines were acquired in regions of relatively easy access along the Haast and Turnbull Rivers in late January 2009. These lines were acquired by detonating small explosions in holes that were ~1.2 m deep and then recording the resulting echoes using sensitive microphones deployed on the surface. The resulting images are analogous to ultrasound images used in medicine except that the scales in question are 100's of metres rather than centimeters. Interpretations of the seismic sections identify the base of the ancient glacially-eroded valley and coastal plain that have now been filled in with as much as 800 m of sediments carried down the valley by the glaciers and rivers. The data also identify sedimentary rock layers (strata) that are broken by the Alpine Fault in the subsurface. Even though there are no reflections from the Alpine Fault itself, the offset strata enable the positioning of the fault at depth. This suggests that the fault is steeply dipping to the southeast. Quantitative measurements of the offset in strata and the erosional base of the old valley can also be used to estimate the uplift rate on the fault. This is seen to agree with earlier work, which set the rate at 5.9 mm per year. Interpretations would be improved by the addition of other seismic lines to better constrain the 3D geometry of the ancient glacial valley in a location where strike-slip motion of 23.1 ± 0.8 mm per year on the Alpine Fault rapidly changes the downstream shape of the valley.

Frontispiece: *The view southeast from the northwest end of the Haast Highway transect showing the distinctive U-shaped Haast Valley in the background.*

INTRODUCTION

The Alpine Fault, running for >400 km along the west side of the South Island of New Zealand, exhibits dextral strike-slip motion estimated at 23.1 ± 0.8 mm/a (Sutherland et al. 2006). It also accommodates ongoing uplift in the Southern Alps on the hanging wall of the fault with rates in the southern sector estimated at 5.9 mm/yr (Bull & Cooper 1986). For much of its length, scarps of earlier Alpine Fault ruptures are readily identifiable, even though there have been no ruptures since the arrival of Europeans in New Zealand (Norris 2001). In the southern sector of the fault, previous paleoseismic work has characterised extensive fault scarps across the valleys of the Haast, Okuru and Turnbull rivers. However, these studies do not provide any direct evidence for the structure of the fault in the subsurface – a factor that is important in assessing earthquake hazard along the Pacific-Australian plate boundary here.

Early work (e.g., Hatherton & Hunt 1968), relying on poorly-constrained gravity and wide-angle seismic refraction interpretations, led to the proposal of a very shallowly-dipping plate boundary in this region (e.g., Allis 1986). Assuming that this is the case, then the geometry of such a low-angle dip-slip reverse fault needs to be constrained in order to evaluate the magnitude, position and size of future surface ruptures of the Alpine Fault in this area. That said, the low-angle geometry of the Alpine Fault here is not universally accepted (Norris & Cooper 2000). The shallow-dipping model also contrasts with more recent work in the central and northern portions of the Alpine Fault that support a steeply dipping fault in those regions (e.g., Stern et al. 2001; Scherwath et al. 2003; van Avendonk et al. 2004).

In January 2009, two seismic reflection profiles and associated gravity surveys were collected along the coastal plain of southern Westland adjacent to the Haast and Turnbull River valleys to provide higher-resolution images of the Alpine Fault at depth. The preliminary results of this work are presented here. The two seismic transects (3.3 km for the Haast line and 2.5 km for the Turnbull line) are orientated perpendicular to the Alpine Fault (Figure 1). They extend inland as far as possible (*i.e.*, until limited by the extreme topography of the Southern Alps) in order to maximise the coverage of the hanging wall. Due to the rugged topography and temperate rainforest vegetation of the Southern Alps and West Coast of the South Island, suitable locations for collecting seismic reflection and detailed gravity data across the Alpine Fault are rare. The combination of gravity and seismic data will enable the development of a subsurface model that provide information to characterise the type of fault motion that will occur on the Alpine Fault during a future earthquake.

This report details the fieldwork that was undertaken in the Haast area from 19 – 29 January 2009 and presents the preliminary results of this work.

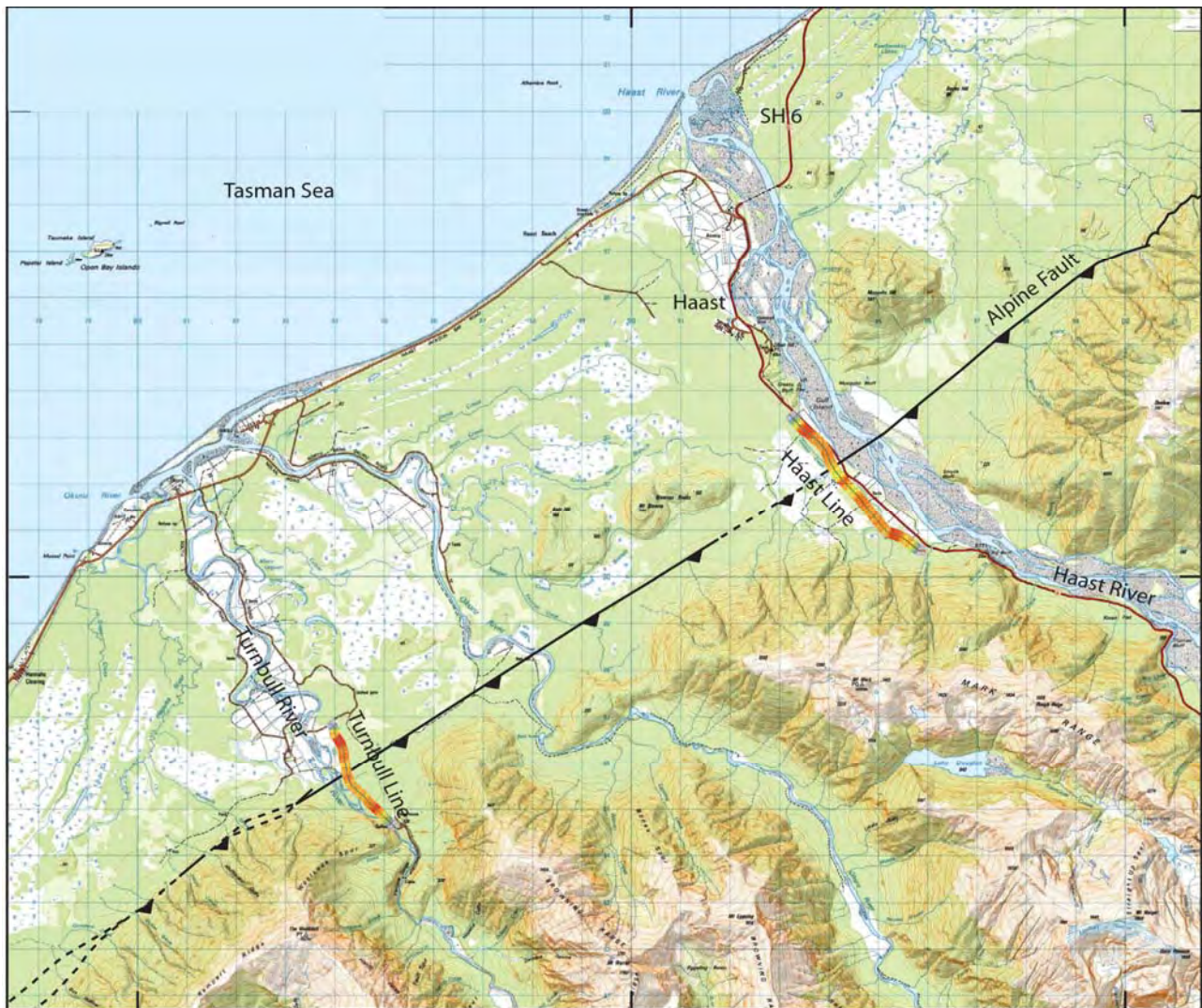


Figure 1. Locations of Haast and Turnbull seismic profiles overlain on a topography map of southern Westland. The trace of the Alpine Fault as mapped by Trevor Wright, Richard Norris and Alan Cooper (Norris 2001) is shown.

METHOD

Seismic Data Acquisition

The primary logistic consideration for this survey – located in boggy coastal plains in a rainforest environment – was access. Access to the two transects was facilitated by State Highway 6, which runs along the left bank of the Haast River, and Turnbull Road, which runs inland to a small hydro-electric power station in the Turnbull Valley. Local land owners (see acknowledgements) were extremely helpful.

Existing geological models suggest that the Quaternary sedimentary deposits northwest of the Alpine Fault should have a thickness of up to a km or more (Hatherton & Hunt 1968). Although no wells have been drilled deep into the sediments at this location, the seismic lines will be correlated to outcrops of basement rock in order to facilitate their geological interpretation. Both of the proposed lines run across the surface rupture trace of the Alpine Fault, which has a last dated movement of AD 1717 (Norris 2001).

The field experiment ran from 19 – 29 January. The first four days involved preparation, including GPS surveying and drilling and loading of shot holes. The last seven days involved a larger field party for seismic acquisition. We were very fortuitous with the weather: no rain delays occurred. However, the West Coast sandflies were out in force.

Seismic Recording Equipment – Single 40-Hz geophones (Fig. 2 left) were deployed every 10 m along the lines. 96 channels could be laid out at a time and connected to cables (Fig. 2 right) that led back to the recording vehicle. An analogue roll switch located at the recording vehicle selected which 48 of the input channels could be recorded from a single shot. The University of Otago's Seistronix RAS-24 system amplified the signals and saved 4 s records with a sampling interval of 0.25 ms as digital computer files on a field computer (Fig. 3 right).



Figure 2. Left: an example of a 40 Hz geophone planted and ready for recording. The geophone is connected to 48 channel line cables by way of alligator clips. **Right:** field assistant Christopher Pooley laying out the line cable along Turnbull Road.



Figure 3. Left: Shooters Tim Lennon and Luke Easterbrook detonating a charge adjacent to Turnbull Road. **Right:** Andrew Gorman attending to the recording instruments.

Source points – Chemical sources consisting of 150-g Pentex charges imbedded with electric detonators were positioned at the bottom of 1.2-m-deep holes (Fig. 4 left) drilled out by a power-auger and filled in with soil and debris (Fig. 4 right). These source points were positioned every 20 m along the line. Over 400 source points were loaded and shot. In order to maximise offset information, every second shot location was detonated twice so that a full 96-channel spread could be recorded. The non-doubled shots were centred within a spread of 48 channels to provide consistent split-spread coverage. This resulted in a nominal average fold of 18 with a CMP spacing of 5 m. Shot points were detonated with a radio-controlled shot firing system (Fig. 3 left) than enabled the determination of the shot time for the seismic record.



Figure 4. Example of a drilled shot location before (left) and after (right) loading with a seismic charge. Shot loaders in right photo are Christopher Pooley and Brent Pooley. Advance shot drilling and loading was undertaken for four days (20 – 23 January 2009) prior to the start of recording.

GPS Surveying – All shot and geophone locations in the field were determined by differential GPS measurements (Fig. 5). These were reduced back in the lab to provide an accuracy in position of ~5 cm laterally.



Figure 5. Kirsty Tinto surveying a geophone position with differential GPS on the Haast transect. Mosquito Hill is in the background.

Coincident Gravity Survey

Gravity measurements were collected using a Warden gravimeter on both lines. Every fourth geophone station (i.e., 40 m gravity station interval) was measured during the gravity survey. The purpose of this work is to constrain the interpretation of the basins by testing our seismic interpretations to make sure that they are consistent with gravity observations.

Results of this work are ongoing; they form part of an undergraduate thesis currently underway.

Seismic Processing

Seismic data have been processed using an academic licence for GLOBE Claritas (Ravens 2001).

A basic seismic processing flow has been established for the initial interpretation of the data (see Table 1.)

Two significant processes were included in this flow to improve the signal-to-noise ratio. The first was a time-variant spectral whitening that was applied to the shot records prior to sorting to CMP. This appears to have helped suppress ground roll in the records. The second was a post-stack FX deconvolution process, which accentuates laterally continuous events.

Table 1 – Data Processing Summary

Claritas Process	Purpose
DISCREAD	Traces read from field files
ADDGEOM	Geometry and CMPs written to trace headers from geometry file
DEBIAS	Between 0 and 4000 ms
DISCWRITE	SEG-Y file shots.csgy created
DISCREAD	SEG-Y file shots.csgy read in
TVSPEQ	Time variant spectral balance. Time-gates in 15-100 Hz.tvs
DISCWRITE	SEG-Y file shots+tvspcq.csgy created
DISCSORT	Sorted by CMP from SEG-Yfile shots+tvspcq.csgy
DISCWRITE	SEG-Y file cmps.csgy created
DISCREAD	SEG-Y file cmps.csgy read in
SETLASTTR	LASTTR flag set for CDP ensembles
NMO	Stacking velocity filename apr18.nmo (created by user) implemented. Stretch mute at 30% with taper length of 20ms
AGC	Normal AGC, window length 199 ms,
STACK	Stack with unity normalisation, Maxfold=50
TRFUDGE	User-written code used to insert Shot Point locations into headers
FXDECON	Filter width: 19 traces, overlap 6 traces, window length 50 ms, window overlap 10 ms, L-R and R-L output averaged
DISCWRITE	SEG-Y file stack.csgy created

PRELIMINARY RESULTS

The experimental set up for this survey was quite different from earlier seismic refraction data collected in the region that aimed to image the entire thickness of the crust with large sources. This experiment's smaller sources combined with more closely-spaced shot point and receiver locations has greatly increase resolution.

Plates 1 – 3 show the initial processing and interpretation of the two seismic lines. In Plate 1, the data are plotted as wiggle traces, whereas in Plate 2 the data are plotted in coloured variable-density plot. Plate 3 gives a preliminary interpretation of the data based on the seismic characters that are seen. Imaging quality has been adversely affected by the high-energy depositional environment of the sediments. However, both lines contain regions of relatively continuous reflections in the shallower sections (possibly sediments) that are abruptly terminated at depth (presumably at the base of the erosional basins.) Both lines also appear to have offset reflections that likely correspond to the position of the Alpine Fault at depth.

Haast Line

This line runs SE-NW from the south side of the mouth of the Haast Valley. As such, the line should provide information on the shape and fill of the ancient glacial valley that once would have been located here. The glacier leaving the Haast Valley would be expected to carve out a substantial U-shaped valley as it headed out to the coast. The original base of this valley would be at some depth beneath the present valley floor, which has been raised by subsequent accumulations of sediment accompanied by rising sea levels.

The position of the Alpine Fault on the surface is known. It is therefore reasonable to expect that we should be able to trace the fault at depth by observing vertical offsets at the fault of rock formations such as stratigraphic layers or the eroded base of the glacial valley.

Complicating this scenario is the strike-slip movement on the Alpine Fault. For example, over the last 18 000 years, a realistic timeframe for the disappearance of the glacier from the Haast valley, and assuming a time averaged slip rate of 23.1 mm/a, the west side of the Alpine Fault will have travelled over 415 m northeastward. This means that significant topographical features to the west, such as Mosquito Hill, are now in a much more northward position than they were during the last glacial period. Similarly, basement features in the seismic data on the Australian Plate will correspond to features farther to the south on the Pacific Plate.

Several laterally continuous reflections (indicated by dashed lines on Plate 3) can be interpreted as sedimentary features lying within a former glacial valley. These reflections are likely the result of contrasting physical properties in regionally-extensive sedimentary facies such as glacial or fluvial outwash gravels or silts. The base of the sediments is assumed to correspond to the erosional base of the old glacial valley. As might be expected, this erosional surface is quite varied in depth ranging from 0.32 s at CMP 560 to 0.84 s at CMP 320. Assuming an average seismic velocity of 2000 m/s in the sediments, these two-way times correspond to depths of 320 m and 840 m.

Beneath the surface scarp of the Alpine Fault, offsets in these sedimentary reflections are interpreted. Note that a unique position for the fault at depth is difficult to ascertain. A bifurcating system of at least two faults is interpreted. A displacement is also interpreted in the eroded

basement surface at CMP 360. Here, the basement jumps from a time of 0.84 to 0.69 s (840 to 690 m at 2000 m/s average velocity.)

This interpretation enables a crude confirmation of the uplift rate on the Alpine Fault. An uplift of 150 m over an unconstrained 18 000 year timeframe gives a uplift rate of 8.33 mm/a. This is slightly higher than the 5.9 mm/a proposed earlier using marine terraces in the region (Bull & Cooper 1986), but if 5.9 mm/a is assumed, then the timeframe for the erosion surface across the fault could be an equally plausible 24 500 years. However, none of these calculations takes into consideration the strike-slip motion that will have happened along the fault in the same time, nor the fact that the erosional cross-sectional profile of the Haast glacial valley should shallow to the southwest of the seismic line.

Turnbull Line

This line runs SE-NW from the mouth of the Turnbull Valley along a relatively straight section of the access road to the Turnbull hydro-electric scheme on the right bank of the Turnbull River. Field conditions were substantially different here than for the Haast transect. Southeast of the fault's mapped position, ground conditions were quite rocky. A large component of the surface cover may, in fact, be alluvial gravels, which should have a different geophysical response from the glacial outwash gravels and finer-grained sediments seen to the north.

This difference is primarily due to the differences in the rivers upstream from the Alpine Fault. Upstream from the fault, the Turnbull River descends from the Southern Alps at a very high gradient (hence its use for hydro-electric generation.) This contrasts strongly with the Haast River, which is a braided river for many kilometres into the Southern Alps. However, downstream from the Alpine Fault, the Turnbull River is more similar to the Haast River.

Knowledge of the glacial environment in the Turnbull Valley during the most recent ice advance is poorly constrained. The U-shaped valley of the Turnbull River is a hanging valley, the base of which is suspended at an elevation of about 200 m above sea level. Therefore, any interpretation of an erosional base on the southeast side of the fault is suspect.

The Australian plate (NW) side of the Turnbull seismic line (Plate 3) contains similar reflections to those seen on the Haast line. Laterally continuous reflections can be identified that may correspond to interbedded glacial outwash gravels and fine-grained sediments. Basement is interpreted at a maximum depth of 0.50 s (500 m at 2000 m/s). However, in the vicinity of the Alpine Fault (CMP 320), the reflections are poorly resolved and they could lie anywhere from 0.33 to 0.24 s (330 – 240 m at 2000 m/s).

CONCLUSIONS

This work has shown that reflection seismology can be successfully used to image sedimentary and basement features associated with the Alpine Fault. Although the Alpine Fault surface has not been imaged directly, it is possible to position the fault and estimate throw by interpreting geological features (*i.e.*, strata and erosional surfaces) that are broken by the fault. Our data support and provide confirmation for earlier Alpine Fault uplift rates in the Haast region.

The results show the Alpine Fault to be steeply dipping in the upper 800 m or more beneath the Haast Valley. The interpretations do not support the shallow dipping structure proposed by Allis (1986).

The positioning of appropriate seismic lines is critical in the success of a survey such as this. In a region where tectonic processes are working at very high rates, care must be taken when evaluating stratigraphic or structural features related to slower geological processes (such as glacial erosion).

Improvements in interpretation would result from more extensive seismic surveys that involve multiple lines both perpendicular and parallel to the Alpine Fault.

Ongoing Work

These preliminary results were presented at the European Geoscience Union General Assembly in Vienna in April 2009 (Gorman 2009).

Additional analysis is planned for 2009 to improve the processing of the seismic lines and to incorporate the results of gravity modelling. Once this is complete a paper will be submitted to an appropriate peer reviewed journal.

Plans are underway to extend this style of research farther north in the Whataroa Valley as part of the ongoing collaborative and multidisciplinary study of the Alpine Fault, which aims to eventually secure funding and international support to drill and examine the fault surface at depth. Planning for this work should be able to make use of the findings from Haast and Turnbull, particularly in considering the layout of seismic lines that would be suitable for understanding the three-dimensional evolution of glacial valley erosion and infilling while simultaneously undergoing dextral displacement due to movement on the Alpine Fault.

ACKNOWLEDGEMENTS

Local landowners were extremely helpful and obliging during the acquisition of these data. Particular thanks are due to John Cowan, owner of much of land that the Haast transect was shot along. During the experiment, John rearranged his tilling and cattle operations to facilitate our access to his land. He also gave helpful advice as to where we could position our lines and provided a secure location for the storage of our explosives magazine. For the Turnbull Valley transect, Kim Landreth provided access to his land – and also provided advice on suitable line positioning.

Our accommodations in Haast were at the Haast Lodge. Greg Hope and his team made us all comfortable and provided a suitable instruments workshop for use when we were not in the field.

Our explosives agent was Paul Mollart at Black Head Quarries in Dunedin. Paul was a great help and even arranged for a mobile explosives magazine that we took to the field.

Technical support staff at the University of Otago's Department of Geology did their usual amazing job of making sure that we were prepared for a safe and enjoyable field experience. Special thanks go to John Williams, Adrien Dever and Kay Swann.

Richard Norris played a critical role in positioning the geophysical transects and added invaluable context to this work by ensuring that we made use of lessons learned by mapping and earlier paleoseismic investigations of the Alpine Fault in the Haast area.

Finally, a huge thank you must go out to the field crew (Figure 6) who performed amazingly well. Their hard work ensured that the data we collected in the field were of the highest quality. It was a pleasure to spend the long days (and nights) together with them in Haast.

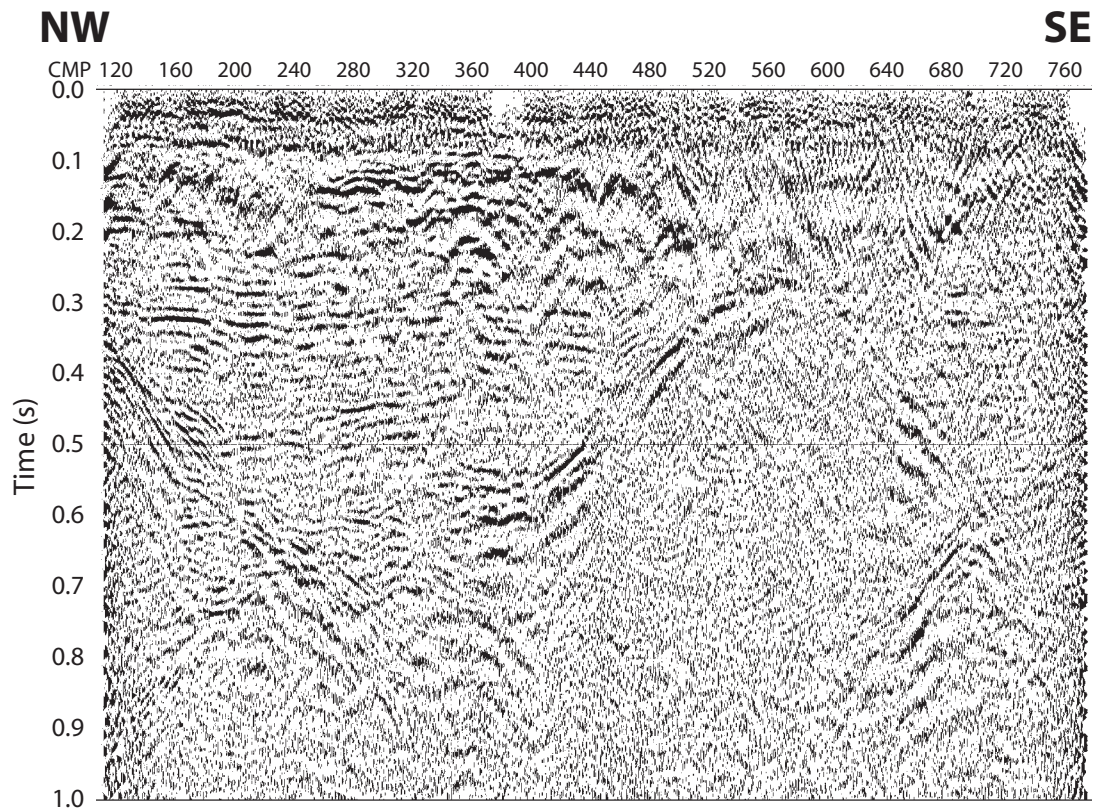


Figure 6. Back row, left to right: Brent Pooley, Christopher Pooley, Luke Easterbrook, Angus King, Daniel Jones, Sebastian Clar, Claudine Curran, Kirsty Tinto, Gareth Crutchley, Paul Viskovic, Tim Lennon. Front row, left to right: Uwe Kaulfuss, Charlotte King, Andrew Gorman.

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Haast Line



Turnbull Line

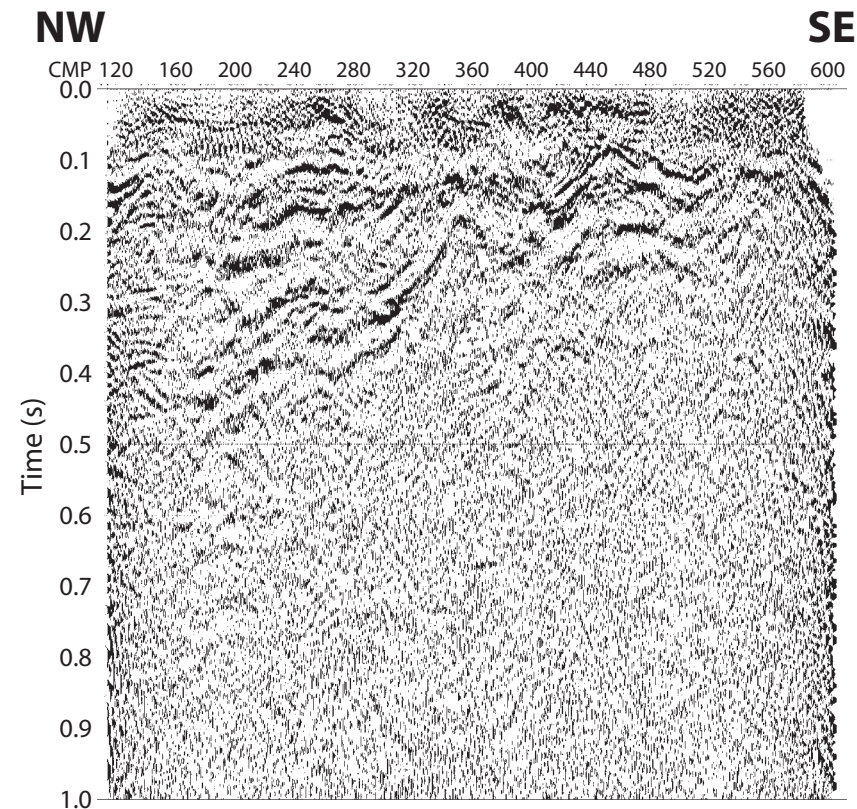
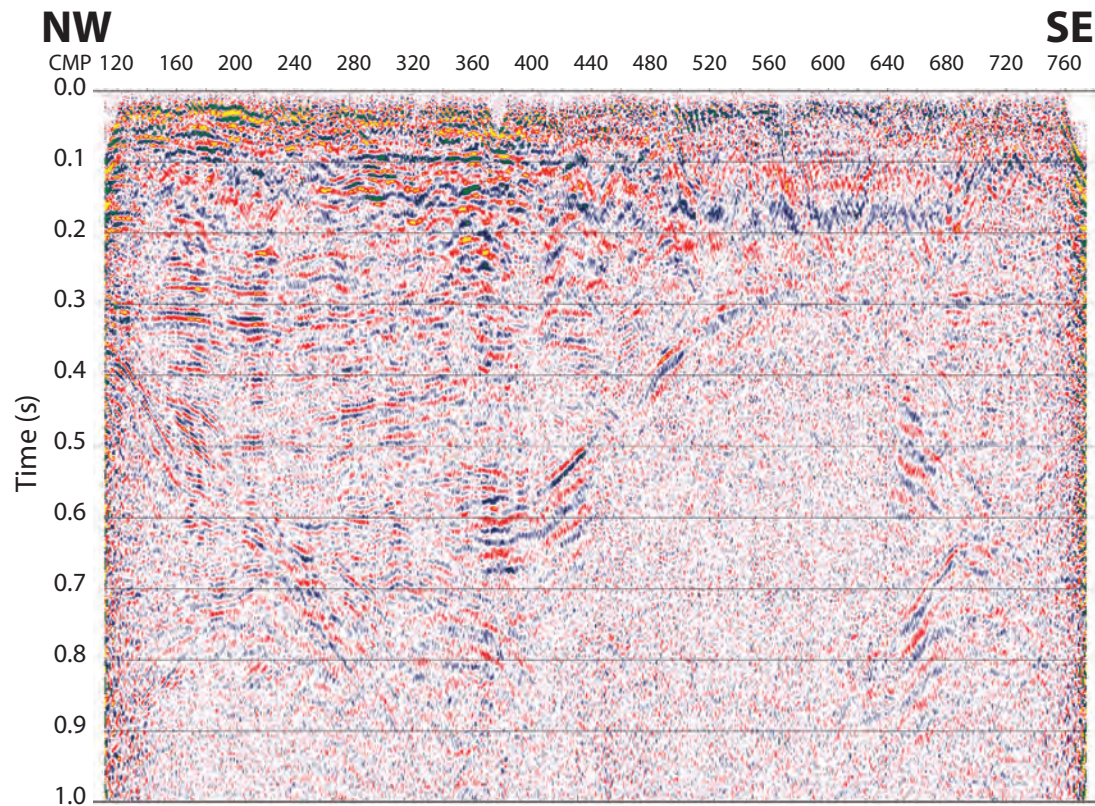


Plate 1. Initial processing of 2009 EQC data. These stacks are displayed in wiggle trace variable area. Note the laterally continuous reflections within the fill of the basin seen on the NW side of the Haast line.

Haast Line



Turnbull Line

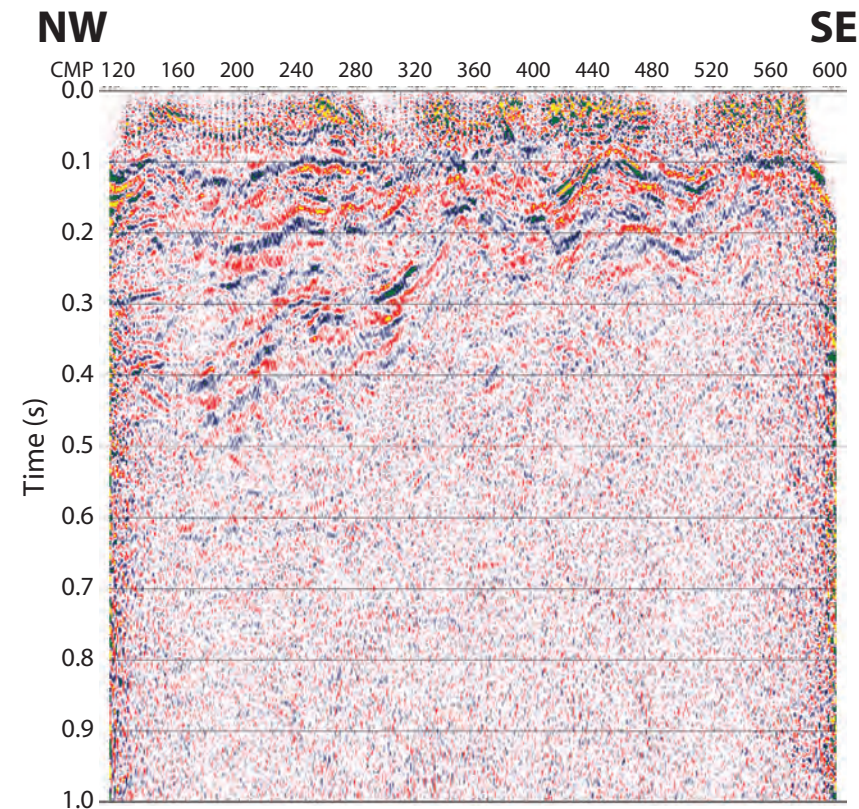
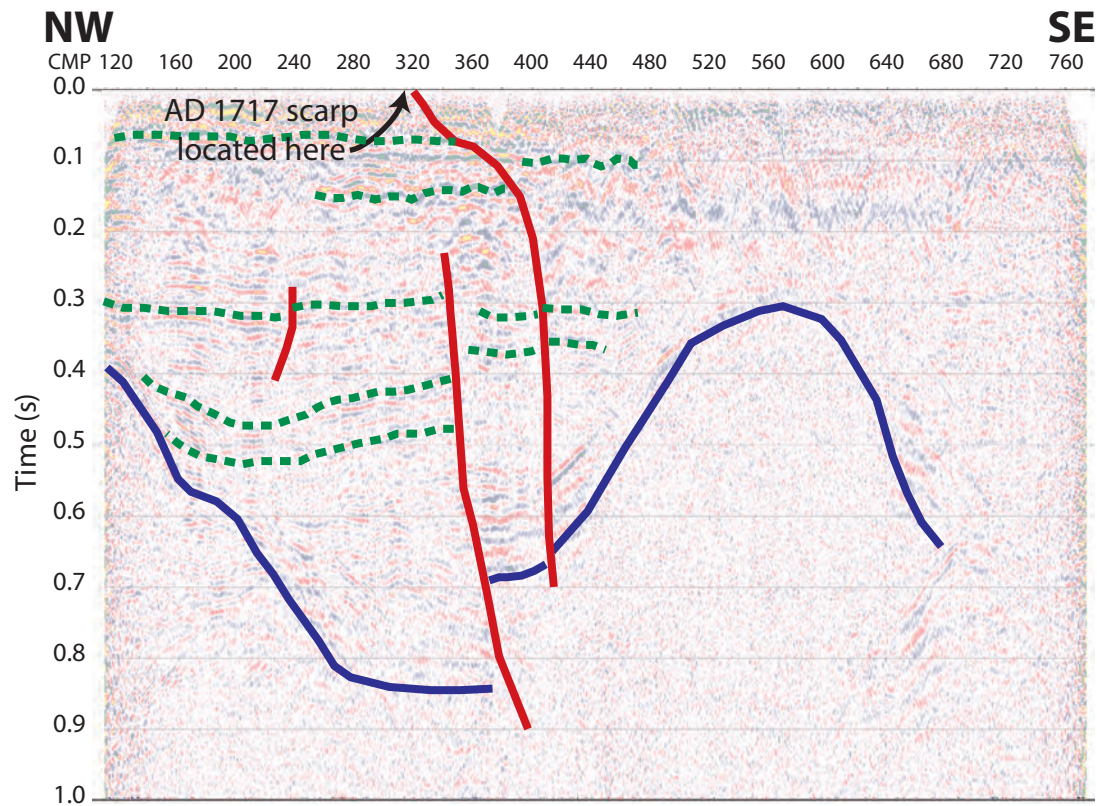


Plate 2. Initial processing of 2009 EQC data. These stacks are displayed in coloured variable density (red is positive and blue is negative.) Note the laterally continuous reflections within the fill of the basin seen on the NW side of the Haast line.

Haast Line



Turnbull Line

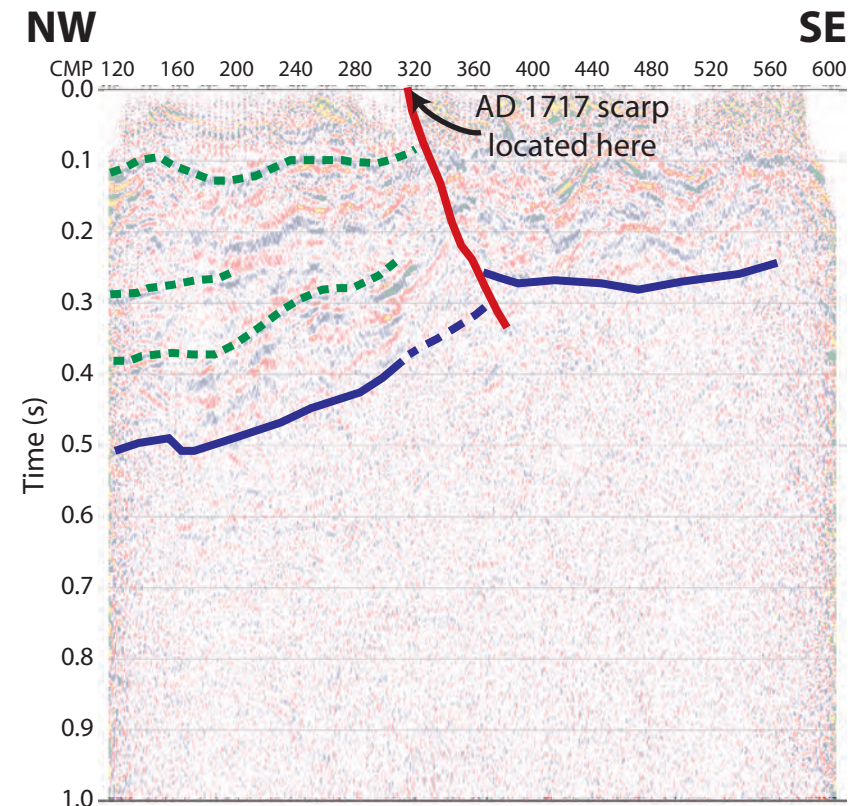


Plate 3. Initial processing and interpretation of 2009 EQC data. These stacks are displayed in coloured variable density (red is positive and blue is negative.) A preliminary, poorly-constrained interpretation has been superimposed on the sections.