Comparison of Fibre Optic Sensor and Borehole Seismometer VSP surveys in a Scientific Borehole — DFDP-2B, Alpine Fault, New Zealand

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Summary

The DFDP-2B scientific borehole was drilled in 2014 to a depth of 893 m into mylonitic fault rocks adjacent to the Alpine Fault, New Zealand, in the second phase of the Deep Fault Drilling Project (DFDP; Sutherland et al, 2015). The borehole was designed to penetrate the fault zone in order to study the physical and chemical properties of a major tectonic boundary in an active continent-continent collision zone. As part of the project, a slim (BQ) casing string containing optical fibre cable was deployed in the borehole from the surface to its base, on the outside of the main casing. This fibre cable was used to measure temperatures at approximately two-month intervals in the year following the completion of drilling using Distributed Temperature Sensing (DTS) techniques. In January 2016, an active source seismic experiment was conducted around the DFDP-2B borehole, as part of which the optical fibre cable was used to collect acoustic data along the length of the borehole. In addition, a conventional four-level, three-component vertical seismic profile (VSP) string was suspended in the accessible top 400 m of the borehole. Zero-offset and multi-azimuth walkaway VSP surveys were undertaken to image around the borehole and determine the velocity structure and reflectivity characteristics in the hanging-wall of the Alpine Fault.

Introduction

Distributed Acoustic Sensing (DAS) using fibre optic cables has the potential to provide detailed seismic images around wells. There are many examples of DAS surveys in sedimentary environments (Mateeva et al., 2013; Dean et al., 2015) but few examples of the technology being used in hard-rock environments. A Schlumberger heterodyne Distributed Vibration Sensing (hDVS) system also known as DAS, was deployed in the Alpine Fault DFDP-2B borehole in New Zealand and is ideal for evaluating the performance of such systems in a metamorphic terrane characterized by unusually high geothermal gradients (Sutherland et al., 2015).

The DFDP-2B borehole was drilled adjacent to the Alpine Fault at Whataroa, on the west coast of New Zealand's South Island (Figure 1). The Alpine Fault is a dramatic 400 km-long oblique strike-slip fault that marks the plate boundary between the Pacific and the Australian Plates. It is an active plate boundary and there is evidence for major earthquakes occurring on the fault approximately every 330 years (Sutherland et al., 2015). The borehole was designed to extend from the hanging wall of the fault through the principal slip zone and into the footwall. Technical problems prevented the borehole from reaching its target depth, but geological observations made on site and pre-existing information suggested that the borehole reached to within 200–300 m of the principal slip zone at it final depth of 893 m.

The DFDP-2B borehole provides a scientific facility for observing the physical properties of the fault zone late in its typical earthquake cycle. The aim of the current study, conducted in January 2016, is to use borehole and surface seismic methods to better image the complex geology surrounding the well and determine the orientation and seismic character of the fault zone ahead of future drilling. This intensive 11 days of seismic shooting included a zero-offset VSP, multiple walk-away VSP's (Figure 2) and overnight passive recording. The DAS, the VSP, and a moving array of 160 passively recording 3C geophones ('cubes') yielded simultaneous surface and downhole records. This contribution, however, focuses only on the initial comparison of the vertical component zero-offset VSP data with the corresponding DAS record at vertical resolutions not normally obtained in VSP recording.

Figure 1. Map of the Alpine Fault of New Zealand showing the location of the well near Whataroa

DAS and VSP Surveys

Downhole signals were recorded simultaneously using the hDVS system and a more conventional three-component (3C) wall-locking borehole seismic system. These two systems complement each other in that the hDVS system provides a high spatial resolution record of the bulk strain over about a wavelength while the geophones provide point measurements of particle velocity.

DAS is a technique based on optical time domain reflectometry in which short laser pulses are launched into the optical fiber deployed into the borehole. In this particular case, the seismic signal that is detected along the fiber is captured by measuring the phase of the Rayleigh backscatter (Hartog, et al, 2013). For this survey, DAS, VSP and 1C geophone systems were able to align, stack and display in real time the acquired data by receiving the time break from the seismic vibrator simultaneously. DAS borehole seismic data were recorded successfully in DFDP-2B using single mode fiber in the BQ metal tube installed behind casing. This trial was the first opportunity to record field data with the new release of hDVS.

A conventional 3C, wall-locking downhole seismic system (Sercel Slimwave) was also deployed by the University of Alberta within the accessible subvertical cased section above 400 m. The system included four separate 3C sondes hosting high-temperature 15-Hz geophones spaced at intervals of 15 m and a digital telemetry sonde to transmit data to the surface panels. Records were obtained at a 500 μs sampling period and comprised the 12 downhole channels, a timebase resolved to microsecond resolution using GPS time, and the vibrator sweep. The sondes are not oriented; at each depth station a weight-drop surface seismic source operated by the University of Otago was activated 93.6 m from the borehole to provide an unambiguous orientation pulse.

A single ‘IVI Enviro Vibe’ vibroseis truck, operated by the University of Calgary, was used for this survey. The hold down weight was 15,000 lbs, base plate 855 lbs and reaction mass 1,750 lbs. A Pelton VibPro Controller Decoder and Encoder system was used to control the vibroseis. Two different 16 s linear sweeps were acquired during the survey: the first was from 10 Hz to 150 Hz and the second one from 10 Hz to 60 Hz. The latter sweep was primarily employed for far offset testing of the hDVS system.

Zero-Offset VSP

The zero-offset VSP was collected with the source located 10 m southwest of the well head. The borehole is vertical for the top 400 m then deviates to the NNE. The well is cased to depth but the casing parted at a depth of 436 m and cement fills the hole below 400 m (Sutherland et al., 2015).
A relatively high vertical spatial sampling of 1 m for the geophone sondes was desired for the zero-offset VSP in order to permit accurate determination of the in situ seismic wave speeds. This survey required approximately 12 hours of active data collection and yielded data over the 400 m to 84 m depth interval, although the records above 125 m are unusable because of casing flexure. Signal strength was strong and typically only two records were required per depth level. Again, the weight drop was activated at each depth in order to provide orientation information. The rate of shooting was primarily controlled by the speed at which the sonde’s arms could be opened and closed for each move.

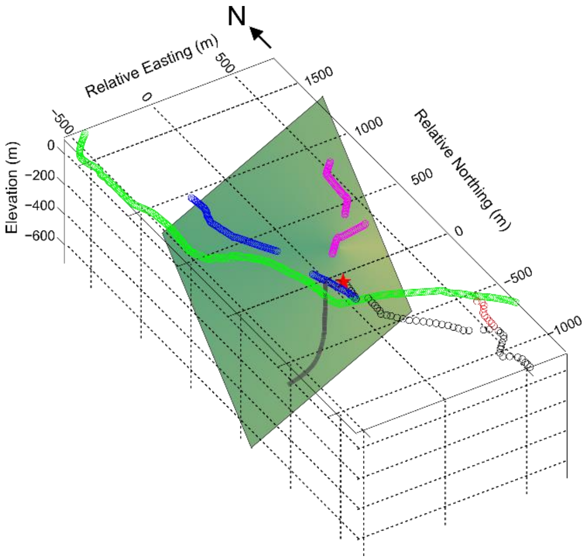

Figure 2. 3D geometry of the field experiment showing the deviated borehole (gray line), the weight drop orienting source (red star), and various offset shot lines. The zero offset source position (not shown) is 23 m SE of the wellhead. The green trapezoid represents the expected but simplified fault geometry.

The high spatial sampling allows for numerous features of the wave-field to be observed that are not normally detected with standard industry spacing. Figure 3 superposes the geophone VSP on the optical fiber record and shows that these compare well with one another. From the surface to about 140 m depth both display strong casing reverberations that indicate sections of one or more of the various casing strings not secured with cement. These reverberations overwhelm any coherent seismic signal from either of the recording systems. A strong down-going P-wave emerges below these reverberations travelling relatively slowly (~2000 m/s) within the sediments above 240 m and rapidly (~6000 m/s) within the metamorphic schists and increasingly mylonitized rocks. The unconformity between the less consolidated sediments and the hard rock is a large impedance contrast and as a result both transmitted P- and S-wave modes propagate downwards. It is important to note that the S-wave travelling with an average speed near 2790 m/s is clearly apparent in both the VSP and the optical records (Figure 4); this provides clear evidence that the DAS system is also sensitive to the strains produced by the shear wave.

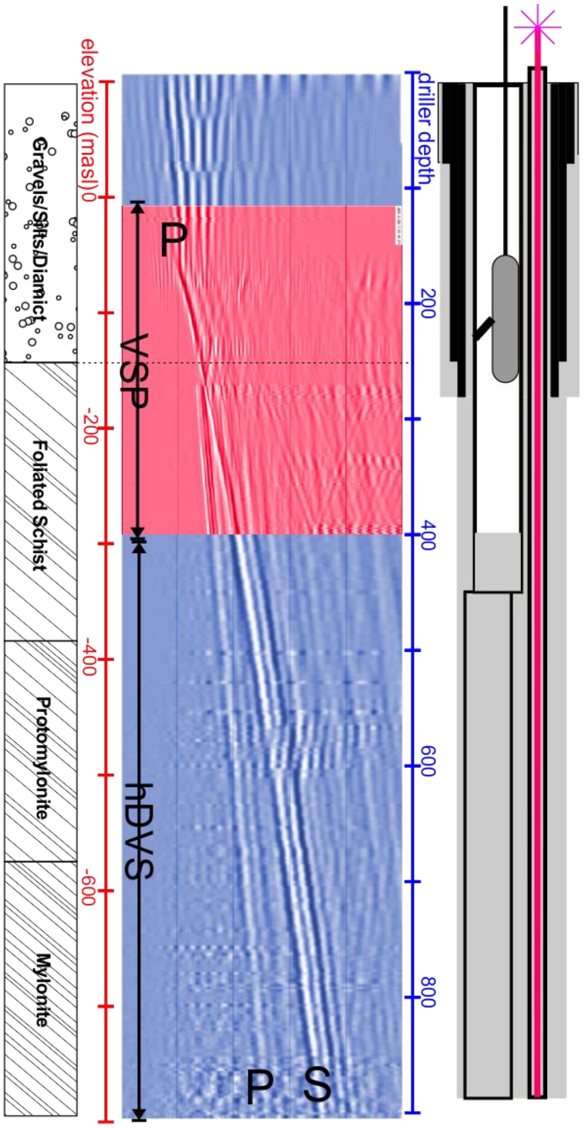

Figure 3. Composite plot of Sercel Z-components (red tint from 120 m to 400 m) and hDVS output (blue tint from the surface to 893 m driller's depth). Traces shown for time window of 500 ms. Simplified geological log shown on left with major unconformity at 240 m driller's depth. On the right is a schematic of the borehole with three interleaved concentric casings to 270 m that contains a PWT casing that separated at 436 m and a BQ casing protecting the fibre optic cables (shown as red line). Cement fills the hole below 400 m driller's depth; only the top 400 m is accessible to the geophones but the optical fiber extends from the surface to the bottom of the borehole. The hDVS data are the output of a median filter of 48 individual shot records at each depth.

Close examination of the zone between 220 m and 260 m depth, if taken at face value, appears to give noncausual arrivals with deeper levels showing the directly down-going P-wave earlier than those above. This impossible situation is only apparent. The amplitude is low due to destructive interference of the down-going and up-going waves immediately above the sediment-hard rock contact; the actual down-going wave cannot be seen.

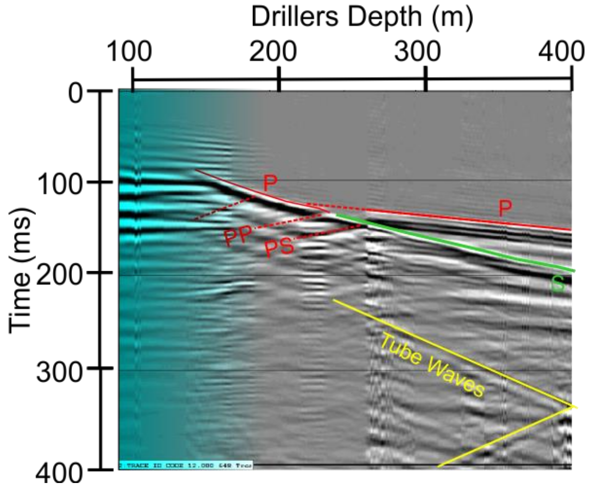

Figure 4. Enlarged image of the vertical geophone response from 84 m to 400 m depth at 1 m spacing showing initial interpretations of loose casing reverberation (green shaded zone), down-going P waves (red) with up-going reflections, both down-going converted S-mode through metamorphic rock (green), and tube wave (yellow).

The dense spatial sampling along the borehole provided by both the VSP and DAS records allows, in principle, for accurate determination of in situ interval wave speeds at seismic frequencies. Simple linear regressions of the picked traveltimes against drillers depth for the five clear 'linear' moveout segments apparent in Figure 3 are provided in Table 1 and these average wave speeds are reasonable for the different lithologies encountered, particularly with regards to the range of wave speeds expected for anisotropic metamorphic rocks on the basis of laboratory measurements (e.g., Okaya et al., 2010).

The analysis is carried further with a direct application of a local slope method to determine interval wave speeds (Schmitt et al., 2007) with the results shown in Figure 5 to 95% confidence intervals. Such an analysis has provided reasonable wave speed values in previous studies. However, here wave speeds up to and even exceeding 8000 m/s are calculated in the zone immediately below the unconformity between the sediments and the basement rock. Even considering the substantial anisotropy of the metamorphic rocks, such wave speeds are unrealistic in these materials. There are likely a number of reasons for this discrepancy that are related to the anisotropy of the formation, errors in down-going wave travel time picking due to contamination of the signal by up-going reflections, and the significant deviation of the borehole from vertical. As such, the wave speeds displayed in Figure 5 and Table 1 should only be considered as apparent values as they are as yet uncorrected for the borehole geometry. The high anisotropy of these rocks will further complicate the corrections required.

Table 1. Apparent wave speeds from linear regression

Segment		Depths	Velocity
Sediments - P	VSP	152 – 230 m	2000 m/s
Metamorphic - P	VSP	263 – 381 m	6220 m/s
Metamorphic - S	VSP	260 – 394 m	2780 m/s
Metamorphic - P	DAS	281 - 858 m	5640 m/s
Metamorphic - S	DAS	283 – 858 m	2780 m/s

Conclusions

The hDVS system produced high-quality VSP images in zero-offset and multi-offset modes. The vibroseis source was ideal for the experiment as it provided the flexibility of multiple shots at the same location and permitted changes to the frequency spectrum of the sweep. The comparison between the three-component geophones with the scalar hDVS measure suggests that combining both techniques will provide complementary information.

Work in progress seeks to make the appropriate corrections to obtain more realistic interval wave speeds and to appropriately rotate the 3C downhole geophone data to account for both borehole deviation and sonde rotation. Once this is accomplished we expect to detect shear wave birefringence within the highly anisotropic metamorphic rocks. The multi-depth and azimuth walk-a-way VSP data are expected to provide additional measures of the anisotropy and to assist in the development of velocity models useful for processing of the surface reflection data. Finally, the hDVS and VSP sondes recorded continuously for a number of evenings and both were able to successfully record regional seismicity. This suggests that DAS systems may also be useful in passive monitoring of earthquakes and microseisms.

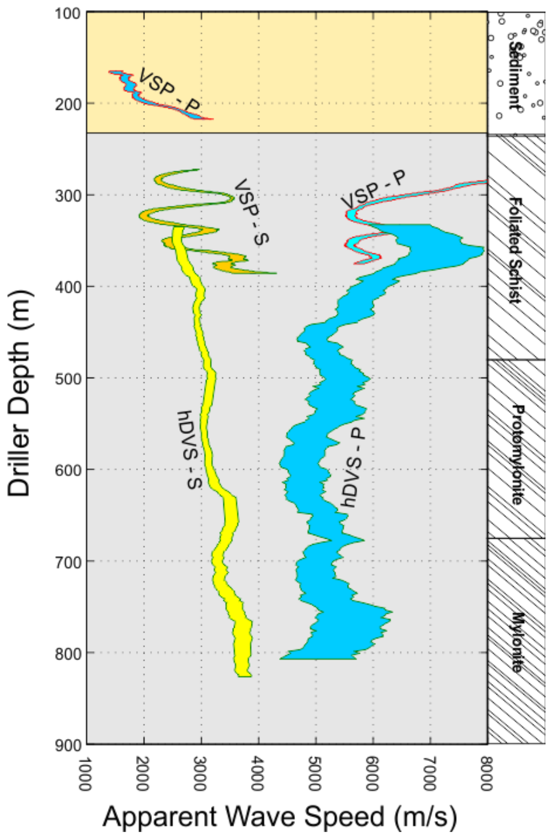

Figure 5. Apparent interval wave speeds with 95% confidence intervals obtained from local slope fits to time picks from the different records.

Acknowledgments

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EDITED REFERENCES

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