Vertical seismic profiling using distributed acoustic sensing with scatter-enhanced fibre-optic cable at the Cu–Au New Afton porphyry deposit, British Columbia, Canada

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ABSTRACT

Wireline logs and vertical seismic profile data were acquired in two boreholes intersecting the main mineralized zone at the Cu–Au New Afton porphyry deposit, Canada, with the objectives of imaging lithological contacts, fault zones that may have acted as conduits that channelled the mineralization, and alteration zones. Log data provide physical rock properties for the main lithologies and alteration zones. Calliper logs reveal many faults and caved-in zones generally indicating rocks with low integrity at the borehole wall. The preponderance of these zones, as indicated by the logs, suggests that their response may dominate the seismic-reflection wavefield. Outside fault zones, compressional and shear-wave velocities exhibit significant variability due to porosity, the heterogeneity of volcanic fragmental rocks and alteration. Distributed acoustic sensing was used to acquire vertical seismic profiling data in the two boreholes surveyed with wireline logs. Straight and helically wound fibre-optic cables housed standard fibres and a fibre engineered to increase the intensity of backscattering at the distributed acoustic sensing interrogator. Standard and engineered optical fibres placed in the two boreholes were daisy-chained together to form two 5-km-long continuous fibres that were interrogated at once with two interrogators. A new generation of interrogator connected to the engineered fibres provided field data with lower noise level and higher signal-to-noise ratio. These data with higher signal-to-noise ratio from straight fibre-optic cable were processed and used for depth imaging. Depth images benefitted from new migration weights that account for the directional sensitivity of the straight fibre-optic cable and limit the extent of migration artefacts. Migration results show several reflectors with shallow dips to the northwest, some explained by faults intersecting the surveyed boreholes. The main sub-vertical lithological and alteration contacts at New Afton generated downgoing reflections that were not considered in the migration.

Key words: Distributed acoustic sensing, Helically wound fibre-optic cable, Porphyry deposit, Vertical seismic profiling.

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INTRODUCTION

Distributed acoustic sensing (DAS) is a distributed sensing technology that utilizes the optical scattering response to a laser pulse to measure changes of strain occurring along a fibre-optic cable (Farhadiroushan, Parker and Shatalin 2009; Parker, Shatalin and Farhadiroushan 2014; Hartog 2018). DAS does not use point receivers but rather sense simultaneously the entire length of a fibre-optic cable for strain changes due to the passage of seismic waves. This ability to measure data over an entire fibre-optic cable at once is particularly advantageous from a data acquisition perspective and has led to the development of a variety of applications, primarily for the oil and gas industry (Hartog 2018). In particular, DAS is well suited for field applications requiring monitoring and deployment in boreholes. For instance, the utility of DAS has been demonstrated for the characterization and monitoring of CO$_2$ reservoirs (Daley et al. 2014; Humphries, Vidal and de Dios 2015; Daley et al. 2016; Harris et al. 2016; Götz et al. 2018). Currently, there are a very limited number of published results on the application of DAS for mineral exploration and mining applications. A potential application of DAS includes real-time monitoring of stress and strain near mine workings to ensure that rock mass integrity is preserved and safe for mining operations. DAS also offers cost-effective solutions for mineral exploration, more particularly for vertical seismic profiling (VSP) surveys that are sometimes used for providing high-resolution images of the subsurface near known deposits or in prospective areas. Steeply dipping ore at the Kyllysalmi Cu–Au–Zn deposit in Finland was properly detected and imaged with DAS-VSP data (Riedel et al. 2018). In situ P- and, unexpectedly, S-wave speeds were obtained from DAS-VSP records acquired in a borehole drilled through mylonites near the Alpine Fault, New Zealand, and compared well with those obtained simultaneously using more conventional downhole 3-C geophones (Constantinou et al. 2016).

This paper presents results from one of the first applications of DAS-VSP for mineral exploration. DAS-VSP data were acquired as part of the Geological Survey of Canada’s Targeted Geoscience Initiative for the development of an integrated geophysical imaging and 3D geological modelling research study of the New Afton porphyry deposit located in the Canadian Cordillera of south-central British Columbia. This alkaline Cu–Au porphyry deposit previously supported an open pit operation and is currently being mined at deeper levels through underground workings, providing geological constraints extending beyond 1.5 km in depth. The study intends to combine new VSP and 3D magneto-telluric surveys, along with multi-parameter deep drillhole geophysical logs, and 3D modelling to elucidate the magmatic hydrothermal processes and structural controls responsible for concentrating metals in this porphyry deposit. Here, we present elastic rock properties from wireline logs and results from a VSP survey acquired with DAS in two boreholes that intersect the main mineralized zone and alteration halo. In general, seismic methods are not the primary exploration tool for porphyry deposits but they were used previously to delineate a porphyry ore zone (Li and Eaton 2005) and to map intrusive rocks that are spatially and genetically associated with such deposits (Roy and Clowes 2000; Schijns et al. 2012). At New Afton, the mineralization consists primarily of disseminated sulphides (up to about 4% in the economic ore zone) unlikely to be detected directly on VSP data. Instead the focus is on fault zones, of which some may have acted as conduits that channelled hydrothermal fluid flow. In addition, lithological contacts and the potential signatures of hydrothermal alteration zones that are key indicators to the presence of porphyry mineralization were of interest.

The VSP survey at New Afton was conducted with two DAS systems: a standard system using conventional telecommunication fibre and an advanced DAS system combined to an optical fibre engineered to increase the intensity of backscattering to the DAS interrogator. The advanced DAS system achieves signal-to-noise ratio comparable with that generally obtained with geophones (Correa et al. 2017). Straight and helically wound fibre-optic cables comprising both types of optical fibre were installed in two boreholes and allowed an unequivocal comparison of the two DAS systems. The helically wound fibre-optic cable was deployed to assess the capability of omni-directional sensing for various wave modes and wave propagation directions. Such broadside sensing is desirable at New Afton due to its complex geological structure and the inclined and deviated geometry of the boreholes. Straight and helically wound fibre-optic cables were daisy-chained together to allow simultaneous recording along the full length of the fibre cables for each shot, thus minimizing the total number of required shots. A total of 50 shallow shot points were distributed in four clusters around the boreholes (Fig. 1).

In this paper, we briefly introduce the local geology of the New Afton deposit and present wireline logging results that are used to support the interpretation of DAS-VSP data. Then, we compare field data acquired with both DAS systems with straight and helically wound fibre-optic cables. DAS-VSP data measured with straight fibre-optic cable were further processed and used to produce an image of the subsurface...
near the two boreholes of the VSP survey. In applying depth migration to the data, we introduce migration weights that account for the directional sensitivity of straight fibre-optic cable. These weights act similarly to parameters that control the aperture in standard depth migration and limit the extent of migration artefacts.

**GEOLOGY**

The Cu–Au New Afton porphyry deposit is dominantly hosted by fragmental and crystalline volcanic rocks (hereafter referred to as BXF) of the Late Triassic Nicola Formation and to a lesser extent by the 204 Ma Cherry Creek monzonite of the Iron Mask batholith, the latter interpreted as the heat source that caused alteration and mineralization in this alkalic porphyry (Lipske and Wade 2014; Bergen, Krutzlmann and Rennie 2015). A sub-vertical SW-plunging zone of primary hypogene mineralization, largely coincident with the potassic alteration zone, contains disseminated chalcopyrite and bornite (Figs 1 and 2). This hypogene ore zone is structurally controlled by two sub-vertical NE-SW striking fault zones, known as the foot wall and hanging wall faults. The hanging wall fault juxtaposes BXF with a sub-vertical body of serpentinized picrite. This tectonic contact along the northern weak serpentinized picrite margin is defined by a high strain zone of brittle-ductile deformation and locally confines a zone of calcic alteration composed of magnetite, epidote, actinolite and apatite. The primary hypogene ore zone is cut by numerous moderately to steeply dipping fault zones that controlled secondary hypogene mineralization of tetraxhedrite and tennantite. Supergene mineralization of native copper and chalcocite in hematite-rich oxidation zones is more abundant at higher structural levels in the vicinity of the open pit, but native copper extends to 700 m below surface beneath the pit along older, long-lived structures (Lipske and Wade 2014; Bergen et al. 2015).
Figure 2 Section (looking west) of the main lithological units (left), alteration zones (middle) and mineralized zone (right) at New Afton. The main hypogene mineralized zone (0.4% Cu equivalent) is outlined in red and is primarily associated with the biotite-dominant potassic alteration zone (Kb). BXF: volcanic fragmentals; Mo: monzonite; Pi: picrite; Di: diorite; Fa: faults; Po: propylitic; Ph: phyllic; Ca: calcic; Kk: feldspar-dominant potassic alteration; Kb: biotite-dominant potassic alteration. Labels D, E, J, HW Flt and FW Flt in all subfigures are faults. Mt and Hm in the mineralization subfigure refer to zones with magnetite and hematite, respectively. Propylitic alteration consists of sericite, carbonate, pyrite, quartz and tourmaline. Calcic alteration minerals include magnetite, actinolite, apatite and epidote. Spatial coordinates shown are mine grid coordinates measured in metres. The 5000 elevation level corresponds to mean sea level (modified from Lipske and Wade 2014).

WIRELINE LOGGING AND PHYSICAL ROCK PROPERTIES

Wireline logs were acquired in two boreholes (EA16-171 and EA17-197) that emanate from the same underground drill bay located approximately 650 m below the surface (see Fig. 1 for location). The two boreholes have different length, dip and azimuth. Both boreholes intersect numerous faults that tend to collapse in open drill holes. This significantly complicated acquisition of the open-hole wireline logs. A drill rig was used to ream the boreholes in order to keep them open for the entire duration of the logging programme. Logging was conducted in short open-hole sections starting from the bottom of the borehole with drill rods covering unstable areas above the interval being measured. Drill rods were then lifted.
to uncover the next interval of stable open hole for logging. In EA17-197, this procedure was time consuming as this borehole was drilled with drill bits with two different diameters. NQ-diameter (75.7-mm hole diameter) drill bits used to reach the lower part of the borehole were telescoped into HQ-size (96-mm hole diameter) rods which covered the interval closer to the surface. Borehole EA16-171 was drilled entirely with HQ-size drill bits. Probes were not deployed over the larger fault zones or sections where caving was extensive. Open-hole logging measurements included 3-arm calliper, natural and spectral gamma-ray spectrometry, magnetic susceptibility, resistivity, induced polarization, induction conductivity and full-waveform sonic logs. Gamma–gamma density logging was conducted through drill rods and subsequently calibrated with values measured over a short section of stable open hole located near the surface. This approach minimized the risk of losing the radioactive source used for density measurements as a result of obstructions in the borehole, an event that would have led to a temporary shutdown of mining operations.

Figure 3 presents selected logs for borehole EA16-171 plotted together with the main fault zones, alteration and lithological units from drill core geological logging conducted by the mine operator. The calliper track provides a good illustration of the difficult borehole conditions, with large values showing caved-in zones associated with brittle faults. Density and P- and S-wave velocity logs are of poor quality in areas with large calliper values due to the effect of the larger diameter of the borehole filled with a mixture of rock and water. Actual rock densities are likely higher in fault zones than shown on the logs but are difficult to estimate accurately. However, the brittle nature of the fault zones suggests that their density is lower than un-fractured rocks. Similarly, the measured P- and S-wave velocity logs are also affected by the fractured rocks and the increase of borehole diameter in the caved-in zones. Acoustic impedance contrasts at these fault zones are
expected to be high enough to generate detectable reflections on VSP data. The significant number of faults further suggests that their response will likely dominate the reflected seismic wavefield.

Outside fault zones, the P- and S-wave velocity logs shown in Fig. 3 exhibit significant variability despite the fact that they were acquired primarily in volcanic fragmental rocks of the Triassic Nicola Formation (BXF on Fig. 3). This rock unit is heterogeneous and comprises clasts of varying size of porphyritic diorite, andesitic flow debris, mafic volcanic rocks, picrite and aphyric volcanic rocks within a fine- to coarse-grained matrix of intermediate to mafic composition. Hydrothermal alteration also changed the mineralogical composition of the volcanic fragmental rocks and other rock units near the deposit (see caption of Fig. 2 for alteration minerals in each zone). Alteration generally increases in intensity with depth, but changes in alteration style are not necessarily smooth and gradual. Thus, in addition to the fault zones, the high variability of P- and S-wave velocities in Fig. 3 is due to the heterogeneity of the volcanic fragmental rocks and alteration. Correlations between logs and lithology/alteration are difficult to establish in such a heterogeneous environment, especially when considering the numerous faults intersected in both boreholes. An analysis of acoustic impedance of alteration at New Afton shows higher mean values and a narrow distribution of acoustic impedance for the potassic-dominant potassic alterations relative to the other altered rocks (Bellefluer et al. 2018). In comparison, propylitic and phyllic alterations have a broader distribution of acoustic impedance and lower mean values. This suggests that reflections between potassic alteration (potassic-dominant) and other alteration zones are possible, but will depend on local context. The contact between potassic alteration and picrite at the bottom of both boreholes may also generate a detectable reflection. No petrophysical measurements confirm this but core samples from the picrite are intensely serpentinized and are mechanically weaker than core samples from the potassic zone. No core samples from the picrite unit below the potassic zone remained sufficiently intact to allow for later pressured velocity measurements. Geophysical logging tools did not reach the picrite located at the bottom of the two boreholes due to the presence of fallen rocks and debris that resulted from borehole reconditioning. Thus, our assessment of the reflectivity of the contact between potassic alteration and picrite is qualitative.

Densities and P-wave velocities from logs were compared with measurements made on core samples (Fig. 3). P-wave velocities were measured at various confining pressures, but only values obtained at atmospheric pressure and 30 MPa are shown in Fig. 3. A lithostatic pressure of 30 MPa corresponds to a depth of approximately 1.1 km when considering a constant density of 2.8 g/cm$^3$ (average value of core samples). Velocities from logs (Fig. 3) are lower than velocities of core samples at atmospheric pressure and significantly less than velocities obtained at 30 MPa. The comparatively lower velocities of the logs reflect the poor in situ rock conditions in the immediate vicinity of the borehole wall. In contrast, core samples for analysis were selected from the most solid and least fractured parts of the core to ensure that they could sustain the confining pressures used for velocity measurements. Velocities measured at atmospheric pressure include effects from porosity which reached 4% on some samples in EA17-197 (up to 10% elsewhere in the mine) and may partly explain their closer relationship with log values (Fig. 3). Velocities at 30 MPa are less affected by porosity and fractures and are more representative of intact rocks and away from fault zones. Some differences are also observed for co-located log and sample density measurements but differences are in general less significant than for velocities. Densities from logs have lower extrema values (2.46 to 2.99 g/cm$^3$) than samples (2.61 to 3.21 g/cm$^3$) but have a slightly higher mean value (2.86 versus 2.80 g/cm$^3$). The lower extrema values of density logs may also be caused by the locally fractured and damaged borehole wall conditions, and possibly due to difficulties in calibrating density logs done through drill rods with density logs done over a short open-hole section.

### VERTICAL SEISMIC PROFILING WITH DISTRIBUTED ACOUSTIC SENSING

The two boreholes surveyed with wireline logs were also instrumented with straight and helically wound fibre-optic cables for the vertical seismic profiling (VSP) survey. The straight fibre-optic cable comprised three standard single-mode fibres and one single-mode fibre engineered to increase the intensity of backscattering to the DAS interrogator (hereafter referred to as engineered fibre). The increase in backscattering is achieved by inserting low-reflectivity reflectors at regular distances along the engineered fibre. The straight fibre-optic cable was installed in both of the boreholes (Fig. 4). The helically wound cable had the same number and types of fibres as the straight cable and was installed only in borehole EA16-171. This cable configuration presented in Fig. 4 ensured that standard and engineered fibres were coincident within boreholes and reduced the number of cables to be deployed to a minimum (i.e. one for straight fibre-optic cable and one for
Figure 4 (a) Schematic diagram of fibre-optic cables installed in two boreholes at New Afton. All straight optical fibres in each borehole (i.e. three standard fibres and one engineered fibre) were built into one cable. A similar design was used for the helically wound cable deployed in EA16-171. Connections between the two boreholes required less than 3 m of fibre-optic cable. (b) Cross-section of boreholes EA17-197 and EA16-171 with installed cables, casing and cement. HQ-size casing is shown in EA16-171.

the helically wound cable). Standard optical fibres placed in the two boreholes were daisy-chained together to form an approximately 5-km-long continuous fibre joining the straight and helically wound cables (Fig. 4). The engineered optical fibres were also daisy-chained together but using standard optical fibres in the upward branches of each borehole (i.e. engineered fibre downward and standard fibre upward – see Fig. 4). In this case, standard fibres were used to allow daisy-chaining of engineered fibres while reducing the cost of fibre-optic cables. Two different DAS interrogators were used for the VSP survey. A standard DAS interrogator was attached to the standard fibres (this combination of interrogator and fibre is hereafter referred to as the V2 system; see Fig. 4), and a new generation of DAS interrogator was used for the daisy-chain that included the engineered fibres (hereafter referred to as the V3 system). The new DAS interrogator was specifically designed to take advantage of the reflectivity characteristics of the engineered fibre. The V3 DAS system produces signal-to-noise ratios higher (by up to 20 dB) than those obtained with standard optical fibres and in general comparable with signal-to-noise ratio of geophones (Correa et al. 2017). Seismic waves from each source were recorded every 0.25 m along
the standard fibre-optic cable and every 1 m along the engineered fibre-optic cable using a sampling rate of 0.5 ms. Final field data from the V2 system were resampled to 1 m by the service company using a proprietary weighted-mean stacking method designed to attenuate system-generated noise (see Daley et al. 2016 for benefits of a similar stacking method). The gauge length utilized during recording with both DAS systems was 10 m. The gauge length is the physical interval along the optical fibre over which the difference between the phases of backscattered signal is measured and used to compute strain rate (Hartog 2018). The gauge length is the main factor controlling the spatial resolution of DAS data. A trace spacing less than the gauge length is generally used during acquisition as data for overlapping gauge lengths generally improve the clarity of events, especially those related to slower waves (Hartog 2018). The same gauge length was used for both straight and helically wound fibres.

**Fibre-optic cable installation in open hole**

In a mining environment, borehole geophysical surveys are typically conducted in open-hole conditions. At New Afton, the poor integrity of borehole walls prevented the deployment of fibre-optic cables in open hole. Dummy probe tests invariably encountered blocked boreholes within the first 200 m from the collar. To prevent borehole collapse during the VSP surveys, fibre-optic cables were installed through drill rods to ensure they would reach the bottom of each borehole. Fibre-optic cables were attached approximately every 4 m to a steel string cable kept under tension with a weight (one steel bar of approximately 35 kg was used in EA17-197, whereas two bars were used in EA16-171). A 19-mm diameter grout tubing was also attached to the steel and fibre-optic cables. This cable assembly was lowered gradually to the bottom of each borehole through drill rods. All fibre-optic cables were cemented in place with the grout tubing and steel cable. The straight fibre-optic cable in EA17-197 was cemented after drill rods were removed from the borehole. Drill rods were left in place and cemented together with the straight and helically wound cables, grout tubing and steel cable in EA16-171. Hydraulic cement pumped through the grout tubing gradually filled the boreholes from the bottom up to the collar. In EA16-171, grout reached surface from both the inside and outside of drill rods, suggesting a proper cementing procedure for drill rods and cable assembly. Grout cured for a period of a month prior to the VSP survey. During this time, the steel string cables were kept under tension to ensure that the fibre-optic cables would remain as straight as possible.

**Sources**

When working in active mine sites, the geometry of the local surface culture plays a strong role in the experimental design. At the New Afton Mine site, surface infrastructure includes a mill, offices, a warehouse, the portal to the underground ramp, tailing ponds and dams. The open pit of the old Afton mine (Fig. 1) was avoided due to slope stability issues. The area immediately southwest of the open pit was also avoided due to subsidence associated with block-caving mining operation. In addition, the trans-Canada highway, two high-pressure gas pipelines, numerous power lines and environmental concerns raised with regard to the protection of a vulnerable spadefoot toad species were addressed during the planning of the survey. These limitations restricted the seismic source placement and did not allow for the deployment of either a regular grid or straight lines of source points. The final authorized survey plan included 50 shot locations located in four clusters (Fig. 1). Most shot points (25) were located in cluster A west of the open pit. At each source location, 1 kg of pentolite explosive with two electronic detonators was placed in a 20-m deep shot hole. Each shot hole was tamped with 90 kg of bentonite mixed with water and drilling sand. Synchronization between surface shots and underground DAS recording units was done with GPS time. A high-precision clock synchronized at surface with GPS time was brought underground and used to keep the time of continuous seismic records on both DAS systems. GPS time stamps recorded at the firing time of each shot point served as the basis to extract simultaneous shot gathers from continuous recording on DAS systems.

**Field data**

In general, the quality of the data is good to excellent for shot points located west of the open pit (cluster A in Fig. 1). Shot holes in this cluster were drilled in competent rocks exposed at surface. Excellent records were also obtained for three shot points located in cluster B north of the trans-Canada highway (Fig. 1). Other shot points in clusters C and D (Fig. 1) provided poor to fair quality data, most likely because they were located in soft unconsolidated sediments and because they were further away from the two boreholes instrumented with fibre-optic cables. Shot records with good to excellent data quality are used for the analysis presented in this paper.

Figure 5 shows channel strips obtained for shot point 8 with both DAS systems (see Fig. 1 for shot location). The equivalent of three VSPs (i.e. data recorded with optical fibre
going downward) was acquired with one seismic source. The channel strip for V3 data contains two zones with strong noise corresponding to parts of the cable with upward standard optical fibre (i.e. between channels 695–1340 and 2165–2980 in Fig. 5a). Data in those two zones are not usable because the V3 DAS interrogator was calibrated for the engineered fibre rather than for standard optical fibre. The V3 DAS interrogator can be calibrated for standard optical fibre, but not for both standard and engineered fibres at the same time. In comparison, data from both downward and upward branches of the fibre-optic cable of the V2 channel strip are usable (Fig. 5b) and are mirror images with an axis of symmetry located at the bottom of each borehole. Thus, data from the two DAS systems were compared only for channels

Figure 5 Channel strips showing all traces recorded along the daisy-chain with (a) a combination of engineered (V3 system) and standard optical fibres and (b) standard optical fibre (V2 system) for one explosive charge fired at shot point 8 (see Fig. 1 for location). Distance between traces is 1.021 m. Traces between DAS interrogators and the collar of the first borehole and for the upward branch of helically wound fibres in EA16-171 are not shown. Fibre-optic cables at surface between boreholes cover a limited number of channels which are not clear at the scale of the plots. Traces corresponding to those channels were excluded from the VSP data. Source–receiver offsets of data shown on Fig. 5 ranged from 760 m at the collar of both boreholes to 1460 m at the bottom of EA16-171 (i.e. at channels 2160 and 3890, respectively). Constant gain has been applied for display in (a) and (b). Labelled phases are A: direct P-waves; B: downgoing S-wave; C and D: weak upgoing reflections. Arrows E and F point to specific direct P-wave arrivals discussed in the text.
corresponding to downward parts of fibre-optic cables. In those parts, the first arrivals, other downgoing waves and weak reflections have almost identical amplitudes on V2 and V3 data (Fig. 5). However, a significantly higher noise level is observed throughout the entire V2 channel strip (Fig. 5b).

This is particularly clear before direct P-wave arrivals and at late times (i.e. after 0.4 s) on V2 data from straight and helically wound cables. Differences in noise levels between the V2 and V3 systems are best demonstrated by comparing coincident seismic traces extracted from the channel strips (Fig. 6a). On such traces, the direct arrivals and strong coda just after have almost identical amplitudes on both DAS systems. Random noise is significantly higher on the trace recorded with the standard fibre-optic cable (V2 in Fig. 6a).

Comparison of root-mean-square (RMS) amplitudes of noise estimated in a window comprising the first 100 samples (50 ms) of all traces from shot point 8 in borehole EA17-197 shows that noise is on average 17 dB lower on the V3 DAS system. Random noise differences of individual traces range between 5 and 21 dB. Signal-to-noise ratios are on average 13 dB higher for the V3 system, with differences ranging between 4 and 19 dB for individual traces. Signal-to-noise ratios were calculated by dividing the RMS amplitude estimated in a 50-ms window starting at the onset of the direct arrivals by the RMS amplitude of noise in a 50-ms window starting at the beginning of each trace. The above signal-to-noise ratios are for relatively large source–receiver offsets, which range from 760 m at the collar of both boreholes to 1460 m at the bottom of EA16-171. A comparison of the signal-to-noise ratio of data acquired with the identical V2 and V3 systems (straight cables only) at the Otway CO₂ sequestration site shows similar average differences for shot points located 680 m and 1025 m from the well (Correa et al. 2017).

Figure 6  Comparison of traces between (a) trace 75 from V2 and V3 DAS data in EA17-197 (straight fibre-optic cable) and (b) trace 200 from straight and helically wound fibre-optic cables in EA16-171 (V3 only).

Helically wound fibre-optic cable

A straight fibre-optic cable is most sensitive to strain induced along the direction of the fibre (i.e. axial or longitudinal
strain). For P-waves, the sensitivity of DAS decays as the square of the cosine of the angle between the direction of the wave propagation and the fibre-optic cable (Mateeva et al. 2014; Kuvshinov 2016). Thus, straight fibre-optic cables are not best suited to record the complete wavefield resulting from complex geological settings often typical of mining environment, especially when fibre-optic cables are deployed in boreholes with deviated geometry and shot locations have a broad spatial distribution. For example, calculations assuming straight ray paths indicate that the contact between volcanic fragmental rocks and picrite (Fig. 2) would generate downgoing reflections arriving with large angles of incidence relative to the fibre-optic cable located in the two boreholes. For these calculations, the contact between volcanic fragmental rocks and picrite was assumed to be a vertical plane intersected at the bottom of the two boreholes. Angles of incidence of P-wave reflections (i.e. incident angle measured relative to the long axis of the cable) from that contact ranged between 35° and 89° for shot points in cluster A. Higher incidence angles are obtained in the upper part of both boreholes for all shot locations (i.e. > 80°).

The helically wound fibre-optic cable was installed in EA16-171 to increase directional sensitivity to reflections arriving with such high angle of incidence on fibre-optic cables. Some field tests previously demonstrated the broadside directional sensitivity of the helically wound cable (Mateeva et al. 2014; Freifeld et al. 2016; Hornman 2017). The helically wound cable at New Afton has a diameter of 25 mm and a wrapping angle of 30°. Kuvshinov (2016) demonstrated that this wrapping angle provides a response that is almost independent of the angle of incidence of seismic waves when the helically wound cable is in direct contact with the hosting soft rock formation (i.e. unconsolidated sediments). When in contact with hard rock, the same wrapping angle has an increased sensitivity to P-waves arriving with a larger angle of incidence (see discussion).

The channel strips provide a first-order comparison of data recorded with straight and helically wound fibre-optic cables with both DAS systems (Fig. 5). This comparison shows that all events common to both fibre configurations have systematically lower amplitudes on the helically wound cable. For instance, amplitudes of direct arrivals near the top of borehole EA16-171 are noticeably lower for the helically wound cable than for the straight cable (compare amplitudes of direct arrivals indicated by arrows E and F in Fig. 5a and 5b). Figure 7 further compares raw field data obtained with straight and helically wound fibre-optic cables in EA16-171 for shot point 35 (V3 data only). Data from the straight fibre are characterized by strong direct P-waves, direct S-waves, a strong and complex downgoing wavefield, and several weaker reflections (Fig. 7b). The exact cause for the strong and complex downgoing wavefield is not known but possibilities include multiple reflections and wave-mode conversion at fault zones or lithological contacts, some likely located above the collar of the two boreholes. Reverberations near the source may also explain the complex downgoing wavefield in Fig. 7(b). In comparison, data from the helically wound cable contains weaker direct P- and S-waves, a very weak downgoing wavefield, and almost no reflections (Fig. 7c). This observation unfortunately also applies to separated upgoing waves (not shown but see the next section below for details on data processing) after data processing. Similar reduced amplitudes are observed on data recorded with helically wound cable from other shot locations. Figure 6(b) compares two traces recorded at the same depth on straight and helically wound cables and also shows weaker signal amplitudes for the helically wound fibre. However, noise levels are similar on both fibre configurations.

RMS amplitudes of direct arrivals calculated using a 25-ms window for co-located traces on straight and helically wound cables (V3 system only) for shot point 35 are on average 11 dB higher for the straight optical fibre (Fig. 7a). This difference is not constant over the entire length of the borehole. RMS amplitudes of direct waves are 12.5 dB higher for the straight cable near the top of borehole EA16-171 (i.e. top 215 channels) and 9 dB stronger near at the bottom of that hole (Fig. 7a). The angle of incidence of direct P-waves at the fibre estimated using straight ray paths on both cables is approximately 40° and 25° in the upper and lower parts of the borehole, respectively (Fig. 7a). Thus, direct P-wave amplitudes on straight cable are larger than amplitudes of the same arrivals on helically wound cable for larger angles of incidence. This observation is counterintuitive when considering only the cos² sensitivity of the straight cable with angle of incidence and the greater sensitivity of the helically wound cable with higher angles of incidence (i.e. when the helically wound cable is in direct contact with hard rocks – see discussion). Differences of direct P-wave amplitudes are less important near the bottom of the hole where angles of incidence are smaller.

**Coupling with borehole wall**

Data recorded with straight fibre-optic cable in EA16-171 comprises several noisy traces in the upper part of the borehole (see traces from the V3 system indicated with vertical arrows in Fig. 7b). In particular, noisy traces near channels 90 and 215 on the straight cable suggest poor coupling of fibre-optic
Figure 7  Comparison of field VSP data in EA16-171 for shot point 35 located in cluster B (Fig. 1). (a) Ratio of direct P-wave RMS amplitudes on data from straight cable and helically wound cable ($20 \log \left( \frac{\text{RMS}_{\text{straight}}}{\text{RMS}_{\text{hel}}}} \right)$) and angle of incidence of direct P-wave on straight fibre-optic cable. (b) VSP data for the straight V3 fibre-optic cable. (c) VSP data for the V3 helically wound fibre-optic cable. The helically wound optical fibre has more channels than the straight fibre for the same length of cable due to the wrapping around the cable core (i.e. 925 channels for the helically wound cable versus 813 for the straight fibre-optic cable). Vertical arrows point to noisy channels. White arrows indicate upgoing reflections. Arrows C and D point to events of the downgoing wavefield with moveout of P-waves and S-waves, respectively. Events D arrive before the direct S-wave and are likely the result of P-to-S conversion at a lithological contact or fault zone. The same display gain was used for (a) and (b). Horizontal banding observed across all channels is optical noise.
cables and/or drill rods with the borehole wall. Such noise is typical of un-cemented or not properly cemented casing and is caused by local casing resonance (Hardage 2000). Density and calliper logs at channels 90 and 215 indicate the presence of fault zones that likely explain noisy traces on the straight cable. Noisy traces are also observed on data from helically wound cable (see vertical arrows in Fig. 7c) but resonance noise on those channels is not as strong as on the straight cable. This observation is in agreement with analysis of 3-C geophone data which indicated that resonance due to poor coupling mostly affects vertical geophones (Gal’perin 1974). The helically wound cable profile also shows the existence of tube waves (Scholte waves) that propagated down and up between fault zones at channels 90 and 215 (Fig. 7c), indicating the presence of liquid and incomplete grouting over that depth interval. Tube waves are observed on helically wound fibre-optic cable from several shot locations but are most obvious on data from shot point 35 (Fig. 7c). Tube waves are usually observed inside liquid-filled boreholes and can be generated by downgoing P-waves intersecting open fractures or rugose borehole (e.g. Chan and Schmitt 2015). They have a longitudinal particle motion in the centre of a borehole with radial particle motion increasing towards the borehole wall and being maximum at the fluid-formation boundary (Cheng and Toksöz 1982; Hardage 2000). The amplitude of tube waves drops exponentially when propagating in the rock formation away from the borehole. At New Afton, tube waves are not observed on data from the straight fibre-optic cable (Fig. 7b), suggesting that the cement inside the drill rods cured properly and contains no liquid. Tube waves likely propagated in the annulus between the drill rods and rock formation rather than within drill rods. Practically, the tube waves indicate that drill rods were not properly cemented between the two fault zones in EA16-171. Thus, poor coupling likely explains the difference in RMS amplitude of direct P-wave arrivals for straight and helically wound cables in the upper part of EA16-171. Poor coupling may also explain the generally lower amplitudes observed throughout data acquired with helically wound cable (see discussion). Fault zones intersected in the other borehole (EA17-197) appeared to have been sealed properly as no traces with vertical noise are observed on data from the straight fibre-optic cable (Fig. 5). This straight cable was cemented in place without drill rods.

PROCESSING AND IMAGING RESULTS

The vertical seismic profiling data recorded with straight fibre-optic cable and V3 distributed acoustic sensing (DAS) interrogator for shot points located in cluster A were further processed and migrated to generate an image of the subsurface. Data from the helically wound cable or acquired with the V2 system were processed but not migrated due to the lack of reflections (helically wound cable) or lower signal-to-noise ratio (V2 data). Data processing aimed primarily at extracting the upgoing wavefield which was used for depth imaging. Processing included depth calibration of DAS channels, numerical integration of the measured signal with respect to time to convert strain rate to strain and align phases to geophone-like data (Daley et al. 2016), spectral balancing combined with band-pass filtering, fk filtering to remove downgoing waves, median filtering to remove optical noise banding and muting of direct arrivals. Explosives in shot points from cluster A generated signal with frequencies as high as 350 Hz but only frequencies between 15 and 225 Hz (15–25–180–225 Hz) were preserved on processed data.

Depth imaging requires true coordinates of receiver locations in boreholes which are typically obtained from a relation connecting the measured receiver depths along a borehole to a deviation survey referenced to a known coordinate. Determination of the depth of DAS measurements is not straightforward because, unlike geophones, receiver positions along the fibre-optic cable are not referenced to a physical marker on the borehole (Madsen, Tondell and Kvam 2016; Dean et al. 2018). At New Afton, depth calibration was accomplished by using a series of tap tests done directly on the fibre-optic cables exposed at the collars of the two boreholes, allowing determination of channel numbers along the optical fibre at entry and exit points in boreholes. Symmetry of the data was used to determine the deepest channels along the daisy-chain with standard fibre. Deepest channels for the engineered fibre were determined from the change of character of the data that coincide with the junction of the engineered and standard optical fibres at the bottom of each borehole (Fig. 5a). Receiver depths along each borehole were distributed linearly between channels at the collar and bottom of each borehole. The maximum depth of all fibre-optic cables is slightly above the bottom of holes reached during original drilling. The presence of drilling mud, cuttings, fallen rocks and the steel bar used as a weight and attached at the lower end of the cable assembly prevented deployment of fibre-optic cables to the bottom of the two boreholes. The deepest position of all fibre-optic cables is above the contact between the mineralized zone and the picrite unit (see Fig. 2). This contact and the picrite beneath it were intersected and cored during drilling.
Figure 8 shows an example of processed data from shot point 8 in borehole EA17-197. Lithology, alteration and some geophysical logs are also shown in this figure. Several reflections indicated by arrows intersect the borehole. Reflections A, B and C in the upper part of the borehole coincide with faults determined from low-density values on logs. Low P-wave velocities and low acoustic impedance values are also observed for reflection A. Reflection D is located in an area with no anomalies on any of the logs. In addition, no lithological contacts or changes in alteration are observed at the location of this reflection. Thus, reflection D remains unexplained. Reflection E is located at a lithological contact (between Bxf and Bxff in Fig. 8) which is almost coincident with a change of alteration (between Kk and Kb in Fig. 8). Velocity logs do not show significant variations on either side of reflection E. A similar observation is made from the density log which, however, does not extend significantly below reflection E (i.e. within the Bxff and Kb in Fig. 8). Thus, logging data appear to preclude both lithological and alteration contact as plausible causes of reflection E. All logs have low values at the location of reflection E, suggesting that a fault explains this reflection. Reflection F does not intersect the fibre-optic cable but originates just below the deepest DAS channel in this borehole. A possible cause for this reflection is the contact between volcanic fragmental rocks with biotite-dominant potassic alteration and picrite. Alternatively, a fault mapped at that contact may also explain reflection F. Note that not all intervals with low density and low velocity values produced reflections (white arrows in Fig. 8). Some of those intervals may be related to caved-in zones that affected only the immediate vicinity of the borehole, or faults may exist at those locations but they may be too thin to be detected on
DAS-VSP data. Reflections that do not intersect the borehole are also observed on the DAS-VSP data (yellow arrows in Fig. 8).

**Migration of DAS-VSP data**

VSP data acquired with a limited number of sparsely distributed shot points are known to create images of the subsurface characterized by numerous migration artefacts and ambiguous positioning of reflectors (Mueller et al. 2012). A few methods were developed to help reduced migration artefacts from such VSP data. Lou, Cheng and Doherty (2009) suppressed migration artefacts by selecting appropriate VSP aperture angles and using a damped least-squares smoothing method to reduce acquisition footprint and noise. Cosma, Balu and Enescu (2010) enhanced VSP reflections originating from planar contacts or structures by applying the image point transform and coherency filtering in the image point domain. The application of the inverse of the image point transform followed by migration results in migrated image with fewer artefacts. Here, we considered the directional sensitivity of the straight fibre-optic cable to reduce migration artefacts due to the VSP acquisition geometry. The directional sensitivity was taken into account with weights determined at each point of the image space (e.g. final depth volume defined with x, z, z coordinates) and applied during migration of the data.

The velocity model used for depth imaging was obtained with traveltime tomography of direct P-wave arrivals following the approach of Huang and Bellefleur (2012). This approach combines a grid-based Eikonal equation solver for traveltime calculations and the adjoint-state technique to obtain the gradient of the objective function to update the velocity model iteratively. We utilized a 3D version of this approach using traveltimes of direct P-waves as input data and a starting model having a constant velocity of 5400 m/s. This velocity is determined from source-receiver offsets and direct P-waves traveltimes. The velocity model volume is not extensive but comprises shot points from cluster A and is extensive enough to image reflectors possibly originating east and south of the boreholes (see Fig. 1 for the extent of the velocity model). The model extends to a maximum depth of 1550 m. Shot points located in clusters B, C and D were excluded from tomography because they would have required a significant extension of the model size while not adding sufficient information to properly estimate velocities in such an extended model. A total of 35,616 direct arrival traveltimes recorded in the two boreholes were used for tomography. The model has a cell spacing of 10 m in all directions and comprises a total of 988,416 cells (88 × 72 × 156).

The final velocity model obtained from tomography is not particularly robust given the sparse distribution of shot points and receiver positions limited to two boreholes. Tomography mostly updated velocities between shot and receiver positions while leaving velocities in areas south of all shot points and north of the two boreholes at their starting values (i.e. 5400 m/s). Similarly, areas directly beneath shot points and directly above the two boreholes remained unchanged after tomography. Convergence was achieved by using a regularization based on a low pass spatial filter with a cut-off value of 60 m. This regularization produced a relatively smooth velocity model that reproduced the measured traveltimes accurately. RMS misfit values decreased from 12.5 to 1 ms in 10 iterations. Velocities in the final model range from 3750 to 5700 m/s (Fig. 9). They are in general higher than velocities from logs, and between measured velocities of samples at atmospheric pressure and 30 MPa.

**DAS migration weights**

The velocity model obtained with traveltime tomography was used for depth imaging of the DAS-VSP data. Depth imaging was achieved using a 3D Kirchhoff depth migration algorithm (Miller and Oristaglio 1987). Two migration weights were used instead of standard migration parameters limiting the aperture and dips on depth images. The first weight excluded points in the image space that would produce a reflection going downward towards the receivers. Such downgoing reflections may exist on the VSP data but are not part of the upgoing wavefield used for migration. Points in the image space potentially producing downgoing reflections were simply assigned a weight of zero, whereas points properly located for upgoing reflections had a weight of one. The second weight is DAS-VSP specific and is based on the angle of incidence of ray path from all points in the image space on the straight fibre-optic cable. The weight applied at one point in the image space is the cosine square of the angle of incidence of the ray path from that point to a specific receiver position in one borehole. Both weights assume that any point in the image space is a potential reflector/scatterer and were determined using ray paths between reflector/scatterer points and receivers. Ray paths were calculated with grid-based raytracing by back-tracking a hypothetical wavefront originating from a receiver position. This consisted in following the reversed direction of the gradient of traveltimes calculated for a receiver to all points in the image space (Rawlinson,
Figure 9 Results from direct P-wave traveltime tomography. (a) Depth slice at 1 km and (b) vertical section through the final velocity model. Red dots in (a) show the location of the shot points.

Hauser and Sambridge (2008). Both weights determined for each source–receiver pair were multiplied together and used to scale migration amplitudes at each point of the image space. Traveltimes used for depth imaging were calculated for source to image point and image point to receiver also with grid-based raytracing in the final tomography velocity model.

In practice, weights defined from the angle of incidence of reflected waves on the fibre-optic cable enhance positions in the image space that are likely to exert longitudinal strain on the straight fibre-optic cable. Those weights act like an aperture-limiting parameter but they are determined from the direction of the fibre-optic cable in the borehole. An example of such weights for one receiver position near the collar of EA17-197 is shown in Fig. 10(a). Figure 10 also compares vertical and horizontal sections obtained without and with the migration weights described above. Sections with weights still contain artefacts, but they are significantly reduced in comparison to migration results obtained using a full 3D aperture. Artefacts are more prominent away from the two boreholes (i.e. areas east and above EA17-197 and west and below EA16-171 in Fig. 10). Our migration results away from the boreholes are not reliable for geological interpretation due to the remaining artefacts.

The vertical section (Fig. 10c) shows many reflectors with a moderate dip to the north. In plan view (Fig. 10e), the reflectors are sub-parallel to the contact between volcanic fragmental rocks with potassic alteration and the picrite unit intersected at the bottom of both boreholes, indicating that the true dip of the reflectors is approximately to the NW. Such shallow dips are not characteristic of the main lithological contacts or contacts between different types of alteration observed on the 3D geological model of the New Afton deposit. A possible explanation is that these reflectors are due to fault zones that were intersected in boreholes and that have low acoustic impedances relative to host rocks (Fig. 8). The nearly vertical contact between volcanic fragmental rocks with potassic alteration and picrite and other sub-vertical contacts between different alteration types are not imaged due to geometrical considerations discussed previously in the subsection on helically wound fibre-optic cable. As discussed above, contacts with steep dips most likely generated downgoing reflections that were not unequivocally identified on downgoing wavefields recorded with straight and helically wound cables and, as a result, were not considered in the migration.

DISCUSSION

Several logistical factors complicated the acquisition of borehole wireline logs and distributed acoustic sensing vertical seismic profiling (DAS-VSP) data at New Afton. One important complication was the instability of the boreholes (i.e. faults and caved-in zones) that required the use of a drill rig for the wireline logging program and for the installation of fibre-optic
cables. Open-hole deployment of any instrument over the entire length of the two boreholes used in this work was simply not possible. The difficult borehole conditions increased the time required to complete the wireline logging programme by a factor of 3. A VSP survey with a string of conventional geophones would have been subject to the same time-consuming complications. To this end, the utilization of DAS simplified greatly the logistics and effort required to collect the VSP data.

Installation of fibre-optic cables in the two boreholes took approximately 2.5 days, including cementing but excluding reaming of the boreholes. The utilization of fibre-optic cable also simplified survey logistics by requiring only one dynamite charge per shot location. This reduced the number of shots and cost of the survey, and simplified the permitting process to use explosives at surface on the mine site. For example, 12 shots per source location would have been required for a

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**Figure 10** Results from the migration of V3 data recorded with a straight fibre-optic cable. (a) Vertical section showing migration weights based on the angle of incidence of reflected wave on the fibre-optic cable. The red dot shows the receiver position used to calculate the weights. (b) Vertical section through migrated results obtained with complete 3D aperture. (c) Vertical section showing migration results obtained with weights described in the text. (d) and (e) are slices at a depth of 1.35 km through migrated results obtained without (d) and with (e) migration weights. Dashed lines in (d) and (e) show the location of the vertical sections in (a), (b) and (c). White arrows point to migration artefacts. Yellow lines are a projection at surface of the northern limit of the picrite body intersected near the bottom of the two boreholes.
conventional slim-hole geophone system with 12 levels to obtain VSP data with a trace spacing of 5 m in the two boreholes used for our survey. The difficult borehole conditions at New Afton would have also required the presence of a drill rig for the deployment of geophones during data acquisition. At New Afton, DAS was a cost-effective alternative to downhole geophones, even when factoring in the cost of fibre-optic cables which were permanently installed only for this survey. The purpose here is not to provide a detailed cost–benefit analysis of DAS and geophones but rather to point to specific factors, including survey design, site characteristics and financial consideration that led us to choose DAS over geophones. DAS systems have advantages but are not appropriate for all situations. For instance, geophones are still the only option when three-component data are required to achieve the objective of a survey.

Deployment of the helically wound cable inside drill rods turned out to be relatively challenging for wireline depths beyond 500 m. A possible cause for this difficulty is friction between the helically wound cable (in fact the entire cable assembly that also included the 19-mm grout tubing) and drilling rods. The material used for mandrel core of the helically wound cable is relatively stiff and partly retained the curvature of the spool used to transport the cable. That curvature remained during the installation of the helically wound cable and likely increased friction within drill rods as more cable was being deployed in the borehole. At greater depths, the weight attached to the steel cable was less effective at pulling the cable assembly downwards. The helically wound cable was successfully deployed to the bottom of EA16-171 but deployment rates below 500 m were significantly slower. Attempts to remove drill rods after cable deployment but before cementation were unsuccessful. The cable assembly did not move freely inside drill rods and was moving up as rods were pulled out of the borehole. Thus, drill rods were cemented with the cable assembly in EA16-171. Having significant weights attached directly at the bottom of the helically wound cable could have helped to straighten the cable. However, this option was discarded due to concerns that heavy weight might have damaged the fibre-optic termination and/or helically wound cable. Meandering helically wound cable inside the borehole also suggests possible depth registration issues that cannot be solved easily for both straight and helically wound cables. The utilization of a mandrel core with minimal shape memory material would certainly facilitate future deployment of a helically wound cable in inclined and deviated boreholes.

Kuvshinov (2016) introduced a framework based on the reflectivity method (Kennett 1974) to evaluate strain induced by seismic waves in a helically wound fibre-optic cable. Using this framework, he demonstrated that a wrapping angle of 30° minimizes surface (Rayleigh) waves and provides a DAS response to P-waves that is nearly independent of the angle of incidence. Those results were obtained assuming a helically wound cable perfectly coupled to poorly consolidated sediments typically found near the surface. He also showed that cementing of the helically wound cable in such poorly consolidated rocks can reduce substantially the sensitivity of the DAS system to P-waves. Figure 11(a) shows results obtained with the approach of Kuvshinov (2016) when a helically wound cable...
Table 1 Properties and diameter of material used to generate Fig. 11

| Lamé Constant | \( \lambda (\rho V_p^2 - 2\rho V_s^2) \) | \( N (\rho V_s^2) \) | Diameter |
|---------------|---------------------------------|------------------|----------|
| Cable         | \( 3.0 \times 10^8 \) Pa   | \( 6.9 \times 10^8 \) Pa | 25 mm    |
| Hard cement   | \( 4.17 \times 10^9 \) Pa   | \( 6.25 \times 10^9 \) Pa | 77.8 mm  |
| Soft cement   | \( 1.39 \times 10^9 \) Pa   | \( 2.08 \times 10^9 \) Pa | 77.8 mm  |
| Casing (steel)| \( 9.94 \times 10^{10} \) Pa| \( 7.81 \times 10^{10} \) Pa | 88.9 mm  |
| Soft rock formation | \( 3.37 \times 10^9 \) Pa | \( 1.87 \times 10^9 \) Pa | Inf      |
| Hard rock formation | \( 3.57 \times 10^9 \) Pa | \( 1.23 \times 10^9 \) Pa | Inf      |

The two boreholes surveyed with wireline logs were instrumented with straight and helically wound fibre-optic cables for the VSP survey. The fibre-optic cables included standard fibres and a fibre engineered to increase the intensity of backscattering at the DAS interrogator. Field data from the V3 DAS system have lower noise level and higher signal-to-noise ratio. Amplitudes of events recorded with a helically wound cable are lower than amplitudes measured on a coincident straight fibre-optic cable. The reduced amplitudes on the helically wound cable are likely due to poor coupling of drill rods (casing) with rock formation and to a lesser degree to the presence of the drilling rods. Data from straight fibre-optic cable measured with the V3 DAS system were processed and used for depth imaging. Depth images benefitted from newly introduced migration weights that account for the directional sensitivity of straight fibre-optic cable and limit the extent of migration artefacts. Migration results show several reflectors with shallow dips to the northwest, some explained by faults intersected in the two boreholes used for the VSP survey. The nearly vertical contact between volcanic fragmental rocks with potassic alteration and picrite and other sub-vertical contacts between different alteration types most likely generated downgoing reflections that were not considered in the migration.

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DATA AVAILABILITY STATEMENT

Geological data and sections presented in this paper are proprietary and not shared. Field DAS data in SEGY format, wireline logs and rock property measurements on core samples used in this paper are public and in the process of being archived on a Government of Canada open data portal [https://open.canada.ca/en/open-data]. Please enquire with the first author for instructions to access the data during the archival process.

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