Seismic imaging of porphyry deposits with distributed acoustic sensing of fibre-optic cables: a summary of results at the New Afton Cu-Au mine, British Columbia

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Abstract: We present a summary of physical rock properties and vertical seismic profiling (VSP) results acquired with distributed acoustic sensing (DAS) in boreholes that intersect the main mineralized zone and alteration halo at the New Afton Cu-Au porphyry deposit, British Columbia. We used an advanced DAS system that achieves signal-to-noise ratio of conventional geophones but offers high-density sensing of the entire fibre-optic cable. Straight and helically wound fibre-optic cables specifically engineered for the advanced DAS system were installed in two boreholes and compared with conventional fibre-optic cables with similar configurations connected to a standard DAS interrogator. Comparison of raw field data and processed data of both systems demonstrates a significantly higher signal-to-noise ratio for the new DAS system. Processed VSP data show several reflections with shallow dips that are mostly explained by faults and fractures observed in wireline logs and intersecting the surveyed boreholes.

Résumé : Nous présentons un résumé des propriétés physiques des roches et des résultats de profilage sismique vertical (PSV) acquis au moyen de la détection acoustique répartie (DAS) dans des trous de forage qui recoupent la zone minéralisée principale et le halo d'altération du gisement porphyrique à Cu-Au de New Afton, en Colombie-Britannique. Nous avons utilisé un système DAS perfectionné qui permet d'obtenir un rapport signal/bruit comparable à celui des géophones classiques, mais qui offre une détection à haute densité sur l'ensemble du câble à fibres optiques. Des câbles à fibres optiques droits et à enroulement hélicoïdal spécialement conçus pour ce système ont été installés dans deux trous de forage et comparés à des câbles à fibres optiques classiques de configuration similaire reliés à un interrogateur DAS standard. La comparaison des données brutes de terrain et des données traitées montre un rapport signal/bruit nettement plus élevé pour le nouveau système DAS. Les données PSV traitées montrent plusieurs réflexions faiblement inclinées qui s'expliquent principalement par la présence de failles et de fractures recoupant les trous de forage étudiés et dont les traces peuvent être observées dans les diagraphies par câble.

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INTRODUCTION

Distributed acoustic sensing (DAS) is a distributed sensing technology that uses the optical scattering response to a laser pulse to measure changes in strain occurring along a fibre-optic cable (Hartog, 2018). Distributed acoustic sensing does not use point receivers but rather simultaneously senses 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). Distributed acoustic sensing also offers cost-effective solutions for mineral exploration, particularly for vertical seismic profiling (VSP) surveys, which are sometimes used to provide high-resolution images of the subsurface near known deposits or in prospective areas. Currently, there is a very limited number of published results on the application of DAS for mineral exploration and mining applications. One early example is the imaging of steeply dipping ore at the Kylylahti polymetallic deposit in Finland using DAS-VSP data (Riedel et al., 2018).

Here we present results from one of the first applications of DAS-VSP data for mineral exploration. We acquired DAS-VSP data as part of the Geological Survey of Canada's Targeted Geoscience Initiative (TGI) for the development of an integrated geophysical imaging and 3-D geological modelling research study of the New Afton porphyry deposit, which is part of the Canadian Cordillera and is located in 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, which provide geological constraints extending beyond 1.5 km in depth. At New Afton, we used an advanced DAS system recently developed by Silixa, which achieves signal-to-noise ratio of conventional geophones but offers high-density sensing of the entire fibre-optic cable. Straight and helically wound fibre-optic cables specifically engineered for the advanced DAS system were installed in two boreholes starting in a drill bay located approximately 650 m below the surface. Conventional straight and helically wound fibre-optic cables connected to a standard DAS interrogator were also deployed in the same boreholes for comparison purposes.

The results presented in this paper are a summary of comprehensive TGI work conducted at New Afton and recently published with open access rights in Geophysical Prospecting (Bellefleur et al., 2020). Here 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 fibre-optic cables. DAS-VSP data measured with straight fibre-optic cables were further processed and compared with geological and wireline logs. Reflections observed in processed data obtained with straight fibre-optic cables spatially correlate with fault and fracture zones intersected in the two boreholes used for acquisition.

NEW AFTON CU-AU PORPHYRY DEPOSIT

This summary of the local mine geology is based on drill core logging, 3-D geological modelling, and surface mapping recently conducted by New Gold Inc. (J. Lipske and D. Wade, unpub. rept., 2014). The New Afton Cu-Au porphyry deposit is dominantly hosted by fragmental and crystalline volcanic rocks of the Late Triassic Nicola Group and to a lesser extent by the 204 Ma Cherry Creek monzonite of the Iron Mask batholith; the latter is interpreted as the heat source that caused alteration and mineralization in this alkalic porphyry (Fig. 1). A subvertical southwest-plunging zone of primary hypogene mineralization, largely coincident with the potassic alteration zone, contains disseminated chalcopyrite and bornite. This hypogene ore zone is controlled structurally by two subvertical northeast-southwest-striking fault zones, known as the footwall and hanging-wall faults. The hanging-wall fault juxtaposes volcanic fragmental rocks with a subvertical body of serpentinized picrite. This tectonic contact within the incompetent serpentinized picrite is defined by a high-strain zone of ductile deformation rich in magnetite that locally confines a zone of calcic alteration. The primary hypogene ore zone is cut by numerous moderately to steeply dipping fault zones that controlled secondary hypogene mineralization of tetrahedrite 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.

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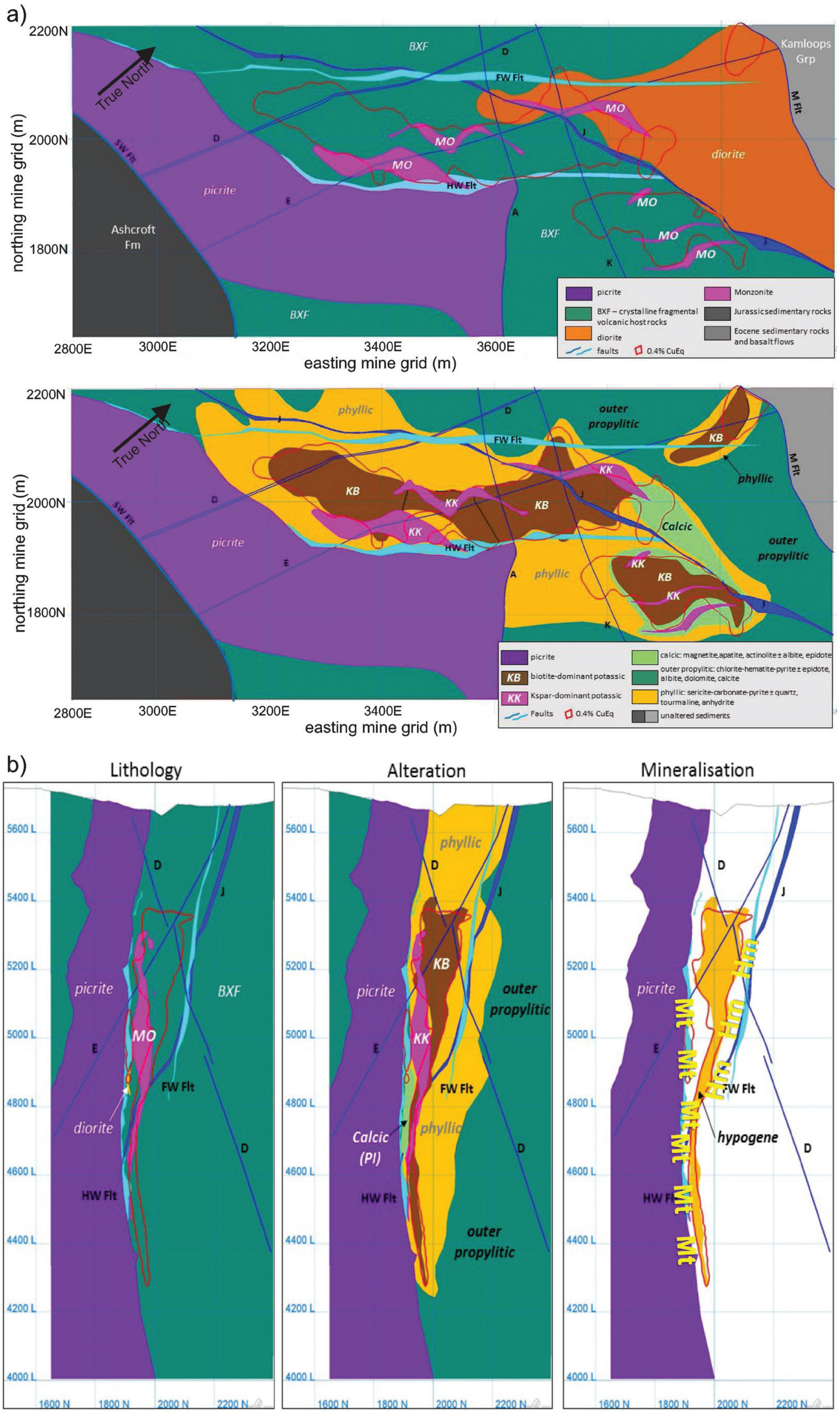
Figure 1. a) Plan view of the main lithological units (top) and main alteration zones (bottom) at New Afton. The main hypogene mineralized zone (0.4% Cu equivalent) is outlined in red with no color fill and coincides with the biotite-dominant and feldspar-dominant potassic alteration zone. HW Flt and FW Flt are the hanging wall and footwall faults, respectively. MO indicates monzonite. **b)** N-S sections showing lithologies, alteration, and mineralization. Mt and Hm in the mineralization subfigure refer to zones with magnetite and hematite, respectively; Pl stands for propylitic. Units are in mine grid co-ordinates (*from* J. Lipske and D. Wade, unpub. rept., 2014).


a)
2200N
2000N
1800N
northing mine grid (m)
True North
BXF
D
J
FW Flt
Kamloops Grp
M Flt
MO
diorite
SW Flt
picrite
E
HW Flt
A
Ashcroft Fm
K
2800E
3000E
3200E
3400E
3600E
easting mine grid (m)
picrite
BXF – crystalline fragmental volcanic host rocks
diorite
faults
0.4% CuEq
Monzonite
Jurassic sedimentary rocks
Eocene sedimentary rocks and basalt flows
phyllic
outer propylitic
KB
KK
Calcic
biotite-dominant potassic
Kspar-dominant potassic
Faults
calcic: magnetite, apatite, actinolite ± albite, epidote
outer propylitic: chlorite-hematite-pyrite ± epidote, albite, dolomite, calcite
phyllic: sericite-carbonate-pyrite ± quartz, tourmaline, anhydrite
unaltered sediments
b)
Lithology
Alteration
Mineralisation
5600 L
5400 L
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5000 L
4800 L
4600 L
4400 L
4200 L
4000 L
1600 N
1800 N
2000 N
2200 N
MO
Calcic (Pl)
hypogene
Mt
Hm

VERTICAL SEISMIC PROFILING WITH DISTRIBUTED ACOUSTIC SENSING

Figure 2 shows the survey area with locations of shot points and surface projection of the two boreholes and of the main hypogene mineralized zone. The mine site has infrastructure including mills, offices, subsidence zones, and tailings ponds that restricted areas where seismic sources could be deployed. The open pit of the old Afton mine was avoided due to slope stability issues. In addition, the presence of the Trans-Canada Highway, two high-pressure gas pipelines, and numerous power lines, along with concerns raised to protect a vulnerable spadefoot toad species, were addressed during the planning of the survey. The survey included 50 shot locations located in 4 clusters, with most shot points located southwest 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.

We acquired VSP-DAS data in boreholes EA16-171 and EA17-197 (Fig. 2), starting in a drill bay located approximately 650 m below the surface. The two boreholes start from the same drill bay but have different dip and azimuth. Borehole EA17-197 has a length of 701 m and borehole EA16-171 is 870 m long. Both boreholes are uncased and intersect numerous faults that tend to cave in, which complicated the acquisition of the open-hole wireline logs and the deployment of the fibre-optic cables. Straight, standard, single-mode and straight Constellation™

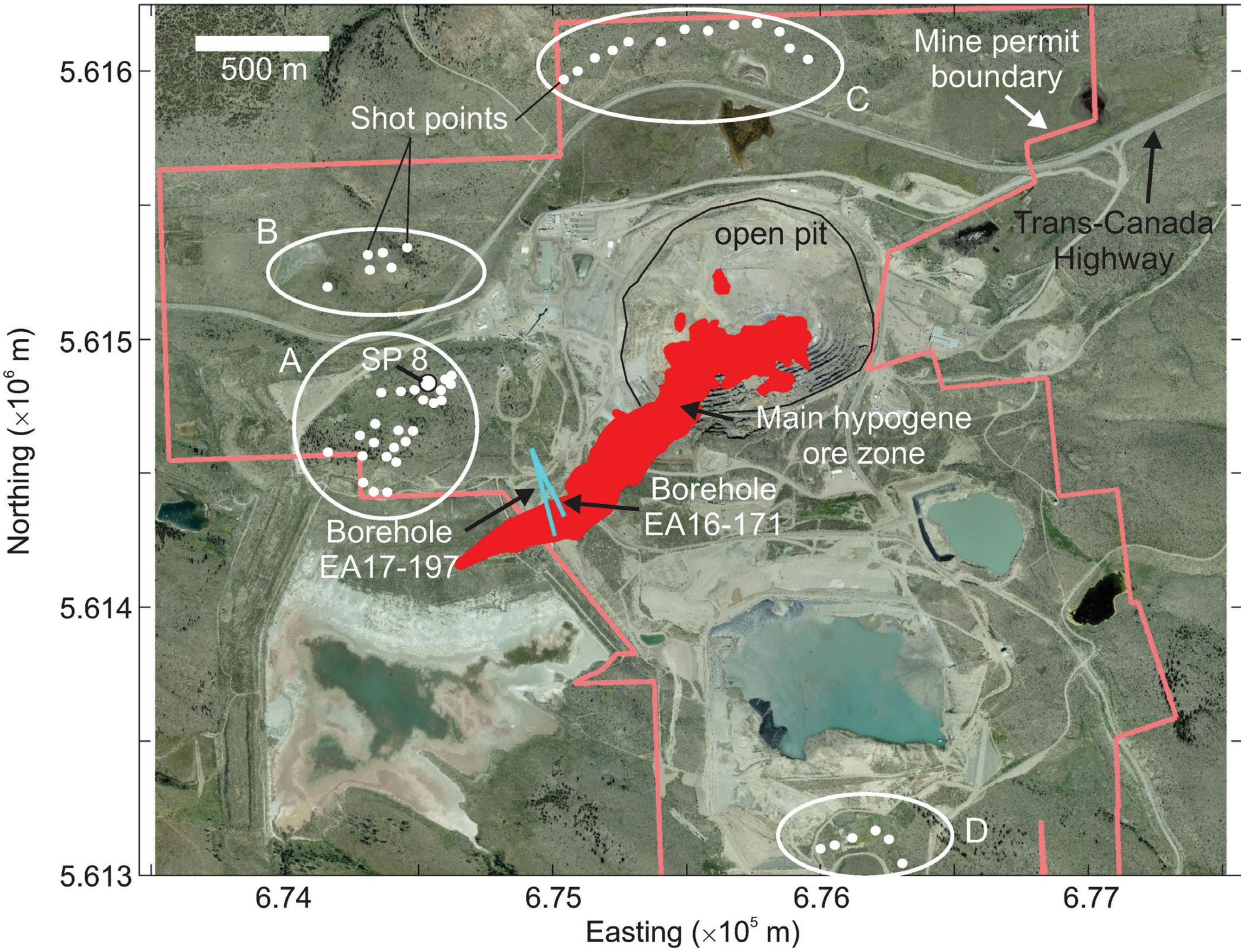

Figure 2. Surface locations of seismic shot points, surface projection of the two surveyed boreholes; and surface projection of the main hypogene mineralized zone. Seismic sources are located in four clusters labelled A, B, C, and D. Borehole EA17-197 and EA16-171 start from the same drill bay, located approximately 650 m below the surface. Borehole EA16-171 dips at approximately 70° and is 870 m long. Borehole EA17-197 dips at approximately 60° and is 701 m long.

single-mode (hereafter referred to as Constellation) fibre-optic cables were installed in the two boreholes. In addition, a helically wound single-mode fibre-optic cable containing both types of fibre was installed in borehole EA16-171. Standard fibre-optic cables placed in the two boreholes were ‘daisy-chained’ together to form an approximately 5 km long continuous fibre combining the straight and helically wound cables. The Constellation fibre-optic cables were also daisy-chained together. All fibre-optic cables were cemented in the boreholes to provide optimal coupling with rock formations.

Two DAS recording systems were used for the VSP survey: one for the standard fibre-optic cables (hereafter referred to as V2) and one for the Constellation fibre-optic cables (V3 — also known as the Carina® sensing system). The Constellation fibre-optic cables combined with the V3 recording unit provides seismic data with a higher signal-to-noise ratio, whereas the helically wound fibre-optic cable has enhanced transverse sensitivity relative to the straight cable, which is most sensitive to wavefields that exert longitudinal strain on the fibre. Seismic waves generated at each source location were recorded every 0.25 m along the standard fibre-optic cable and every 1 m along the Constellation fibre-optic cable using a sampling rate of 0.5 ms. Synchronization between surface shots and underground DAS recording units was done using GPS time. A high-precision clock synchronized at surface using GPS time was brought underground and used to keep the time of continuous seismic records. At surface, the GPS time stamp was saved at the firing time of each shot point and served as the basis to extract shot gathers from continuous DAS recordings.

Figure 3 shows the field data acquired for the straight fibre-optic cable in borehole EA17-197 at shot point 8 (*see* Fig. 2 for location). Figure 3a compares the field records for the V2 and V3 systems with the same gain display. Both V2 and V3 data show clear down-going waves and some weaker reflections. The signal-to-noise ratio is significantly higher for V3 data. Figure 3b shows the same data after the application of an f-k filter to remove down-going waves and first-break muting. Several reflections are observed on both V2 and V3 data. V3 data show more detail and clearer reflections, again due to a higher signal-to-noise ratio.

WIRELINE LOGGING AND PHYSICAL ROCK PROPERTIES

Wireline logs were acquired prior to the VSP survey from the same boreholes instrumented with fibre-optic cables (EA16-171 and EA17-197). Logging measurements included caliper, density, natural and gamma-ray spectrometry, magnetic susceptibility, resistivity, induced polarization, induction conductivity, and full-waveform sonic logs. Caliper, density, and sonic logs were used to support the interpretation of the DAS-VSP data. Additional physical rock property measurements were taken from core samples. In general, low density and velocity values exhibit a strong correlation with caved-in zones, indicated with large caliper values and corresponding to faults and/or fracture zones (*see* Bellefleur et al., 2020). The significant number of faults intersected in both boreholes further indicates that their response likely dominates the reflected seismic wavefield. Figure 4 shows violin plots of acoustic impedances (product of density and velocity) for the various lithological units and alteration types intersected in the boreholes. The feldspar-dominant potassic zones (Kk in Fig. 4) are characterized by higher acoustic impedances, suggesting that such alteration may be detectable on VSP data when juxtaposed against rocks with lower acoustic impedances.

RESULTS

Figure 5 shows an example of processed data from shot point 8 in borehole EA17-197. Lithological units, alteration, and some geophysical logs are also shown in this figure. Several reflections intersect the borehole and are indicated by arrows. 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 reported 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. 5), which is almost coincident with a change in alteration (between Kk and Kb in Fig. 5). Velocity logs do not show significant variations on either side of reflection E. A similar observation is made from the density log; however, the log does not extend significantly below reflection E (i.e. within the Bxff and Kb in Fig. 5). Thus, logging data appears to preclude both lithological and alteration contacts 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. 5). 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 locations that are too thin to be detected with DAS-VSP data. Reflections that do not intersect the borehole are also observed in the DAS-VSP data (yellow arrows in Fig. 5).

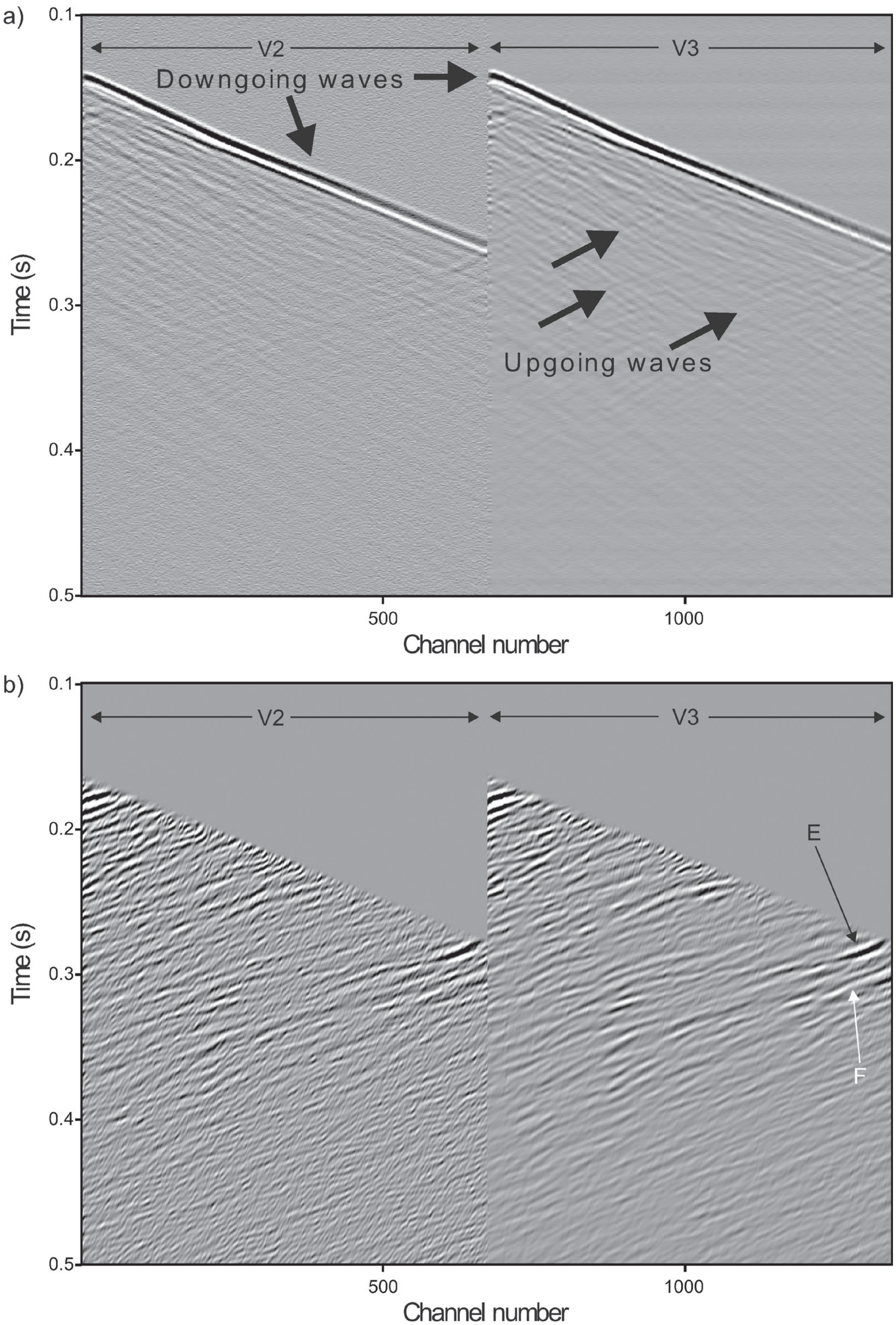

Figure 3. Comparison of standard DAS interrogator combined with a standard fibre-optic cable (V2) and the advanced DAS interrogator combined with the Constellation fibre-optic cable (V3) distributed acoustic sensing data sampled at 1 m intervals (one channel corresponds to 1 m) from EA17-197. The first channel is at 116 m above sea level, approximately 650 m below surface. **a)** Field data without any processing showing strong downgoing waves and some reflections. Both V2 and V3 data have the same gain for display. Signal-to-noise ratio is lower for the standard fibre-optic cable (V2) than for the Constellation fibre-optic cable (V3). **b)** Reflections and other upgoing signals after the application of an f-k filter and muting of first breaks. Arrows E and F point to reflections discussed in Figure 5.

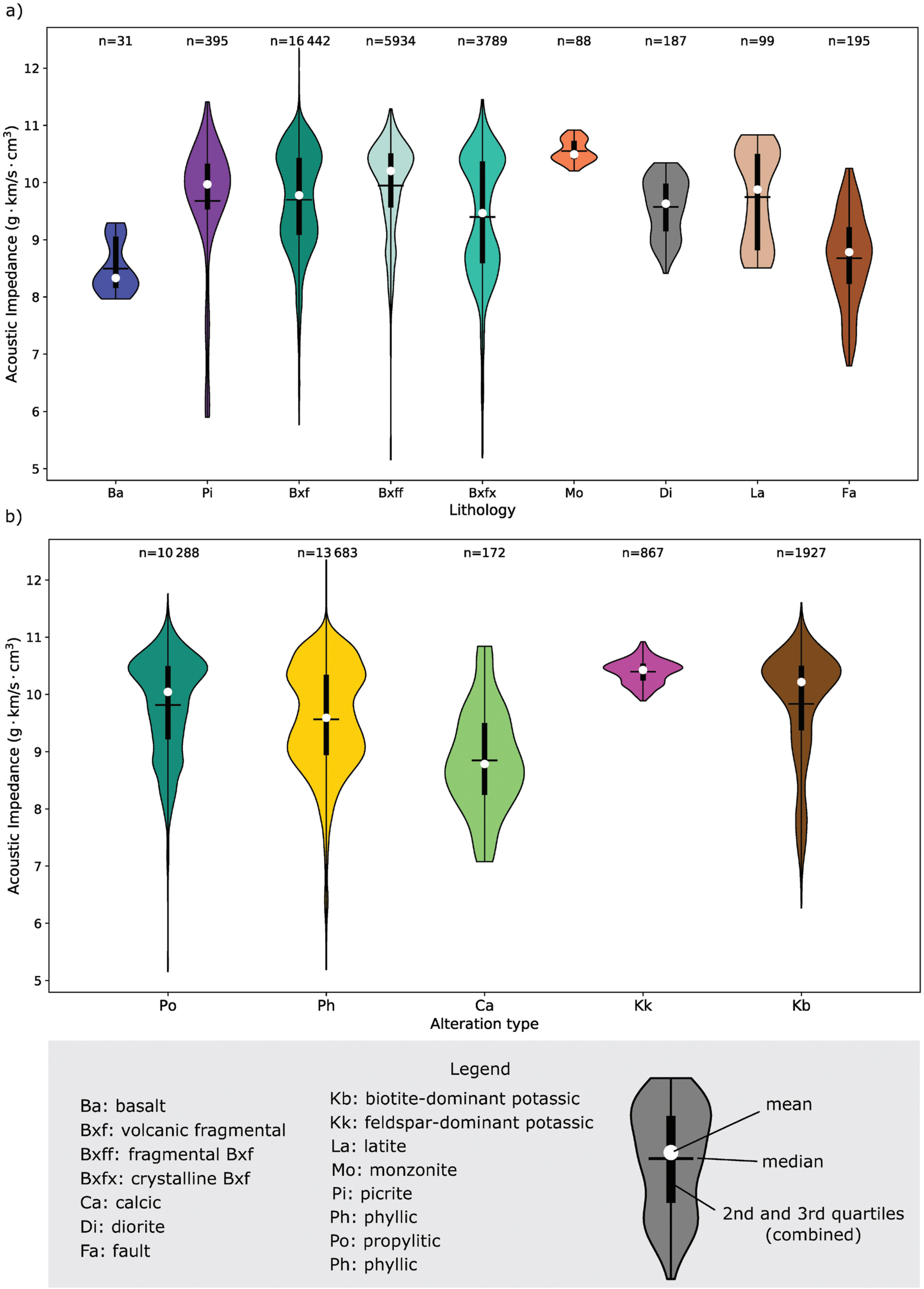

Figure 4. Distribution of acoustic impedance from logs for **a)** lithological units and **b)** alteration types at New Afton. Adjacent lithological units with sufficient acoustic impedance contrast will generate a detectable seismic reflection when juxtaposed.

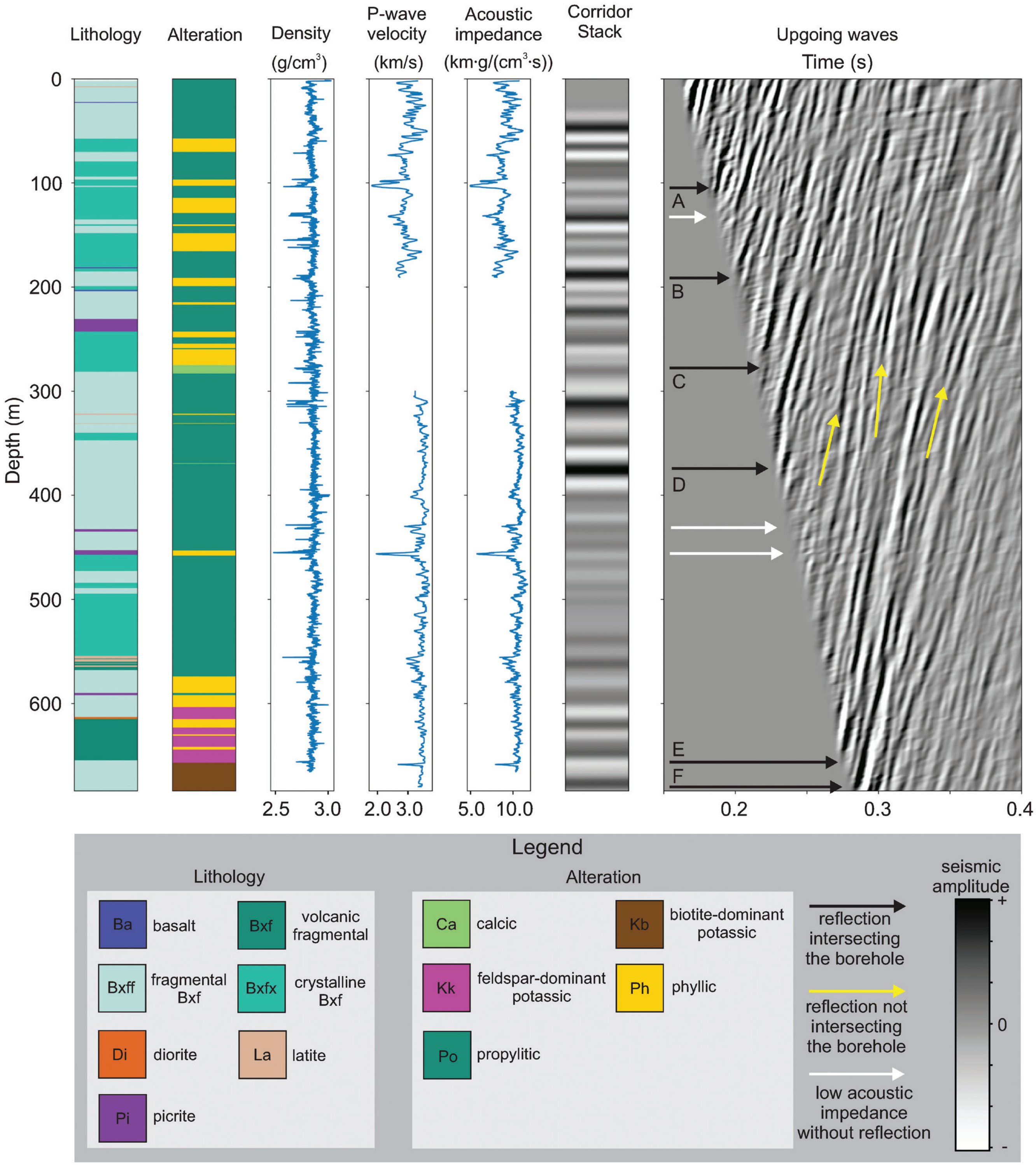

Figure 5. Lithology, alteration, density, P-wave velocity, acoustic impedance, seismic corridor stack (inside corridor stack), and upgoing waves (reflections) from the VSP data from borehole EA17-197. Arrows with labels (A–F) are discussed in the text.

ADVANTAGES OF DAS

Several logistical factors complicated the acquisition of borehole wireline logs and 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 the 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 program by a factor of three. A VSP survey with a string of conventional geophones would have been subject to the same time-consuming complications. To this end, the use of DAS greatly simplified 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 use of fibre-optic cable also simplified survey logistics by requiring only one dynamite charge per shot location. This reduced the number of shots and the cost of the survey and simplified the permitting process to use explosives at surface on the mine site. By comparison, 12 shots per source location would have been required for a conventional slim-hole geophone system with 12 levels to obtain VSP data with a trace spacing of 5 m in the two boreholes. 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 down-hole geophones, even when factoring in the cost of fibre-optic cables, which were permanently installed for this survey.

CONCLUSIONS

Wireline logs and DAS-VSP data were acquired from two boreholes intersecting the New Afton Cu-Au porphyry deposit located in south-central British Columbia. Wireline logs, and in particular caliper logs, revealed many faults and caved-in zones indicating generally poor rock conditions in the immediate vicinity of borehole wall. The significant number of faults and caved-in zones on logs suggests that their response may dominate the seismic wavefield. Logs also suggest that reflections between potassic alterations (i.e. between feldspar-dominant and biotite-dominant potassic alteration) and other types of alteration may be possible, depending on local geological context.

The use of DAS greatly simplified the logistics and effort required to collect VSP data at New Afton. This includes the use of only one dynamite charge per shot location to simultaneously collect V2 and V3 data in the two acquisition boreholes, which reduced the cost of survey and simplified the permitting process to use explosives for seismic surveying at the mine site. Comparison of raw field data and processed data of both DAS systems for straight fibre-optic cables demonstrated a significantly higher signal-to-noise ratio for V3 data. Reflections revealed by processingV3 data measured with straight fibre-optic cables show a strong correlation with fault and fracture zones intersected in the two boreholes. Although most of the imaged faults and fractures are significant for geotechnical characterization of the rock mass at the mine, their relationship with the ore zone, alteration, and ore genesis could not be unequivocally determined. Readers are invited to consult Bellefleur et al. (2020) for detailed information about the physical rock properties and VSP-DAS data acquired at the New Afton porphyry deposit.

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