Baird, A. F., Stork, A. L., Horne, S. A., Naldrett, G., Kendall, J-M., Wookey, J., Verdon, J. P., & Clarke, A. (2020). Characteristics of microseismic data recorded by distributed acousticsensing systems in anisotropic media. *Geophysics*, 85(4), KS139-KS147.
<https://doi.org/10.1190/geo2019-0776.1>

Peer reviewed version

Link to published version (if available):
[10.1190/geo2019-0776.1](https://doi.org/10.1190/geo2019-0776.1)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the author accepted manuscript (AAM). The final published version (version of record) is available online via Society of Exploration Geophysicists at <https://library.seg.org/doi/10.1190/geo2019-0776.1> . Please refer to any applicable terms of use of the publisher.publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

Characteristics of microseismic data recorded by Distributed Acoustic Sensing (DAS) systems in anisotropic media

A.F. Baird*, A.L. Stork*[†], S.A. Horne[‡], G. Naldrett[†], J-M. Kendall*[§], J.

Wookey*, J.P. Verdon* and A. Clarke[†]

**School of Earth Sciences, University of Bristol, Bristol, UK*

[†]Silixa Ltd., London, UK

[‡]Formerly: Chevron Energy Technology Company, London, UK

[§]Department of Earth Sciences, University of Oxford, Oxford, UK

(March 27, 2020)

Running head: **Microseismic DAS in anisotropic media**

ABSTRACT

Fiber-optic Distributed Acoustic Sensing (DAS) cables are now used to monitor microseismicity during hydraulic fracture stimulations of unconventional gas reservoirs. Unlike geophone arrays, DAS systems are sensitive to uniaxial strain or strain-rate along the fiber direction and thus provide a single-component recording, which makes identifying the directionality and polarisation of incoming waves difficult. Using synthetic examples, we show some fundamental characteristics of microseismic recordings on DAS systems for purposes of hydraulic fracture monitoring in a horizontal well in anisotropic (vertical transverse isotropy, VTI) shales. We demonstrate that SH arrivals dominate the recorded signals since their polarization is aligned along the horizontal cable at near offset, though SV will typically dominate for events directly above or below the array. The amplitude of coherent S-wave arrivals along the cable exhibits a characteristic pattern with bimodal peaks, the width of

21 which relates to the distance of the event from the cable. Furthermore, we find that shear-
22 wave splitting recorded on DAS systems can be used to infer the inclination of the incoming
23 waves, overcoming a current limitation of event locations which have constrained events
24 to lie in a horizontal plane. Low amplitude SV arrivals suggest an event depth similar to
25 that of the DAS cable. Conversely, steep arrivals produce higher amplitude SV waves, with
26 shear-wave splitting increasing with offset along the cable. Finally we show how polarity
27 reversals observed in the P and SH phases can be used to provide strong constraints on the
28 source mechanisms.

INTRODUCTION

29 In the last decade, fiber-optic technology has developed to use distributed acoustic sensing
30 (DAS) cables to measure the dynamic strain or strain-rate induced by seismic waves (Parker
31 et al., 2014). The technology has been increasingly used to acquire downhole seismic data,
32 predominately for vertical seismic profiling (VSP), but more recently also for monitoring of
33 hydraulic fracture stimulation (Karrenbach et al., 2019).

34 The technology makes use of Rayleigh scattering of light along the fiber optic cable.
35 An interrogator unit is used to send laser pulses into a fiber and detect the back-scattered
36 response due to interaction with inhomogeneities along the fiber. If the fiber undergoes a
37 localized strain, caused, for example, by a passing seismic wave, this lengthens (or shortens)
38 the fiber causing a phase shift in the back-scattered response. These changes in phase are
39 used to compute strain or strain-rate at a series of regularly spaced channels (or receivers)
40 along the cable. The strain that is computed is not a point measurement, but the average
41 value over a ‘gauge’ length along the cable centred at each channel.

42 DAS technology has a number of advantages over traditional geophone recordings. For
43 example, a cable can be several kilometers long with the strain field sampled at closely
44 spaced channels (on the order of meters), resulting in thousands of receivers and a very
45 dense wavefield sampling at a relatively low cost per sensor. Conversely, downhole geophone
46 arrays typically consist of 10s to 100s of receivers at a much wider spacing. Additionally
47 fiber optic cables can be deployed behind casing allowing the well to be used for other
48 purposes during monitoring, and allowing the ability to easily record and repeat surveys
49 over months to years.

50 The technology also presents a number of challenges that must be overcome for use

51 in microseismic monitoring. For example, the large volumes of data produced by DAS
52 systems may require the development of novel approaches, such as machine learning algo-
53 rithms, to quickly process and detect events in real time (e.g. Horne et al., 2019; Binder and
54 Chakraborty, 2019). Additionally, unlike conventional seismic sensors that measure particle
55 motion, DAS systems are sensitive to the uniaxial strain or strain-rate along the direction
56 of the fiber optic cable. As a result, the systems provide a single-component recording,
57 polarized in the cable direction rather than the standard three components provided by
58 geophones. Such differences lead to an ambiguity in the directionality of incoming waves,
59 and some of the patterns observed in strain may run counter to intuition for those more
60 familiar with geophone recordings of particle motion.

61 Here we investigate some fundamental characteristics of microseismic data recorded on
62 DAS systems for the purposes of hydraulic fracture monitoring in anisotropic shales. We
63 consider a simple homogeneous anisotropic velocity model, with VTI (Vertical Transverse
64 Isotropy) symmetry, as is commonly found in shales. We use a ray-based forward modeling
65 approach to generate synthetic DAS data from the model, to investigate features of the data,
66 further illustrated with examples from a real dataset. We demonstrate how simple patterns
67 may be extracted from the data to quickly provide insight into useful parameters such as
68 event distance, depth and fault-plane orientation. We envisage these techniques could be
69 employed to rapidly analyze large datasets through more advanced algorithm development.

70 [Figure 1 about here.]

DATASET

71 We design our model based on a real microseismic dataset recorded during a single stage
72 of a hydraulic fracturing stimulation. The data were acquired using a Silixa iDAS system
73 recording strain-rate along a fiber optic cable deployed in a horizontal monitoring well. The
74 stimulation occurred in a parallel well at the same depth located approximately 200 m away.
75 The data were recorded at 2000 Hz along a standard fiber with 3765 channels with a 1 m
76 channel spacing and a gauge length of 10 m.

77 Figure 1 shows the monitoring setup with event locations estimated from a surface
78 geophone array. We note that most of the events occur near the depth of injection, with
79 some events extending above, thus we expect most of the recorded ray paths to be nearly
80 horizontal, but with some steeper arrivals, and all within a few hundred meters of the
81 monitoring well.

82 Vertical and horizontal seismic velocities within the reservoir were estimated using cross-
83 dipole sonic logs from the horizontal monitoring well, and a nearby vertical well. They were
84 found to be strongly anisotropic. Assuming a VTI model, the anisotropy can be character-
85 ized using the vertical P- and S-wave velocities $V_{P0} = 2800$ m/s and $V_{S0} = 1750$ m/s; and
86 the Thomsen (1986) parameters $\varepsilon = 0.42$, and $\gamma = 0.36$, which determine the horizontal
87 velocities of P and SH, respectively. Thomsen’s δ parameter controlling the P and SV ve-
88 locities at intermediate inclinations could not be constrained by the vertical and horizontal
89 sonic logs. However, for modeling purposes we have assumed that it is equal to half the ε
90 (i.e. $\delta = 0.21$), which is a reasonable assumption for shales (Horne, 2013).

91 Figure 1b shows a plot of the predicted group velocity surfaces from the inferred velocity
92 model. We note that P and SH waves are much faster in the horizontal direction than in the

vertical direction, and that for horizontal propagation there is a significant amount of shear-wave splitting (i.e. SH and SV have different wave speeds). For steeper inclinations, the gap between SH and SV wave narrows until they reach a singularity (the velocity surfaces cross) for inclinations of approximately 40° from vertical. For inclinations steeper than this singularity, SV is slightly faster than SH until they converge again along the vertical symmetry axis.

SYNTHETIC MODELING

Theory

We use a ray based approach to compute synthetic DAS data for a homogeneous VTI medium. Assuming a moment tensor point source, a ray-tracer is used to calculate travel-times to each channel for P, SV, and SH wave arrivals. Displacement amplitudes and polarizations are provided by dynamic ray theory Green’s function derived by Chapman (2004,Chapter 5).

For a fiber oriented along the x axis we can relate the x-component of displacement (u_x) provided by the ray-tracer to strain along the fiber (e_{xx}) using the following relation (e.g. Daley et al., 2016):

$$e_{xx} = \frac{\partial u_x}{\partial x} = \frac{\partial u_x}{\partial t} \frac{\partial t}{\partial x} = \frac{\partial u_x}{\partial t} p_x, \quad (1)$$

where p_x is the x-component of the slowness of the phase in question. We see from this relation that there are two possible approaches to generating synthetic strain data. The first is to generate synthetic displacement data, project the displacement onto the cable axis direction, and simply compute the spatial derivative of the resulting waveforms along the fiber to find strain. The second option is to multiply the time-derivative of displacement

114 by the axial slowness. Since the slowness vectors are already computed as part of the ray
 115 tracing, we choose the second method.

116 To create the waveforms from the Green’s function, we convolve them with a third-order
 117 Brune pulse source wavelet (Beresnev and Atkinson, 1997; Leaney, 2014):

$$118 \quad s(t) = \frac{\omega_c^3 t^2}{2} e^{-\omega_c t} H(t), \quad (2)$$

119 where $\omega_c = 2\pi f_c$ with f_c being the corner frequency of the source spectra and $H(t)$ the
 120 Heaviside step function. Practically speaking, the time derivative in equation 1 can be
 121 applied to the source wavelet prior to convolution. Additionally, since the iDAS system
 122 records strain-rate ($\dot{e}_{xx}$) rather than strain, an additional time derivative is required.

123 At this point we have created synthetics of point measurements of infinitesimal axial
 124 strain-rate at each channel location. However, DAS systems do not record a point mea-
 125 surement, rather they measure the strain over a finite length along the fiber, known as the
 126 gauge length, centred at each channel. This acts as a spatial averaging filter along the cable
 127 equivalent to convolving with a boxcar function (Dean et al., 2017). Thus the DAS response
 128 at channel coordinate x_{ch} is approximately equivalent to

$$129 \quad d_{DAS}(x_{ch}) = \frac{1}{L_G} \int_{x_{ch}-L_G/2}^{x_{ch}+L_G/2} \dot{e}_{xx} dx, \quad (3)$$

130 where L_G denotes the gauge length (Hartog, 2017).

131 Comparison with geophones

132 In this section, rather than model the DAS synthetics directly, we first model the more
 133 conventional geophone response showing particle velocity and then show the equivalent DAS
 134 response to highlight the difference (see Martin, 2018, for a discussion of this relationship

for isotropic media). For modeling purposes we consider Cartesian coordinate system with receivers (fiber optic cable) aligned along the horizontal x_1 axis, and a microseismic source located in the plane perpendicular to the midpoint of the array, offset in the horizontal (x_2) and vertical (x_3) directions.

[Figure 2 about here.]

The single-component nature of the recordings has some implications for the sensitivity of different body-wave phases depending on their propagation direction and polarization. In VTI media the P, SV and SH phases travel independently; P and SV waves are both polarized in the vertical plane containing the ray vector, with P polarized nearly parallel to the ray and SV nearly perpendicular, whereas SH waves are polarized in the horizontal axis perpendicular to this plane. In Figure 2a we consider a horizontal fiber and a microseismic point source offset from the fiber both horizontally and vertically. At the closest point to the array from the source, the first arrivals are purely broadside (i.e. the rays are perpendicular to the fiber); thus we expect high sensitivity to SH phases because they are polarized parallel to the fiber, but low sensitivity to P and SV because they are both polarized perpendicular to the fiber. Conversely, at long offsets along the cable the angle between the ray propagation direction and the fiber is small, such that there is a larger sensitivity to P and SV waves and smaller sensitivity to SH. For the special case of an event at the same depth as the cable, such that all rays are purely horizontal (Figure 2b), SV polarization is strictly vertical for all ray azimuths and is thus not recorded.

[Figure 3 about here.]

Figure 3a shows modeled particle velocity from a moment-tensor point-source recorded

157 along a horizontal array of receivers with 1 m spacing (equal to the channel spacing). It
 158 shows only the component of velocity projected on to the direction of the array. The source
 159 is located at a horizontal distance of 75 m from the array with a vertical offset of 30 m. As
 160 expected P and SV amplitudes both vanish at the apices of the moveout curves, where their
 161 polarizations are perpendicular to the arrays. Conversely, SH, which is polarized parallel
 162 to the fiber, shows peak amplitude at the apex.

163 To convert the particle motion to DAS strain-rate equivalent we take the spatial gradient
 164 of the particle velocity projected along the direction of the array (equation 1), and then apply
 165 a smoothing operator to account for the gauge length of 10 m (equation 3). An interesting,
 166 and somewhat counterintuitive consequence of this is that the peak SH amplitude in the
 167 particle velocities translates to zero amplitude when converted to DAS strain-rate (Fig 3b-
 168 c).

169 [Figure 4 about here.]

170 Figure 4 shows the resulting synthetic DAS data compared to an example of an ob-
 171 served microseismic event. In addition to the raw waveforms we have also plotted absolute
 172 amplitudes summed over space, which is useful for identifying the arrival time of the P and
 173 SH waves at the apex. Below the waveforms is a similar amplitude stack, but summed over
 174 time, which shows a very interesting pattern. Like the velocity data the strongest signal is
 175 contained in the SH phase; however, it is no longer centered at zero offset. Instead, there
 176 is a bimodal amplitude pattern with a local minimum at the zero-offset point to the fiber.
 177 This pattern closely matches those observed in real data.

Strain receiver sensitivity patterns

[Figure 5 about here.]

The contrast in the unimodal amplitude peak in SH observed in particle velocity versus the bimodal peaks in strain-rate highlights an important difference between geophones and DAS. Single-component geophone recordings involve the projection of a simple vector (particle displacement or velocity) onto the component axis, whereas DAS sensors involve projecting a tensor (strain or strain-rate) onto the cable direction, which inevitably results in more complex patterns. The strain sensitivity pattern of body waves depends on the relative orientation of their slowness and polarization vectors. Figure 5 shows DAS strain sensitivity patterns for P and SH waves propagating in the horizontal plane. For P waves (Figure 5a) the slowness and polarization vectors are parallel, which results in a $\cos^2 \theta$ sensitivity pattern, where θ is the angle between the propagation vector and the fiber, resulting in maximum axial strain parallel to the propagation direction and zero strain perpendicular to it (e.g. Benioff, 1935; Kuvshinov, 2016). Conversely, for SH waves, the polarization and slowness vectors are perpendicular, such that the principal axial strain components are at 45° to both vectors and alternate in sign, varying like $\sin 2\theta$. This means that the DAS response to SH waves vanishes when measuring either perpendicular or parallel to the ray direction and will alternate between extension and compression for other angles. Note that these simple $\cos^2 \theta$ and $\sin 2\theta$ relationships are only strictly true for isotropic media, or for propagation within the horizontal symmetry plane for VTI media. For inclined propagation of P and SV waves where phase and polarization vectors are not parallel or perpendicular the resulting sensitivity will be more complicated (e.g. Leaney et al., 2019).

Beyond these geometric effects on sensitivity of DAS to P and S waves, there is also a

wavenumber response due to the gauge length of DAS system (Martin, 2018; Karrenbach et al., 2019). This introduces notches in the sensitivity which depend on frequency, velocity and propagation direction relative to the fiber. See Karrenbach et al. (2019) for a more thorough discussion of this effect.

[Figure 6 about here.]

Given that the sensitivity is a geometric effect it is likely that we can use the separation distance between the bimodal amplitude peaks in SH observed in the data (Figure 4) to estimate the distance to the event from the array. Figure 6a shows axial strain along the fiber for SH arrivals modeled using ray theory for events located in the horizontal plane at 50 m, 200 m and 500 m from the cable. A uniform radiation pattern is used, and the modeled amplitudes include geometrical spreading. It is clear that the separation between the amplitude peaks is proportional to the distance of the event from the cable. We can estimate the distance to the event, d , by

$$d \sim \sqrt{2}x_{1/2}, \quad (4)$$

where $x_{1/2}$ is the half-width of the peak-to-peak distance. Figure 6b shows a similar plot, but for SV arrivals using events located in the vertical plane. Note that this also shows a bimodal pattern, but with much sharper and focused amplitude peaks. This is because of a ray-focusing effect for SV propagation at inclinations of $\sim 40^\circ$ due to the anisotropy. This effect is common for anisotropic shales where Thomsen's δ is less than ε . While the precise pattern is dependent on the Thomsen parameters, the angle inclination where it occurs is typically similar for most models. In some cases where $\delta \ll \varepsilon$ the ray focussing is large enough to cause the SV wavefront to fold in on itself causing shear-wave triplications or cusps (e.g. Thomsen and Dellinger, 2003; Baird et al., 2017).

224 In practice, the relationship between the observed amplitude patterns and distance
225 may be more complex due to non-uniform source radiation patterns as well as arrivals
226 from inclinations outside the anisotropic symmetry planes. Nevertheless, the separation of
227 amplitude peaks provides a first-order estimate of event distance.

228 **Event depth constraints**

229 One of the major limitations of DAS recordings for microseismic monitoring is that the
230 1D nature of the recording makes it difficult to infer the directionality of waves and thus
231 fully constrain the event locations. Some approaches to reducing the ambiguity include
232 recording DAS in multiple wells simultaneously, or recording in both the horizontal and
233 vertical sections of the same deviated well (e.g. Williams et al., 2017; Verdon et al., 2020).
234 In the absence of more complex array geometries, however, insight into the directionality
235 of waves may still be inferred by taking advantage of the anisotropy of the medium.

236 [Figure 7 about here.]

237 Here we demonstrate how the angular dependence of seismic velocities due to anisotropy
238 can be used to constrain the inclination of the incoming waves, which when combined
239 with estimates of event distance can be used to infer source location including event depth
240 relative to the cable. To do this we model five microseismic sources, all located 100 m
241 from the cable but at inclinations ranging from 90° (horizontal) to 0° (vertical) at 22.5°
242 increments (Figure 7a). For the event located within the horizontal plane (Figure 7b),
243 we might expect to observe significant shear-wave splitting based on the model's Thomsen
244 parameters (Figure 1b). However, since all the ray-paths from the source to the fiber are
245 horizontal, the SV phase is polarized in the vertical direction (Figure 2b), and does not

246 generate any axial strain along the horizontal cable, and thus is not observed in the DAS
247 data.

248 The next source is placed at the same distance from the cable, but at a shallower source
249 depth such that the incoming ray inclination at zero offset is steepened by 22.5° (Figure 7c).
250 In this configuration the SV arrivals project a small horizontal component and generate axial
251 strain along the fiber and hence it is observed on the DAS recording. At this inclination SH
252 is still much faster than SV (Figure 1b) thus a significant amount of shear-wave splitting
253 can be observed close to the apex and at longer offsets along the cable. This contrasts
254 with the next source where the rays at the apex propagate at an inclination of 45° from
255 vertical (Figure 7d), which is close to the inclination of the expected shear-wave singularity
256 where the two shear waves propagate with the same velocity (Figure 1b). Thus, no S wave
257 splitting is observed at short offsets along the cable, although it is observed at larger offsets
258 since inclination shallows as you move along the cable, resulting in an increase in apparent
259 shear wave splitting with distance.

260 At steeper inclinations SV is slightly faster than SH. The difference is not large enough
261 to readily detect S-wave splitting close to the apex; however, we can see that the S-wave
262 singularities are now offset from the apex (Figure 7e). Finally for events located vertically
263 above (or below) the cable, only SV is recorded since SH is polarized perpendicular to the
264 fiber (Figure 7f). We note that the moveout of SV is more complicated than that of SH,
265 with an abrupt change in apparent slowness at ~ 80 m offset. This change is related to the
266 ray focusing effect of the anisotropy, which also causes the sharp bi-modal amplitude peaks
267 in the SV sensitivity pattern (Figure 6b), and thus provides a strong geometric indicator
268 of event location. The precise inclination at which the ray focussing occurs depends on
269 knowledge of the Thomsen parameters, including the δ parameter which can be difficult

270 to measure from sonic logs. However, the inclination typically falls within the relatively
271 small range of 40-45° from vertical for a wide variety of shale anisotropies (Thomsen and
272 Dellinger, 2003); thus it can provide good geometric constraints, even for cases where δ is
273 not well known.

274 [Figure 8 about here.]

275 Figure 8 shows an observed microseismic event with weak P arrival followed by two larger
276 amplitude S arrivals exhibiting clear S-wave singularities offset from the apex, compared
277 with a synthetic event exhibiting similar features. The precise inclination of the singularities
278 is dependent on the relative magnitudes of the Thomsen parameters. Nonetheless, if such
279 singularities are observed it is a strong indicator of a steep incidence angle, and a good
280 geometric constraint on the event location. Note also that the sharp amplitude peaks
281 observed in the amplitude stack over time is similar to the sensitivity pattern expected for
282 SV arrivals (Figure 6b), providing an additional indicator of steep arrival angle.

283 **Source mechanism effects**

284 To this point we have discussed how DAS recordings of microseismic data are dependent on
285 the wave type, propagation angle relative to the cable axis and inclination in a VTI medium.
286 Another important consideration, however, is the radiation pattern of the microseismic
287 source. Figure 9 shows strike-slip radiation patterns in displacement (Figure 9a,d) and the
288 e_{11} component of strain (Figure 9b,e) for P and SH waves in the horizontal plane. Figure 9c,f
289 shows strain radiation for a rotated source mechanism such that the source symmetries and
290 receiver symmetries are not aligned.

291

[Figure 9 about here.]

292 For P waves we see that the relationship between displacement radiation and strain
 293 radiation is quite simple. The fault plane and auxiliary plane separate the focal sphere
 294 into quadrants of outward- and inward-pointing displacement that coincide with quadrants
 295 of compressional and extensional strain in e_{11} , respectively. The additional effect of the
 296 receiver sensitivity (Figure 5a) acts to gradually fade out the broadside sensitivity of strain
 297 without introducing a polarity reversal.

298 Conversely, the SH radiation pattern is more complicated. We see that there are two sets
 299 of polarity reversals observed in the strain radiation. The first set is controlled by the source
 300 parameters defined by the planes bisecting the fault and auxiliary planes, which separate
 301 quadrants of displacement with a clockwise sense of rotation relative to the source from
 302 those with an anti-clockwise sense. This pattern will vary for different source mechanisms.
 303 The second pattern is controlled by the receiver geometry and is defined by the receiver
 304 sensitivity pattern (Figure 5b). This pattern remains fixed for all events and imposes
 305 polarity reversals for rays propagating parallel and perpendicular to the fiber.

306

[Figure 10 about here.]

307 Figure 10 shows synthetic DAS recordings of events with the mechanisms shown in
 308 Figure 9, located at the same depth as the fiber. The conventional approach to constrain
 309 fault plane solutions using geophones involves mapping the polarity of P waves to identify
 310 the nodal planes where the amplitude reduces to zero and their polarity reverses. However,
 311 given the low sensitivity for broadside P arrivals these polarity reversals can be hard to
 312 identify in DAS data when they occur at near offset. Conversely, SH polarity reversals can

313 be more readily identified due to the high amplitude of the SH recorded signal as well as
 314 the large aperture of the continuous fiber recording. It is impossible to fully constrain the
 315 moment tensor due to the 1D nature of the DAS recording, however if a double couple
 316 mechanism is assumed there are clear geometric relationships between the location of the
 317 polarity reversals observed in the SH and P phases and the orientation of the fault and
 318 auxiliary planes. Indeed recent studies have shown remarkable consistencies in the patterns
 319 of polarity reversals observed in DAS recordings of stimulated events (Cole et al., 2018;
 320 Karrenbach and Cole, 2019), suggesting this approach can be used to quickly constrain
 321 possible source mechanisms.

322 [Figure 11 about here.]

323 Figure 11a shows an observed microseismic recording with clear P, SH, and SV arrivals.
 324 We note that the highest amplitudes are observed in the SH arrival with a relatively weak
 325 SV arriving later. There is significant shear-wave splitting for all offsets along the cable
 326 indicating the incoming inclination is relatively shallow, though not horizontal. In addition
 327 to the polarity reversal in the apex of the SH arrival due to the receiver sensitivity pattern,
 328 we can also see clear polarity reversals due to the source radiation pattern at offsets of
 329 approximately -100 m and 190 m. These reversals can also be seen as local minima in the
 330 sum of absolute amplitudes over time plotted below, although it is not as clear as in the
 331 synthetics (Figure 10) due to the additional background noise.

332 In Figure 11b we attempt to reproduce many of the characteristics found in the observed
 333 event with a simple synthetic model. We place the source a horizontal distance of 100 m
 334 with a vertical offset of 65 m giving a zero-offset inclination of $\sim 57^\circ$ from vertical. Unique
 335 fault plane solutions are only possible if the three-dimensional pattern of amplitudes are

adequately sampled, which cannot be done with a simple 1D DAS recording. Instead, we choose a source mechanism based on a representative fault plane solution inferred from surface geophones, but with 10° anti-clockwise rotation in strike to better match the observed polarity reversals. Projections of the modeled polarity reversal locations along the cable have been overlaid on the amplitude stack of both the modeled and real data. We also show the confidence limits of these projections for fault strikes of $\pm 3^\circ$. Thus, we have demonstrated that DAS recordings can be used to provide clear constraints and improvements to source mechanism estimates.

CONCLUSIONS

Using a ray-based method of creating synthetic waveforms we have explored some fundamental characteristics of microseismic data recorded on horizontal DAS arrays in VTI media, which may aid in constraining event locations and source mechanisms while reducing ambiguity in the directionality of waves. For events located close to the array depth, we have shown that the SH phase usually dominates the signal due to its polarization along the cable at near offsets. The amplitude of the SH phase along the cable produces a characteristic pattern with bimodal peaks surrounding the zero-offset point, with the separation between the peaks providing an indication of the distance of the event from the cable. A similar bimodal pattern can be observed in the amplitude of the SV phase for steep arrivals, but with much sharper amplitude peaks due to a ray focussing effect for SV common in anisotropic shales.

Insight into the event depth relative to the cable can be gained by observing characteristics of the shear-wave splitting. For events located in the horizontal plane, the SV phase will not be recorded because of its polarization perpendicular to the fiber. For events

358 above or below the horizontal plane the SV phase can be observed and the details of shear-
359 wave splitting and how it changes with offset along the cable can provide insight into the
360 near offset inclination. The presence of S-wave singularities, for example, provides a strong
361 indication of a steep arrival. Using these features in VTI media can reduce some of the
362 uncertainty of the directionality of waves inherent in using single-component data.

363 Finally, the effect of microseismic source mechanisms on the observed strain amplitude
364 patterns was explored. Although moment tensors cannot be fully constrained using a single
365 one-dimensional array, the high-fold continuous nature of DAS recordings allows for accurate
366 picking of polarity reversals, particularly in the SH phase, providing strong constraints
367 on possible fault plane solutions and allowing existing source mechanism estimates to be
368 validated and calibrated.

369 As DAS arrays become increasingly used for microseismic monitoring in industrial set-
370 tings, one of the major challenges is developing techniques to deal with the large data
371 volumes associated with the dense spatial and temporal sampling provided by these sys-
372 tems. We have shown using synthetic modeling how simple patterns extracted from the data
373 can be used to quickly provide estimates and constraints on event distance, inclination, and
374 fault-plane solutions. Machine learning techniques provide a possible approach for rapidly
375 classifying data using pattern recognition. Recent studies have shown great potential for
376 event detection of DAS data using machine learning, and one could envisage expanding such
377 systems to also classify events by distance, location and mechanism using simple pattern
378 recognition.

ACKNOWLEDGMENTS

379 The authors thank Chevron ETC and Silixa Ltd. for permission to publish the work. We
380 thank the reviewers and editors for their constructive comments, which helped improve the
381 manuscript. This work was funded by the Natural Environment Research Council (NERC)
382 under the FAST-MoDE project (Grant No. NE/R014531/1).

REFERENCES

- 383 Baird, A. F., J.-M. Kendall, Q. J. Fisher, and J. Budge, 2017, The role of texture, cracks
384 and fractures in highly anisotropic shales: *Journal of Geophysical Research: Solid Earth*,
385 **122**.
- 386 Benioff, H., 1935, A linear strain seismograph: *Bulletin of the Seismological Society of*
387 *America*, **25**, 283–309.
- 388 Beresnev, I. A., and G. M. Atkinson, 1997, Modeling finite-fault radiation from the ω^n
389 spectrum: *Bulletin of the Seismological Society of America*, **87**, 67–84.
- 390 Binder, G., and D. Chakraborty, 2019, Detecting microseismic events in downhole dis-
391 tributed acoustic sensing data using convolutional neural networks, *in* SEG Technical
392 Program Expanded Abstracts 2019: Society of Exploration Geophysicists, 4864–4868.
- 393 Chapman, C., 2004, *Fundamentals of seismic wave propagation*: Cambridge University
394 Press.
- 395 Cole, S., M. Karrenbach, D. Kahn, J. Rich, K. Silver, and D. Langton, 2018, Source pa-
396 rameter estimation from DAS microseismic data, *in* SEG Technical Program Expanded
397 Abstracts 2018: Society of Exploration Geophysicists, 4928–4932.
- 398 Daley, T. M., D. E. Miller, K. Dodds, P. Cook, and B. M. Freifeld, 2016, Field test-
399 ing of modular borehole monitoring with simultaneous distributed acoustic sensing and
400 geophone vertical seismic profiles at Citronelle, Alabama: *Geophysical Prospecting*, **64**,
401 1318–1334.
- 402 Dean, T., T. Cuny, and A. H. Hartog, 2017, The effect of gauge length on axially incident p-
403 waves measured using fibre optic distributed vibration sensing: *Geophysical Prospecting*,
404 **65**, 184–193.
- 405 Hartog, A. H., 2017, *An introduction to distributed optical fibre sensors*: CRC press.

406 Horne, S., A. Baird, A. Stork, and G. Naldrett, 2019, Machine learning for DAS microseismic
 407 event detection: Presented at the 81st EAGE Conference and Exhibition 2019 Workshop
 408 Programme.

409 Horne, S. A., 2013, A statistical review of mudrock elastic anisotropy: Geophysical Prospect-
 410 ing, **61**, 817–826.

411 Karrenbach, M., and S. Cole, 2019, DAS microseismic source mechanism estimation by
 412 forward-modeling, *in* SEG Technical Program Expanded Abstracts 2019: Society of Ex-
 413 ploration Geophysicists, 1004–1008.

414 Karrenbach, M., S. Cole, A. Ridge, K. Boone, D. Kahn, J. Rich, K. Silver, and D. Langton,
 415 2019, Fiber-optic distributed acoustic sensing of microseismicity, strain and temperature
 416 during hydraulic fracturing: Geophysics, **84**, no. 1, D11–D23.

417 Kuvshinov, B., 2016, Interaction of helically wound fibre-optic cables with plane seismic
 418 waves: Geophysical Prospecting, **64**, 671–688.

419 Leaney, S., T. Mizuno, E. Velez, T. Cuny, and M. Perez, 2019, Integrated anisotropic model
 420 building, DAS simulation and imaging, *in* SEG Technical Program Expanded Abstracts
 421 2019: Society of Exploration Geophysicists, 999–1003.

422 Leaney, W. S., 2014, Microseismic source inversion in anisotropic media: PhD thesis, Uni-
 423 versity of British Columbia.

424 Martin, E. R., 2018, Passive imaging and characterization of the subsurface with distributed
 425 acoustic sensing: PhD thesis, Stanford University.

426 Parker, T., S. Shatalin, and M. Farhadiroushan, 2014, Distributed acoustic sensing—a new
 427 tool for seismic applications: First Break, **32**, 61–69.

428 Thomsen, L., 1986, Weak elastic anisotropy: Geophysics, **51**, 1954–1966.

429 Thomsen, L., and J. Dellinger, 2003, On shear-wave triplication in transversely isotropic

media: Journal of Applied Geophysics, **54**, 289–296.

Verdon, J. P., S. A. Horne, A. Clarke, A. L. Stork, A. F. Baird, and J.-M. Kendall, 2020, Microseismic monitoring using a fibre-optic distributed acoustic sensor (DAS) array: Geophysics, **In press**, 1–48. DOI: 10.1190/geo2019-0752.1

Williams, A., J. M. Kendall, A. Clarke, and J. Verdon, 2017, Challenges in locating microseismic events using distributed acoustic sensors: Presented at the AGU Fall Meeting Abstracts.

LIST OF FIGURES

437 438 439 440	1	(a) Schematic diagram showing array geometry and event locations for the DAS dataset. (b) Group velocity surfaces for P, SV and SH waves for the homogeneous VTI velocity model based on cross-dipole sonic logs in the reservoir. Polar angle from the origin indicates ray propagation vector. . .	25
441 442 443 444 445 446	2	Cartoon showing polarization vectors for P (green), SV (blue) and SH (red) waves relative to horizontal array geometry for (a) and inclined ray, and (b) a horizontal ray. Sensitivity for geophones is controlled by the projection of the polarization vector on to the receiver component, thus we expect high sensitivity for broadside SH arrivals and low sensitivity for broadside P and SV arrivals.	26
447 448 449 450 451 452 453	3	(a) Modeled particle velocity along the horizontal well direction for a microseismic source in a homogeneous VTI medium. The lower panel shows snapshots of (b) particle velocity and (c) strain rate along the fiber axis direction at the peak amplitude of SH arrival (indicated by blue horizontal line in (a)). Since strain rate is the spatial derivative of particle velocity along the fiber the peak amplitude for particle velocity translates to zero amplitude in DAS data.	27
454 455 456 457 458 459 460	4	(a) Synthetic DAS data along a horizontal well for a microseismic source in a homogeneous VTI medium. (b) An example of observed microseismic event recorded on a DAS. To improve signal to noise in the observed data frequency-wavenumber (f-k) filtering has been applied to suppress frequencies above 300 Hz and wavenumbers above 0.1 m^{-1} . Plots to the right and below the waveforms show the absolute amplitudes summed over space and time, respectively.	28
461 462 463 464 465	5	Top view of axial strain on a horizontal fiber as a function of fiber angle for (a) a horizontally propagating P wave and (b) a horizontally propagating SH wave. Polar angle indicates fiber orientation. Large arrow indicates ray propagation direction with smaller double-headed arrows indicating polarization direction. Blue lines indicate compression and red extension.	29
466 467 468 469 470 471 472	6	Predicted axial strain of the (a) SH and (b) SV, phases as a function of fiber offset for sources of uniform radiation pattern with varying distances from the fiber within the horizontal and vertical planes, respectively. The blue rectangles indicate the separation along the cable between the bimodal amplitude peaks, which is proportional to the distance to the source. Note that the sharp amplitude peaks in SV are due to the ray focussing effect of the VTI anisotropy.	30
473 474 475 476 477	7	Synthetic DAS data for events located 100 m from the horizontal cable in a VTI medium at progressively steeper inclinations from horizontal. Panel a: Cross-section view showing the source locations (green dots, labelled b to f) distributed around the fiber (blue dot). Dashed lines indicate the ray paths at zero offset. Panels b-f: Synthetic DAS data for each event.	31

478	8	Observed DAS recording (a) of an event showing S wave singularities compared with a synthetic example (b) showing a similar feature. The synthetic event was modeled at a distance of 180 m from the cable with an incoming inclination of 25° from vertical. The presence of S wave singularities is a strong indicator of a steep incident angle. Note also the sharp amplitude peaks in SV similar to the sensitivity pattern expected for SV arrivals for steep propagation angles (Figure 6b). Real data in (a) has been filtered as described in Figure 4.	32
479			
480			
481			
482			
483			
484			
485			
486	9	Radiation pattern for a strike-slip source mechanism in terms of (a) displacement and (b) the e_{11} component of strain for P waves. (c) Same as in (b) but with the source mechanism rotated such that the symmetries of source radiation and receiver sensitivity patterns are misaligned. (d-f) Same as (a-b) but for SH waves. Black arrows indicate particle displacement; colored arrows represent extensional (red) or compressional (blue) strain.	33
487			
488			
489			
490			
491			
492	10	Example synthetic DAS recordings due to the source mechanisms shown in Figure 9b and c, with the event at the same depth as the fiber. Panels a and b show a map view of source location relative to cable (blue line). Panels c and d show the synthetic recordings along the cable, and a stack of absolute amplitudes summed over time. Dashed lines indicate projections of polarity reversals in: SH due to receiver sensitivity (black), SH due to source mechanism (red) and P due to source mechanism (blue).	34
493			
494			
495			
496			
497			
498			
499	11	(a) Example DAS recording of an event with clear P, SH and SV arrivals, with polarity reversals observed in the SH and P. (b) synthetic event showing many of the same features as the observed recording. The modeled event is located at a horizontal distance 100 m and a vertical offset of 65 m above the cable. The source is modeled with a strike/dip/rake of 350°/90°/-120°, similar to mechanisms inferred from surface stations but with a slight rotation in strike to better match the observed polarity reversals. Red and blue dashed lines indicate projections of the modeled polarity reversals on the amplitude stack for SH and P waves, respectively. Dotted red lines indicate predicted SH polarity reversals if the fault strike were varied by $\pm 3^\circ$. Real data in (a) has been filtered as described in Figure 4.	35
500			
501			
502			
503			
504			
505			
506			
507			
508			
509

Figure 1: (a) Schematic diagram showing array geometry and event locations for the DAS dataset. (b) Group velocity surfaces for P, SV and SH waves for the homogeneous VTI velocity model based on cross-dipole sonic logs in the reservoir. Polar angle from the origin indicates ray propagation vector.

Figure 2: Cartoon showing polarization vectors for P (green), SV (blue) and SH (red) waves relative to horizontal array geometry for (a) and inclined ray, and (b) a horizontal ray. Sensitivity for geophones is controlled by the projection of the polarization vector on to the receiver component, thus we expect high sensitivity for broadside SH arrivals and low sensitivity for broadside P and SV arrivals.

Figure 3: (a) Modeled particle velocity along the horizontal well direction for a microseismic source in a homogeneous VTI medium. The lower panel shows snapshots of (b) particle velocity and (c) strain rate along the fiber axis direction at the peak amplitude of SH arrival (indicated by blue horizontal line in (a)). Since strain rate is the spatial derivative of particle velocity along the fiber the peak amplitude for particle velocity translates to zero amplitude in DAS data.

Figure 4: (a) Synthetic DAS data along a horizontal well for a microseismic source in a homogeneous VTI medium. (b) An example of observed microseismic event recorded on a DAS. To improve signal to noise in the observed data frequency-wavenumber (f-k) filtering has been applied to suppress frequencies above 300 Hz and wavenumbers above 0.1 m^{-1} . Plots to the right and below the waveforms show the absolute amplitudes summed over space and time, respectively.

Figure 5: Top view of axial strain on a horizontal fiber as a function of fiber angle for (a) a horizontally propagating P wave and (b) a horizontally propagating SH wave. Polar angle indicates fiber orientation. Large arrow indicates ray propagation direction with smaller double-headed arrows indicating polarization direction. Blue lines indicate compression and red extension.

Figure 6: Predicted axial strain of the (a) SH and (b) SV, phases as a function of fiber offset for sources of uniform radiation pattern with varying distances from the fiber within the horizontal and vertical planes, respectively. The blue rectangles indicate the separation along the cable between the bimodal amplitude peaks, which is proportional to the distance to the source. Note that the sharp amplitude peaks in SV are due to the ray focussing effect of the VTI anisotropy.

Figure 7: Synthetic DAS data for events located 100 m from the horizontal cable in a VTI medium at progressively steeper inclinations from horizontal. Panel a: Cross-section view showing the source locations (green dots, labelled b to f) distributed around the fiber (blue dot). Dashed lines indicate the ray paths at zero offset. Panels b-f: Synthetic DAS data for each event.

Figure 8: Observed DAS recording (a) of an event showing S wave singularities compared with a synthetic example (b) showing a similar feature. The synthetic event was modeled at a distance of 180 m from the cable with an incoming inclination of 25° from vertical. The presence of S wave singularities is a strong indicator of a steep incident angle. Note also the sharp amplitude peaks in SV similar to the sensitivity pattern expected for SV arrivals for steep propagation angles (Figure 6b). Real data in (a) has been filtered as described in Figure 4.

Figure 9: Radiation pattern for a strike-slip source mechanism in terms of (a) displacement and (b) the e_{11} component of strain for P waves. (c) Same as in (b) but with the source mechanism rotated such that the symmetries of source radiation and receiver sensitivity patterns are misaligned. (d-f) Same as (a-b) but for SH waves. Black arrows indicate particle displacement; colored arrows represent extensional (red) or compressional (blue) strain.

Figure 10: Example synthetic DAS recordings due to the source mechanisms shown in Figure 9b and c, with the event at the same depth as the fiber. Panels a and b show a map view of source location relative to cable (blue line). Panels c and d show the synthetic recordings along the cable, and a stack of absolute amplitudes summed over time. Dashed lines indicate projections of polarity reversals in: SH due to receiver sensitivity (black), SH due to source mechanism (red) and P due to source mechanism (blue).

Figure 11: (a) Example DAS recording of an event with clear P, SH and SV arrivals, with polarity reversals observed in the SH and P. (b) synthetic event showing many of the same features as the observed recording. The modeled event is located at a horizontal distance 100 m and a vertical offset of 65 m above the cable. The source is modeled with a strike/dip/rake of $350^\circ/90^\circ/-120^\circ$, similar to mechanisms inferred from surface stations but with a slight rotation in strike to better match the observed polarity reversals. Red and blue dashed lines indicate projections of the modeled polarity reversals on the amplitude stack for SH and P waves, respectively. Dotted red lines indicate predicted SH polarity reversals if the fault strike were varied by $\pm 3^\circ$. Real data in (a) has been filtered as described in Figure 4.