Abstract  We show the capabilities of a downhole distributed acoustic sensing (DAS) array in detecting, locating, and characterizing low-magnitude earthquakes occurring in the vicinity of the Frontier Observatory for Research in Geothermal Energy (FORGE) site in Utah. Continuous data for 10.5 days were acquired in a monitoring well at the FORGE geothermal site during the initial stimulation of an enhanced geothermal system in April–May 2019. Earthquake activity beneath Mineral Mountains, Utah also occurred within 10 km of the FORGE monitoring well. During the experiment, four earthquakes were cataloged by routine processing of the University of Utah Seismograph Stations. Our processing of DAS data finds 77 earthquakes during that period, of which 16 are visible on the regional network. Five additional events are found by template matching DAS data. The magnitude of completeness obtained by DAS processing is better by at least $M = 0.5$ than the dense surface array around the FORGE site. Depth estimation using DAS is more reliable than using a surface array. While a single vertical DAS array is limited in terms of event location due to its azimuthal ambiguity, multiple DAS wells or a combination of a downhole array with surface stations or near-surface horizontal DAS could jointly resolve locations. All detected events probably originated from the two active source areas, located 3–5 and 8–10 km away from the FORGE site, respectively. Recorded events can be reliably clustered into several distinct families thanks to the spatial density and large number of DAS channels.

1. Introduction

Enhanced geothermal systems (EGS) have great potential for baseload low-carbon energy. However, in order to be economically feasible, the hot rock mass has to be sufficiently permeable to allow for economical amounts of fluid to pass through it, accumulating heat in the process (Majer et al., 2007; Tester et al., 2006). In order to increase permeability, techniques often used in tight unconventional hydrocarbon extraction are employed. In hydrofracturing, the fluid pressure in the well is increased until it exceeds the fracture gradient of the rock formation. As a result, a tensile failure occurs, and fluid permeates the newly opened Mode-I crack. The fracture keeps propagating away from the well until the pressure drops below the fracture gradient. However, shear failure, or mode II, has also been associated with hydraulic fracturing (Martín-ez-Garzón et al., 2013; McClure & Horne, 2014). Microseismic monitoring is the primary tool to detect, locate, and characterize weak seismic waves associated with fracture opening (S. Maxwell, 2014). Through the use of proppant, fractures can be prevented from closing once pressure in the well is returned to normal. As such, fluid can be circulated through them with much lower pressure. For an EGS project to be successful, the created fracture network has to connect an injection and production well with sufficient flow between the two without short-circuiting due to pre-existing or newly created flow paths. While EGS experiments have been conducted for more than three decades (Fehler, 1989; Garcia et al., 2012), understanding fracture networks and their behavior has remained elusive, thus limiting the economic success of EGS.

To address those limitations and others, the U.S. Department of Energy created the Frontier Observatory for Research in Geothermal Energy (FORGE) experiment, a dedicated underground field laboratory in Utah whose purpose is to develop, test, and accelerate breakthroughs in EGS. FORGE is located near the town of Milford in Beaver County, Utah, on the western flank of the Mineral Mountains (Figure 1a), close to the active Blundell geothermal plant in the Roosevelt Hot Springs (Gwynn et al., 2016; Ross et al., 1982). Phase 2-C of the experiment, conducted in 2019 between 21 April and 3 May, consisted of hydraulic stimulation of the target rock and recording seismicity in a nearby monitoring well, shallow boreholes, and on the surface.
Various stimulation regimes were tested to find the optimal method for fracture network creation. In the context of this paper, the resulting seismic activity can be coarsely separated into two categories—stimulated fractures and induced seismicity. Stimulated fracture events are caused by the energy released when natural fractures open (or shear) due to stimulation, and they generally have microseismic magnitudes. Induced seismicity, on the other hand, refers to earthquakes caused by stimulation and/or fluid injection that reactivates pre-existing faults (Lee et al., 2019; McGarr et al., 2015; Schultz et al., 2020). As several EGS projects have been previously halted due to induced seismicity (Deichmann et al., 2009; Ellsworth et al., 2019; Grigoli et al., 2018), it is important to monitor the seismic activity. However, earthquakes that are unrelated to the stimulation also occur in the area of interest, and separating them from induced seismicity is mandatory.

Downhole geophones are highly sensitive tools for seismic monitoring (S. C. Maxwell et al., 2012). They offer three axes of measurement, high sensitivity, and have well-known response functions. Through polarization analysis, they can provide information on the events’ direction of arrival. However, they do have several downsides. First, the operating temperature and pressure for conventional digital tools is limited. In EGS conditions, where the target rock reaches temperatures of more than 200°C, deploying conventional geophones close to the reservoir is impractical, as these sensors are not designed for long-term monitoring in such areas (Zhidong et al., 2019). There are other designs that avoid deploying electronic circuits in the high-temperature zones, notably fiber-based sensors, but they require deploying additional wires in the well. Moreover, all downhole geophones prohibit almost any operation in the well in which they are installed. As a result, a dedicated monitoring well has to be drilled, which incurs large additional costs. Any deployment or retrieval of the geophones in the well also requires significant time and effort. In practice, downhole geophones are often only deployed for microseismic monitoring during stimulation, whereas surface arrays are used to monitor induced seismicity continuously. Since potential induced events of concern are larger than stimulation events, a surface array can be expected to detect them despite higher anthropogenic noise, near-surface scattering, and anelastic losses due to propagation in sediments. The FORGE experiment followed that approach, and downhole recording is available only for the stimulation period, while a surface array was permanently installed.

An enticing alternative for both short- and long-term monitoring of EGS is the use of distributed acoustic sensing (DAS). In DAS, an optical fiber is turned into a seismic sensor thanks to a dedicated optical apparatus, known as an interrogator, that continuously sends laser pulses through the fiber. DAS has been deployed...
in wells for almost a decade, mostly in the oil and gas industry (Jin & Roy, 2017; Karrenbach et al., 2019; Mateeva et al., 2013, 2014), but also to study tectonic seismicity (Lellouch et al., 2019a). It has proven useful in active seismic surveys, mostly VSP, low-frequency strain measurements, and microseismic monitoring. From a practical point of view, DAS is well suited to EGS projects. Fibers can be deployed behind casing and reoccupied for seismic surveying when convenient. As such, any active cased well, either injection or production, can be monitored during operations. More noise is expected in such wells, particularly in the form of tube waves. However, tube wave properties are predictable and have a much lower apparent velocity than the desired signal, and can thus be filtered out during processing. Acquisition using fibers deployed inside active wells is also possible, albeit significantly noisier (Kimura et al., 2019; Uematsu et al., 2019). The fibers can withstand harsh temperature and pressure conditions and can thus record close to or within the reservoir (Zhidong et al., 2019). They can also be left in the subsurface for long periods of time, as they are a purely passive component. For example, at the San Andreas Fault Observatory at Depth (Lellouch et al., 2019b), a fiber was interrogated 12 years after its installation. Nonetheless, especially in high-temperature environments, chemical degradation processes, primarily hydrogen darkening, may decrease signal quality with time. Methods have and are currently being developed to address this problem, but sufficient data are not available for a quantitative estimation of the average lifespan of a fiber in EGS conditions. At any time, connecting an interrogator to the fiber at the surface can provide immediate seismic recording, without any effect on field operations.

In a previous study of the FORGE experiment (Lellouch et al., 2020), we conducted a thorough comparison between DAS and downhole geophones for microseismic monitoring. The events of interest originated from stimulated fractures in the vicinity of the stimulation well. We found out that DAS is not performing as well as downhole geophones in terms of event detection and yields a magnitude completeness of $M = -1.4$ versus $M = -1.7$ for a codeployed downhole geophone array. However, given all its previously described benefits, we think it is worthwhile to estimate its performance in monitoring larger and more distant earthquakes as well. The two sets of events are mutually exclusive and stimulated fracture events are purposely not treated in this paper. EGS projects require long-term monitoring of induced seismicity, commonly based on surface seismometer arrays. Therefore, we compare DAS performance to that of a regional surface array.

The application of the previously described detection workflow (Lellouch et al., 2020) yielded 77 new events. After event clustering and template matching, we detect five additional events. All 82 earthquake events are not directly associated with the stimulation. They have visible P and S arrivals, are located within 15 km of the monitoring well, and occurred between April 23rd 00:00 and May 3rd 13:00 UTC. In that time period, the regional network reported 10 events in the University of Utah Seismograph Stations (UUSS) catalog, out of which only four were earthquakes not directly associated with the stimulation. We also show that DAS-based event locations, despite being limited to depth and horizontal distance from the array, align with two major source areas of historical seismicity in the region. By examining the seismograms recorded by the regional network at the times of DAS detections, we detect 16 of the 82 events and coarsely locate them in good agreement with the historically active source areas. Finally, we compare seismicity rates during the stimulation period with the background seismicity levels. The number of DAS detections exceeds the expected seismicity levels, indicating the quality and benefits of a downhole DAS-based-detection.

2. Study Area and Monitoring Arrays

Central Utah has a tectonically complex concentration of seismicity in the Intermountain Seismic Belt; the transition area between the northwestern Colorado Plateau and the eastern Great Basin of the Basin and Range (Arabasz & Julander, 1986). Natural seismicity in Utah exhibits both strike-slip and normal faulting with tens of M3+ events occurring per year (Arabasz et al., 2016). In the broader context, induced earthquake cases have been noted in association with both coal mining (Arabasz et al., 2005; Pechmann et al., 2008) and subsurface injection operations (Brown & Liu, 2016). Focusing slightly closer to the FORGE project, in the Marysvale volcanic field, swarm activity dominates the seismic activity, is typically associated with events in the upper crust, and is thought to be related to either hydrothermal or volcanic activity (Arabasz et al., 2007). The largest historical event nearby to our study area was a $M \sim 5$ south of Milford in 1908, with more recent events indicating steeply dipping strike-slip faults (Potter, 2017; Whidden & Pankow, 2012).
To the southeast of the FORGE project site (~4 and 8 km), two concentrations of seismicity underlying the Mineral Mountains are apparent in the UUSS earthquake catalog (Figure 1a). Corroborating the swarm-volcanism association, low velocity bodies under this mountain have been interpreted as partial melt related to volcanic activity (Robinson & Iyer, 1981). These swarms were described in studies related to FORGE, characterizing the baseline rates of earthquakes in the immediate area (Pankow et al., 2019, 2020). Most notably, a study of these Mineral Mountains swarms was conducted prior to the development of the Blundell power plant exploiting the Roosevelt Hot Springs geothermal system (Zandt et al., 1982). This study found more than 1,000 small magnitude (ML < 1.5) normal faulting events, trending along (but offset from) the previously mapped Negro Mag Fault. Zandt et al. (1982) concluded that these swarms were likely related to natural hydrothermal fluid-flow processes and not related to geothermal pumping activities. Despite this, they acknowledged that these swarms indicated a potential susceptibility of nearby geothermal systems to induced seismicity.

Figure 1 contains an overview of the FORGE experiment elements involved in this study. We focus on DAS data acquired in the monitoring well. The fiber was installed in a metal tube cemented behind the casing. The well and fiber reach a 985 m depth, crossing into granitic basement at approximately 800 m depth. In order to improve signal-to-noise ratio (SNR), an engineered fiber was used and interrogated by a Silixa Carina system. This form of recording has been shown to improve the optical SNR by 20 dB (Correa et al., 2017). Acquisition has been quasi-continuously active from April 23, 2019 to May 3, 2019. A total of about 40 min were not recorded. DAS data have been recorded with a 1-m channel spacing, 10-m gauge length, and 2,000 samples per second after a 16-fold internal stacking of the laser sampling rate prior to writing to disk. The output of the DAS interrogator is an optical phase measurement of the strain-rate, which can be converted from radians per second to physical strain-rate (measured in nm/m per second) using a linear conversion.

In addition to the DAS fiber, the monitoring well was equipped with a Schlumberger 12-geophone string, spanning depths of 650–980 m. The data recorded by the geophones have also been fully processed and cataloged by Schlumberger, albeit for microseismic events only. No earthquakes from beyond the stimulation zone are present in the downhole geophone catalog, almost certainly due to intended filtration of non-stimulation events. In addition, the geophones did not continuously record for the entire duration of the experiment, and there were significant temporal gaps in acquired data. As a surface array is a more realistic point of comparison for long-term seismic monitoring, we did not reprocess the raw downhole geophone data to build an earthquake catalog ourselves.

Surface instruments deployed by the UUSS were active before, during, and after the stimulation experiment and are shown as blue triangles in Figure 1a. Within the nearby area, seismometers sample the wavefield at 100 Hz and are predominantly broadband instruments. In particular, many of the stations use Nanometrics Trillium 120 instruments, with others using Kinematics Episensors, OMNI-2400s, and Guralp CMG-40Ts. More information on the instrumentation in the nearby area can be found in prior studies (e.g., K. Pankow et al., 2020; Potter, 2017) and on IRIS (https://ds.iris.edu/mda/UU/). Temporary deployments during the stimulation of additional surface and shallow borehole receivers are not used in this study due to their proximity to anthropogenic noise sources.

The stimulation of well 58-32 (magenta line in Figure 1b) was separated into three phases, each containing nine different stages. The first phase was in an open hole section, and the other two were in areas in which the casing was perforated (Moore et al., 2019). Different stimulation profiles were tested during the various phases. We use the casing pressure measured in the stimulation well throughout this manuscript.

3. Earthquake Detection and Recorded Events

3.1. Initial Detection Method

The workflow we used to detect earthquakes is almost identical to that for stimulated fracture events described in Lellouch et al. (2020). Here we will only briefly recapitulate the main steps. More details can also be found in Lellouch et al. (2019a, 2019b).

1. Data preprocessing—median removal, band-pass filter (5–100 Hz unless mentioned otherwise), removal of noisy channels, and trace-by-trace $L^2$ normalization
2. Building the P- and S-wave velocity model along the fiber. For the P-wave velocity, this can be done using recordings of the perforation shots, with known locations. For the S-wave velocity, strong microseismic events with good control on location are used.

3. Computing predicted P and S first-arrival times along the array based on the estimated velocity models and angle of incidence, measured in relation to the vertical axis. Events are assumed to reach the bottom of the array first as planar wavefronts.

4. Finding the optimal angle of arrival for continuous data records. Different angles of arrival predict different travel-time curves. For each scanned possible angle, we align the data along the relative predicted times (no absolute timing), and measure their coherency using semblance (Neidell & Taner, 1971). Due to the DAS directivity, the amplitude of P and S phases varies along the array. The semblance-based detection does not directly account for it, as predicting these patterns would require knowledge of the source location and focal mechanism.

5. Event detection by applying a semblance value threshold, and aggregating temporally close events to a single detection. This step also yields initial P- and S-arrival time picks.

With this approach, both stimulated fracture microseismic events and earthquakes are detected. We filter out all events in the geophone-based microseismic catalog based on their detection times (Lellouch et al., 2020). As a result, we only analyze earthquakes that do not originate from the stimulated area. We manually adjust P- and S- picks to more accurately represent the first arrival times. Following our initial assumptions of planar events, the picks represent the arrival time at the bottom of the DAS array. Such corrections are sometimes required as phase conversions at the granite contact or coda events can have semblance values higher than the first P-wave arrival. This is especially important for weak events, in which only a single phase (either S or P) is detected by the angle scan. If we manually confirm that only a single phase can be manually picked, the event is discarded. Finally, we remove all events in which the S-P time difference is larger than 2 s. We are focused on events in the vicinity (15 km) of the FORGE site, and more distant earthquakes are ambiguous to analyze. After these steps, we obtain a catalog containing 77 events, along with their P- and S-arrival times.

3.2. Earthquakes Recorded by DAS

Examples of DAS records in which earthquakes were detected are shown in Figure 2. They demonstrate the major advantage of DAS—quasi-continuous spatial and temporal sampling of the seismic wavefield with high resolution. Even with low SNR, one can see that the earthquakes have distinct arrival patterns as a function of depth along the fiber. We also observe major differences between the six earthquakes as shown in Figure 2. The S-P time difference is quite similar for events (a)-(c), but not for (d)-(f). This indicates that the events originate from different locations. The relative amplitude distribution between the P and S phases indicates differences in the source mechanism. For example, in event (b), the S wave is relatively stronger, whereas in event (c), the P wave dominates.

3.3. Matched Filtering Using DAS Records

Given this catalog of event detections, we seek to enrich the number of detections using matched-filtering techniques. Matched filtering typically has the potential to increase event detections by an order of magnitude or more in conventional seismology studies (Schaff & Waldhauser, 2010). However, the use of this technique to DAS seismology has been relatively limited and used only with surface DAS applications (Li & Zhan, 2018, Yuan et al., 2020). Because of the strong variability between DAS datasets due to instrumentation, optical parameters, and fiber coupling, methodologies that handle multiple spatially coherent channels are often site-dependent. To ensure the rigorous application of this technique to our downhole dataset, we first re-examine prior rules-of-thumb, such as using thresholds of 0.30 cross-correlation coefficient (CC) in single-station techniques (e.g., Gibbons & Ringdal, 2006; Schaff, 2008). From a set of ~300 detected events (including, among others, the previously studied microseismicity from Lellouch et al., 2020), we examine the CC values of all ~50,000 event pairings to get a sense of both event clustering and the statistical distribution of CC values. In this context, CC values are determined by performing N independent cross-correlations for the N channels in the DAS fiber. The N channel correlograms are stacked,
using weights based on the average channel-SNR for all events, to enhance stacking performance (Beaucé et al., 2018; Liu et al., 2020). Based on the statistical distribution of CC values, we ascertain a median absolute deviation (MAD) of \( \sim 0.03 \) CC. Typically, studies have considered detection thresholds of 5–15 \( \times \) MAD (Huang et al., 2017; Tang et al., 2010). We initially consider the 6 \( \times \) MAD value of \( \sim 0.20 \) CC as a reasonable minimum threshold for clustering events into families for matched filtering, which is slightly more sensitive than the often-used CC value of 0.30 for single-channel seismometer detections. This reduces the 77 candidate earthquakes detections by three-fold, into 24 distinct families of events that may be used as templates. In addition, to test if this 6 \( \times \) MAD detection threshold is adequate for detection, we apply the matched filtering technique to the entire continuous DAS dataset, using a time-reversed acausal template. By applying the time-reversed template, we assure that the output CC values will be purely random as they do not represent any real correlation between physical events. Therefore, output detections will ascertain the false-positive rate. This test finds that none of the acausal CC values were higher than 0.09.

Given a robust matched-filtering approach and detection thresholds, we apply them to the entire continuous DAS dataset using the 18 out of the 24 families of events as templates. Only families containing more than one event were used in order to increase the SNR of the templates. This template choice was selected to highlight events that are already most active during the DAS recording period and to ensure higher template SNR. To produce a single template from a family of events, we align all events based on their picked
S-wave arrival time and stack them. We then cut the templates at 50 ms before the earliest P-arrival pick in the family to 500 ms after the latest S-arrival pick. Therefore, trailing and leading noise is limited to the necessary minimum. For the detection of new events, we relax the CC cut-off threshold. Instead of 0.20 used for clustering, we use 0.09 CC. While this potentially increases the number of false alarms, it also allows for the detection of weak events. From this analysis, we find 32 new events above the cut-off threshold, 16 of which are visibly discernable in the DAS data. None of these events were above 0.20 CC, justifying our choice of a lower threshold. Out of the visible events, five have clear P and S arrivals, and we thus include them in our finalized DAS catalog that includes 82 events. This increase in event detections is significantly less accentuated than conventional seismology applications (Schaff, 2008). One potential reason could be related to the primary detection algorithm that, by design, has already taken early advantage of the spatio-temporal patterns present in the dense DAS data. In conventional studies, on the contrary, matched-filtering methods represent the earliest processing step to gain additional information from such patterns. As a result, the benefits of template matching after the application of our DAS detection workflow are rather limited. Nonetheless, they ensure that our catalog is complete for events that match the templates.

3.4. Surface Array Recordings of DAS Detections

Four earthquakes outside of the stimulation zone were present in the UUSS earthquake catalog during the experiment (and one within the USGS catalog), and were detected by DAS. We also examined the seismograms recorded by the local surface array around the times of the 82 events in the DAS catalog. One of the stations (FORK) is in a shallow borehole. We show the surface seismograms (Figure 3) from the same times as the DAS events shown earlier (Figure 2). Based on the timings of DAS events, we visually inspect the data (Figure 3) using the Antelope software package. We note that these events were likely below the standard completeness magnitude of the UUSS catalog.

As we show later, the majority of the surface stations are closer to the earthquakes than the monitoring well. Nonetheless, the events are unequivocally clearer in the DAS records. It is worth mentioning that the surface seismograms are unusually noisy in the bandwidth of local earthquakes, primarily because of anthropogenic activity (McNamara & Buland, 2004). For example, station FOR4, which is collocated with the monitoring well, is so noisy that no earthquakes are visible in the seismograms. As can be seen from the DAS records, surface noise at depths of 100 m and more is negligible even when compared to the weaker earthquakes. This result is corroborated by prior studies on the impact of emplacement depth on station performance (Hutt et al., 2017). As such, DAS records enjoy the benefits of a much quieter environment for the majority of the channels.

3.5. Summary of Detected Earthquakes Stimulation Activity

Figure 4 summarizes both DAS and surface earthquake detections during the stimulation period. As mentioned earlier, all stimulated fracture events were filtered out. Therefore, Figure 4 shows only earthquakes. We use a semblance measure to estimate the certainty of the detections using the DAS array. It represents the maximal semblance (on a scale of 0–1) value for either the P or S phase obtained during the detection step. We use it as a proxy for event clarity and certainty in the DAS data. Figure 4 shows several temporal clusters. In addition, it shows that the surface array is clearly biased towards the detection of events with higher DAS semblance, which is rather unsurprising. The average semblance value for all DAS events is 0.17, whereas it is 0.31 for the events identified by the surface array.

4. Event Analysis

4.1. Event Location Using DAS

DAS records in this configuration can be used to estimate the distance from the array and the depth of the source. The azimuthal information is, as always with a single vertical DAS array, lost, due to the cylindrical symmetry of the problem (Karrenbach et al., 2019). For computational feasibility of the detection method, we assume that any earthquake reaches the bottom of the array first, as a planar wavefront. Otherwise, there
is not a single angle of arrival, and an infinite number of different travel-time curves can be possible. As a result, the location depends on the same limitation—there are two single angles of arrival, one for P-waves and one for S-waves, measured at the bottom of the array. We have previously discussed the measurement of P- and S-arrival times at the bottom of the DAS array (Figure 2).

The combination of S-P time difference and angle of incidence can recover the event’s depth and horizontal distance from the array. In its simplest form, such location procedure would assume straight ray propagation in the granitic basement. As the seismic velocities in granite are more or less homogeneous (see sonic logs in Figure 1), this approach is acceptable. Each event will be positioned somewhere along a straight ray, originating at the bottom of the DAS array with the measured incidence angle. The exact location along the ray would be determined by the S-P time difference and P- and S-wave propagation velocities in the granitic basement.
However, this straightforward approach suffers from two main limitations. First, the velocity gradient in deeper sections (below logging depth) may influence ray propagation. Especially for distant earthquakes and strong gradients, ray bending might be significant, thus causing the straight-ray approach to overestimate event depth. Second, it will wrongly locate shallow events. Since we assume that events reach the bottom of the array first, the maximal measurable angle of incidence is 90° (horizontal incidence). By using straight rays, we limit the estimated depths of shallow events to the bottom of the DAS array.

Therefore, we implement a more accurate technique of event location, based on ray tracing in a general velocity model. It requires the knowledge of the velocity structure below the maximal logged depth, possibly obtainable from surface seismic surveys (Moore et al., 2019). In this approach, rays are propagated through the velocity structure, following the high-frequency (ray) approximation of the acoustic wave equation, instead of assumed straight rays. The event is located somewhere along the ray shot with the incidence angle measured along the DAS array. By integrating propagation times of P and S waves along their respective trajectories, the location can be inferred by the S-P time difference.

There are several practical issues with this approach. In the general case, the P and S ray trajectories can be different, and they will intersect at the true source location. However, given errors in the velocity model and estimated angles of incidence, and limitations of ray theory, there is no guarantee that such intersection will indeed happen. In addition, for 56 out of the 82 events that we detected, only one of the seismic phases can be used to reliably estimate the angle of incidence. Therefore, we have to rely on single-phase location, which will be either P or S, depending on which phase yields a higher semblance in the angle scan. We assume a constant $V_p/V_s$ ratio and locate each event along the P or S ray trajectory using the measured S-P time.

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**Figure 4.** Summary of DAS and surface event detection and stimulation operations. The DAS acquisition was not continuous in the gray intervals and we thus did not process the data from that period. DAS detections are plotted in orange circles as a function of time and maximal semblance value obtained from the angle-scan procedure. Semblance values (0–1) are scaled to the vertical dimension of the figure. Several clusters are visible by their temporal density. Events that are also visible in the surface array are additionally denoted by black crosses. The casing pressure is in blue and shows the three different stimulation intervals. The total volume of injected fluid is in red, indicating that overall, a very limited volume of fluid was injected. The flowback rate is not shown. DAS, Distributed Acoustic Sensing.
Since the azimuth to the events cannot be recovered, we build a 2-D slice that is as representative as possible of the velocity structure that wavefronts propagate through. We choose the plane connecting the monitoring well and, approximately, the center of the active seismic areas. This plane was chosen at 20° below the horizon, towards the south-south-east. The 1-D velocity model at the monitoring well location was built by combining DAS velocity measurements (Lellouch et al., 2020) and sonic logs (see Figure 1). We extended it to a 2-D structure using the granite depth, mapped by surface seismic surveys, and the elevation at the surface (see Acknowledgments for details). The used P-wave velocity model, as well as P and S ray trajectories compared to straight rays, can be seen in Figure 5.

Despite taking into account velocity variations, the location procedure suffers from uncertainty. The most obvious factors, which we can also quantify, are uncertainty in the angle of incidence and S-P time difference estimation. Based on a semblance sensitivity analysis and the dominating frequencies in the records, we approximately estimate them at ±5° and ±20 ms, respectively. These are only average representative values. Their complete description should depend on the signal-to-noise ratio of recorded events and the angle of incidence, as there is higher angular sensitivity in near-horizontal angles. However, these are issues relevant to any location method and not within the scope of this paper. The estimated angles of incidence can differ between the P and S phases. In 26 out of 82 events, both P and S phases are above the reliability threshold for angle estimation. The mean difference between the P and S estimated angles is about 1.4°, with a standard deviation of 9.5°. While this number is higher than the ±5° we estimate, it is influenced by analyzing events with different certainty levels. Even though P and S events are above the detection threshold for 26 events, they are not equally reliable in terms of angle estimation. In addition, there are structural differences between the P and S velocities. Their influence on the incidence angle is non-linear, and angle-dependent variations are to be expected. However, this source of uncertainty is expected to be
at least partially mitigated by the ray-tracing procedure. Therefore, we conclude that uncertainties we estimate are representative. By shooting rays with different angles and varying the measured S-P time, we can estimate the uncertainty region for the located events. For one event, ray trajectories displayed non-regular behavior, and we thus do not display its uncertainty. Errors in the velocity structure as well as the validity of the ray approximation, especially for near-horizontal events, are harder to quantify and are not in the scope of this study.

Figure 6 summarizes the DAS location and compares them to those of historical seismicity in the region. Due to the lack of DAS azimuthal resolution, locations for the historical seismicity have been mapped from 3-D points to their depth and horizontal distance from the monitoring well. This projection reveals strong correlation with the DAS locations. The three events marked with gray arrows and discussed in the next section were visually identified as refraction events and located differently. Refractive waves cannot be accurately represented by conventional ray-tracing. Instead, we assume they propagate along the granite interface. By integrating the propagation distance along it, after spatial smoothing, we obtain an equivalent raypath along which we can position the event using the S-P time and propagation velocities directly below the granite contact. This location will be along the granite contact, whereas the events almost certainly originated above it, but it is nonetheless highly useful in this particular scenario due to the thinning of the sedimentary basin.

4.2. A Refracting Earthquake

Figure 7 depicts an interesting earthquake that does not abide to our primary assumption about events reaching the bottom of the array first. In contrary to the vast majority of events, the first arrival occurs at a depth of \( \sim 840 \) m, close to the granite contact estimated at \( \sim 800 \) m. This is indicative of an event originating above the granite contact and refracting off it. The lack of a strong S-P conversion, visible in other events, corroborates that the impinging wavefront follows the down-dipping granitic contact. Due to the eastward thinning of the sedimentary section (see Figure 5), we deduce that the sources of the refraction events are very shallow (<200 m from the surface) and could have also originated at the surface.

4.3. Comparison to Location Using Surface Stations

Only a single event out of the 82 events located with DAS was located during routine processing of the surface array. Therefore, we located the 16 events visible on the surface array ourselves. We emphasize that these are previously uncataloged events with low SNR and usually very few picks. Phase arrivals are manually picked and events are located using the GENLOC package (Pavlis et al., 2004) using the local velocity model, which is a combination between DAS-derived models and sonic logging, and depth constraints from the DAS recordings. We use extrapolated constant velocities below the bottom of the logged area. Such a simplified model carries limitations and is expected to affect location results. For these events, we could manually detect and locate the earthquakes using at least two surface stations and four P/S picks. Events were predominantly located using three stations, with the most clearly defined hypocenters recorded on up to seven stations.

Figure 8 shows that the majority of the events are indeed originating from the source area underlying Mineral Mountains closest to the monitoring well. The surface derived event locations (within the local array footprint) do show some degree of accuracy: events coincide with a previously known activity, and some microseismic events related to stimulation (not shown in the figure) were also recognized and located closely to the FORGE stimulation well. These locations confirm that all events visible in both DAS and surface arrays are related to the ongoing seismicity underlying the Mineral Mountains. We find it likely that all of the DAS-detected seismicity was also related to these swarms (details are elaborated on in a later section).

The feebleness of the events recorded by the surface array likely impacts their reported spatial distribution, as events were only visible at the western most edges of the source region that is most adequately covered by local seismometers. Therefore, the locations are not expected to be precise. In fact, standard error estimates of the epicenter horizontal location are of the order of \( \sim 1.5 \) km, while the depth uncertainty is \( \sim 3 \) km. Outside of the footprint of the local surface array, two DAS-derived events suspected to be related to the
Further/eastern swarm show a west bias in their surface derived location. This west-bias in locations could be related to the inaccuracies in our velocity model, which is 1-D in nature. We note that these velocity model biases are in addition to the aforementioned sparsity of arrival picks and station geometry. As the surface-derived locations are highly uncertain, we do not conduct a direct comparison of location uncertainties between the two arrays. We can nonetheless conclude that DAS depth estimation is significantly more reliable. While DAS location is also significantly more reliable in terms of distance from the array, the azimuth of the events cannot be recovered.

### 4.4. Clustering DAS Events

Clustering approaches (Kaufman & Rousseeuw, 2009) have often been applied to discern similarity between earthquake waveforms. In Figure 9, we show a final application of the clustering algorithm repeated on the full DAS catalog containing all 82 events. This approach provides a simple means to examine and quality
control potential groupings of events. Our similarity matrix is grouped into clusters via an agglomerative hierarchical cluster linkage algorithm using an average distance metric and a CC threshold of $\sim 0.06$ chosen near the MAD that visually highlights groupings. We note that this choice of CC threshold is more lenient than the one used for the template matching, and thus produces fewer families. This average metric was chosen to emphasize overall groupings of clusters, rather than nearest-neighbor type groupings. We then compare this CC-derived clustering to the DAS-derived radial distances and event detection timings. Clear delineations of clusters are noted between these datasets (Figure 9). For example, ongoing swarm activity is noted at 3–4 km distance, with punctuated bursts of relatively independent clusters. In general, clusters tend to be at distinct distances (e.g., C2, C8, & C7). This clustering approach provides some corroborating evidence to the DAS-derived location results. Nonetheless, we also note that the current dataset produces distinct clusters that are not readily discernible (e.g., C2 vs. C1, C5, & C4). Likely, additional information on earthquake focal mechanisms would be useful to better discern the subtleties of the inter-cluster groupings.

### 4.5. DAS Magnitude Estimation

We use the DAS records to estimate earthquake magnitudes as well. Our approach is only approximate, as it is based on empirical relations, uses only a single component of the measurement, and does not account for fiber response. We describe the methodology and show (Lellouch et al., 2020) that for stimulated fracture events, magnitudes are in good agreement with a conventionally processed downhole-geophone-based catalog. In brief, we integrate strain-rate records in time to obtain strain, and then multiply them by the gauge length to derive the displacement of each DAS channel. We then choose, from the bottom 100 channels, the one with the maximal displacement. This value is used in conjunction with the estimated source distance from the array and yields the magnitude. In this study, we use the same approach, based on measuring cumulative strain in the DAS channels, but with events filtered between 10 and 100 Hz. After applying this
methodology, we obtain a magnitude distribution that we compare to the last 5.5 years of the surface catalog (Figure 10). It is difficult to conduct a meaningful statistical analysis based on only 82 DAS events, in which the magnitude estimation is only approximate. However, this comparison unequivocally shows that the downhole DAS array is more sensitive than the surface one. While it is difficult to accurately quantify the difference between them, we estimate the DAS catalog is between 0.5 and 1.0 magnitude units more complete. This is corroborated by the fact that from the 82 events detected by the DAS array, only four were in the UUSS catalog (and one in the USGS catalog). The $b$-value obtained for the DAS array is not statistically significant enough to be treated reliably, but the value estimated ($b \sim 1$) using the last five years of the surface catalog is probably indicative of the regional seismicity.

5. Natural or FORGE-Induced Seismicity?

Enhanced geothermal systems and the process of stimulation by hydraulic fracturing are known to induce or trigger earthquakes (Grigoli et al., 2018; Majer et al., 2007; Schultz et al., 2020). Due to large number of events detected by DAS, we examine the possibility that the events detected by DAS outside of the stimulation volume were induced by stimulation of the 58-32 well in the FORGE project. It is important to note that the total amount of injected fluid was very low (<300 m$^3$), and thus it is highly unlikely that they are caused by induced seismicity. In addition, DAS-derived magnitudes are approximate, and could skew results.

To determine if a sequence of earthquakes might have been induced or not, a set of criteria were established (Davis & Frohlich, 1993; Verdon et al., 2019). The first of these criteria measure the statistical significance of changing earthquake rates. To begin a rudimentary examination of the rates of seismicity,
we analyze ~5.5 years’ worth (Jan 2015–May 2020) of UUSS-recorded swarm seismicity near Mineral Mountains (Figure 10). Rates are established through a maximum likelihood parameter estimation of the frequency magnitude distribution of events (Gutenberg & Richter, 1945; Marzocchi & Sandri, 2009; Schultz et al., 2018), where the magnitude of completeness is estimated as the value that maximizes the goodness-of-fit (Woessner & Wiemer, 2005). Based on this, we estimate that the rate of M0+ events in this area is of the order of 50 events per year, and that around six events of $M > -0.6$ or greater would be expected for the 10.5 days of DAS recording. Our visually confirmed DAS events with $M > -0.6$ during this time is higher (52), but on the order we would expect from natural rates. Obfuscating this result, swarm seismicity has the propensity to naturally change earthquake rates by orders of magnitude (e.g., Crone et al., 2010; Farrell et al., 2009; Klein et al., 1977). In the hydrothermal context, this is often thought to be related to episodic slip where fault valving processes allow for a transient migration of fluid along faults (Sibson, 2020). In particular, swarms underlying Mineral Mountains have been documented to naturally change rates by an order of magnitude over a period of weeks (Zandt et al., 1982). Based on this rationale, we conclude that we are unable to discern any systematic differences from natural variabilities. More enriched catalogs, over a greater period of time, would be required to better discern the potential for triggered or induced seismicity.

Figure 9. Agglomerative hierarchical clustering of DAS data. (a) The similarity matrix (center box) displays the CC values of all 82 event pairs (see scale bar). The ordering of events has been sorted, via a clustering approach shown in the associated dendrogram (left of the center box), where thresholded clusters are shown by shaded boxes and labeled with text (C#). (b) Statistical distribution of all of the event-pair CC values, with various MAD values (dashed lines). (c) DAS-derived event times and distances (circles + stems), clustered (shaded boxes and text labels) according to the results in (a). CC, cross-correlation coefficient; DAS, Distributed Acoustic Sensing; MAD, median absolute deviation.
6. Discussion

This study shows that a vertical downhole DAS array can retrieve low-magnitude earthquakes at a range of up to 10 km from the well. A single DAS well shows a clear benefit in earthquake detection over the available surface array. To obtain these results, DAS data undergo array processing methods that take advantage of their dense spatial continuity. We estimate an improvement of 0.5–1.0 in the magnitude completeness, going well into the negative magnitude range, despite the fact that the well is located 3–4 km from the nearest seismically active region. In addition, DAS records below approximately 100 m depth are almost unaffected by the strong anthropogenic noise present in the area, whereas a collocated surface station was rendered practically useless by it. We therefore believe that for $M < 0$ seismic events, the usage of downhole DAS should be further explored, especially in noisy environments. Notwithstanding, it is somewhat difficult to make sustained claims on the potential and capabilities of DAS for earthquake monitoring, whether natural or induced, based on 10.5 days of recording. The statistical certainty can only be achieved through much longer experiments.

The spatial and temporal continuity of DAS records allows for a much deeper physical understanding of recorded events. Studies regarding coda waves, attenuation, scattering, and so forth will inherently benefit from the spatially continuous observation of the seismic wavefield. The direct observation of events refracting off the granite contact is yet another example of the wealth of information DAS can provide. In terms of event location, a single vertical DAS well will always be limited due to its azimuthal ambiguity. Nonetheless, we have shown that derived horizontal distances from the monitoring well agree with known seismic source areas. DAS locations offer a much more reliable depth estimation than the surface array. In this specific scenario, DAS can also single out events originating above the granitic contact, thanks to their refractive arrivals. In addition, thanks to the spatial density and number of DAS channels, clustering of earthquakes into distinct families is highly reliable and can help understand swarm-like behavior.

Figure 10. Magnitude estimation using DAS for the 10.5-day FORGE experiment compared to the 5.5-years USGS catalog based on surface stations. DAS event occurrences are plotted as a dark green histogram, their cumulative distribution in red circled line, and the maximum likelihood fit to that line in blue. We estimate the DAS FORGE catalog to be complete above $M = -0.7$ (dashed vertical blue line) and use those magnitudes to estimate a $b$-value of 0.69. However, due to the brief recording duration and low number of events, this value is unreliable. The much longer USGS catalog is shown with a light green histogram of occurrences, black crossed line for the cumulative distribution, and the maximum likelihood fit to that line in magenta. The $b$-value is very close to 1, and the catalog is complete above $M = 0.2$ (dashed vertical magenta line). DAS, distributed acoustic sensing; FORGE, Frontier Observatory for Research in Geothermal Energy.
Therefore, our view is that downhole vertical DAS can complement existing local networks, even in the form of a single well. We found 82 using DAS, 77 without themplate matching, and 16 of those were visible on the local surface network when guided by the DAS catalog; only four of these events were found in the routinely processed UUSS catalog. The number of events detected during the FORGE experiment is much higher than the background rate of events in the surface catalog, acquired during significantly quieter periods. The potential enrichment of the catalog and the ability to analyze each event with unprecedented resolution underscores the value of borehole DAS data for monitoring microearthquakes. The higher depth resolution obtained by DAS, or any other borehole array for that matter, is critical for induced seismicity monitoring, as it complements the weakest point of surface arrays. On the other hand, a single vertical DAS array suffers from azimuthal uncertainty, which can be more reliably estimated using a surface array. A combination of downhole and surface receivers could thus accurately locate and identify fault activations and separate them from naturally occurring earthquakes.

A complete 3-D location may be also obtained by using additional DAS wells. Two wells would yield two possible mirrored locations for each event, and three would be sufficient for a unique location. Alternatively, surface or shallow horizontal DAS can be deployed at a much lower cost. However, as we have seen, data quality in the shallow section may be problematic, especially in the presence of anthropogenic noise, and its advantage over standard surface receivers remains to be proven. If a horizontal DAS array could be deployed at a depth of ~100 m and more, it could prove extremely useful.

Magnitude and focal mechanism estimation using DAS still remain an open question, despite our simple yet useful approximation of the magnitudes. A true moment magnitude can only be obtained if the source mechanism is fully described. Conducting this with single-component DAS records is challenging, especially as the fiber response is hard to quantify in the field (Lindsey et al., 2020). More complex acquisition geometries have shown promise for DAS-based focal mechanism estimation (Karrenbach et al., 2019), but research is still in its early stages.

Despite some limitations, our joint analysis of DAS and local surface stations yielded an improved understanding of the seismicity during the period of the FORGE stimulation experiment. While seismicity outside of the stimulation volume was more active than the long-term rate for area, it is not directly related to the FORGE injections. Changes can be attributed to the natural variability of swarm activity, with the closest active area potentially affected by the Blundell geothermal plant.

7. Conclusions

DAS holds many operational benefits for monitoring Enhanced Geothermal Systems. It is resistant to heat and pressure with fiber adaptations to more extreme environments, can operate for extended periods of times, and can be acquired in an active well. In this study, we show the potential of a downhole DAS array in an EGS setting. Using an array processing workflow, DAS detects 82 events from outside of the stimulation volume in a 10.5-day period in which only four events were found in the routinely processed UUSS catalog. 16 of these events can be visually identified in the local surface array, albeit with lower signal-to-noise ratio. We estimate the magnitude completeness obtained using our DAS detection workflow to be better by $M = 0.5$ to $M = 1.0$ than the surface network. While locations obtained from a single DAS well suffer from azimuthal symmetry, their depth accuracy is much higher than that obtained from a regional surface array. More elaborate DAS acquisition geometries can lead to complete 3-D location estimations, and better help constrain the magnitude and focal mechanism. For now, we are only able to use a simplistic approach to magnitude estimation. A joint analysis of DAS and surface data reveals a clear increase in seismicity at a distance of 3–10 km from the treatment well during the FORGE stimulation experiment. It cannot be attributed to the stimulation and is more likely due to the natural variability of earthquake swarm seismicity.

Data Availability Statement

Both geophone and fiber data have been made openly accessible by the FORGE project and are available in the US DOE Geothermal Data Repository (https://doi.org/10.15121/1603679). Sonic logs and miscellaneous well information are found at https://dx.doi.org/10.15121/1542648 and site and regional characterization at https://dx.doi.org/10.15121/1495398. Seismometer data for stations in the University of Utah Seismographic Stations (https://doi.org/10.7914/SN/UU) were accessed through the Incorporated Research Institutions
for Seismology (https://ds.iris.edu/mda/UAU/). The catalog of DAS events can be accessed on https://github.com/ariellelouch/FORGE or 10.5281/zenodo.3909840 (Lellouch, 2020).

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