Fibre optic distributed sensing of geothermal reservoirs: first results from the University of Leeds Geothermal Campus boreholes

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ABSTRACT

Fibre optic distributed sensing is an emerging technology that allows long-term high-resolution subsurface monitoring. We report on experimental fibre optic surveys using distributed acoustic sensing (DAS) in boreholes in the University of Leeds campus. These boreholes were drilled during 2024 as part of plans to decarbonise campus heating and cooling operations. Drilled to depths up to 250 m, they investigate the Elland Flags and Rough Rock sandstones and their suitability for geothermal reservoirs and include fibre optic instrumentation for DAS monitoring. DAS data, recording in autumn 2024, show that seismic arrivals are visible through the 250 m depth extent of the borehole, and seismic velocities can be derived to ~160 m depth. Furthermore, these appear consistent (to within ±100 m/s) with velocities observed in wireline sonic logs. With additional insight from ambient noise tomography, DAS monitoring could potentially detect local changes in seismic velocity associated with changes in elasticity of the reservoir's pore water on heating. These data provide a valuable baseline ahead of planned thermal testing and subsequent system operation.

1. INTRODUCTION

Heating accounts for around half of global energy demand, with 75% of that supplied by fossil fuels (European Commission, 2016). In the UK, heating buildings is responsible for ~20% of carbon emissions (CCC, 2016). Compared with the challenge of decarbonising heating, greening the supply of electricity has been relatively straightforward since the interventions required have not significantly impacted people's lives. By contrast, innovative solutions to heating are required to minimise the degree of retrofitting needed to decarbonise heating systems in every UK building. Geothermal energy is attractive for decarbonising heating/cooling systems in the urban environment. Many urban centres are underlain by potential geothermal reservoirs, offering storage and extraction options for excess heat and providing significant reductions in carbon demand (Abesser, 2020). Nevertheless, the UK has been slow to explore geothermal heating solutions, owing to i) lack of knowledge about the geological and hydrological complexities of geothermal reservoirs, and ii) stakeholder concerns about the long-term sustainability, and thus cost-effectiveness, of geothermal heating.

As part of local decarbonisation initiatives and to provide a 'living lab' for exploring geothermal heating/cooling systems more widely, the University of Leeds is exploring geothermal solutions to campus energy provision. Located on interbedded sand- and siltstones of the Coal Measures, two fractured sandstone aquifers – the Elland Flags (~40 m depth) and the Rough Rock (~200 m depth) – represent potential geothermal reservoirs. Eleven boreholes were drilled around campus (nine shown in Fig.1), equipped with different instrumentation for assessing geothermal potential. Four closed loop (CL) boreholes contain HDPE U-loops to facilitate thermal response testing, and two open loop (OL) wells allow extraction, injection and circulation of hot and cold water through the Elland Flags aquifers. Pilot wells (PW) are fully cored and logged with wireline tools and are kept open for further geophysical testing. Additionally, most boreholes are equipped with fibre optic cable to explore the potential of distributed acoustic and temperature sensing (DAS and DTS, respectively) to monitor aquifer properties throughout thermal response testing. These technologies are attractive in borehole deployments because, in principle, they provide high-resolution *in situ* seismic characterisation of geothermal reservoirs and their surrounding geology, but this paper represents their first appraisal for the University of Leeds facility. In this paper, we present initial DAS observations in borehole PW02a, a pilot well immediately outside the Leeds School of Earth and Environment. We review data quality and explore the insight offered by DAS with respect to models of seismic velocity derived from wireline logging. We suggest that DAS could be used to characterise stratig-

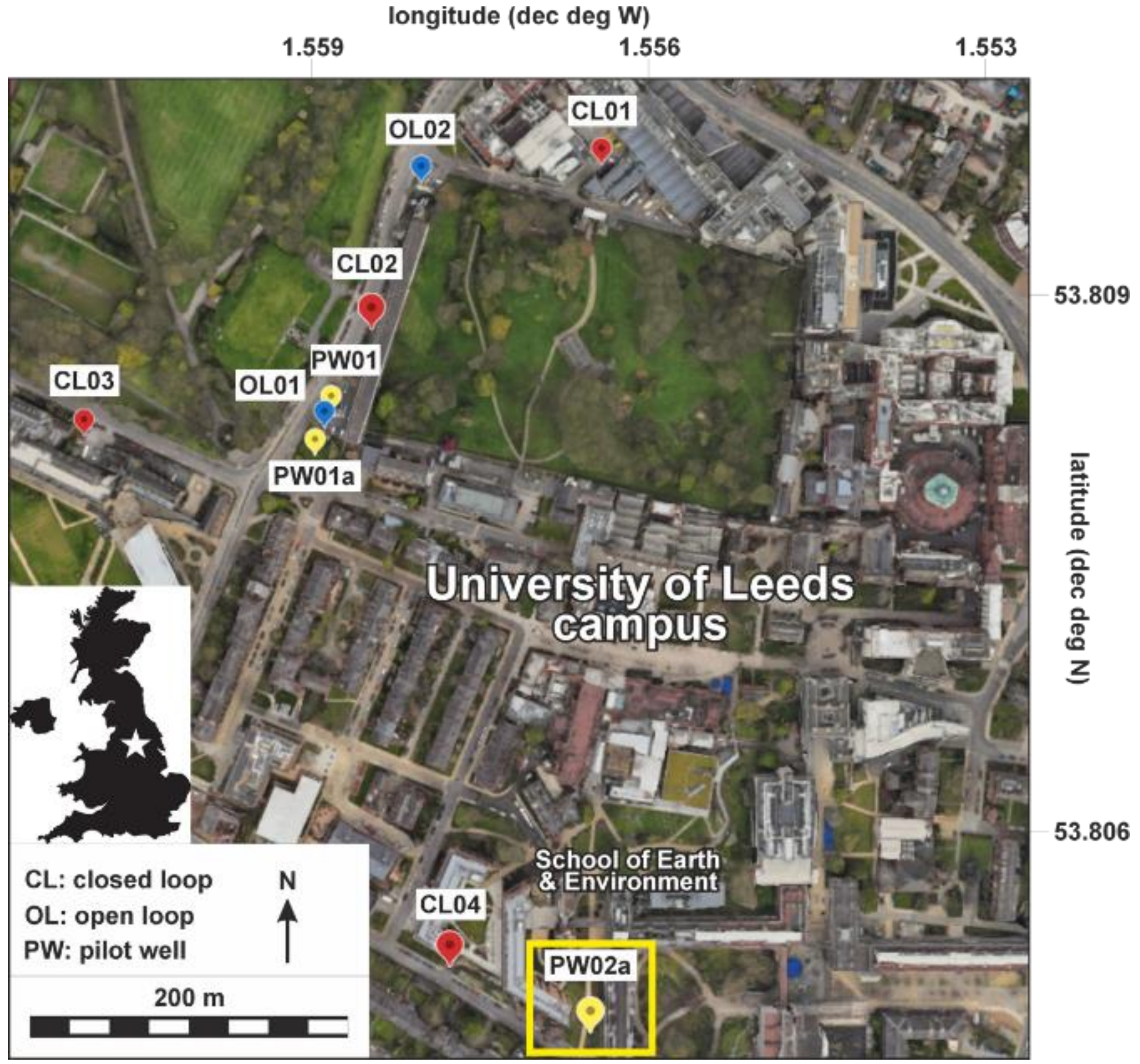

Figure 1: University of Leeds campus map and the location of geothermal boreholes. The southernmost borehole, PW02a, is the primary focus of this paper. Aerial imagery from Google Earth, featuring data from Data SIO, NOAA, U.S. Navy, NGA, GEBCOLandsat / Copernicus.

raphy between boreholes that are not logged with wireline tools, and that there is some potential to detect the seismic expression of heating or cooling within the Elland Flags aquifer. Regardless, our initial velocity models provide a baseline ahead of any future seismic monitoring during thermal testing and system operation.

2. DAS AND THE CAMPUS EXPERIMENT

Distributed Acoustic Sensing (DAS) is a maturing technology that allows a length of fibre optic cable to be used as a string of seismic receivers. DAS is based on the backscatter of laser pulses through the length of a fibre-optic cable: variations in backscatter characteristics, sampled by an ‘interrogator’ unit, indicate local strain in the cable. Strains can be caused by thermal or mechanical deformation of the cable (Distributed Temperature and Strain Sensing, DTSS), and the rate of change of strain gives sensitivity to seismic vibrations (DAS). DAS exploits the Rayleigh backscatter mechanism, in which scattering occurs due to an interaction between the propagating laser pulse and heterogeneities in the fibre wall (inset, Fig. 2).

As a section of the cable is deformed by seismic vibration, the pattern of heterogeneities changes, which affects the local phase of the backscattered signal. The interrogator can therefore reconstruct the timing and location of seismic disturbance along the cable. Strain rates are measured over a finite distance of the cable, referred to as the ‘gauge length’ (typically 2-10 m for the typical wavelengths used in seismic exploration): this is often considered to be the spatial resolution of the DAS survey. Compared to data recorded with more conventional seismic sensors (geophones), DAS data tend to have lower signal-to-noise ratio, but the near-continuous sampling in space is a major advantage of the technology. The seismic properties of a reservoir are themselves valuable to monitor since they i) could indicate changes in fluid content, ii) evidence stratigraphic correlation between successive boreholes, and iii) de-risk the geothermal operation by monitoring seismic emissions during operation.

Single-mode fibre optic cable, compatible with DAS (and, scheduled later, Brillouin-mode DTS), was installed through the 250 m depth of pilot well PW02a following coring and wireline logging, and set behind its casing. The casing is slotted in the reservoir intervals (Elland Flags at ~37-80 m BGL (below ground level) and Rough Rock at ~198-250 m BGL) to allow water flow. The cable was originally planned to be grouted in place, ensuring good coupling (i.e., mechanical continuity) with the surrounding rock. However, grout was lost from the borehole in intervals 2-36 m BGL, 37-80 m BGL and 198-250 m BGL, and a backfill of packed pea shingle was used instead. A consideration in DAS surveying is therefore whether there is a reduction in data quality where the cable is ungrouted.

For the DAS experiment presented here, the 250 m length of cable (plus its surface surplus) was connected into a FEBUS Optics A1-R interrogator, sampling with a 0.5 millisecond temporal interval and 5 m gauge length, with a seismic observation output every 1.6 m along the cable length. A 6 kg sledgehammer was used to generate seismic energy, striking a polymer impact plate positioned at the top of the borehole. Observations from 37 individual hammer strikes were summed, to boost signal-to-noise ratio in an output vertical seismic profile (VSP – a dataset that shows the timing of seismic arrivals varies with depth, allowing the depth variation of seismic velocity to be measured and reflective horizons to be identified). To benchmark the recorded VSP, a prognostic VSP (Fig.3) was simulated from uncalibrated wireline density and sonic logs from PW02a (note that the upper section of these is taken from an abandoned borehole, PW02, located within ~3 m of PW02a).

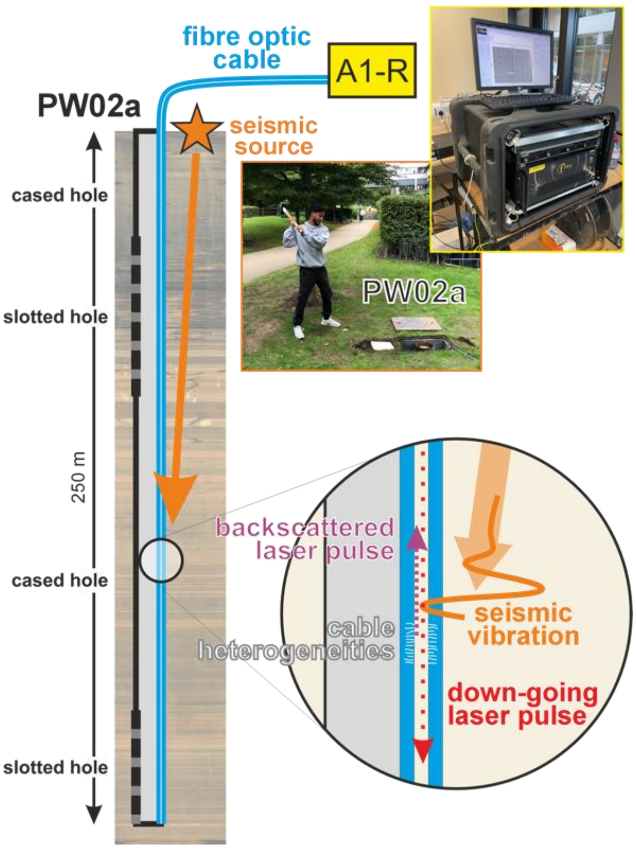

Figure 2: Schematic representation of PW02a and (circular inset) the mechanism of Rayleigh backscatter for DAS. The other inset panels figures show the deployment of the FEBUS A1-R interrogator and an illustrative seismic shot being taken at the top of borehole PW02a.

For unknown reasons, the upper 110 m of the sonic log contains many noise spikes hence is replaced with compressional (P-) velocity (v_P) derived from the density (ρ) log following the application of a locally derived Gardner-type (Gardner et al., 1974) power law, stating $v_P = 0.387\,\rho^{2.581}$ (Fig.3a,b). The logs were smoothed with a 20 m median filter (approximating the distance scale over which a wavelet with this wavelength would sense properties), and the resulting reflectivity series (Fig.3c) was convolved with a zero-phase 80 Hz Ricker wavelet to produce the simulated DAS VSP (Fig.3d). Band-limited random noise was added to the synthetic, scaled to give signal-to-noise ratio of ~10 dB in the region of the reflections.

The strongest arrival in the synthetic VSP is the *direct* wave, which travels directly from surface source to depth position without undergoing any reflection. The travel-time gradient of this event represents the local seismic velocity, and changes therein express vertical velocity variations (e.g., Booth et al., 2020). Events which diverge from the direct wave are reflections, and the depth of the divergence indicates the depth of a reflective interface. The most prominent reflection is predicted at ~38 m depth, consistent with upper contact of the Elland Flags. Elsewhere, reflectivity is low but there are reflective packages between 130-200 m depth, and at ~240 m.

3. RECORDED DAS DATASET

Fig.4 shows the DAS VSP recorded in borehole PW02a. Reassuringly, it appears that the installation of the fibre optic cable was successful, since seismic arrivals can be perceived from the full depth extent of the borehole. In particular, the direct P-wave can be perceived throughout, even if the signal-to-noise ratio is poor beyond ~175 m depth. There are no systematic changes in data quality with depth that can be correlated with the ungrouted zones and potential regions of poor cable coupling: instead, the seismic data show the expected degradation of signal quality with depth as energy is progressively attenuated.

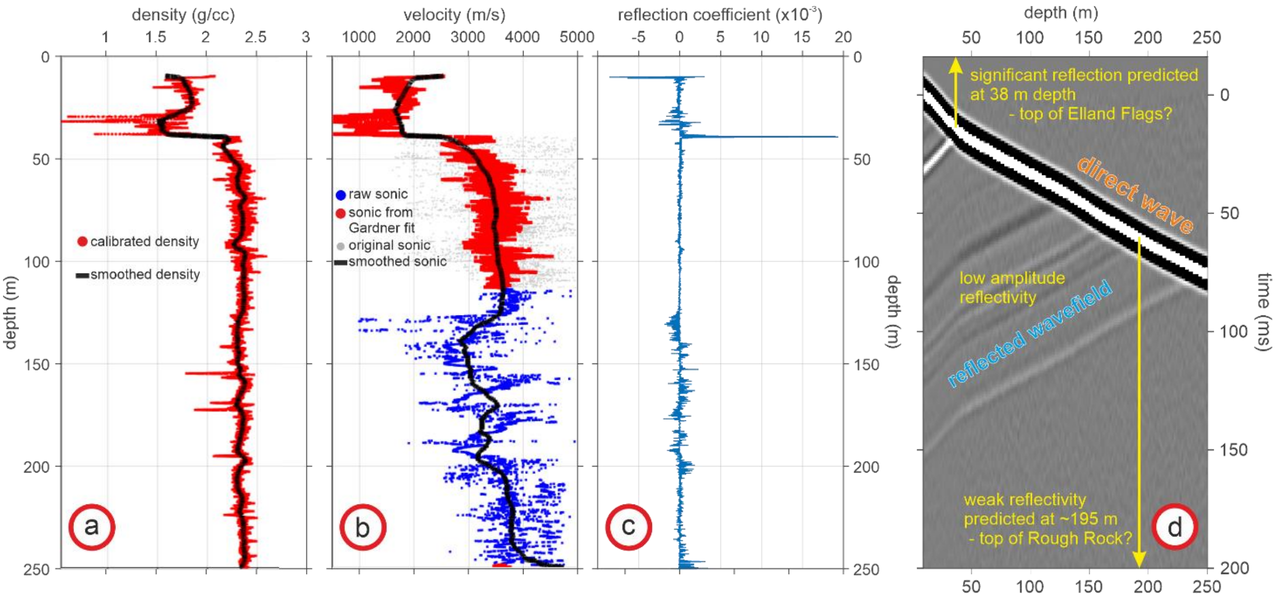

Figure 3: Simulation of DAS VSP dataset. a) Density log. b) Velocity log, partly replaced with velocities predicted from density log. c) Reflection coefficient based on smoothed variants of (a) and (b). d) Simulated VSP (note that, consistent with conventional VSP presentation, depth is presented on the horizontal axis of the figure). A strong reflection appears at a depth consistent with the upper contact of the Elland Flags, with low reflectivity packages elsewhere.

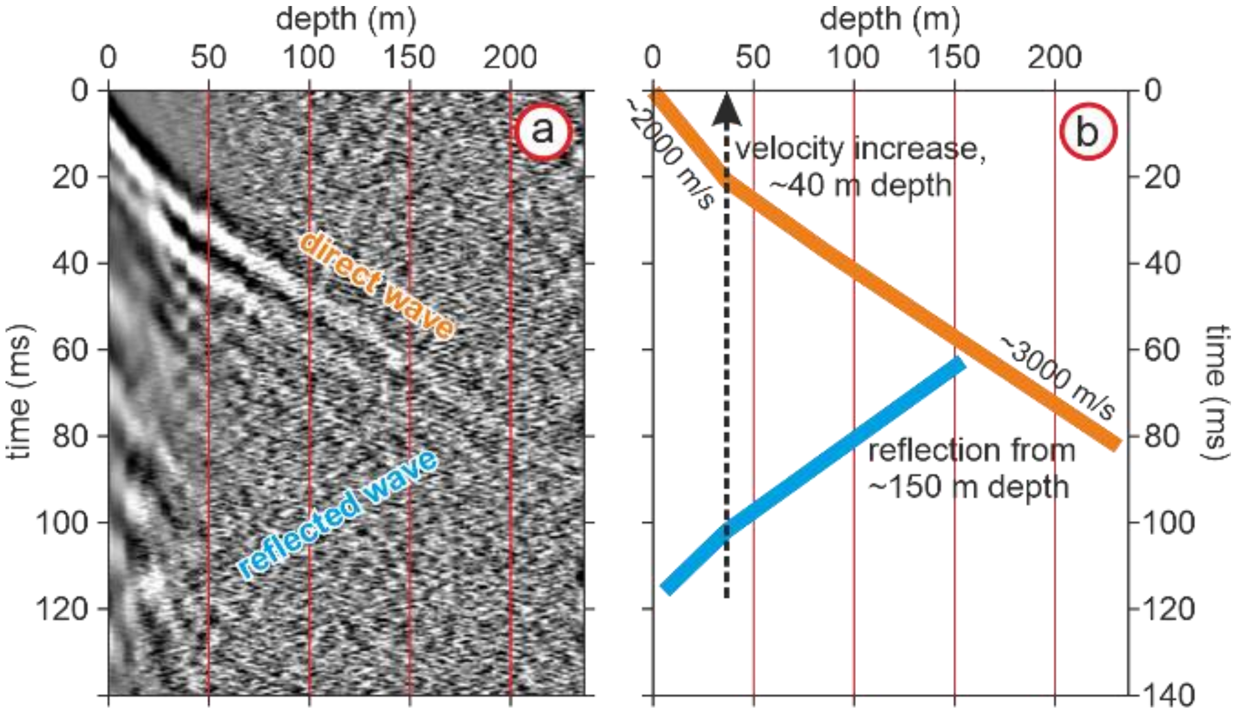

Figure 4: Recorded DAS dataset and summary interpretation. a) DAS VSP, showing a prominent direct wave to 250 m depth and weak amplitude reflectivity. b) Initial appraisal: the direct wave shows a velocity increase at ~40 m depth, from ~2000 to ~3000 m/s, and the most prominent reflection (although low signal-to-noise ratio) originates from ~ 150 m depth.

The slope of the direct wave implies a velocity that is similar to that in the wireline log and thus in the synthetic: the typical velocity in the uppermost ~40 m is ~2000 m/s, increasing to ~3000 m/s thereafter. A P-wave reflection is visible (blue, Fig.4b), diverging from the direct wave at ~150 m depth, but it is surprising that no reflection can be associated with the velocity change at 40 m depth. It is possible that the appearance of this reflection is masked by high amplitude reverberations in the upper ~30 m of the cable, potentially due to cultural noise around campus.

To obtain a higher resolution velocity trend, cross-correlation is used to obtain the travel-time lag between pairs of traces from the DAS record, separated by some known distance. Fig.5a shows the isolated and filtered

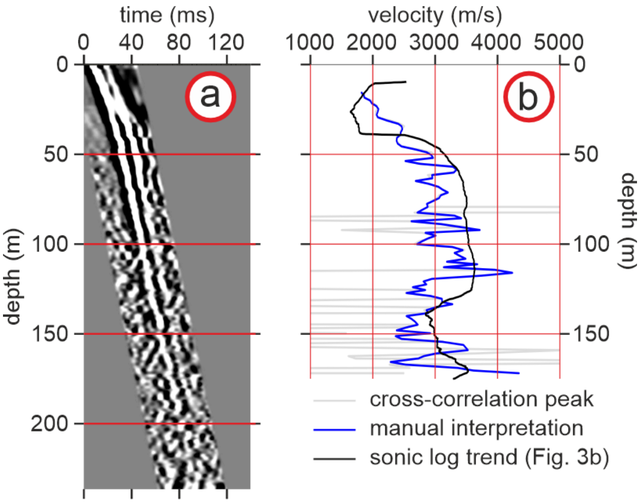

Figure 5. Velocity analysis of DAS VSP direct wave. a) Direct wave, isolated and bandpass filtered (rotated, compared to other figures, for better comparison to velocity log). b) Estimates of velocity, derived objectively from (grey) cross-correlation lag and a manual interpretation of cross-correlations (blue). The median filtered trend (black) from Fig.3b is included for reference.

direct wave, also upsampled in time to 0.1 ms sampling interval to improve the resolution of cross-correlations. Pairs of arrivals are cross-correlated across a 30 m trace separation (corresponding to the typical wavelength of an 80 Hz wavelet) to a depth of 175 m, with peak cross-correlations converted to a velocity model (grey, Fig.5b).

At least three distinct units are implied by the velocity models. The shallowest, from surface to ~40 m depth, is characterised by velocities < 2500 m/s, as apparent within the velocity logs. Between ~40-125 m depth, commencing at the presumed contact with the Elland Flags, velocity steadily increases from ~2500-3500 m/s although with some variability. At greater depth, velocity reduces to ~3000 m/s but, beyond ~160 m depth, cross-correlations are too noisy to derive reliable velocities therefore characterising the Rough Rock reservoir is likely beyond the capability of this experimental design. Comparison with core and borehole imaging from PW02a is currently on-going to provide a more detailed geological interpretation.

4. DISCUSSION: FEASIBILITY OF DETECTING HEATING IN DAS DATA

DAS VSP data show promise for deriving seismic velocity trends in the University of Leeds campus boreholes. The seismic source applied here permits the derivation of apparently reliable velocities to around ~160 m depth, potentially supporting stratigraphic mapping between locations across campus.

Could seismic velocities also be used to track thermal plumes in the campus aquifers? For this, we first consider the sensitivity of our correlation-based velocity analysis. With a temporal sampling interval of 0.1 ms, we suggest that a one-sample error in the cross-correlation equates to a velocity error of ~23 m/s, for the average velocity observed in PW02a. We therefore use this benchmark to indicate velocity sensitivity and thus establish a threshold for thermal detection.

Modelling the temperature variation of v_P through the Elland Flags unit uses the Hashin-Shtrikman (HS) bounds (Mavko et al., 2009). Making no assumptions about the matrix architecture of a rock, these predict the maximum possible range of elastic moduli given the bulk (κ) and shear (μ) modulus of constituents and their volume fraction. The upper HS bound gives the stiffest possible assemblage: the stiffest bulk modulus κ_{HS}^{+}, is

$$\kappa_1 + \frac{f_2}{(\kappa_2-\kappa_1)^{-1}+f_1\left(\kappa_1-\frac{4}{3}\mu_1\right)^{-1}} \quad (1)$$

and shear modulus, μ_{HS}^{+}, is

$$\mu_1 + \frac{f_2}{(\mu_2-\mu_1)^{-1}+2f_1(\kappa_1+2\mu_1)/\left[5\mu_1\left(\kappa_1+\frac{4}{3}\mu_1\right)\right]^{-1}} \quad (2)$$

where f_1 and f_2 are the fractions associated with constituent moduli $\kappa_{1,2}$ and $\mu_{1,2}$. The lower bound describes the softest possible assemblage, and is accessed when constituents associated with indices 1 and 2 are interchanged. When then combined with a volumetric average density, the range $v_P^{\pm} = \sqrt{(\kappa^{\pm} + \frac{4}{3}\mu^{\pm})/\rho}$. When one of the constituents is a fluid, the upper bound is usually expressed as a *modified* upper bound to acknowledge a critical porosity of ~40%.

Properties of the Elland Flags matrix are fixed and assumed to be quartz, having ρ = 2530 kg/m^3, κ = 30.8 GPa and μ = 11.6 GPa; no direct measurement of μ is available, but it is scaled to give a compressional-to-shear velocity ratio of 2. The model of Ewing et al. (1948) is used to describe the temperature dependency in water of v_P and κ, fixing κ at 1000 kg/m^3; the shear modulus for fluid is 0 GPa. The constituent fractions are set to 0.15 and 0.85, reflecting the 15% porosity in the Elland Flags. We assume that all water at ambient temperature can be replaced by water at warmer or cooler temperature, and thus the sensitivities we predict are likely "best case scenarios". The ambient temperature in PW02a is measured at 12°C: we model cooling to a minimum of 5°C and heating to a maximum of 32°C.

Figure 6 shows the variation of v_P with temperature, for the upper and lower HS bounds. The green-shaded areas of this figure show where the velocity change exceeds the ±23 m/s sensitivity threshold. This indicates that our approach could detect the expression of heating when > 6°C and cooling when > 5°C, if the aquifer architecture conforms to the lower HS bound. This sensitivity to thermal change is promising, suggesting that our approach could be used to monitor

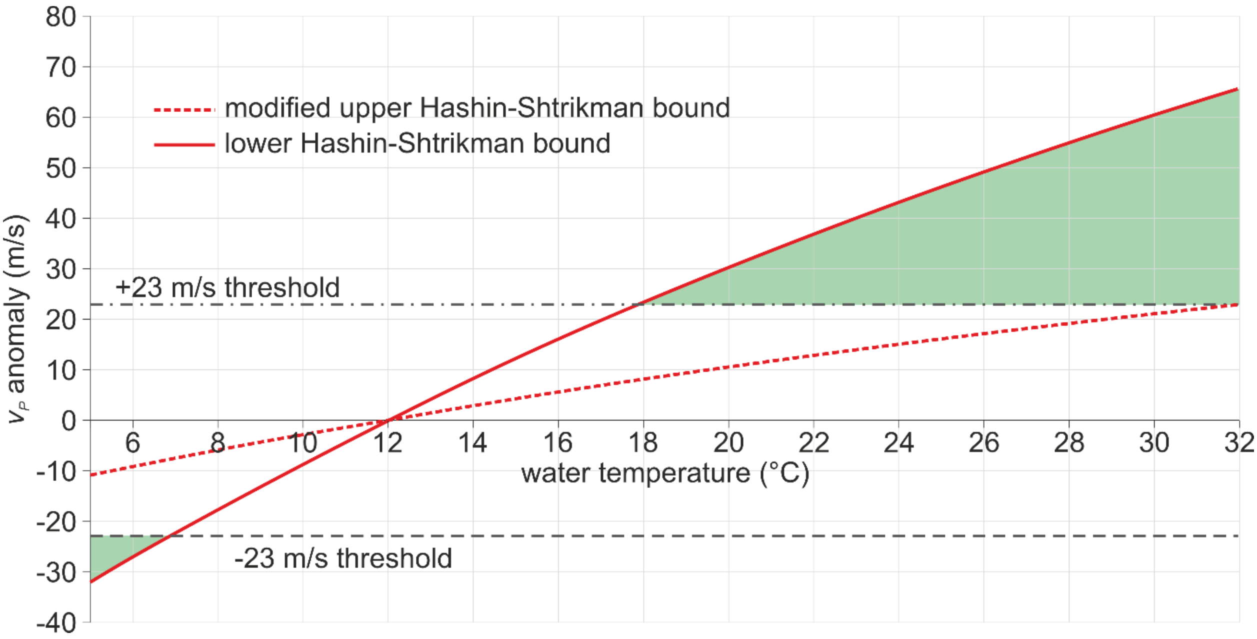

Figure 6. Variation of P-wave velocity, v_P, with water temperature in the Elland Flags. The solid red line shows the velocity anomaly associated with the lower Hashin-Shtrikman bound, the dashed red line with the upper. The range of possible velocities that also exceed a ±23 m/s sensitivity threshold, are shaded green. Ambient temperatures in PW02a are observed to be 12°C.

the geothermal system beneath the University of Leeds campus and elsewhere. However, if the Elland Flags architecture was more consistent with the upper HS bound, then only temperature increases exceeding 20°C may be detected: this would only likely ever be plausible near to a heat injection borehole. A conservative estimate is that our approach could only detect a warming anomaly of 10°C.

Improved sensitivity may be achieved with a more impactful seismic source, which would improve the underlying signal-to-noise ratio in the data, or by using an alternate method to evaluate velocity. One such method could be through analysis of ambient noise (Sens-Schönfelder and Wegler, 2006) in long-duration DAS recordings. Additionally, the same fibre optic cable is compatible with Brillouin DTS, and experiments with this interrogator are scheduled for autumn 2025: temperature changes greater than ± 0.5°C should be highly detectable with this apparatus.

5. CONCLUSIONS

In this paper, we present the first DAS data from the University of Leeds geothermal boreholes. The appearance of coherent seismic energy through the entire depth range of the fibre optic cable shows that its installation was successful, with no evident breakages or zones of poor coupling. Furthermore, data quality from simple hammer impacts is sufficient to allow seismic characterisation of the subsurface to ~250 m depth and the derivation of robust velocity models to ~160 m depth. More energetic seismic sources, or more sophisticated processing regimes, could improve this performance.

For this experimental set-up, the precision of seismic velocity models shows some promise for resolving plausible changes in subsurface elastic properties related to heat storage, especially close to the point of injection. However, the velocity models are valuable as constraint for more sensitive seismic methods such as ambient noise tomography.

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