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Pengxiao Fan

Institute of Geophysics, China Earthquake Administration

Li Li

fanpx@cea-igp.ac.cn

Institute of Geophysics, China Earthquake Administration

Shouji Pang

China Geological Survey

Baoqing Tian

Institute of Geophysics, China Earthquake Administration

Yue Zhang

China University of Mining and Technology - Beijing

Research Article

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Posted Date: October 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11247202/v1>

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Additional Declarations: No competing interests reported.

Winter-to-spring changes in borehole seismic noise beneath permafrost in the northeastern Tibetan Plateau

Pengxiao Fan¹, Li Li^{1,*}, Shouji Pang^{2,3}, Baoqing Tian¹ and Yue Zhang⁴

¹*Institute of Geophysics, China Earthquake Administration, Beijing 100081, China*

²*Oil and Gas Survey, China Geological Survey, Beijing, 100083, China.*

³*Observation and Research Station of Gas Hydrate and Permafrost Environment in Muli Town (Qinghai Province), Ministry of Natural Resources, Beijing, 100083, China.*

⁴*China University of Mining and Technology (Beijing), Beijing 100083, China*

Abstract

Characterizing winter-to-spring seismic noise beneath the permafrost base helps define the recording background at borehole stations. We analysed continuous vertical-component records from 27 January to 20 April 2019 at JXSKD, installed at approximately 300 m depth in the DK-8 borehole, Muli, northeastern Tibetan Plateau. Probabilistic power spectral density (PPSD), normalized velocity spectra, and spectral entropy were used to examine noise power and spectral shape. Median acceleration PSD near 3.4 Hz increased by up to 21 dB relative to 27 January–5 February, whereas median PSD near 0.2 Hz varied over a range of 4 dB. Within 0.67–3.33 Hz, spectra shifted from concentration near the lower band boundary to broader distributions with peaks near 2–3 Hz; the early-to-late median daily entropy increased from 0.867 to 0.943. Matched-window comparisons between 8–17 March and 7–16 April showed similar entropy but higher band power. The increase was 3.36 dB with at least one accepted window per day and 2.86 and 2.77 dB at thresholds of 72 and 114 windows; the strictest threshold retained only three March days. Both matched-window Welch velocity-power measures declined during 17–20 April. The entropy increase persisted after response correction and under stricter daily-coverage thresholds. Shallow daily mean temperatures documented warming below 0 °C, without establishing thawing as the cause. These observations characterize frequency-selective noise changes beneath permafrost and show why absolute power and relative spectral distribution should be considered together when evaluating this station’s recording background.

Article Highlights

- Noise power increased near 3.4 Hz without a comparable increase near 0.2 Hz.
- Normalized spectra became less concentrated, with broad peaks near 2–3 Hz.
- Matched-window comparisons reveal different noise powers at similar entropy levels.

Keywords: Borehole seismology; Permafrost; Ambient seismic noise; Spectral entropy; Tibetan Plateau

*Corresponding author. E-mail: lilygrace@cea-igp.ac.cn.

1. Introduction

Seasonal freeze-thaw cycles alter the mechanical properties of near-surface materials and

modify seismic-wave propagation in cold environments. Continuous seismic records offer an effective way to monitor such temporal changes. Ambient-noise interferometry has revealed seasonal velocity variations associated with active-layer dynamics in Alaska and freeze-thaw processes in Alpine permafrost, demonstrating the sensitivity of passive seismic observations to changes in frozen-ground conditions (James et al. 2019; Lindner et al. 2021). Controlled heating experiments have further linked permafrost thaw to measurable changes in seismic velocity and spectral response (Cheng et al. 2022). On the Tibetan Plateau, recent studies have investigated frequency-dependent velocity variations and combined seismic observations with thermal modelling to examine the evolution of seasonally frozen ground (Yu et al. 2025; Zhao et al. 2026). Collectively, these prior works lay the groundwork for using continuous seismic data to monitor environmental change.

The spectral characteristics of ambient seismic noise provide another perspective on the response of frozen-ground environments. Guillemot et al. (2021) tracked seasonal changes in rock-glacier resonance frequencies and interpreted them using models of the elastic properties of partially frozen materials. Köhler and Weidle (2019) identified seasonal changes in horizontal-to-vertical spectral ratios associated with active-layer evolution, while also documenting substantial effects from wind, noise-source variability, and changing instrument coupling. Environmental influences on spectral response have also been identified in earthquake recordings: Händel et al. (2025) observed seasonal variations in a high-frequency site-response parameter derived from surface-borehole records. These findings show that environmental variability can affect the frequency content of seismic observations through changes in both wave excitation and propagation. Accordingly, characterizing this variability needs to consider both the overall noise level and its frequency-domain power distribution.

Borehole observations offer a complementary setting for examining these effects. By placing sensors below the ground surface, borehole installations can reduce some surface-related disturbances, although the reduction depends on frequency and installation conditions. For example, Rossi et al. (2023) documented frequency-dependent noise reduction using a surface station and a vertical array extending to 285 m depth, together with improved signal-to-noise ratios for most of the selected seismic events. In a permafrost setting, a sensor installed beneath the permafrost base records a wavefield shaped by sources and propagation paths extending beyond its immediate surroundings. This configuration raises a specific observational question: how does ambient seismic noise at a fixed depth below permafrost evolve during the winter-to-spring transition? Addressing this question requires characterizing which frequencies change and whether the changes involve a redistribution of relative spectral power within the affected bands.

Power spectral density (PSD) and its statistical distributions provide established measures of seismic noise levels and their frequency dependence (Peterson 1993; McNamara and Buland 2004). Normalizing a spectrum within a selected frequency band allows its shape to be examined separately from its absolute power. Spectral entropy provides a compact measure of this normalized distribution, with lower values indicating concentration in fewer frequency bins and higher values indicating a more uniform distribution. Spectral-entropy methods have been applied to microseismic event detection in noisy records (da Silva and Corso 2022). Here, their relevance lies in summarizing the evolution of background spectral shape. Joint examination of PSD, normalized spectra, and spectral entropy can help distinguish changes in power level from changes

in the relative contributions of frequency components. Available shallow ground-temperature information can provide seasonal context for interpreting the timing of these changes.

We use continuous vertical-component records from 27 January to 20 April 2019 at JXSKD to examine ambient-noise variability at approximately 300 m depth, beneath the local permafrost base. We address two questions: which frequency components change in power, and do power and spectral concentration follow the same temporal progression? We first characterize frequency-dependent power changes using PPSD, then examine spectral shape using normalized velocity spectra and entropy. Band power and entropy are also compared using identical accepted windows. Daily mean ground temperatures at 0.5 m depth provide shallow thermal context, and eight regional earthquakes serve as recording examples. The aim is to characterize noise variability during this observation period and its implications for describing the borehole recording background.

2. Study area and borehole observation system

The study site is located in the Juhugeng mining area of the Muli coalfield, Qinghai Province, in the Qilian Mountains on the northeastern Tibetan Plateau (Fig. 1). The area is characterized by alpine permafrost and seasonal freezing and thawing of the active layer. The DK-8 borehole forms part of the Muli long-term observation site and hosts the JXSKD borehole seismic station (Fig. S1).

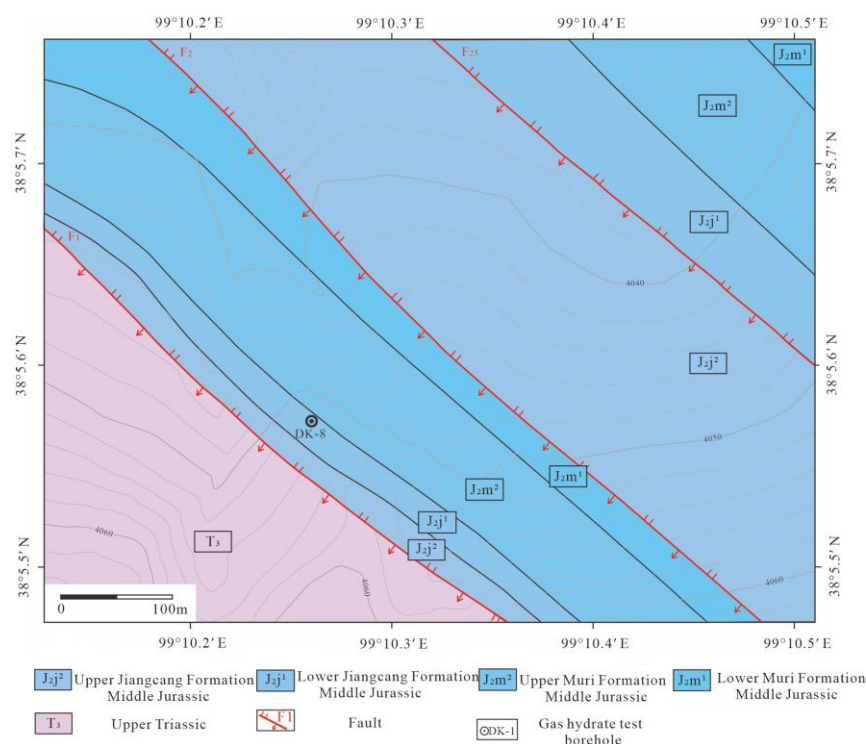


Fig. 1. Geological setting and location of the DK-8 borehole in the Muli permafrost region, northeastern Tibetan Plateau. The map shows the lithostratigraphic units, faults, topographic contours, and location of the borehole hosting the JXSKD seismic station.

The DK-8 borehole extends to approximately 300 m depth, with casing extending to the borehole bottom. Drilling records indicate that the shallow section was not cored, whereas the recovered bedrock section consists mainly of oil shale and silty mudstone with interbedded sandstone. The local permafrost thickness is approximately 100 m. The seismometer is installed

near the bottom of the borehole, approximately 200 m below the local permafrost base (Fig. 2). This configuration places the sensor beneath both the seasonally active layer and the underlying permafrost.

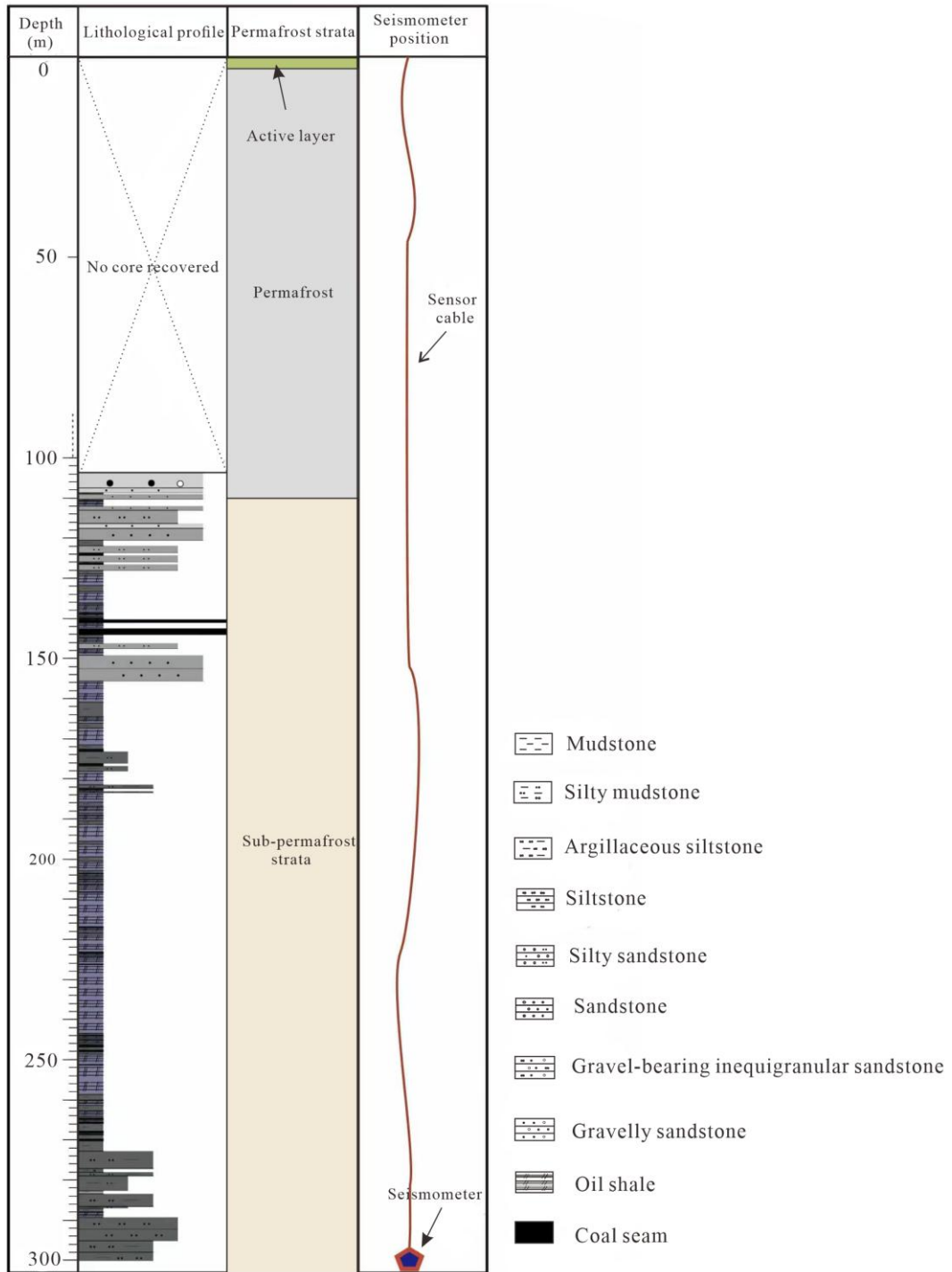


Fig. 2. Borehole structure and seismometer installation at the DK-8 site. The diagram shows the lithological profile, active layer, permafrost interval, underlying strata, sensor cable, and seismometer position. The sensor is installed at approximately 300 m depth, beneath the local permafrost layer, which is approximately 100 m thick.

JXSKD is equipped with a TDE-120VB three-component very-broadband borehole seismometer independently developed in China. This model has also been deployed at 1972.7 m

depth at Changde, Hunan Province; Fan et al. (2026) reported a response range of 0.008-40 Hz (± 0.3 dB) and a dynamic range of at least 140 dB for the instruments installed there. The present analysis concerns the DK-8 recordings and uses response metadata matched to the JXSKD channel and observation period.

Ground temperature at 0.5 m depth near the DK-8 borehole was supplied as daily means derived from measurements acquired every 30 minutes. The daily means follow Beijing calendar days (UTC+8) and provide a shallow thermal reference for seasonal warming. They do not constrain temperature at the seismometer depth or determine thaw depth.

3. Data and methods

3.1 Continuous waveform data and preprocessing

We used continuous vertical-component seismic records acquired at the JXSKD station during the winter-to-spring transition in 2019. The temporal noise analysis covered 27 January-20 April, with 00:00 UTC on 21 April used as the exclusive upper time boundary. The vertical component was used to compare ambient-noise power, spectral shape, and regional earthquake recordings.

The waveforms were recorded in digital counts. StationXML response metadata were used to estimate acceleration PSD with ObsPy PPSD and to correct Welch PSD to velocity for normalized-spectrum and entropy analysis. Uncorrected count-spectrum entropy was retained as a paired sensitivity comparison. Background preprocessing is described below; regional event selection, arrival identification and recording metrics are described in Section 3.4.

For the continuous background spectral analysis, all available waveform files overlapping each UTC day were identified from their header times. A single full channel identifier and native sampling rate were retained throughout the analysis, without resampling. Missing samples, non-finite values, and conflicting overlaps were flagged, and affected analysis windows were excluded. Identical duplicate samples were counted once; gaps were not interpolated. Each accepted 30-min window was demeaned, linearly detrended, and tapered using a cosine taper over 2% of its length at each end. The entropy analysis used the same 11-file exclusion list as PPSD and retained LN.JXSKD.00.BHZ at 100 Hz, yielding 9834 accepted 30-min windows across 81 UTC days with valid estimates.

The supplied ground-temperature series comprises daily means at 0.5 m depth, calculated by Beijing calendar day (UTC+8) from measurements acquired every 30 minutes. We retained these means unchanged. Each local day spans 16:00 UTC on the preceding date to 16:00 UTC on the labelled date; its mean is plotted at the interval midpoint, 04:00 UTC on the labelled date. This placement does not convert the values into UTC daily means. Seismic daily statistics retain their original UTC boundaries. Missing temperature values were not interpolated, and no values were extrapolated to January. Actual valid measurement counts per day were not supplied. The temperature and seismic indicators were compared descriptively; no paired daily correlation or lag analysis was performed.

3.2 Probabilistic power spectral density analysis

We used probabilistic power spectral density (PPSD) analysis to characterize frequency-dependent borehole noise variability (McNamara and Buland 2004). Records from 27 January to 20 April 2019 were grouped into consecutive 10-day intervals; the final interval covered 17-20 April, with 00:00 UTC on 21 April excluded. PPSD used complete 1-h windows advanced by 30 min. The selected channel was LN.JXSKD.00.BHZ at its native sampling rate of

100 Hz. We adopted the same gap-handling and window-exclusion rules described in Section 3.1. Eleven waveform files associated with Steim2 integrity warnings were conservatively excluded in their entirety. The retained record duration was 1666.50 h, or 82.66% of the 84-day study interval, and 3311 PPSD windows were accepted.

StationXML metadata were supplied to ObsPy PPSD for instrument-response correction and estimation of acceleration PSD, expressed in decibels relative to $1 \text{ m}^2 \text{ s}^{-4} \text{ Hz}^{-1}$. The metadata were checked for channel identifier, sampling rate, epoch coverage, and evaluable response. PPSD used internal one-octave smoothing, a period step of 0.125 octaves, and 1 dB histogram bins spanning -260 to 20 dB. Main-text spectra and tabulated values are histogram-derived 50th percentiles without additional smoothing. A normalized 13-point Hann window applied in decibels was used only as a sensitivity comparison. The New Low Noise Model (NLNM) and New High Noise Model (NHNM) of Peterson (1993) were included as references.

Median PSD was extracted at the period-bin centres nearest to 0.3 s and 5 s : 0.29344 s (approximately 3.408 Hz) and 5.12 s (approximately 0.1953 Hz), respectively. These points represent contrasting parts of the spectrum. The short-period point lies just above the upper limit of the $0.67\text{--}3.33 \text{ Hz}$ entropy band and is not an estimate of power integrated over that band. Using 27 January–5 February as the reference interval, the PSD difference was defined as

$$\Delta \text{PSD}_{0.3\text{s}}(t) = \text{PSD}_{0.3\text{s}}(t) - \text{PSD}_{0.3\text{s}}(t_0) \quad (1)$$

where $\text{PSD}_{0.3\text{s}}(t)$ is the median PSD at 0.29344 s for the t -th time window, and $\text{PSD}_{0.3\text{s}}(t_0)$ is the corresponding value for the reference window.

3.3 Normalized spectra and spectral entropy

We used normalized response-corrected velocity spectra and spectral entropy to characterize temporal changes in the spectral shape of borehole ambient noise. For each accepted window, Welch's (1967) method was used to estimate the count PSD. This PSD was divided by the squared magnitude of the full StationXML response evaluated for velocity, yielding velocity PSD in $(\text{m/s})^2/\text{Hz}$. The same response metadata as in the PPSD analysis were used; channel, sampling rate and epoch coverage were checked. Correction was applied over $0.50\text{--}10.00 \text{ Hz}$ in the spectral domain without an additional prefilter or water-level regularization. No corrected time-domain waveform was reconstructed. Within each band, a fixed frequency grid was used for all windows, and finite, non-negative linear velocity PSD values were normalized by their sum as

$$p_i = \frac{P_i}{\sum_{j=1}^N P_j} \quad (2)$$

where P_i is the power spectral density at the i -th frequency point and N is the number of frequency bins used within the target band. For the background analysis, this number includes zero-power bins. The normalized values satisfy $\sum_{i=1}^N p_i = 1$ and describe the relative distribution of spectral power within that band. Normalization was performed on linear PSD values, before any conversion to decibels.

Normalized spectral entropy was calculated from the normalized power distribution following Shannon (1948):

$$SE = -\frac{1}{\ln N} \sum_{i=1}^N p_i \ln p_i \quad (3)$$

For $N > 1$ and positive total power within the selected band, normalized spectral entropy ranges from 0 to 1 ; each zero-probability bin contributes zero. Lower values indicate

concentration of power in fewer bins, whereas higher values indicate a more even distribution. Uniform scaling of all PSD values leaves entropy unchanged, but normalization alone does not remove frequency-dependent response effects. We therefore also calculated uncorrected count-spectrum entropy using the identical windows and frequency grids, to quantify the effect of response correction.

The continuous background analysis used complete 30-min windows advanced by 10 min within each UTC day. Welch PSD estimates used 120-s periodic Hann segments, 50% overlap, and arithmetic averaging of the segment periodograms. The Fourier transform length equalled the segment length, giving a frequency spacing of approximately 0.00833 Hz. The same window spectra were used for the 0.67–3.33 Hz primary band and the broader 0.50–4.00 Hz and 0.50–10.00 Hz bands. Daily values were the medians of accepted window-level entropy estimates. Days with no accepted windows were retained as missing; a day with at least one accepted window received an estimate. A centred five-calendar-day moving median and interquartile range were calculated from the available daily estimates within each moving window.

To examine dependence on frequency-band selection, we compared daily median entropy in an early interval (27 January–25 February; 30 calendar days) and a later interval (18 March–20 April; 34 calendar days). These intervals flank the descriptive transition from 26 February to 17 March. Within each band and interval, the unsmoothed daily estimates were summarized by their median and 25th and 75th percentiles, with equal weight assigned to each day with an estimate. Quartiles were calculated by linear interpolation, and the later-minus-early difference was calculated before rounding. The summaries describe variation among daily estimates; the overlapping analysis windows are not independent observational replicates.

The normalized spectra in Fig. 5 were obtained from the same accepted windows and Welch estimates used for the daily background entropy. For each selected date, a pointwise median was calculated across the window spectra normalized within 0.67–3.33 Hz, and this median spectrum was renormalized to unit sum. No additional frequency smoothing was applied. SE_{day} denotes the median of that day’s window-level entropy estimates, whereas SE_{curve} denotes entropy calculated from the displayed aggregate spectrum. These statistics summarize different operations and need not be equal. The number of accepted windows contributing to each selected date is denoted by n .

To assess daily coverage, the early-to-late statistics were repeated with at least 72 and 114 accepted windows per day (approximately 50% and 80% of the 142 candidate windows). For an additional matched-window comparison, velocity PSD was integrated by summing bins within each band and multiplying by the frequency increment. Velocity PSD was also extracted at 3.40833 Hz, the Welch bin nearest the short-period PPSD centre. Daily medians of both power measures used the identical accepted windows as entropy. For comparisons between 8–17 March and 7–16 April, daily medians were summarized by their median, and power changes were expressed as ten times the base-10 logarithm of the ratio of these linear-power summaries. These velocity metrics were not substituted for acceleration PPSD. The 8–17 March versus 7–16 April comparison was also repeated at minimum daily counts of 1, 72, and 114 windows. At each threshold, the same retained dates were used for entropy and both velocity-power metrics, and valid-day counts were reported separately for each interval (Table 3).

3.4 Regional earthquake selection and analysis of recording characteristics

Eight regional earthquakes were selected from the International Seismological Centre (ISC) catalogue as examples of JXSKD recordings at the sampled times. Selection considered

magnitude, epicentral distance, temporal coverage, and waveform identifiability. Catalogue magnitudes were 3.6-4.8 and epicentral distances were 5.29°-9.72° (Table 4). Because selection included waveform identifiability, the sample describes individual recordings and does not provide an estimate of catalogue-wide detection rates.

Theoretical P-wave arrival times were calculated using the ak135 velocity model (Kennett et al. 1995), considering the candidate phases P, p, Pn, and Pg and selecting the earliest predicted arrival. Arrival identification used a search window extending from 15 s before to 25 s after the predicted arrival. A short-term average/long-term average (STA/LTA) detector identified candidate onsets, with short- and long-term windows of 0.5 s and 5 s, respectively, a trigger threshold of 2.2, and a minimum trigger duration of 0.8 s. For the waveform analysis in Fig. 7 and Table 4, the reported picks were obtained after visual review and adjustment based on waveform morphology. The picked-minus-predicted arrival difference was reported as a travel-time residual. This residual includes contributions from the velocity model, catalogue parameters, phase identification, and picking uncertainty, and was not interpreted as an independent measure of clock accuracy.

Signal-to-noise ratio (SNR) is defined here as the ratio of the root-mean-square (RMS) amplitudes of the signal and background windows:

$$SNR = \frac{RMS_{signal}}{RMS_{background}} \quad (4)$$

For the waveform analysis in Fig. 7 and Table 4, the background window extended from 40 s to 10 s before the reported P-wave pick, and the signal window extended from the pick to 40 s afterward. SNR was expressed as a dimensionless amplitude ratio.

4. Results

4.1 Frequency-dependent changes in ambient-noise power

The median acceleration spectra show frequency-dependent changes in borehole ambient noise during the observation period (Fig. 3). Temporal differences were most pronounced at periods shorter than approximately 1 s, particularly near 0.3 s. No comparable enhancement occurred near 5 s, indicating that the increase was concentrated in the higher-frequency portion of the spectrum.

At the actual period-bin centre of 0.29344 s (approximately 3.4 Hz), median acceleration PSD increased from late February and remained elevated during March and April (Table 1). It reached -131 dB during both 7–16 April and 17–20 April, representing a maximum increase of 21 dB relative to 27 January–5 February.

At a period of approximately 5 s, corresponding to approximately 0.2 Hz, median PSD ranged from -137 to -133 dB across the observation intervals, giving an inter-interval range of 4 dB. Thus, the pronounced increase near 3.4 Hz was not accompanied by a comparable increase near 0.2 Hz. This contrast demonstrates the frequency-selective evolution of the recorded borehole noise.

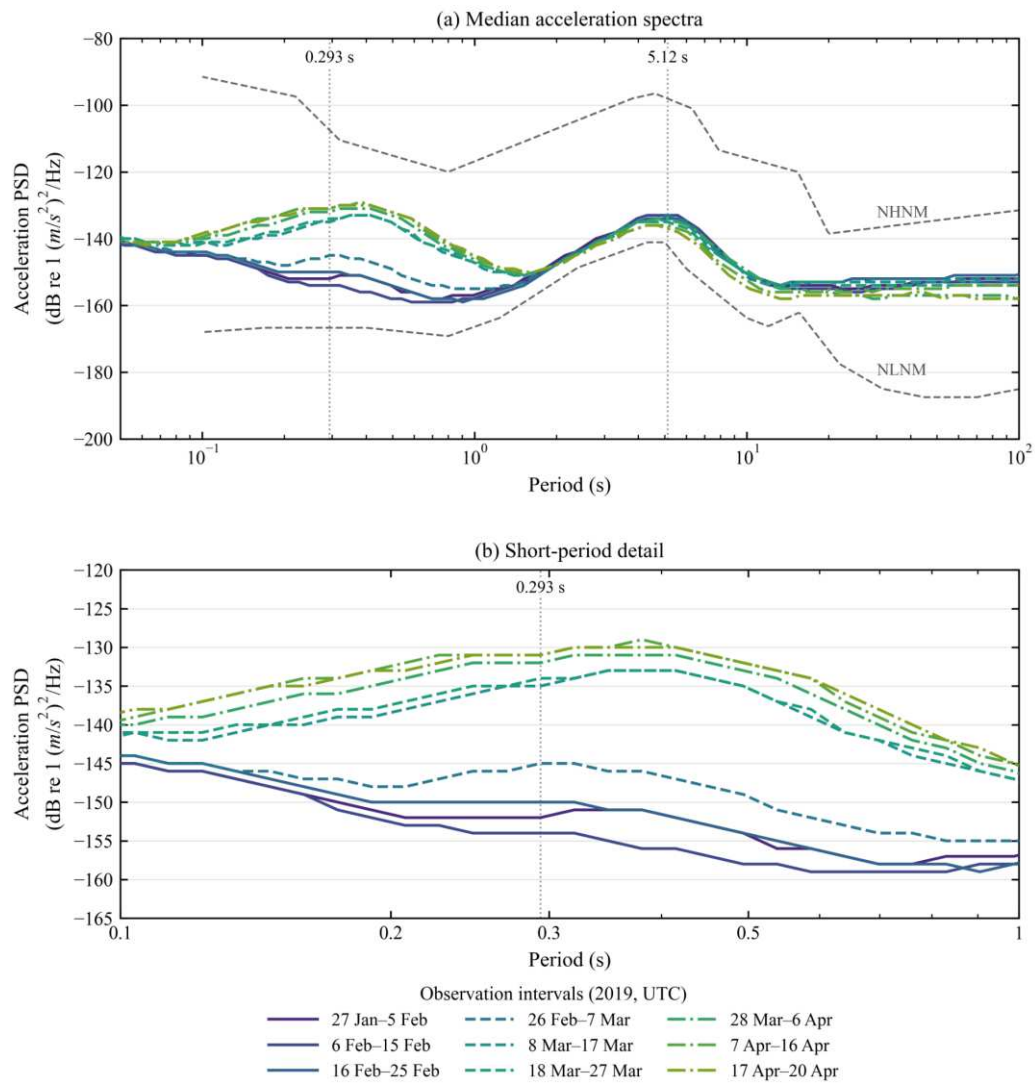


Fig. 3. Temporal changes in median ambient-noise acceleration power spectral density at the JXSKD borehole station from 27 January to 20 April 2019. (a) Median spectra from PPSD analysis over the full plotted period range. (b) Detail over 0.1-1 s, with a different vertical scale from (a). Colours and line styles identify statistical intervals, each spanning 10 days except for 17-20 April. Vertical dotted lines mark the actual analysis periods of 0.293 s and 5.12 s. The spectra retain internal one-octave smoothing, with no additional 13-point Hann smoothing. Grey dashed curves show the New High Noise Model (NHNM) and New Low Noise Model (NLNM) of Peterson (1993).

Table 1. Median acceleration PSD near periods of 0.3 s and 5 s and the number of accepted PPSD windows for successive observation intervals at JXSKD.

Observation interval (2019)	PSD at 0.29344 s (dB)	PSD at 5.12 s (dB)	Δ PSD (dB)	Accepted windows
27 Jan-5 Feb	-152	-134	0	265
6-15 Feb	-154	-133	-2	381
16-25 Feb	-150	-134	+2	390
26 Feb-7 Mar	-145	-133	+7	398
8-17 Mar	-135	-135	+17	265
18-27 Mar	-134	-135	+18	479
28 Mar-6 Apr	-132	-134	+20	479
7-16 Apr	-131	-136	+21	479
17-20 Apr	-131	-137	+21	175

Note: Actual period-bin centres are 0.29344 s and 5.12 s (approximately 3.408 Hz and 0.1953 Hz). PSD is in decibels relative to $1 \text{ m}^2 \text{ s}^{-4} \text{ Hz}^{-1}$. Δ PSD is the shorter-period difference relative to 27 January-5 February 2019. Medians are estimated from 1 dB PPSD histogram bins without additional Hann smoothing. Accepted windows are 1 h long with 50% overlap; the total of 3311 windows does not represent 3311 independent samples. Dates are inclusive; the final interval spans four days.

4.2 Temporal evolution of spectral entropy and noise power

The response-corrected daily entropy series shows a marked rise in late February-early March, followed by a comparatively stable interval, while median acceleration PSD near 3.4 Hz increased further into April (Fig. 4a, b). The supplied daily mean ground temperatures at 0.5 m depth provide shallow environmental context (Fig. 4c). A separate comparison using identical 30-min windows assessed whether velocity-spectrum power increased while entropy remained high (Fig. 6).

Before late February, the centred five-day median entropy fluctuated mostly between approximately 0.84 and 0.91, with a higher value at the beginning of the record. It rose in late February, reached approximately 0.95 in early March, and subsequently remained near 0.94 (Figs. 4a and 5a). The dates 3 February, 4 February and 24 February had no accepted entropy windows and are retained as missing. Acceleration PSD near 0.3 s also increased across the transition (Section 4.1).

The available daily mean ground temperatures remained below 0°C throughout the displayed February-April 2019 record, with more pronounced warming from mid-March onward (Fig. 4c). The initial entropy increase in late February preceded this pronounced warming. The temperature series therefore documents shallow warming but does not identify an onset of thaw at 0.5 m depth.

Daily means alone do not resolve temperature fluctuations within each day.

The matched-window comparison shows that comparatively stable entropy did not imply constant power. Interval entropy summaries were approximately 0.941 during both 8-17 March and 7-16 April, while band power within 0.67–3.33 Hz increased by 3.36 dB and velocity PSD at 3.40833 Hz increased by 3.33 dB (Fig. 6). Each interval summary was the median of the corresponding daily medians. Both power metrics declined during 17-20 April, so the later evolution was not a monotonic increase through the end of the record. Although these Welch velocity-spectrum metrics use a different estimator from the acceleration PPSD in Table 1, the matched-window comparison directly demonstrates that similar entropy values can accompany different noise powers. Applying daily thresholds of 1, 72, and 114 windows retained 10/10, 5/10, and 3/10 March/April days, respectively. The corresponding band-power increases were 3.36, 2.86, and 2.77 dB; single-frequency PSD increases were 3.33, 3.30, and 3.30 dB (Table 3). Entropy remained similar, with interval medians of 0.941/0.941, 0.939/0.941, and 0.939/0.941. Thus, the direction of the power contrast persisted, although its magnitude and temporal representation depended on coverage. The three retained March days at the strictest threshold limit the representativeness of that comparison.

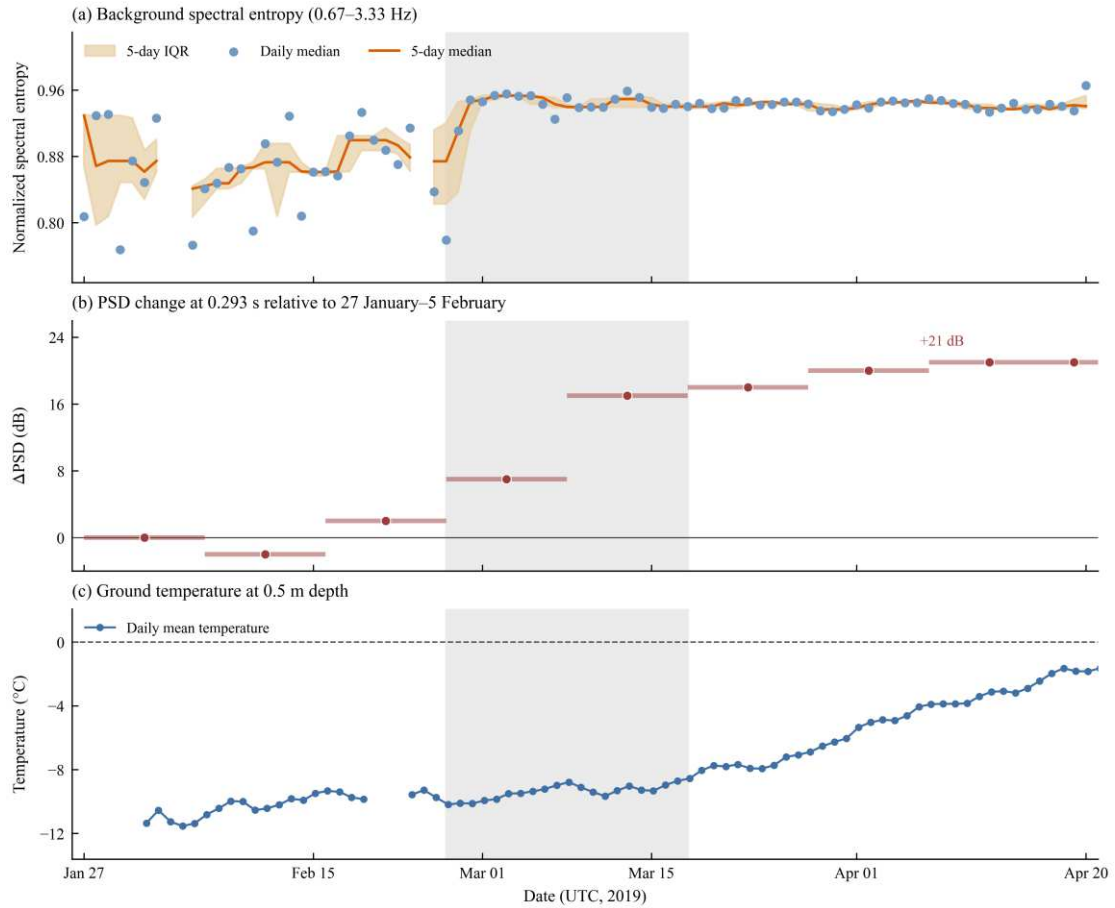


Fig. 4. Temporal comparison of borehole noise and shallow thermal conditions. (a) Daily median spectral entropy from response-corrected velocity PSD in the 0.67–3.33 Hz band (blue points), its centred five-calendar-day moving median (orange line), and the interquartile range of daily medians within the same window (tan band). (b) Changes in median acceleration PSD at 0.29344 s relative to 27 January–5 February 2019; horizontal bars indicate statistical intervals and points mark their midpoints. (c) Daily mean ground temperature at 0.5 m depth, aggregated by Beijing calendar day (UTC+8) from measurements acquired every 30 minutes. Values are plotted at their UTC interval midpoints (04:00 UTC on the labelled dates); missing values are not interpolated. Connecting lines guide the eye; the horizontal dashed line marks 0 °C. Panels (a) and (b) retain UTC statistical intervals. Grey shading denotes 26 February–17 March as a descriptive comparison interval, not an independently determined thaw period.

Entropy increased in all three analysis bands (Table 2). Comparing 27 January–25 February with 18 March–20 April, the median of daily entropy increased from 0.867 to 0.943 in 0.67–3.33 Hz, from 0.691 to 0.940 in 0.50–4.00 Hz, and from 0.707 to 0.872 in 0.50–10.00 Hz. The differences calculated before rounding were 0.076, 0.249 and 0.166, respectively. Each band contained 27 valid early daily estimates and 34 later estimates, and the later interval had a narrower interquartile range. The direction of change was consistent across bands, although its magnitude depended on the frequency limits.

The daily entropy difference between corrected velocity and counts was small. In 0.67–3.33 Hz, its absolute median and maximum were 0.000016 and 0.000069; the maximum absolute differences in 0.50–4.00 Hz and 0.50–10.00 Hz were 0.000071 and 0.000113. Raising the daily

acceptance threshold from 1 to 72 and 114 windows retained positive early-to-late differences in all three bands. In the primary band, the differences were 0.076, 0.069 and 0.071, based on 27/34, 22/34 and 16/33 early/late valid days, respectively. The direction was therefore insensitive to these coverage thresholds, although effect size and representation changed. These descriptive checks do not constitute a significance test.

Table 2. Background spectral entropy from response-corrected velocity spectra in the early and later observation intervals.

Frequency band (Hz)	27 Jan-25 Feb 27 valid days Median [Q1-Q3]	18 Mar-20 Apr 34 valid days Median [Q1-Q3]	Difference (later – early)
0.67–3.33	0.867 [0.844-0.902]	0.943 [0.938-0.945]	+0.076
0.50-4.00	0.691 [0.667-0.730]	0.940 [0.935-0.942]	+0.249
0.50-10.00	0.707 [0.677-0.740]	0.872 [0.866-0.882]	+0.166

Note. Values are the median [Q1-Q3] of daily median normalized spectral entropy, with each valid day given equal weight. Q1 and Q3 are the 25th and 75th percentiles; they describe between-day variability and are not confidence limits. All dates refer to 2019 (UTC), and interval endpoints are inclusive. Valid-day counts represent days with an available daily entropy estimate, not necessarily complete waveform coverage. All values are dimensionless. Differences were calculated from unrounded interval medians before rounding to three decimal places.

Table 3. Coverage sensitivity of the matched-window comparison between 8-17 March and 7-16 April 2019.

Minimum windows/day	Valid days Mar / Apr	Median entropy Mar / Apr	Band-power change (dB)	PSD change at 3.40833 Hz (dB)
1	10 / 10	0.941 / 0.941	+3.36	+3.33
72	5 / 10	0.939 / 0.941	+2.86	+3.30
114	3 / 10	0.939 / 0.941	+2.77	+3.30

Note. March and April denote the two intervals above. Each interval value is the median of retained daily medians. Power differences are $10\log_{10}$ of the ratio of interval medians in linear units (April/March), calculated before rounding. The same retained days are used for all metrics at each threshold. These are descriptive coverage checks, not significance tests.

4.3 Changes in the shape of normalized ambient-noise spectra

To examine the spectral shapes associated with the entropy variations, we compared daily aggregate normalized spectra for six selected dates in the 0.67–3.33 Hz band (Fig. 5). The dates span the early observation period, the marked entropy increase around late February-early March, and the subsequent period of elevated entropy. Each displayed spectrum was constructed from 142 accepted, overlapping windows, as indicated in the figure.

On 6 February (A), the aggregate spectrum was dominated by a pronounced peak near the lower boundary of the analysis band, with relatively small contributions at higher frequencies. The daily median spectral entropy was 0.841. On 20 February (B), the low-frequency peak remained prominent but was lower in normalized height, and the daily median entropy was 0.899. On 3 March (C), the spectrum had a more even distribution across the band, with a broad enhancement at approximately 2-3 Hz. The daily median entropy was 0.956, the highest among the six selected dates.

The later aggregate spectra, from 28 March (D), 6 April (E), and 13 April (F), retained broad peaks at approximately 2-3 Hz. Their daily median spectral entropy values were 0.943, 0.945, and 0.938, respectively. Relative power was less concentrated than in the early spectrum dominated by the low-frequency edge, although the later spectra were not flat. The examples show persistent higher-frequency contributions during a period when daily median entropy varied within a relatively narrow range.

Entropy calculated from the displayed aggregate curves differed from the corresponding daily median entropy. For example, the 3 March spectrum had $SE_{\text{curve}} = 0.976$, compared with $SE_{\text{day}} = 0.956$; the corresponding values for 13 April were 0.962 and 0.938. These differences reflect the order of spectral aggregation and entropy calculation and should not be interpreted as estimation errors or uncertainty bounds.

Together, Figs. 3-5 show frequency-selective power enhancement and a change in relative spectral distribution. The early low-frequency-edge concentration was replaced by broader contributions with persistent peaks near 2-3 Hz. The matched-window velocity analysis additionally shows higher power in early-to-mid-April than in mid-March while entropy remained similar (Fig. 6). A smaller relative contribution at one frequency in a normalized spectrum does not establish a reduction in its absolute PSD. The main-text normalized spectra and entropy describe response-corrected velocity; numerical comparisons with uncorrected count-spectrum entropy are reported in Section 4.2.

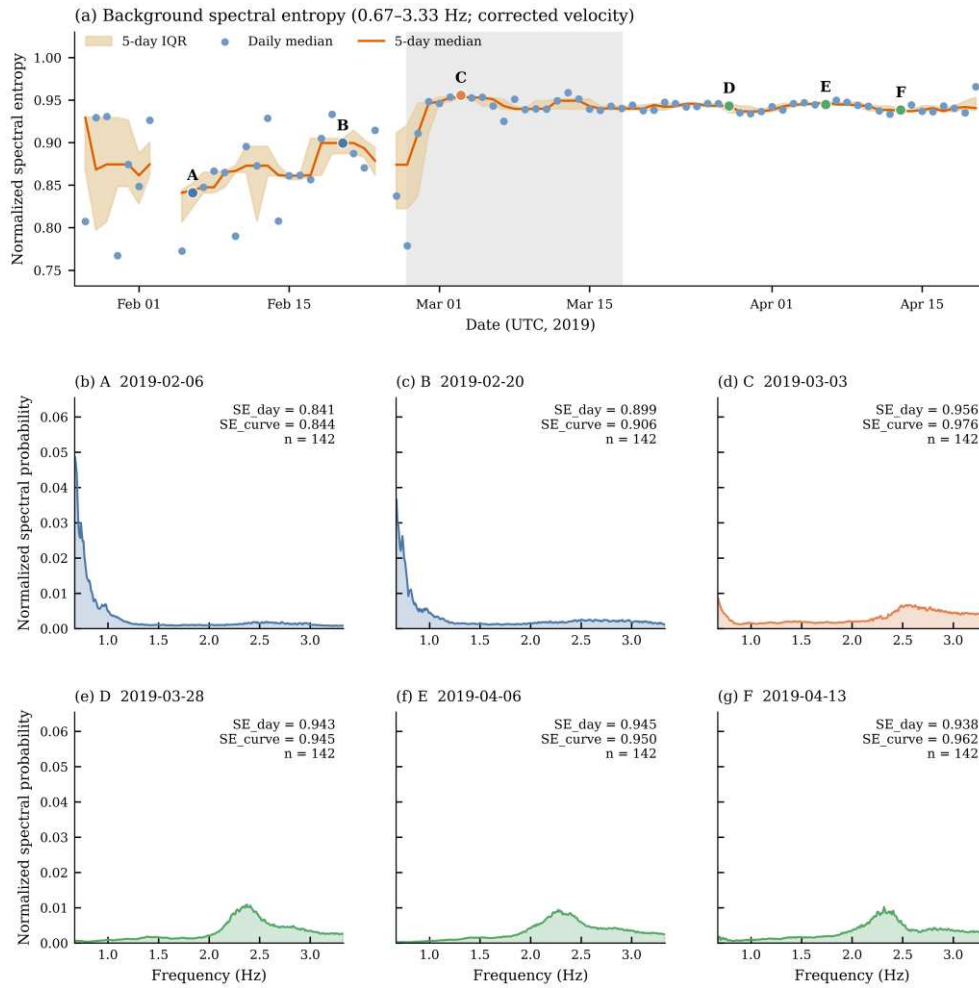


Fig. 5. Temporal evolution of background spectral entropy and normalized response-corrected velocity spectra in the 0.67–3.33 Hz band. (a) Daily median entropy (blue points), its centred five-calendar-day moving median (orange line), and the interquartile range of daily medians within the same moving window (light-orange shading). Grey shading marks the descriptive transition interval in Fig. 4. Labels A-F identify 6 February, 20 February, 3 March, 28 March, 6 April, and 13 April 2019, respectively. (b-g) Pointwise medians of the normalized window spectra for each selected date, renormalized to unit sum. All six panels share the same vertical scale. SE_{day} is the median of window-level entropy; SE_{curve} is entropy of the displayed aggregate curve; n is the number of accepted overlapping windows. The two entropy statistics need not be equal. Shading in (a) describes temporal variability and is not a confidence interval.

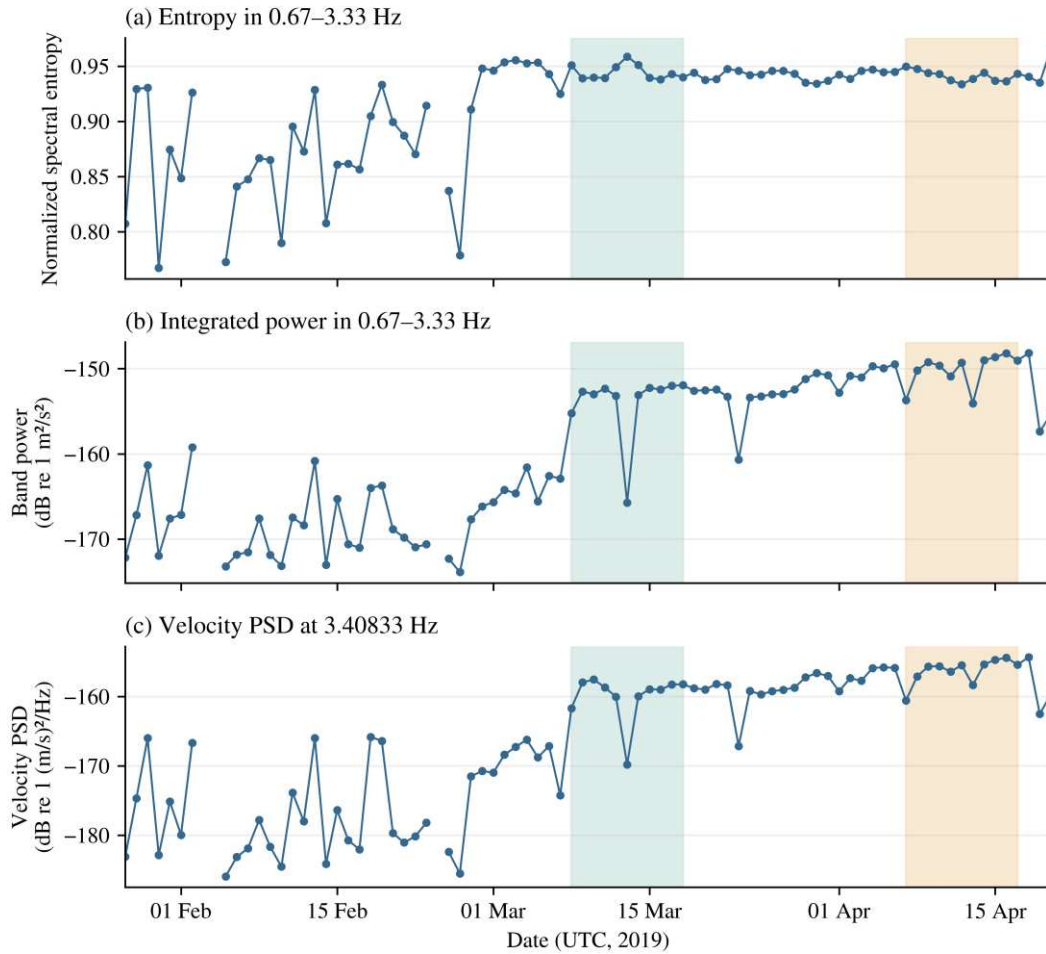


Fig. 6. Daily summaries of response-corrected velocity spectra calculated from identical accepted 30-min windows. (a) Median normalized entropy within 0.67–3.33 Hz. (b) Median power integrated over the same band. (c) Median velocity PSD at 3.40833 Hz, just above the band boundary. At least one accepted window is required per day; missing days remain gaps. Green and tan shading identify 8-17 March and 7-16 April, respectively. Table 3 reports interval comparisons under stricter daily-coverage thresholds. Connecting lines guide the eye; overlapping windows are not independent replicates.

4.4 Regional earthquake recording examples

The selected catalogue events, spanning 1 February-1 April 2019, were identifiable in the vertical-component recordings through amplitude increases near predicted P-wave arrivals (Fig. 7). The waveform analysis retained in Table 4 reports SNR values of 2.85-23.07 and picked-minus-predicted arrival residuals of -0.1 to 6.2 s. The waveform examples support basic recording capability at the sampled times.

438 **Table 4. Catalogue events and reported recording metrics. M denotes catalogue magnitude;**
439 **Δ , epicentral distance; Theo. P and Picked P, arrival times after the origin; Δt , their**
440 **picked-minus-predicted difference; and SNR, the signal-to-background RMS amplitude**
441 **ratio.**

Event ID	Origin time (UTC)	M	Δ (°)	Theo. P (s)	Picked P (s)	Δt (s)	SNR
614953149	2019-02-01 04:12	4.1	6.75	99.2	105.4	6.2	6.57
617413737	2019-02-08 17:18	3.8	6.04	89.4	92.8	3.4	11.19
617413847	2019-02-09 21:36	3.9	7.69	111.5	113.9	2.4	2.85
617414264	2019-02-15 19:35	3.6	6.24	89.5	94.7	5.2	6.19
614973721	2019-02-25 05:15	4.8	9.72	139.8	143.2	3.4	13.84
615301123	2019-03-23 13:53	4.1	5.29	79.0	85.2	6.2	23.07
615332811	2019-04-01 03:11	4.5	6.36	93.7	96.9	3.2	4.03
617417631	2019-04-01 23:05	3.8	5.64	82.1	82.0	-0.1	3.28

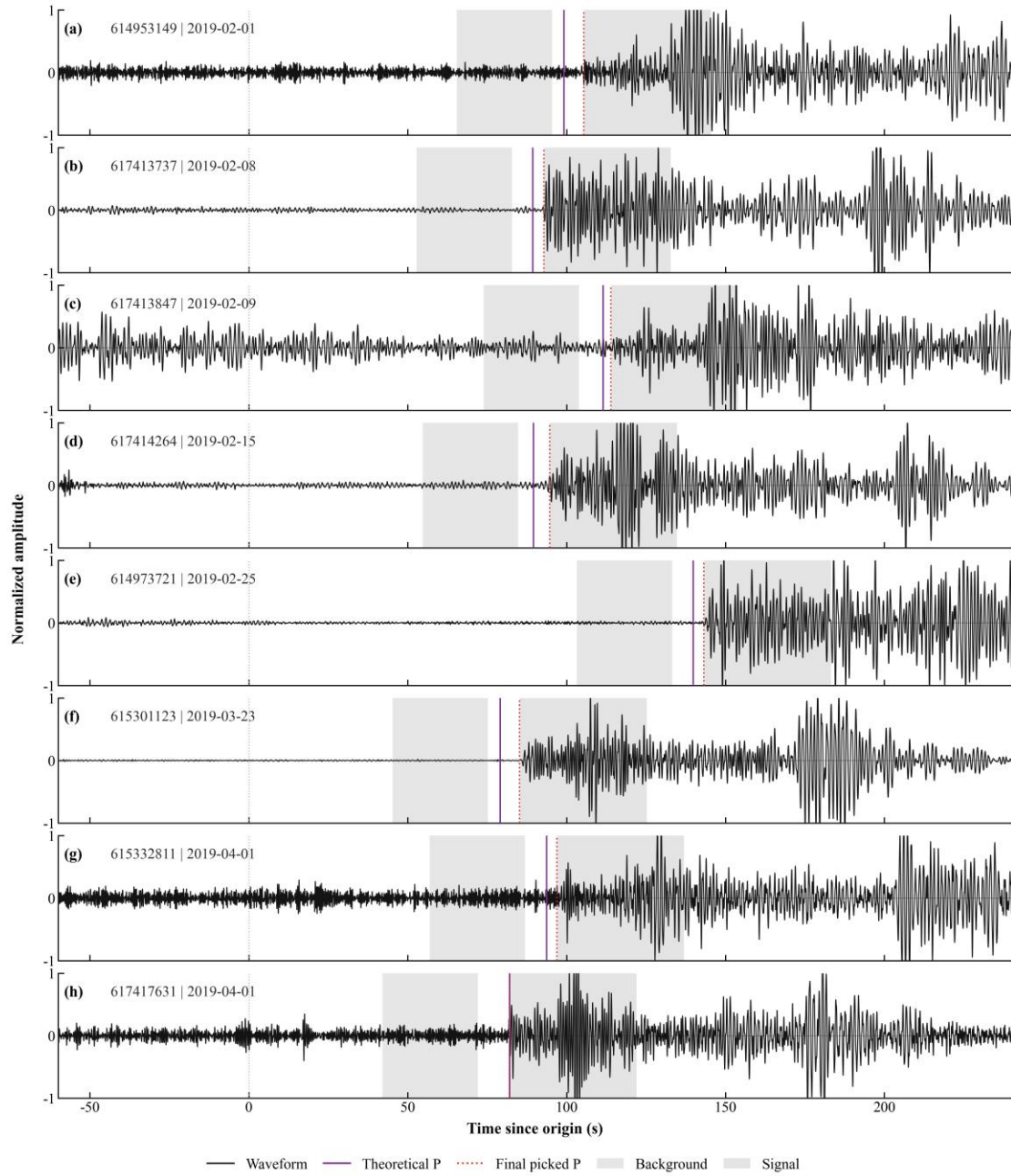


Fig. 7. Normalized vertical-component recordings of the selected regional earthquakes at JXSKD. Black curves show waveforms, purple solid lines mark predicted P-wave arrivals, and red dotted lines mark the reported picked arrivals. Shaded intervals indicate the waveform-analysis background and signal windows described in Section 3.4. Time is measured relative to the catalogue origin time. Event identifiers and dates are labelled in each panel.

5. Discussion

5.1 Interpreting winter-to-spring changes in the borehole ambient wavefield

The observations reveal two features of winter-to-spring borehole noise variability: power enhancement was frequency selective, and power and spectral concentration did not follow identical temporal progressions. Median acceleration PSD near 3.4 Hz increased by up to 21 dB relative to 27 January–5 February, whereas median PSD near 0.2 Hz varied over a range of 4 dB.

Within 0.67–3.33 Hz, early concentration near the lower band boundary gave way to a broader distribution with peaks near 2-3 Hz. Entropy rose in late February-early March and subsequently occupied a relatively narrow range, while power increased further between early-to-mid-March and early-to-mid-April. Together, these results characterize the changing wavefield at the receiver; identifying its cause requires additional constraints on sources, propagation paths, and recording conditions.

The positive entropy changes in all three tested bands (Table 2) show that the early-to-late contrast is not restricted to the primary 0.67–3.33 Hz limits, although its magnitude depends on band definition. The bands overlap and use the same waveform records, so this comparison evaluates sensitivity to frequency limits rather than providing independent replication. Entropy is derived from normalized PSD and summarizes spectral concentration; it is not independent evidence of a separate physical process.

The matched-window comparison links the power and spectral-shape observations using the same accepted records (Fig. 6). Between 8-17 March and 7-16 April, band power increased by 3.36 dB while interval entropy remained near 0.941. The positive power contrast persisted at stricter daily-coverage thresholds, with increases of 2.86 and 2.77 dB and entropy near 0.939 and 0.941 in the respective intervals (Table 3). Only three March days survived the strictest threshold, so this check supports the direction of the contrast without establishing a precise population effect or statistical significance. The observed contrast is not explained solely by different PPSD and entropy window lengths. Entropy's invariance to uniform amplitude scaling is a mathematical property, not a new finding; the field result is the measured evolution of power and spectral concentration beneath permafrost. Similar entropy values need not imply identical spectral shapes, so normalized spectra remain necessary (Fig. 5). No change-point separation or lag was statistically established.

An environmental contribution remains a possible explanation, although the daily mean ground temperatures do not identify the mechanism of the spectral changes. Guillemot et al. (2021) linked seasonal resonance-frequency variations in Alpine rock glaciers to changes in elastic properties through seismic observations and mechanical modelling. That study provides a physical precedent for environmentally sensitive seismic spectra. At JXSKD, however, the observed change concerns the relative contributions across a fixed frequency band; a specific resonance mode has not been identified. The broad peaks in Fig. 5 therefore cannot yet be assigned to the same mechanism.

Changes in noise excitation and propagation offer additional explanations. In Svalbard, Köhler and Weidle (2019) found that seasonal spectral variability included effects of wind, changing instrument coupling, and shallow structural changes. Their findings illustrate why spectral variations require consideration of both environmental sources and subsurface properties. At Muli, possible contributors include changes in shallow material properties, environmental noise sources, and human activity around the mining area. These remain candidate explanations because their individual contributions were not measured in the present study.

The borehole setting adds a depth perspective to these observations. The seismic sensor was installed below the local permafrost base, whereas the temperature reference concerns a depth of 0.5 m. Shallow thermal information cannot determine the thermal state at approximately 300 m depth. Any proposed environmental explanation must therefore account for how source or propagation changes affect the wavefield recorded in the borehole. The initial entropy increase

preceded the more pronounced warming in the daily mean ground-temperature series; the available daily means remained below 0 °C. The observations document spectral variability during the seasonal transition, but do not establish a causal link to thawing.

5.2 Observational implications and limitations

Installation below the permafrost base did not ensure a constant recording background during this winter-to-spring period. The DK-8 records show that noise characterization must specify both frequency and time interval: the early background near 3.4 Hz does not represent later conditions. Comparisons of records acquired at different times should therefore consider power together with spectral shape. Entropy alone can miss power differences during intervals with similar relative spectral distributions.

The eight regional earthquakes demonstrate recording functionality at the sampled times (Fig. 7), but do not assess temporal changes in monitoring capability. Their SNRs depend on event characteristics, propagation paths, and background noise, while arrival residuals include model and picking uncertainties. The events extend only to 1 April, do not sample the later maximum noise increase, and were selected partly for waveform identifiability. A detection assessment would require a catalogue sample selected independently of waveform visibility and explicit accounting for data availability.

The analysis covers one vertical-component borehole record from January to April 2019. It cannot establish annual recurrence or separate contributions from noise sources, propagation paths, and local recording conditions. Full annual records would test repeatability, while simultaneous surface, multi-depth, and horizontal-component observations would constrain the spatial and directional characteristics of the changes. Mining-activity and instrument-operation records would provide additional constraints on anthropogenic noise and changes in recording conditions.

The temperature data comprise daily means at 0.5 m depth. Without the underlying half-hourly measurements and daily valid counts, their completeness cannot be independently verified; they also cannot determine thaw depth or thermal conditions at the receiver. Temperature means follow Beijing calendar days, whereas seismic daily statistics use UTC, so the comparison is descriptive and no quantitative correlation or lag analysis was performed. Temperature profiles, snow-cover observations, and meteorological measurements would strengthen the environmental interpretation.

The interpretation also depends on processing choices and data coverage. The early peak lies near the lower boundary of the primary band. Broader bands and stricter coverage thresholds retained the entropy increase, but sensitivity to alternative window lengths remains untested. Overlapping windows and adjacent daily values should not be treated as independent replicates. The small entropy differences before and after response correction indicate limited sensitivity to this processing step for the supplied metadata; metadata consistency does not replace independent calibration of the installed sensor-digitizer system. These limitations define the scope of the findings: noise power and spectral shape changed during the observation period, but their physical cause remains unresolved.

6. Conclusions

The JXSKD records from 27 January to 20 April 2019 document frequency-selective changes in noise power and spectral shape at approximately 300 m depth, beneath the local permafrost base. Power and spectral concentration followed different temporal progressions. The principal findings are as follows.

Noise-power enhancement was frequency selective. Median acceleration PSD near 3.4 Hz increased from late February and reached a maximum increase of 21 dB during both 7–16 April and 17–20 April relative to 27 January–5 February. Median PSD near 0.2 Hz varied over a range of 4 dB and showed no comparable enhancement.

Relative spectral power became less concentrated within 0.67 – 3.33 Hz. Early normalized velocity spectra were dominated by contributions near the lower band boundary, whereas later spectra exhibited broad peaks near 2–3 Hz. The median of daily spectral entropy increased from 0.867 in the early interval to 0.943 in the later interval, a difference of 0.076. The increase persisted in both broader frequency bands and under stricter daily-coverage thresholds. Response correction had only a small effect on daily entropy for the supplied metadata.

Matched-window velocity spectra showed higher power during 7–16 April than during 8–17 March despite similar spectral entropy. Band power within 0.67 – 3.33 Hz increased by 3.36 dB under the primary daily-coverage rule and by 2.86 and 2.77 dB under the stricter rules. The strictest comparison retained only three March days, limiting its temporal representativeness. Velocity PSD at 3.40833 Hz increased by approximately 3.30–3.33 dB across these rules. During 17–20 April, both the matched-window Welch velocity band power and single-frequency PSD declined relative to 7–16 April, while entropy remained comparatively stable. Thus, similar entropy levels did not imply constant noise power.

These observations provide a frequency- and time-resolved description of the borehole recording background and demonstrate the value of examining absolute power together with relative spectral distribution. Shallow ground temperatures document winter-to-spring warming below 0 °C, but the available evidence does not establish thawing as the cause of the spectral changes or demonstrate a temporal change in earthquake detection capability.

7. Data availability

Regional earthquake catalogue information was obtained from the International Seismological Centre (ISC). Continuous seismic waveform data were recorded at the JXSKD station in the DK-8 borehole, Muli permafrost region, northeastern Tibetan Plateau. Ground temperature at 0.5 m depth was supplied as numerical daily means aggregated by Beijing calendar day (UTC+8) from measurements acquired every 30 minutes. The underlying half-hourly records and actual valid measurement counts per day were not available for independent verification.

The waveform data are not publicly available owing to data-sharing restrictions. Requests for access may be directed to the corresponding author and are subject to the applicable data-sharing permissions. The custom Python scripts are available from the corresponding author upon reasonable request. Enquiries about access to the daily mean ground-temperature data should be directed to the corresponding author; sharing is subject to the data provider's permission.

8. Statements and Declarations

Author contributions. Pengxiao Fan: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing - original draft. Li Li: Conceptualization, Supervision, Writing, review and editing. Shouji Pang: Investigation, Resources, Data curation, Writing, review and editing. Baoqing Tian: Methodology, Supervision, Writing, review and editing. Yue Zhang: Methodology, Supervision and review.

Competing interests. The authors declare that they have no competing interests.

Funding

This study was supported by the Broadband Seismic 3D Array Detection (Phase I) project

under China's National Science and Technology Major Project, Deep Earth Probe and Mineral Resources Exploration (Grant No. 2024ZD1000300).

9. Acknowledgments

We thank the field personnel and supporting institutions involved in the construction, operation, and maintenance of the DK-8/JXSKD borehole observation system in the Muli permafrost region. We also thank the International Seismological Centre (ISC) for providing the earthquake catalogue used in this study.

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Supplementary Figures

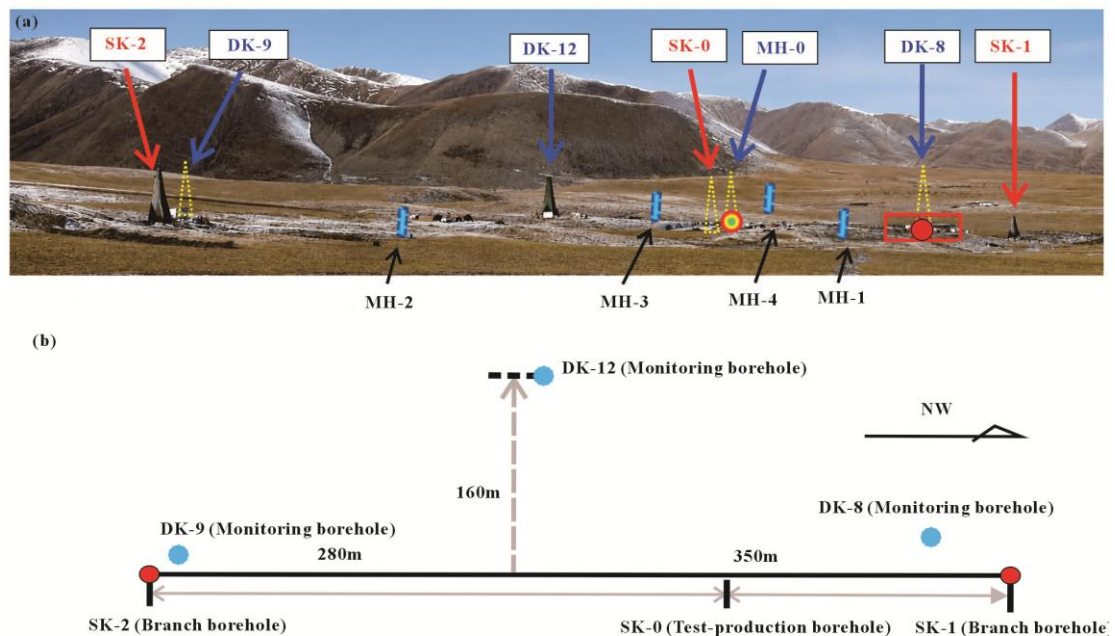


Fig. S1. Layout of the DK-8 borehole and surrounding auxiliary boreholes. (a) Field photograph showing labelled boreholes and monitoring wells. (b) Simplified plan-view layout of DK-8, DK-9, DK-12, SK-0, SK-1, and SK-2. The figure illustrates the borehole configuration around the JXSKD station; MH-0 and MH-1 to MH-4 are identified in the photograph.

Supplementary Files

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