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Ice-core break-off as an opportunistic seismic source on the Northeast Greenland Ice Stream

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Abstract. Ice-core drilling generates repeated mechanical disturbances within the ice column, raising the possibility that operational drilling signals could be used as opportunistic seismic sources. We test whether impulsive ice-core break-off events during the 2022 EastGRIP (Greenland) field season can be detected on surface-based, near-offset three-component geophones and used to estimate apparent P-wave velocity. A catalogue of 67 candidate core-break times was identified from drill-log load peaks, of which 37 had sufficient simultaneous near-offset seismic station coverage for assessment. Only three of these assessable events produced plausible impulsive arrivals. Automatic STA/LTA triggering was useful for identifying candidate windows, but did not reliably pick first arrivals. Where clear arrivals were identifiable above the background noise, manually picked arrivals gave apparent P-wave velocities consistent with firn/ice propagation, and showed a small across-flow faster-than-along-flow tendency, though this difference remains below the level of uncertainty required for robust anisotropy interpretation. These results show that ice-core break-off may provide a useful opportunistic seismic source, but only if future deployments include direct source-time measurement, quiet acquisition conditions, and receiver geometries designed for this purpose.

1 Introduction

Seismic while drilling (SWD) uses seismic energy generated during drilling operations to obtain information about the surrounding subsurface. In conventional applications, particularly in hydrocarbon exploration, SWD has been used to provide seismic information without interrupting drilling operations (e.g. Jaksch et al., 2010). In an ice-core drilling context, the same method can be applied, as deep drilling already involves repeated mechanical activity within the ice column. If this energy can be utilised, it would provide information about the internal structure and physical properties of ice, the distance to the ice–bed interface during drilling as well as the properties of the bed, without requiring separate active-source seismic acquisition.

SWD in glaciology could have two potential sources during mechanical ice-core drilling. First, a strong impulsive dilatational signal may be generated when the ice core is broken from the bottom of the borehole before being returned to the surface. This core break-off event is a particularly interesting potential source because it may produce impulsive seismic energy repeatedly during drilling and at increasing depth. Therefore, repeated core break-off events could provide a source geometry similar to a vertical seismic profile (VSP), with sources at depth and receivers at the surface. However, unlike a designed active-source experiment, the source time, source strength, and surrounding noise conditions are not directly controlled. This makes core break-off a promising but uncertain seismic source.

Second, during actual coring, the cutters of the drill are grinding on the ice at the bottom of the borehole. Although this is expected to be a much smaller source of energy, it would be consistently occurring. As already deployed in conventional solid-Earth drilling operations, a receiver in the actual drill unit would record the most original source signal, which could then be potentially used for noise correlation analysis with receivers at the surface. As we do not have these capabilities for ice-core drills and the general noise level at the surface is too high (e.g., from Diesel generators and activities at the camp) to perform correlation measurements, we do not consider this type of source signal in this study any further.

The East Greenland Ice-core Project (EastGRIP) provided a useful setting in which to test the use of ice-core break-off as an impulsive seismic signal. EastGRIP is located on the Northeast Greenland Ice Stream (NEGIS), where the internal structure, bed properties, crystal orientation fabric, and anisotropy of the ice are important controls on ice-stream flow (e.g. Gerber et al., 2023; Franke et al., 2021). Seismic measurements are sensitive to these properties because wave speeds vary with density, temperature, fabric, and direction of propagation. Previous surface-wave observations from NEGIS showed that firn seismic anisotropy can be recovered from ambient-noise measurements, and that the firn–ice transition is shallower across flow than along flow (Pearce et al., 2024). A detectable core-break source could therefore provide a complementary seismic observation, particularly if apparent velocities vary systematically with source depth and receiver orientation.

Here, we assess whether impulsive core-break signals can be identified and used as opportunistic seismic sources in an operational deep-drilling environment. We use drill-log-derived candidate break times and depths to define expected P-wave arrival windows, and establish whether arrivals can be identified in near-offset seismometer recordings. We use the clearest manually picked signal arrivals to estimate apparent P-wave velocity and to test whether the signals produce velocity models consistent with previous observations from NEGIS (e.g. Pearce et al., 2024; Fichtner et al., 2023). The analysis therefore focuses on what can and cannot be inferred from this opportunistic dataset, and on the future experimental requirements for using ice-core break-off signals more robustly, hence we frame the study as a LESSONS Report.

2 Field experiment and data

The EastGRIP field site is situated on NEGIS, one of the major outlets draining the Greenland Ice Sheet. The EastGRIP borehole is located at approximately 75.63° N, 35.99° W. In 2022, the borehole was approximately 2.4 km deep, and drilling reached the bed of the ice stream in 2023, at 2690 m.

The EastGRIP drilling operation used an electromechanical deep ice-core drill provided by the Centre for Ice and Climate, University of Copenhagen. The drill was instrumented with operational sensors that recorded drill depth, drill speed and tower load. These time-stamped records were not designed as seismic source logs, but they provide the closest available proxy for identifying candidate core-break events.

Table 1. Receiver and borehole coordinates used in the core-break analysis. Offsets are horizontal offsets from the EastGRIP borehole and are used for the simplified apparent-velocity calculations (ignoring refraction in firn).

Site	Latitude/°	Longitude/°	Horizontal offset/m
Borehole	75.63248	-35.98911	0
B69	75.63240254	-35.98929113	10
B6G	75.63252502	-35.98942236	10
B68	75.63232501	-35.98947219	20
B6D	75.63256996	-35.98973467	20
B6E	75.63270480	-35.99067159	50
B6C	75.63170479	-35.99092062	100

The 2022 surface seismic network consisted of 33 instruments arranged in a radial pattern around the drill site, including 24 IGU-16HR-3C 5 Hz SmartSolo nodes and 9 DataCube recorders recording at 400 Hz with three-component geophones. The receiver geometry was not designed specifically for a seismic-while-drilling experiment, therefore this study focuses on the near-offset DataCube records to provide the highest likelihood of identifying impulsive P-wave signals. The DataCube stations used in the final analysis are listed in Table 1, and the source–receiver geometry used for apparent-velocity estimates is shown in Figure 1.

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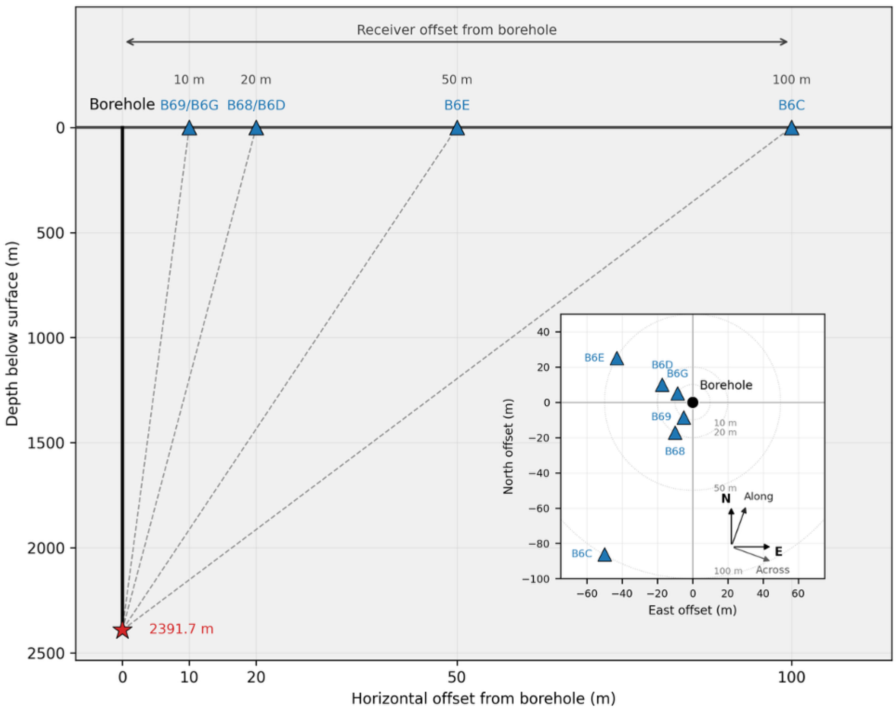

Figure 1. Schematic geometry of the EastGRIP core-break seismic test. The assumed source location (red star) is the base of the borehole at the logged core-break depth, and receivers are plotted at their offset from the borehole. Dashed lines show the simplified source–receiver paths used for apparent-velocity calculations. The inset shows the near-offset DataCube station geometry with the along-flow and across-flow direction of the ice stream.

3 Method

3.1 Identification of candidate core-break times

Candidate core-break events were identified from the EastGRIP drill-log records. During each drilling run, the drill descends to the bottom of the borehole, cuts a section of ice core, and then pulls back, increasing the load, to break the core from the surrounding ice before returning to the surface. The core drill log will therefore show a maximum in load just before a core breaks, with a rapid decrease in load once a core has broken. We therefore used both maximum drill depth and maximum tower load to identify likely core-break times. Candidate peaks were required to exceed a load-cell threshold of 1600 kg and to be separated by at least 3600 s. This produced a catalogue of 67 candidate core-break times between 12 July and 6 August 2022, each assigned a UTC time, drill depth and event number (Figure 2).

The load maximum is an indirect proxy for the core-break source time rather than a direct measurement of the seismic origin time. This timing ambiguity is one of the main limitations of the experiment. The logged load peak may occur before, during,

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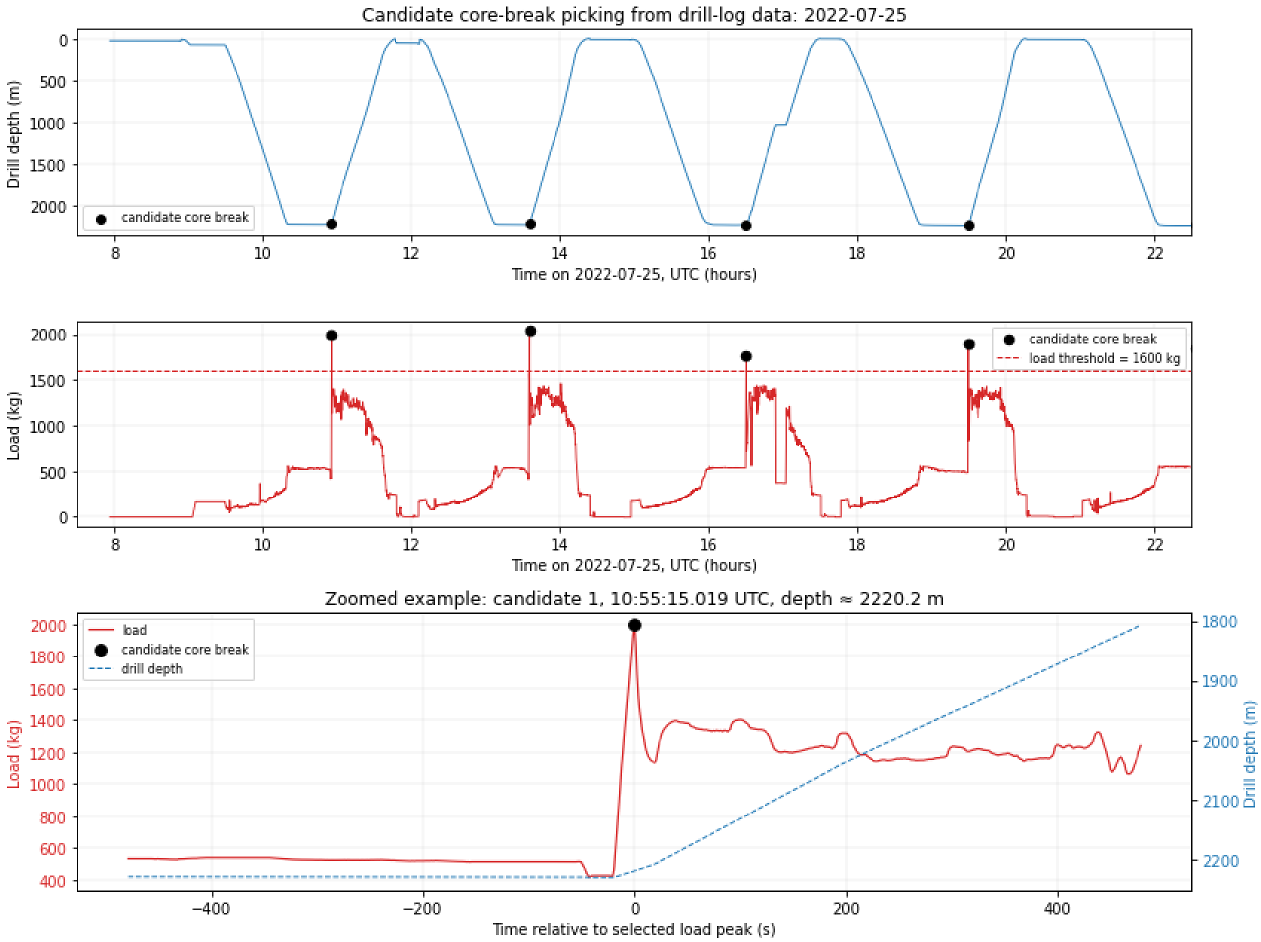

Figure 2. Identification of candidate core-break times from EastGRIP drill-log data. The upper panel shows drill depth through time, with black markers indicating candidate core-break events near the deepest point of each drilling cycle. The middle panel shows the load-cell record and the load threshold used to identify candidate load peaks. The lower panel shows a zoomed example of the first candidate break, where the selected load peak is used as the logged source-time proxy.

or after the actual fracture of the core, depending on the mechanical response of the drill, cable, tower and load-cell system. The candidate times should therefore be interpreted as approximate source-time estimates, rather than exact origin times.

75 3.2 Expected P-wave arrival window and event picking

For each candidate core break, we extracted seismic data from the six available DataCube stations B69, B6G, B68, B6D, B6E, and B6C, at offsets of 10, 10, 20, 20, 50, and 100 m from the borehole, respectively.

To establish if a core-break signal is visible in the seismic record, we first estimated the expected P-wave travel time from the logged drill depth and receiver offset, in order to extract a window of seismic data to investigate. The source was assumed to propogate from the base of the borehole at depth z, and each receiver was assigned a horizontal offset x. The straight-line source–receiver distance was calculated as $r = \sqrt{z^2 + x^2}$, and the expected travel time was estimated as $t_{\mathrm{P}} = r/v_{\mathrm{P}}$, where v_{P} is as defined by Pearce et al. (2024). This approach gives an estimate of the straight-ray seismic velocity, without accounting for firn refraction.

For each of the extracted data windows, we then defined a broad expected P-wave arrival window using apparent velocities between 2000 and 6000 m s^{-1}. This deliberately wide range was chosen to include plausible firn and ice velocities, including the expected value of approximately 3800 m s^{-1} for glacier ice, while also allowing for uncertainty in the true core-break time relative to the logged load maximum.

The seismic traces were demeaned and filtered using a 20–200 Hz bandpass before picking. An STA/LTA characteristic function was then calculated using a 0.020 s short-term average and a 0.200 s long-term average. Candidate automatic picks were retained when the characteristic function exceeded a dynamic threshold based on the local median absolute deviation. Up to eight candidate picks were allowed on each trace, with a minimum separation of 0.004 s between picks.

The automatic STA/LTA picker was used only to identify possible signals within the expected P-wave arrival window. It did not consistently pick the first arrival, and often selected a later or higher-amplitude part of the waveform rather than the earliest visible onset. Final velocity estimates therefore use only manually selected first-arrival picks. The automatic picks are retained in the figures to illustrate the uncertainty and instability of automatic picking in this noisy operational dataset (Figure 3).Events with ambiguous waveforms, inconsistent timing between stations, or ambiguious due to drilling noise were classified as non-detections.

4 Results

From the drill log load and depth data, we identified 67 candidate core-break times. Of these, 37 occurred when more than one near-offset seismic station was recording and could therefore be assessed for coherent arrival timing. The remaining 30 candidate breaks did not have enough simultaneous seismic station coverage to assess whether a core-break signal was present. Of the 37 assessable candidate breaks, only three, breaks 29, 60 and 67, produced seismic records that could be interpreted as coherent impulsive arrivals. A fourth example, break 31, is shown as a non-detection despite the presence of waveform energy in the expected time window (Figure 3). This contrast illustrates a central limitation of the dataset, that not every candidate load peak produces a clear seismic arrival that can be confidently attributed to core break-off.

The manually selected P-wave arrivals give apparent P-wave velocities in a physically plausible range for firn/ice propagation (Figure 4). Median velocities are approximately 3600 m s^{-1} for break 29, 3875 m s^{-1} for break 60, and 3808 m s^{-1} for break 67, respectively. The spread within each event reflects uncertainty in the source-time proxy, manual pick confidence, signal-to-noise ratio, and uncertainty in the exact depth of the core break relative to the logged drill depth.

To test whether the data contain any directional signal, manual picks were also grouped by receiver line. The across-flow group has a slightly higher median apparent velocity than the along-flow group, with median values of approximately 3729 and 3677 m s^{-1}, respectively.

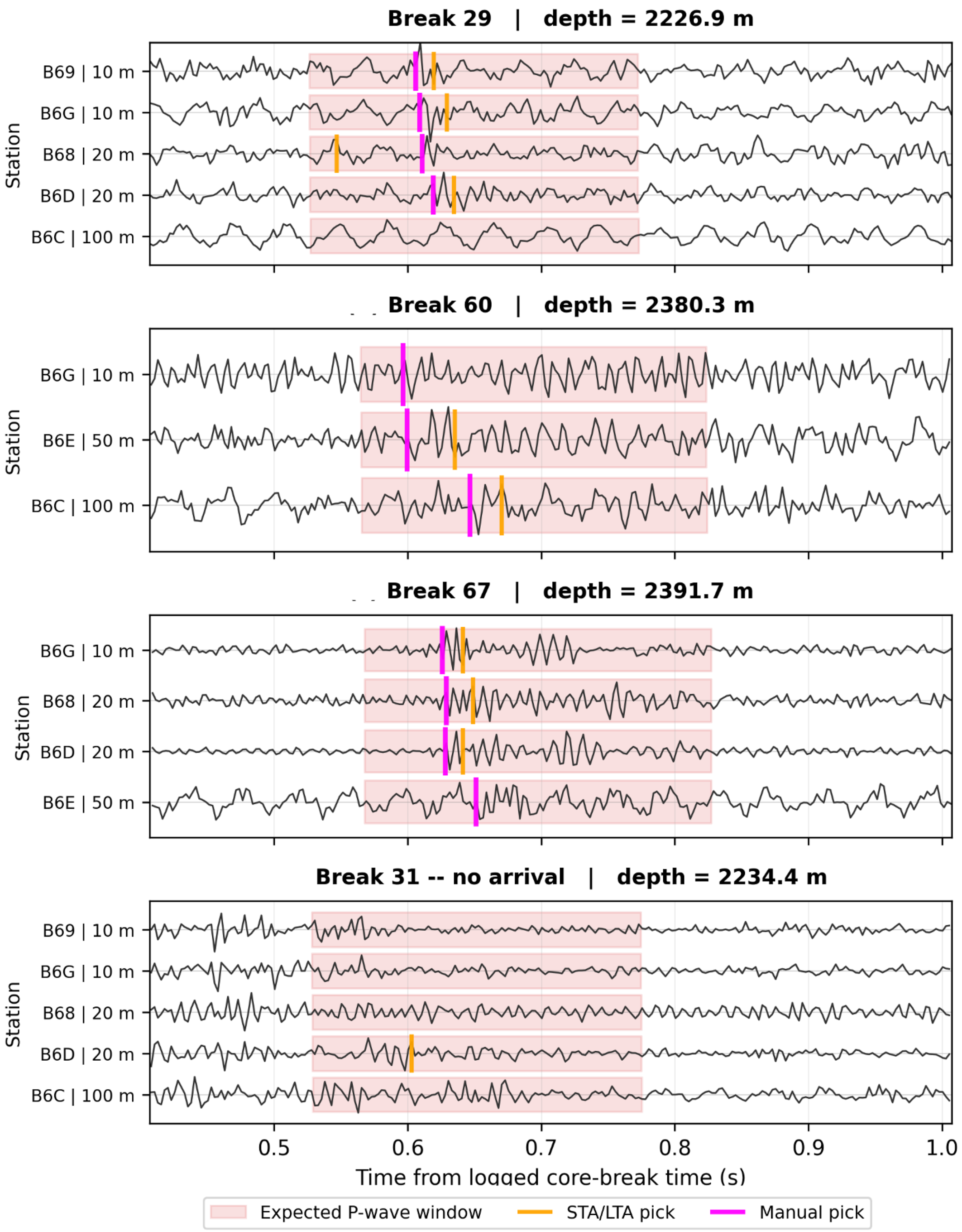

Figure 3. Examples of filtered seismic records around selected candidate core breaks. Breaks 29, 60, and 67 show the clearest manually interpreted arrivals, whereas break 31 is shown as an example with no convincing first arrival. Shaded regions indicate the plausible P-wave arrival window, and coloured vertical lines show manual (pink) and automatic (orange) picks where present. Although STA/LTA picks were useful for screening candidate windows, they did not consistently identify the first arrival and are not used for the velocity interpretation.

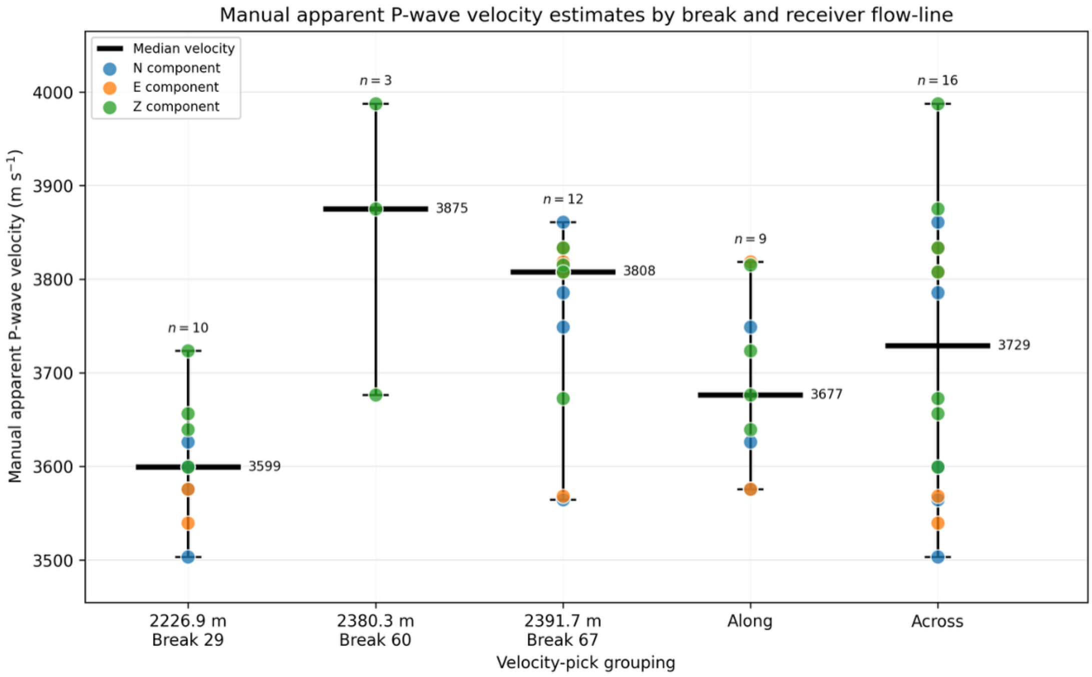

Figure 4. Manual apparent P-wave velocity estimates for the three core-break detections. Points show first-arrival apparent velocities for each station pick (where n is the number of stations the arrival was visible on), coloured by component. Black vertical lines show the observed minimum–maximum range for each category, and black horizontal bars show the median velocity. The final two categories group all picks from stations aligned with the along-flow and across-flow receiver lines.

5 Discussion

The EastGRIP core-break signals show both the promise and the limitation of using ice-core break-off as an opportunistic seismic source. In this dataset, the signals were not reliable enough to provide a routine seismic source, and most assessable candidate breaks did not produce clear arrivals. However, the three manually picked core-break signals are consistent with plausible P-wave propagation from a source at depth within the ice column. This demonstrates that core break-off can generate detectable seismic energy under favourable conditions, even though the method did not produce a large, repeatable dataset of clear arrivals.

The along/across-flow grouping provides a useful diagnostic, but uncertainty in our data overshadows the signals we expect from anisotropy. The across-flow group is slightly faster than the along-flow group, which is qualitatively consistent with previous ambient-noise work at NEGIS. Pearce et al. (2024) showed that firn seismic structure varies along and across flow, with a shallower firn–ice transition across flow than along flow. These constraints are on shear-wave velocity structure, but the relevant link to our P-wave traveltimes is the firn structure itself, since the firn–ice transition depth governs both P- and S-wave velocity. A shallower transition implies that waves sampling the across-flow direction encounter denser, faster material at shallower depth, so a faster across-flow tendency is physically plausible. However, the effect observed here is small (approximately 50 $\mathrm{m\ s^{-1}}$) relative to the experimental uncertainties, including uncertainty in the source-time proxy, manual pick confidence, signal-to-noise ratio, and the small number of detections. We therefore interpret the directional tendency as encouraging consistency with independent seismic observations, rather than as a new anisotropy measurement.

Given the difficulty of identifying a reliable source, we did not attempt to retrieve ice–bed reflections from the records, nor did we infer bed properties or the stratigraphy of the sub-ice material.

Despite these limitations, the results identify a clear opportunity for future experiments. Ice-core break-off could become a useful opportunistic borehole seismic source, but only if future deployments are designed around this objective. The most important requirement is an accurate measurement of the true core-break time. In this study, the maximum tower load provides only an indirect proxy for the seismic source time, and the true fracture may occur before, during, or after the logged load peak. Future acquisition would therefore benefit from direct recording of the break event, for example, through improved drill instrumentation, high-rate load measurements, or an additional sensor at the borehole surface.

Future acquisition would also need to be carried out under quieter operational conditions. The method is most likely to work when camp noise is low, when generators and other machinery are positioned away from the borehole, and when additional impulsive noise from the drill tower, cable, and core barrel is limited. These noise sources are particularly important because they can produce short-duration signals that resemble possible first arrivals but are not generated by core break-off.

A future receiver geometry should include at least one three-component seismic receiver installed at the surface directly beside the borehole. This station would provide the shortest possible source–receiver path and would help reduce uncertainty in source timing. Signals beyond 100 m were not detectable in this analysis, thus additional near-offset three-component receivers along and across flow would allow more robust event detection and azimuthal velocity estimations.

For noise-correlation-based SWD using rotational drilling as the source, it would also be necessary to record the source signal directly in the drill, preferably in the drill head. SWD based on core break-off would also benefit from such a recording.

Under those conditions, repeated core-break sources could potentially contribute to firn and ice velocity estimation and may provide useful complementary information on directional seismic structure.

6 Conclusions

This study shows that ice-core break-off can generate detectable seismic energy, but that it was not a reliable operational seismic source in this opportunistic EastGRIP dataset. Clear arrivals were identified for only a small subset of candidate core breaks, and the successful examples depended on favourable noise conditions, near-offset receiver coverage, and manual first-arrival interpretation. The resulting apparent P-wave velocities were physically plausible for firn and ice, but the dataset is too limited to support a robust velocity model, anisotropy measurement, or interpretation of ice–bed reflections.

Future use of core break-off as a seismic source will require direct measurement of the true break time through additional sensors on the drill head, low camp and drill-related noise, and receivers placed for near-offset source detection.

Presently, ice core-break signals may therefore provide useful opportunistic seismic sources in future experiments, but our dataset presented here should be interpreted primarily as a feasibility test and as evidence for the experimental requirements needed to make the method robust.

Code availability.

The analysis in this study was carried out using custom Python scripts developed for data processing and figure generation. These scripts were created specifically for this study and are not maintained as a reusable resource.

Data availability.

Seismic data used in this study are available at PANGAEA, Pearce et al. (2022).

Author contributions.

EP carried out the data analysis and wrote the manuscript. OE and DZ designed the original idea, secured logistic access, provided funding, contributed to the study layout, and reviewed and edited the manuscript. CH and AF performed the measurements in the field.

Competing interests.

The authors declare no competing interests.

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