

Cryoseismic activity and dynamics of the Astrolabe Coastal Glacier, East Antarctica – The SEIS-ADELICE experiment (2020-2025)

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Abstract Between 2020 and 2025, as part of the SEIS-ADELICE project, nearly two hundreds seismological instruments were deployed on and around the Astrolabe Glacier in Terre Adélie, East Antarctica. This project aimed to monitor the cryoseismic activity of the glacier as it reaches the ocean, to image its internal structure and thickness, and to investigate its interactions with the underlying ocean and the local bedrock. In this paper, we describe the field experiment and its sequential deployments involving multi-year broadband and mid-band instruments on land and at sea, as well as multi-week dense arrays of short-period instruments and two fibre-optic cables on the glacier. We quantify the noise levels obtained in various environments on and near the glacier and assess the quality of the seismological data in different frequency bands using their spectral density. We also present a few selected examples to demonstrate the potential of the data for analysing various tidally modulated cryoseismic sources, such as surface icequakes and basal stick-slip events and for characterising glacier structure. Although most of the results presented are still preliminary and require further analysis, they should stimulate ongoing and future research.

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1 Introduction

Antarctic outlet glaciers, which are in direct contact with the warming ocean, can be regarded as sentinels of global climate change (“Ocean, Cryosphere and Sea Level Change,” 2023). In order to better understand the impact of climate warming on the stability of coastal glaciers in Antarctica and its consequence on sea-level rise, it is crucial to monitor the dynamics of these glaciers as they reach the ocean (Rignot et al., 2013).

The dynamics of Antarctic coastal glaciers is complex due to numerous thermal and mechanical interactions at their basal and lateral boundaries (Schoof, 2007). Several processes are particularly critical for glacier stability and sea-level rise. First, basal melting beneath ice shelves – the floating extensions of glaciers that buttress upstream ice – can destabilise these buttresses by allowing more warm ocean water to penetrate inland (DeConto and Pollard, 2016; Rintoul et al., 2016). Second, vertical tidal motion causes the glacier to flex in the so-called grounding zone (GZ), where it transitions from

resting on the bedrock to floating on the ocean. This tidal flexuring creates differential vertical displacement between grounded and floating ice (e.g., Robel et al., 2017). During tidal highs, such motion can allow ocean water to reach further inland (Freer et al., 2023; Rignot et al., 2024), accelerating basal melting, especially in case of a subglacial ocean water thermal anomaly (Dutrieux et al., 2014; Rignot, 2023; Rintoul et al., 2016). Thirdly, the shearing of ice along the lateral boundaries of glaciers has a buttressing effect on ice flow (Gagliardini et al., 2010), but this may be significantly impacted by basal melting and the thinning of the floating ice (e.g., Wild et al., 2025). Together, these processes may promote the GZ retreat and the loss of buttressing effect, thereby destabilising the whole glacial basin. This highlights the urgent need to investigate dynamics of glaciers at their grounding zone and lateral boundaries.

Evaluating glacier kinematics, strain, stress, and internal structure (e.g., Brisbourne et al., 2019; Kufner et al., 2023) requires methods that are sensitive to dynamic behaviour throughout the ice thickness, to complement those more traditionally used in glaciology such as GNSS, radar, and satellite imagery (Rignot et al.,

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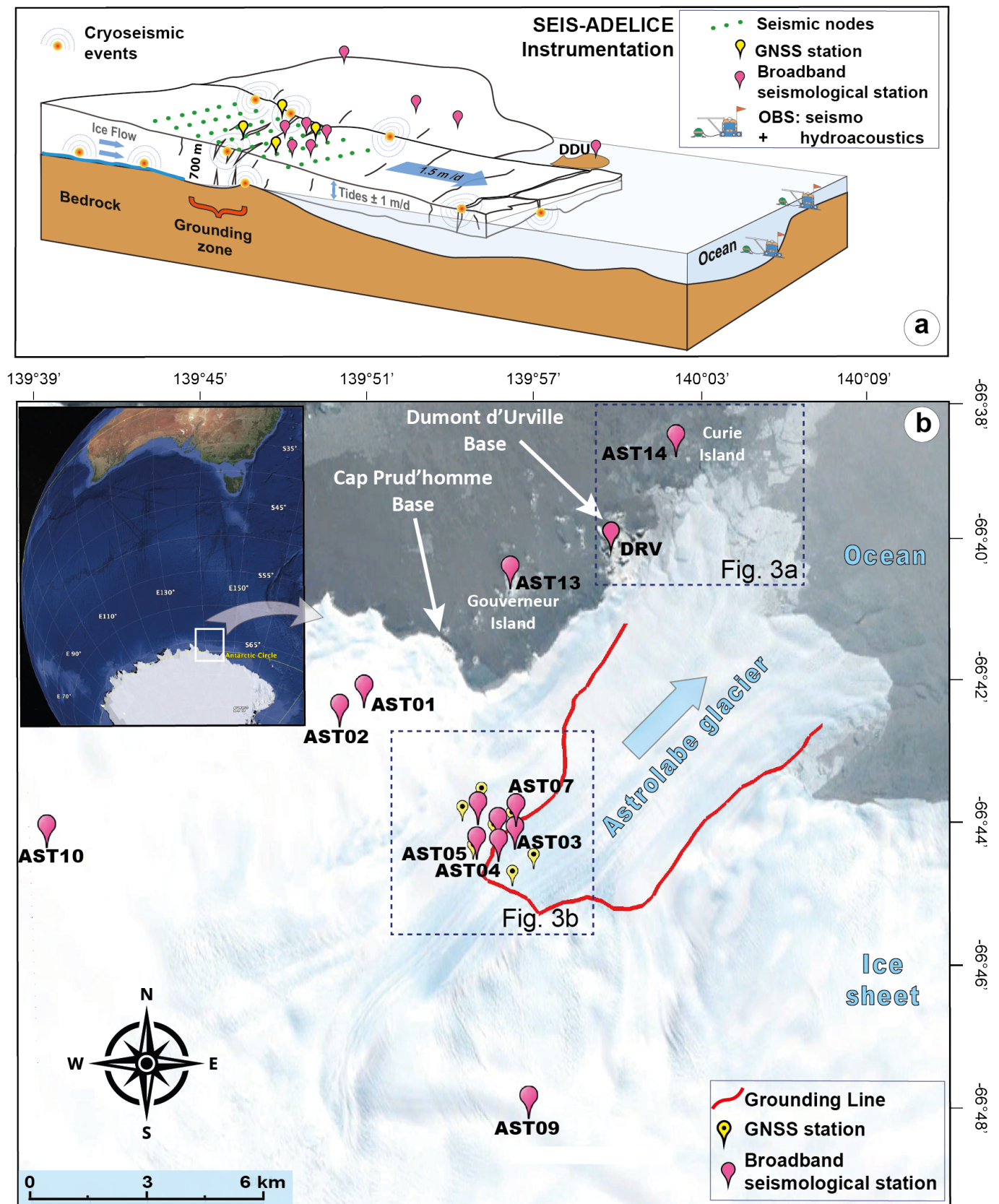


Figure 1 a) schematic representation of the Astrolabe Glacier and its floating tongue entering the ocean, along with the instrumentation deployed on and around it, as part of SEIS-ADELICE. b) Map of the instrumented area with a background Landsat satellite image and its general location shown in the inset, with the Antarctic polar circle as a yellow line. Are located broadband seismological stations (pink pins) deployed on and around the Astrolabe Glacier, together with the Geoscope station DRV at Dumont d'Urville base (DDU). The red line corresponds to the grounding line defined by [Le Meur et al. \(2014\)](#). Yellow pins indicate the position of the permanent GNSS stations from the Glacioclim observatory during the 2022 summer field season ([Le Meur et al., 2014](#)).

2011, 2026; Scheinert et al., 2026; Franke et al., 2026). Studying seismic activity in ice – a field called cryoseismology (e.g., Aster and Winberry, 2017; Podolskiy and Walter, 2016) – offers such an approach. By detecting and locating seismic events within and around glaciers, seismology can characterise internal glacier deformation and identify the mechanisms and forces at play, particularly in GZ areas (e.g., Agnew et al., 2025; Anandakrishnan and Alley, 1997; Davis et al., 2022; Hammer et al., 2015; Pirli et al., 2018). By using short period sensors sampling data at several hundreds of Hertz, and broadband instruments deployed for several years, seismology can achieve a spatial resolution of a few tens of metres and detect temporal variability ranging from seconds to seasons, and therefore provides this invaluable tool complementing surface glaciological measurements.

The SEIS-ADELICE project aimed to analyse the cryoseismic activity of the Astrolabe Glacier in Terre Adélie, East Antarctica (Fig. 1), to image its internal structure, and to characterize its interaction with the ocean and with the underlying bedrock, as schematized in Fig. 1a. The multi-year field deployment (2020-2025) targeted three critical regions of the glacier: the grounding zone, the lateral shear margins where the flowing glacier is in contact with stable ice, and the terminus where calving events create icebergs. Targeting enhanced spatial and temporal resolution across these three regions required integrating simultaneous terrestrial and ocean-bottom observations at multiple scales. We employed long-term (multi-year) broadband, mid-band and short-period stations for continuous monitoring, complemented by temporary (multi-week) dense seismic arrays of short-period seismic nodes and distributed acoustic sensing (DAS) technology. The balance between deployment duration and spatial density was constrained by the logistical and maintenance challenges of operating in this harsh and remote environment.

In this paper, we document the instrumental deployments performed in the frame of SEIS-ADELICE, then describe the data quality using the seismic frequency spectra and finally present a few representative examples of recorded signals and preliminary analyses that demonstrate the dataset's potential for investigating glacier dynamics, ice-ocean interactions, and structural properties.

2 The Astrolabe Glacier

The Astrolabe Glacier in Terre Adélie (East Antarctica, Fig. 1b), in the immediate vicinity of the French Dumont d'Urville (DDU) permanent research station, flows at a speed of up to 500 m/year and is fed by a basin extending over 200 km into the interior of the continent (Mouginot et al., 2019; Provost et al., 2024). The floating part of the glacier (4 km x 10 km) is confined within a deep glacial valley. The ice thickness is estimated at around 700 m at the GZ, then gradually thins to around 300 m at its front (Le Meur et al., 2014). The submerged valley beneath the glacier terminus is deeper than 1,000 m (Beaman et al., 2011), suggesting the presence of a large

ocean cavity beneath the floating ice tongue.

The small size of the glacier and its closeness to DDU offer a unique opportunity to monitor, over several years, an Antarctic outlet glacier system from its grounding zone to its oceanic termination, as illustrated in Fig. 1a.

3 SEIS-ADELICE temporary seismic deployments

3.1 Field logistics

All instrumental deployments were carried out with the logistical support from the French polar institute IPEV (Institut Paul Emile Victor). Since access to the GZ area of the glacier by land vehicles was strongly limited by surface crevassing, staff and instruments were transported by helicopter. Then, operations were carried out on foot, pulling pulkas to transport material. At sea, releases and recoveries of ocean bottom seismometers (OBS) were carried out using the small boats available at the DDU base such as a 10 m-long barge equipped with a small crane or with the help of the logistical polar supply vessel L'Astrolabe. Finally, on the stable, grounded ice, installation and maintenance work was carried out from Robert Guillard-Cap Prud'homme base (see Fig. 1b), making use of land-based resources (e.g., tractors, caterpillars) when necessary.

3.2 Broadband terrestrial deployments (2020-2025)

The broadband permanent Geoscope seismological station DRV (Institut de physique du globe de Paris (IPGP) & Ecole et Observatoire des Sciences de la Terre de Strasbourg (EOST), 1982) at DDU base was used as the backbone of the project and provided long-term seismological investigation over several decades (Grob et al., 2011; Stutzmann et al., 2000). It began operating in 1986 (Leroy et al., 2023) and has continuously collected data at a sampling frequency of 20 Hz since 1991 (STS-1 sensors, location code “00”) and at 100 Hz since 2022 (STS-2 sensor, location code “10”).

Starting in 2020, the SEIS-ADELICE deployment of broadband stations (Fig. 1b) was conducted over five years in various locations on and around the glacier, with particular attention paid to areas of grounded ice and rocky outcrops. The sampling rate of these stations was set to 100 Hz (see Suppl. Table S1).

First, a Q330S+Trillium 120PA station was installed in January 2020 on grounded ice (AST01) in the vicinity of Robert Guillard-Cap Prud'homme base. Following the cancellation of the 2020/2021 summer campaign (initially scheduled in December 2020 and January 2021) due to the global COVID pandemic, a series of similar deployments was conducted in January 2022 at larger distances from the coast (AST10), including a station situated on the right bank of the glacier (AST09). Station AST02 was also installed during the same campaign, close to the Robert Guillard-Cap Prud'homme landing strip on the continent (Fig. 1b). It was equipped with a

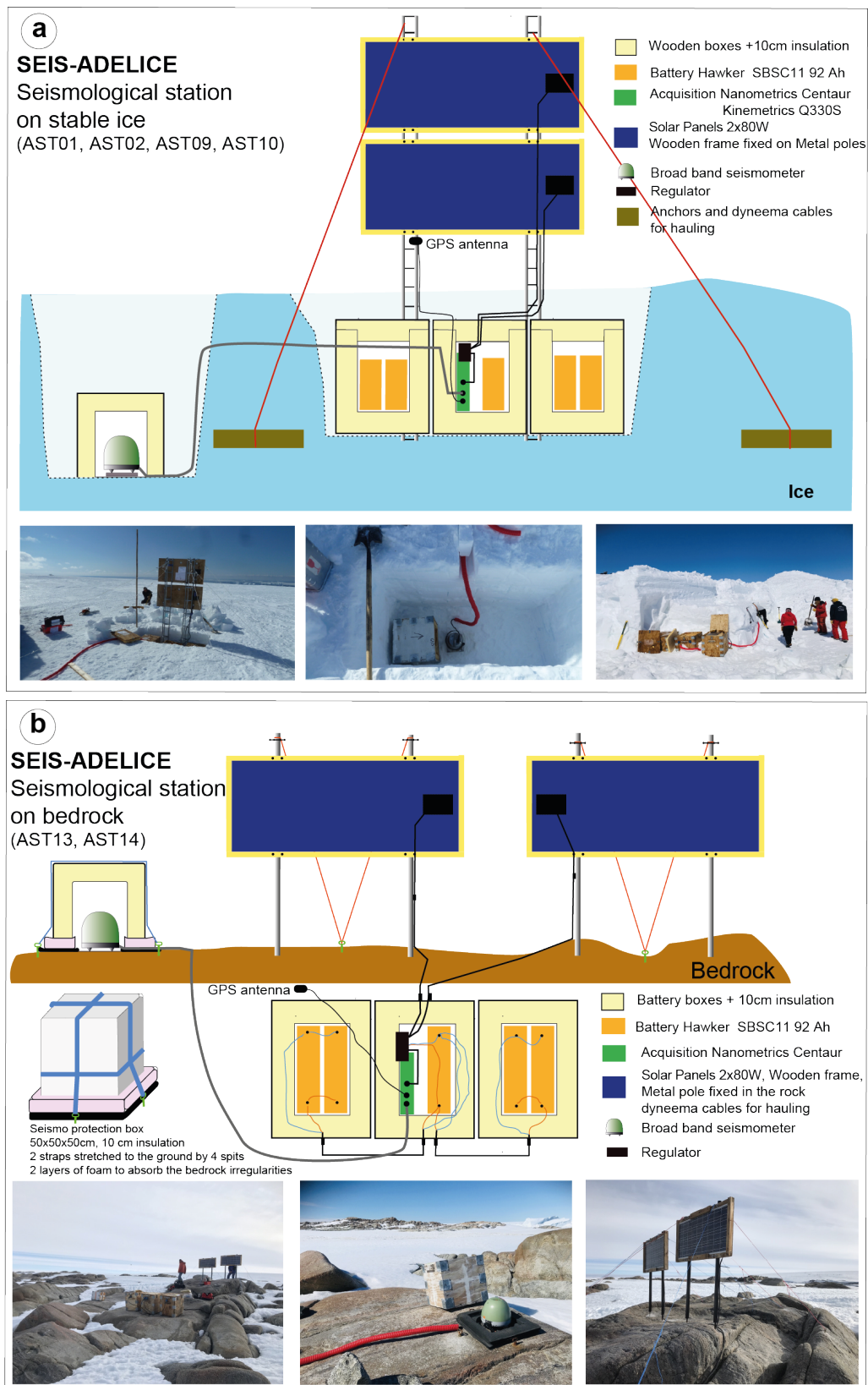


Figure 2 SEIS-ADELICE broadband seismological station setup. a) Schematic set-up of a broadband station installed on the stable ice. Boxes are seen from the side. The broadband seismic sensor is deployed ~10 m from the acquisition and solar panels. Photographs illustrate, from left to right, the field set-up of station AST02 during its installation in Jan. 2022, the sensor installation in the firn and the station recovery three years later in Jan. 2025. b) Schematic set-up for a broadband station installed on a rocky outcrop. Acquisition/battery boxes are seen from above. Photographs illustrate, from left to right, the general field setup at station AST13 on Gouverneur Island, the broadband sensor on the bedrock and the solar panels anchored on the bedrock.

Nanometrics Centaur acquisition system and a Trillium Horizon 120 s sensor.

These broadband seismic stations installed on the stable (or slow-moving) ice followed the set-up presented in Fig. 2a. Sensors were installed in the ice at ~1.5 m depth and protected by a wooden box, placed at a distance of ~10 m from the solar panels, to minimise vibrations induced by the katabatic winds on the surface equipment (poles, solar panels, cables) (Frankinet et al., 2021). The boxes containing the batteries and acquisition systems (Nanometrics Centaur for AST02, Kinometrics Q330S for AST01, AST09 and AST10) were placed in a trench around 1 m deep, ensuring that their tops were levelled with the surface. Due to strong katabatic winds on the Antarctic coast, solar panels were attached to poles tightly secured to the ice through Dyneema cables, attached to wooden planks buried in the ice and serving as dead weights. These long-term broadband deployments were not impacted by ice melting. Depending on the location, some stations (e.g., AST02 and AST10) experienced snow accumulation of up to 1 m per year. This required the solar panels to be removed and raised annually, as well as drilling through snow and ice to access the acquisition system and retrieve the data. Fig. 2a shows pictures of the station AST02 deployed at the ice surface in January 2022 and recovered in January 2025. It was buried under more than 3 metres of snow and ice, requiring the use of a tractor (PistenBully 300) to create a large, deep trench for the extraction of the instruments.

In January 2022, a temporary network of six broadband seismometers (AST03 to AST08) was deployed in the GZ area of the glacier for a period of three weeks (Fig. 1b and Suppl. Table S1) and recorded at a sampling rate of 200 Hz. These six stations were provided by the French EPOS-SISMOB seismic pool. The stations comprised a Nanometrics Centaur for the data acquisition and a Trillium 120QA for the broadband sensor (to measure the ground velocity), except for station AST03, which comprised a Nanometrics Taurus acquisition system and a Trillium Compact seismometer. The sensors were deployed in a ~1 m deep hole in the ice and powered by two 92 Ah pure-lead batteries installed within a protection box on the surface. This provided about three weeks of continuous autonomous operation without the need of solar panels. Three of these stations (AST05, AST08, AST07, see Fig. 1b) were collocated with permanent GNSS stations from the Glacioclim observatory. The data obtained from AST05 were mostly unusable due to sensor tilting because of surface ice melting.

In January 2023 and January 2024, two of the six EPOS-SISMOB stations (Nanometrics Centaur + Trillium 120 QA) were installed on rocky islands: respectively AST13 on Gouverneur Island and AST14 on Curie Island (see locations on Fig. 1b). This set-up is shown in Fig. 2b and built upon the experience and materials from the ARLITA project (2009–2012), during which land stations were deployed on rocky outcrops between DDU and the Mertz Glacier (Barruol et al., 2013; Lamarque et al., 2015). The sensors were installed directly onto a flat rocky surface and protected by a wooden box that was screwed tightly to the bedrock. Two layers of

foam of different densities at the bottom of the box ensured good contact with the uneven rock surface and reduced the effect of wind, snow, and pressure changes on the broadband sensor inside the box. As shown in the following of the paper, the quality of their records was surprisingly good, even approaching the quality of the signal recorded by the permanent Geoscope station DRV (whose sensors are installed within a closed, sealed vault), in particular over the long period range 10–100 s. For these bedrock setups, batteries and recording systems were installed in three pre-plugged independent boxes, that were linked together by external electrical connections. This setup avoided the need for any complex electrical work during the station deployment, optimising installation time, crucial in harsh and remote environments. The solar panels were mounted on poles, at about 1 m above the ground to avoid snow accumulation and were fixed tightly to the bedrock using several Dyneema cables attached to bolts. The solar panels were designed to be independent of each other, ensuring that the system would still be powered even if one of them failed. This was demonstrated at station AST13 in 2023 when a solar panel fell to the ground during a storm, yet the continuous recording of seismic data was not affected. Suppl. Table S1 provides a synopsis of the names, types, and deployment periods of all these broadband stations. In the supplementary material, we also describe how broadband seismic stations were powered in this Antarctic environment. Figure S1 illustrates the evolution of the battery voltage and internal temperature over the course of a full year in 2024 at two broadband stations installed on bedrock (AST13) and in ice (AST02) and shows how the batteries behave during the polar night.

3.3 Marine deployments at the glacier terminus (2022–2023)

To monitor cryoseismic activity related to glacier calving, as well as sea ice and iceberg activity near the glacier terminus, OBSs were deployed for approximately two years as part of the SEIS-ADELICE project.

The experiment involved two types of instruments. The first was a short-period OBS (SPOBS) from the French INSU-IPGP pool. This instrument is composed of three-component 4.5 Hz geophones and a broadband (20 Hz to 15 kHz) hydrophone. To ensure compatibility with the recording capacity, data were sampled at 250 and 62.5 Hz for the short-term (two weeks) and long-term (one year) deployments, respectively, as indicated in Suppl. Table S2. This instrument is equipped with an oil-bath-damped levelling system that aligns the three geophones as one vertical and two horizontal components. The second type consisted of three-component, mid-band (0.1–100 Hz) accelerometer OBSs, which were modified at IPGP from a Güralp BREVE OBS system (Inset photograph, Fig. 3a). These were associated with short-period hydrophones (2 Hz – 30 kHz) and can operate at all static tilt angles. These instruments sampled data at 100 Hz or 125 Hz, as detailed in Suppl. Table S2. They were initially designed for deployment and recovery in shallow water by a Remotely Operated Vehicle

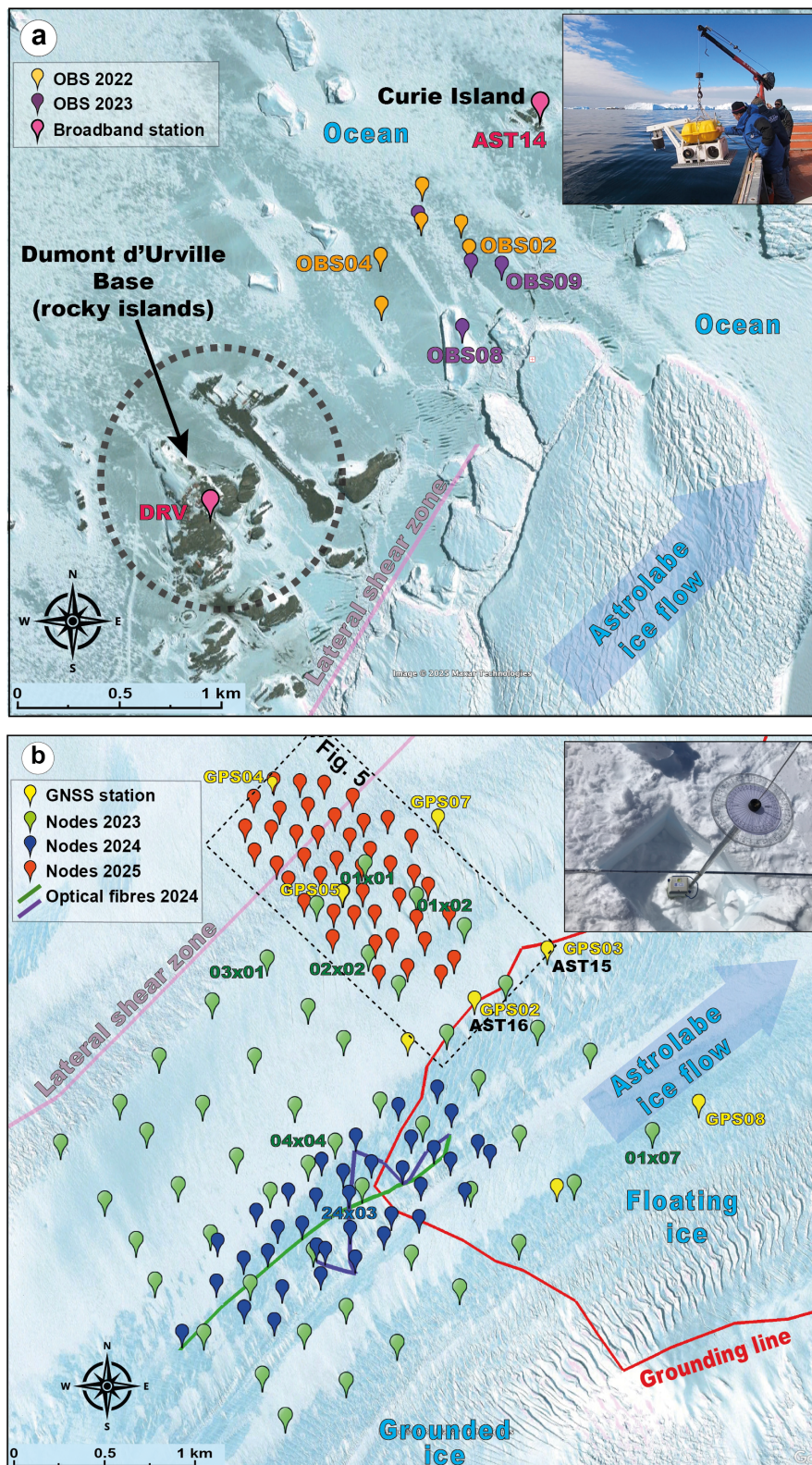


Figure 3 OBS and seismic nodes deployments. a) Map of the OBS deployments performed in 2022 (orange) and 2023 (purple) close to DDU polar base where the Geoscope station DRV is installed. The terminus of the Astrolabe floating tongue is well visible on the east of DDU base. Inset shows a photograph of a (modified) Güralp BREVE OBS deployment in Jan. 2022. b) Map of the three successive seismic node deployments in the GZ area of the Astrolabe Glacier. Green: array of 50 nodes deployed in Jan. 2023; Blue: array of 38 nodes deployed in Jan. 2024; Red: array of 45 nodes deployed in Jan. 2025 over the west lateral shear zone. Background is a Maxar satellite image. The red line indicates the GL defined by Le Meur et al. (2014). Green and purple lines represent two fibre-optic cables deployed in Jan. 2024 and used for DAS applications. Yellow pins indicate the location of the 7 permanent GNSS stations from the Glacioclim observatory during the 2025 summer field season. An additional GNSS sensor (GPS04) was temporarily deployed on the slow-moving ice, west of the shear zone in Jan. 2025. Inset displays a photograph of a "gnomon" used to determine geographic North and orient a seismic node in the field.

(ROV). To enable their use at greater depths (down to 2,000 metres) and their deployment from the surface, these instruments were modified to incorporate floatability and a surface-controlled release system. Although the submerged glacial valley in front of the Astrolabe Glacier terminus is more than 1,000 metres deep, it is an area of significant iceberg release activity, which makes deployment and recovery highly risky. Therefore, we avoided the terminus front and deployed the OBSs on the western side of the valley (see Fig. 3a and Suppl. Table S2), in water shallower than 100 metres. This made deployments and recoveries much safer, even though some instruments were delayed in being recovered due to transiting icebergs.

In January 2022, three SPOBS and one BREVE OBS were deployed in front of the glacier terminus for a period of two to three weeks (see Fig. 3a). Following their successful recovery, two of these instruments (one of each type) were reconfigured and redeployed in early February 2022 for a year-long period, which included a winter beneath the sea ice. After these two instruments were retrieved in January 2023, four additional OBSs (one INSU SPOBS and three BREVE OBSs) were deployed for a further 12-months, again including a sub-sea-ice wintering period. Despite some data gaps caused by component or power failures, rather continuous time series were obtained, for 9–12 months per year in 2022 and 2023. This will allow us to study the seasonal variations in cryoseismic activity, and particularly the influence of the surface sea ice on the glacier dynamics in winter. OBS location and deployment details are summarized in Suppl. Table S2.

3.4 Deployment of seismic nodes in the glacier grounding area (2023-2025)

To improve the detection of seismic events and structural imaging of the GZ and lateral shear zone of the Astrolabe Glacier, arrays of seismic nodes have been deployed during three successive summer campaigns (Fig. 3b). The nodes (SmartSolo IGU-16HR three-component, 5 Hz instruments, with a sampling frequency of 500 Hz) were buried in 50-centimetre-deep holes. For the first 2023 deployment, these holes were made with a chainsaw; for the subsequent deployments in 2024 and 2025, a 12-centimetre-diameter auger was used, allowing the nodes to remain in a vertical position within the ice, reducing potential vertical tilt. However, in blue ice environments, we experienced tilt for some sensors due to ice melting around the instruments. During deployment, the nodes were oriented towards geographic north using a gnomon (see explanation below). In addition to their GPS coordinates, the locations of the nodes were marked on the ice surface with two bamboo sticks aligned in an east-west direction, 50 cm from each node. This made recovery easier at the end of the experiment, as horizontal displacements of the glacier of up to 20 m were often observed. For the node recovery, we used a chainsaw to cut out the ice block containing the instrument and then an ice axe to extract the instrument from the ice.

3.4.1 Sensor orientation to the geographic North

Due to the proximity of the south magnetic pole in this region of Antarctica, it is not possible to orient vectorial geophysical instruments, such as seismic sensors, into a geographic reference frame using a magnetic compass. Although a hand GPS was used at a few sites, this technique requires walking a few tens of metres away from the site to obtain an accurate geographic azimuth. This simple process can be challenging and hazardous on a glacier such as the Astrolabe, due to its crevassed surface. During the SEIS-ADELICE deployment phases, we therefore oriented most of the seismic sensors using a gnomon equipped with a 360° protractor (see inset in Fig. 3b). Although this tool cannot achieve an accuracy better than a few degrees, it has proven to be easy to use in the field. In practice, we used one of the two methods described below, depending on the field and weather conditions: i) The first method involves taking a visual sighting towards a ground point of known location (e.g. a distant building, a permanent instrument or a topographic site), which allows the geographic azimuth to be determined. This technique requires a list of well-positioned points to be calculated in advance in order to determine the actual geographic azimuth between the two points and deduce the true geographic north. Obviously, these points must be visible from the ground at the time of deployment, since they could otherwise be obscured by the topography, falling snow or local clouds. ii) The second method involves a visual sighting towards the sun's position, using the gnomon and the protractor as a sundial (Fig. 3b). This technique requires the user to anticipate the sun's position (azimuth and inclination) before going in the field. These calculations have been pre-determined for a given region (here, the Astrolabe Glacier) and for the given day of field work, down to the minute (code availability in the data section). The presence of the sun is required to optimally position the shadow of the gnomon on the 360° protractor. The horizontal position of the protractor (and the verticality of the gnomon) is obtained by checking a small bubble during the sighting, after which true geographic North can be geometrically deduced. This second method produced particularly satisfying results.

3.4.2 Seismic nodes across the glacier grounding zone (2023)

In January 2023, we deployed an array of 50 three-component seismic nodes over the grounding zone of the Astrolabe Glacier (see Fig. 3b and Suppl. Table S3), for three weeks. Spaced on a roughly regular 7x7 grid, the nodes were installed at intervals of ~300–400 m, covering an area of ~2 km x 2 km.

3.4.3 Fibre-optics/DAS and seismic nodes across the grounding zone (2024)

In January 2024, we deployed two 2 km-long fibre-optic cables ('flat-drop' type) on the glacier surface, for Distributed Acoustic Sensing (DAS). We deployed the first cable linearly along the glacier's flow line, crossing the GZ. We deployed the second cable along a 'Z'-shaped

line, forming triangles whose sides measured about 300 m each (Fig. 3b). Similar fibre-optic cable shapes have been used to locate seismic sources more accurately (Walter et al., 2020) and could also be used to quantify seismic anisotropy (Brisbourne et al., 2021; Hudson et al., 2021).

We deployed the fibre-optic cables on foot, using a pulka to pull a drum containing 2 km of fibre on a vertical axis drum uncoiler. At the moment of deployment, the cables lay on the ice surface; they embedded themselves in the ice within a few hours. At the end of the experiment, the effort required to remove the fibres from the ice depended on the condition of the ice surface. The 'Z'-shaped cable was removed with difficulty on a cold day; it was likely sealed within the ice. The linear cable was removed easily, on a sunny, warmer afternoon; we removed it in two segments of 1 km each, simply by pulling on it. This suggests the possible presence of a melt film around the fibre despite its penetration depth into the ice (between 10 and 20 cm, except where it crossed crevasses).

The two fibre-optic cables were interrogated by a Febus-1A laser system. The DAS interrogator was set up in a 2x2x1 m³ metal container inside which we installed a small tent to prevent direct contact with wind-blown snow. Electric power was provided by a gas generator installed in a separate wooden box. Although the generator enabled continuous, autonomous recording over several days, we experienced several unexpected generator shut-offs, likely due to a lack of cold air to cool the generator. We interrogated the two fibre-optic cables with a gauge length of 10 m, a channel spacing of 2.4 m, and a sampling rate of 500 Hz, providing the equivalent of 864 seismic channels along each 2 km fibre. Due to an energy outage and a storm that prevented any field visits for several days and delayed the installation of the 'Z'-shaped fibre, we ended up with a total recording time of approximately seven days on the linear fibre and three days on the 'Z'-shaped fibre.

Around the two fibres, we deployed a grid of 38 seismic nodes in boreholes drilled to approximately 50 cm depth (see Fig. 3b and Suppl. Table S4), covering an area of 2,000 m x 700 m, with an interstation distance ranging from 150 to 200 metres. Thirteen nodes were located alongside the optical fibres to act as reference points. Hammer tap tests were performed at eleven of these points to georeference the fibres, to check the quality of the recordings, and to investigate the local velocity structure of the glacier, as well as the depth of the underlying bedrock and the ice-water interface. The nodes were recovered from the ice after approximately two weeks of continuous recording.

3.4.4 Seismic nodes across the lateral shear zone (2025)

During two weeks in January 2025, we deployed a dense network of 45 nodes, also installed in shallow drilled boreholes, on the western rim of the glacier (see Fig. 3b and Suppl. Table S5), to study deformation associated with the lateral shear zone. Before the deployment, the shear zone was outlined based on the maximum ve-

locity gradient extracted from satellite image analyses (Provost et al., 2024). To have a good constraint on ice displacement during the 2025 deployment, we deployed the nodes around the positions of two permanent GNSS stations (GPS05 and GPS07 in Fig. 3b). We also installed a temporary GNSS station (GPS04 in Fig. 3b) west of the lateral shear zone, to provide a reference point on stable or slow-moving ice. We designed the 5 x 9 grid array of nodes using the 'square-triangle' model proposed by Mordret and Grushin (2025), which is expected to minimise aliasing during array beamforming analyses. This array covered an area of 1,500 m x 700 m with interstation distances ranging from 100 to 150 m.

3.5 Short-period station on the grounding zone(2024-2025)

In 2024, we deployed a short-period Digos DATA-CUBE acquisition system with a three-component 4.5 Hz geophone (HGS 3D-geophone HL-6B) in the ice to obtain a continuous, long-duration record of the seismic activity at the glacier's GZ at a sampling frequency of 200 Hz. This station, named AST15, was co-located with the GNSS station GPS03 (Fig. 3b) and ran on three 92 Ah pure-lead batteries, which provided enough power to make recordings from January to November 2024. The same instrument was then reinstalled as station AST16 and co-located with GNSS station GPS02 (Fig. 3b) for approximately 10 days in January 2025, during the seismic node experiment.

3.6 GNSS monitoring

Seven GNSS stations have been continuously recording the three-dimensional glacier motion on the Astrolabe Glacier for over a decade (Le Meur et al., 2014) as part of the Glacioclim observatory. Each station is equipped with a Trimble Alloy multifrequency receiver and a Trimble Zephyr antenna, to collect GPS, GLONASS, and Galileo signals at a 15-second sampling interval. The antennas are mounted on beacons that are anchored up to 2 m deep in the ice. Due to the glacier's yearly flow of ~500 m, the three downstream stations must be relocated upstream every year. During the Austral winter, the receivers record for only six hours per day. During the summer campaigns, the GNSS stations are set to continuous mode, enabling the construction of high-resolution time series for direct comparison with data collected from seismic stations collocated with the GNSS (see location in Fig. 1b and 3b). We processed GNSS phase observables in kinematic mode using the TRACK software, incorporating double-difference and linear combination techniques (Chen, 1999; Herring et al., 2018). The positions of the survey stations on the glacier were determined relative to the reference station DUMG, located at DDU.

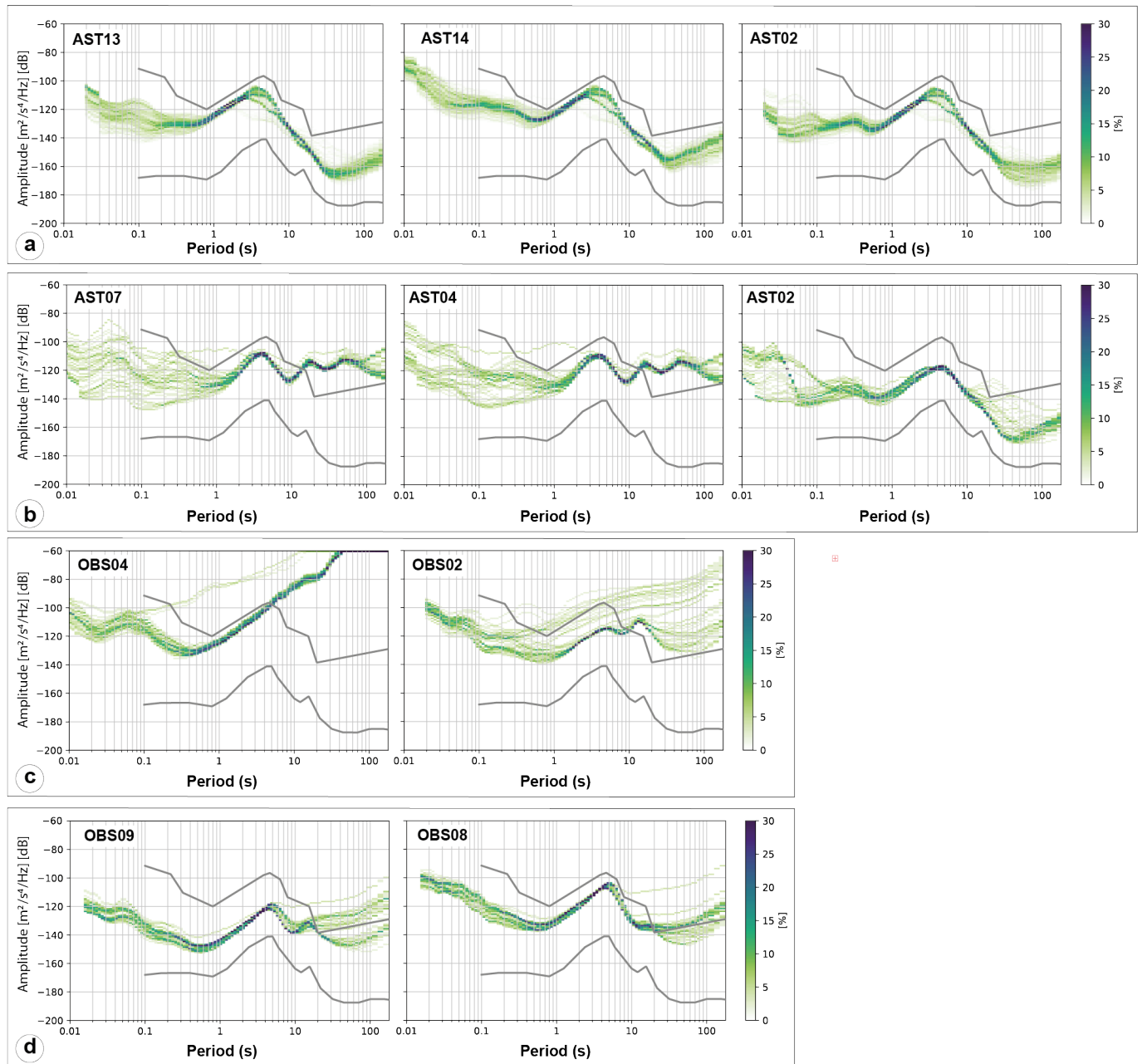


Figure 4 Seismic noise levels as probabilistic power spectral densities (PPSD) of the vertical component of: a) broadband seismological stations deployed on rocky islands (AST13 and AST14) and on stable ice (AST02), for the period Jan. 25 to 30, 2024; b) broadband stations deployed on the floating ice (AST07 and AST04) and on stable ice (AST02) over 5 days (Jan. 15 to 20, 2022); c) OBS04 (SPOBS INSU) and OBS02 (Güralp BREVE) for one day of record (Jan. 20, 2022); d) OBS09 and OBS08 (both BREVE OBS type) for Mar. 29, 2023. The gray lines show the New High and Low Noise models from [Peterson \(1993\)](#).

4 Data quality and noise spectra

4.1 Broadband seismology in stable environment: rocky islands vs stable ice

Figure 4a shows a comparison of the probabilistic power spectral densities (PPSDs) of two broadband seismological stations (AST13 and AST14) installed on a rocky outcrop, and one (AST02) installed on stable ice. The spectra were calculated from the vertical components (HHZ) during the same five-day recording period in January 2024.

The three examples show strong similarities in term of the shape and amplitude of their spectral content over periods ranging from one to 30 seconds. A max-

imum amplitude is observed at a period of four seconds, which is typical of ocean-induced secondary microseisms ([Ardhuin et al., 2011](#); [Cannata et al., 2019](#); [Davy et al., 2015](#); [Stutzmann et al., 2009](#)). Rocky sites display slightly higher noise levels at periods longer than 30 seconds. Sensors buried in snow and ice (such as AST02) are probably better protected from long-period noise such as atmospheric pressure variations and better insulated from temperature variations than sensors installed on bedrock and simply covered by a wooden box for protection from snow and wind. We also observe higher noise levels at rocky sites at periods lower than 3 seconds. This is probably due to the proximity of the ocean, sea ice and iceberg activity, which

generate high-frequency noise (e.g., Grob et al., 2011; Schlindwein et al., 2025; Müller et al., 2005). It is also likely due to the structure of the station itself. During windy periods, high-frequency vibrations are generated by the solar panels attached to the poles, the cables and the ground (e.g., Frankinet et al., 2021; Le Bris et al., 2025). These vibrations are clearly recorded by the seismic sensor located ~10 m from the solar panels.

4.2 Broadband seismology on the glacier: grounded vs floating ice

Figure 4b shows PPSDs (vertical components; HHZ) at three typical broadband seismological stations, calculated over the same five-day period (15-20 January 2022). Two of the stations were deployed on the floating ice tongue of the Astrolabe Glacier (AST07 and AST04, see location in Fig. 1b), while a third was installed 5 km away on stable ice (AST02). At periods below 1 s, the three stations exhibit low enough spectral amplitudes to enable them to detect low-amplitude cryoseismic events, such as high-frequency icequakes and stick-slip events (Le Bris et al., 2025). For periods between 1 and 10 seconds (i.e. over the secondary microseism peak), the noise spectra of these three stations are similar, with maximum energy peaking around 4 seconds. At periods longer than 10 seconds, however, the noise spectra differ significantly. AST02, which was installed on stable ice, exhibits a typical decrease in noise levels to a noise notch around 50 seconds, following the noise model curves (Peterson, 1993). The horizontal components (shown in Suppl. Fig. S2) display higher noise but still well below the New High Noise Level Model (Peterson, 1993). In contrast, the stations on floating ice display high noise levels, exceeding the New High Noise Level Model (Peterson, 1993). Indeed, two visible peaks emerge at ~16 seconds (also well visible at the seismic nodes, see following section) and ~50 seconds. On the horizontal components (PPSD shown in Suppl. Fig. S2), the peak around 16 seconds is clearly visible and above the high-noise model (although with a slightly lower amplitude), while the peak around 50 seconds is less visible and is embedded within a higher noise level. The peaks in energy at 16 and 50 s observed at stations on floating ice could be related to the natural vibration frequencies of the floating ice tongue (Okal and MacAyeal, 2006), or to the signature of infragravity waves (e.g., Bromirski et al., 2017; Rawat et al., 2014) penetrating the subglacial cavity. More detailed descriptions and analyses of these long period vibrations is out of the scope of the present paper and will be the subject of a dedicated study.

4.3 Seismic noise at the glacier terminus from ocean bottom seismology

Figure 4c illustrates how records from two independent instruments differ in the same environment. We compare the noise spectra of the vertical component at SPOBS OBS04 and the mid-band BREVE OBS02 for the same day (20 January 2022). At low periods (below 1 s), the two sensors display similar low level of noise, en-

abling them to record high-frequency events. For periods longer than 1 s, SPOBS OBS04 (equipped with 4.5 Hz geophones) clearly operates outside its range. In contrast, the mid-band BREVE OBS02 records a secondary microseismic peak well at a period of five seconds, as well as a relatively strong peak at approximately 13 seconds period, which could correspond to primary microseisms, i.e., the pressure of the swell on the coastal bathymetry in the vicinity of the OBS (Ardhuin et al., 2015; Barruol et al., 2006).

Figure 4d illustrates how noise levels may vary over short spatial scales. We present the noise spectra calculated on the same day (29 March 2023) at two BREVE OBSs (OBS09 and OBS08), which were only 400 m apart. Both stations display a well-defined secondary microseismic peak at a period of 5 s, similar to that observed at OBS02. However, OBS09 also exhibits a clearly defined primary peak at a period of 15 s, which is less visible at OBS08. The noise level is overall much lower at OBS09 (-150/-120 dB) than at OBS08 (-140/-100 dB) across most of the spectrum. These short-scale spatial variations in the PPSD at two sites equipped with the same instruments likely indicate different coupling of the stations with the seabed.

4.4 Seismic noise across the lateral shear zone, from grounded to floating ice

Figure 5 presents PPSDs calculated on data recorded on January 15, 2025 for the vertical components (DPZ) of four seismic nodes from the array deployed across the west lateral shear zone of the Astrolabe Glacier in 2025. The nodes were selected along a roughly linear profile perpendicular to the shear zone, ranging from stable ice to the glacier's floating area. The noise spectra from these seismic nodes show significant spatial variation, especially when transitioning from grounded to floating sites. The nodes display a common energy peak centred around 3-4 seconds, which is classically interpreted as being related to secondary microseisms caused by distant swells (Ardhuin et al., 2015). At periods below 1 s, all stations display low noise levels (around -130 dB), enabling both icequakes and stick-slip events with small amplitudes to be detected. As can be seen on the broadband stations, a significant feature appears on the long-period side of the nodes PPSD: a strong, systematic energy peak centred on a 16-second period is visible at the seismic nodes located on or close to the floating part of the glacier, as indicated by the dashed red square in Fig. 5. This 16 s noise peak is absent on the spectra of the grounded stations to the west of the shear zone (such as node 33X01), and gradually increases on spectra of stations located east of the shear zone, such as node 33X09. The amplitude of this spectral bump gradually exceeds that of the New High Noise Model (Peterson, 1993) when approaching the floating ice. The observation of these 16-second peaks on short-period (5 Hz) sensors is unexpected and suggests that these short-period sensors can be sensitive to long-period ice vibrations. The 16 s peak appears to be consistently present in space on the floating ice and over time, as it was also clearly recorded by broadband stations deployed in 2022 (see Fig. 4b),

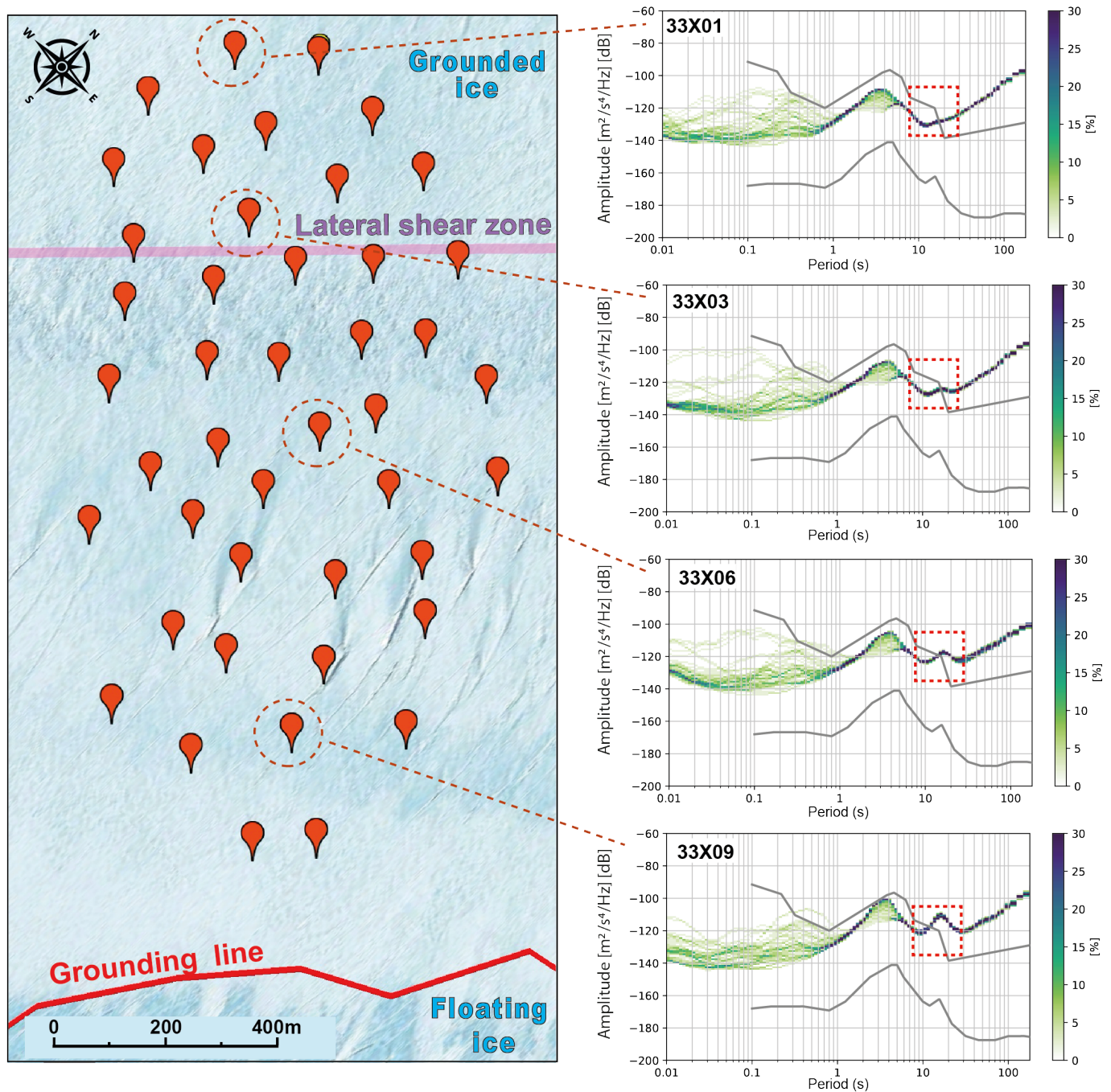


Figure 5 Seismic noise levels of seismic nodes (vertical components DPZ) deployed in Jan. 2025 across the west lateral shear zone of the Astrolabe Glacier, pink line, defined from the ice velocity field (Provost et al., 2024). The 4 presented PSD are calculated for 1 day (Jan. 15, 2025) at 4 stations along a NW-SE trending line perpendicular to the shear zone and to the GZ, from the stable ice (top, node 33X01) to approaching the floating part of the glacier (bottom, node 33X09). The 16 s peak is underlined in the spectra by a red dashed box. The continuous red line at the bottom of the map indicates the grounding line defined by GPS displacement (Le Meur et al., 2014). Background is a Maxar satellite image.

and pervasively by nodes deployed in 2023 and 2024 (not shown here). This peak occurs at a period close to the primary microseismic peak (8-20 s), with no evident correlation with the swell height, motivating further investigation to determine its origin. The 50 s peak observed at broadband instruments in 2022 is clearly not detected by the short-period sensors.

4.5 DAS and nodes across the glacier grounding zone

So far, the DAS data has only undergone preliminary exploratory analysis. Fig. 6 provides some indications of the data quality. Fig. 6a shows two minutes of DAS data recorded on 16 January 2024 along the fibre, between 0 m (the location of the DAS interrogator) and 2,000 m (the end of the fibre). The amplitude saturation of the vertical stripes indicates a high noise level and a poor fibre coupling, particularly where the fibre was free to

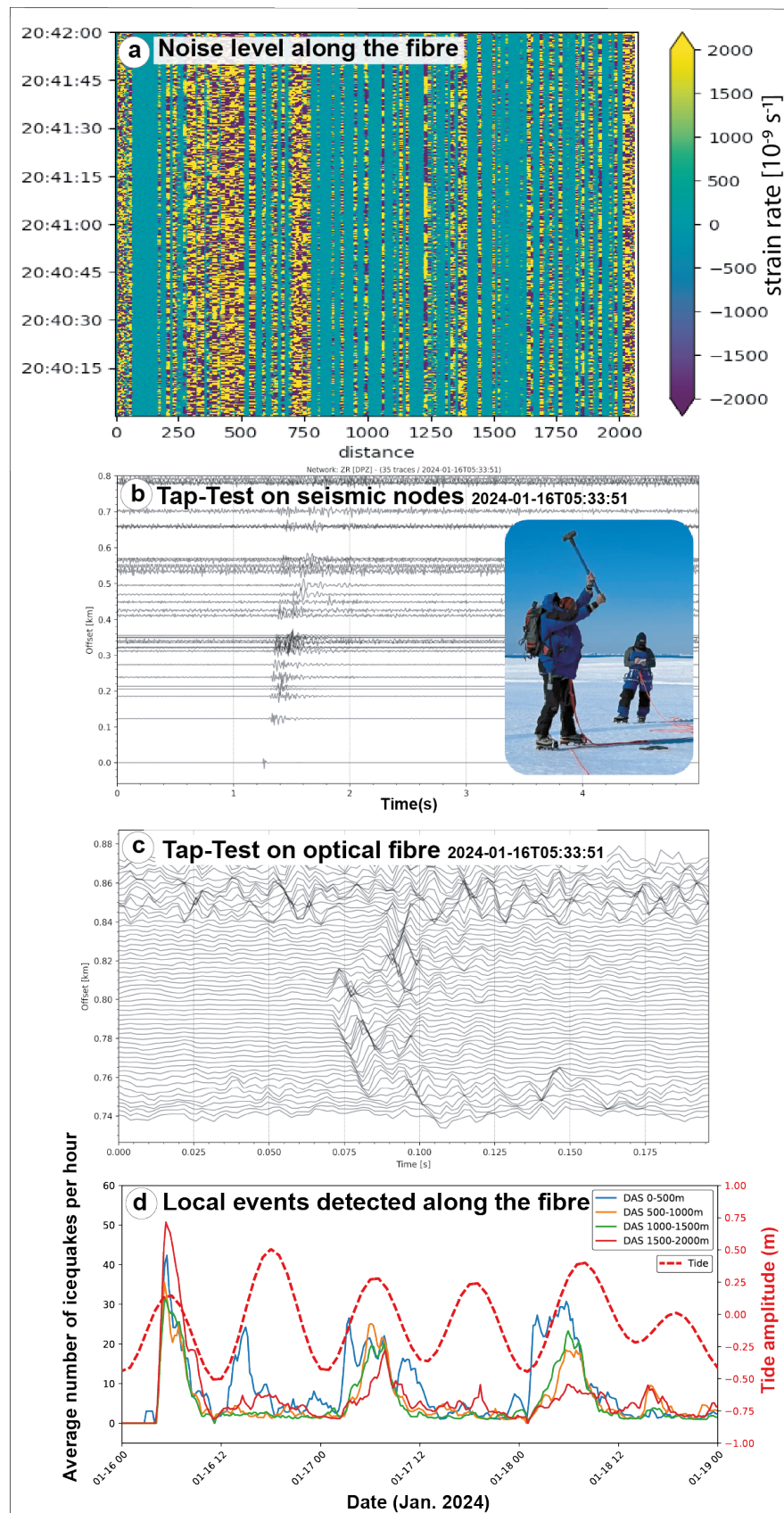


Figure 6 Exploration of DAS data quality from the linear fibre deployed in Jan. 2024. (a) Raster plot of 2 minutes of DAS data on Jan. 16, 2024, in nanostrain-rate against optical distance along the whole linear fibre in metres. (b) Vertical seismic signals generated by a hammer shot performed adjacent to seismic node 24x03 and recorded on all the nodes of the 2024 network (amplitude indicates ground velocity). All traces are scaled by their maximum amplitude. Inset photograph shows the method of generating the signal (hammer and metal plate). (c) The same shot as in (b), recorded on the optical fibre (amplitude indicates strain-rate). All traces are scaled by their maximum amplitude. (d) Hourly rate of STA/LTA event detections over 3 days of continuous DAS data (Jan. 16 to 18) that were transformed from strain-rate to ground velocity. Each curve represents the average number of detections across all sensors within four 500-long segments.

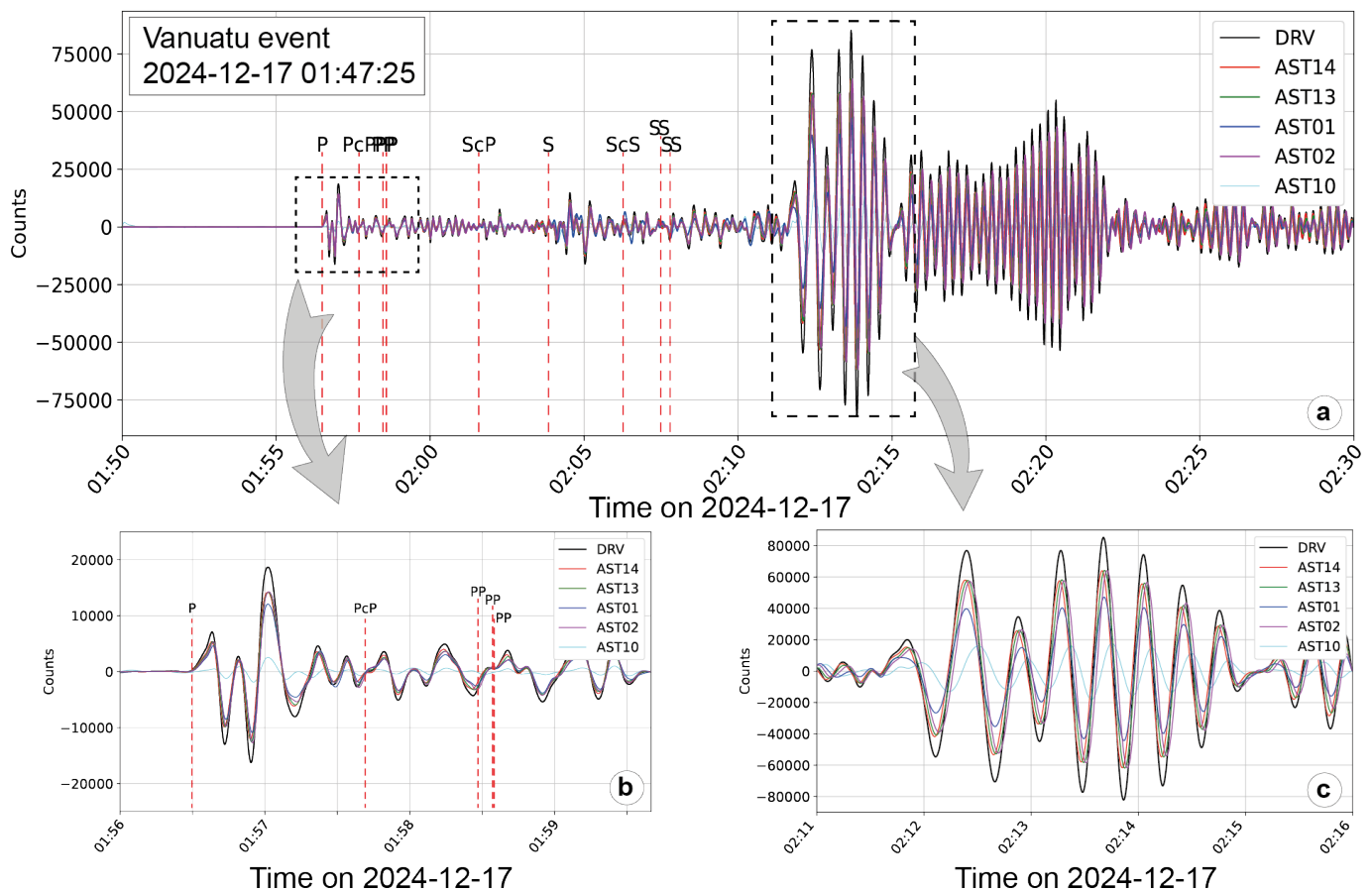


Figure 7 a) Example of 40min-long vertical seismograms from a teleseismic earthquake recorded on 5 SEIS-ADELICE broadband seismological stations (colour lines) compared to the permanent Geoscope station DRV (HHZ component from the STS2 sensor - location code “10”, black line) filtered in the [0.01 - 0.1] Hz band. The earthquake occurred in Vanuatu on 2024-12-17 01:47:25 UTC and was located at 17.710°S 168.030°E, 54 km depth, had a magnitude $M_w=7.3$, and occurred at an epicentral distance of 52°. b) and c) zoom on the P-wave and on the surface waves, respectively.

oscillate, e.g., over crevasses.

Fig. 6b and 6c compare the ground velocity signal recorded by the network of nodes with the strain-rate signal recorded by the fibre following an active seismic hammer blow. Although the waveforms are not directly comparable, we note the very different propagation distances of the signal: up to 650 metres away from the blow on the nodes, and only 45 metres on either side of the blow on the DAS data. Fibre data also show significant variability in the waveforms depending on position, probably because strain-rate data are more sensitive to small-scale surface structure than ground-velocity data.

While we cannot yet pinpoint the exact reasons why the DAS data appear to be much less sensitive to seismic waves than the nodes during these tap-tests, we can hypothesise that poor coupling may have played a role: as the hammer blows were carried out in the afternoon, the sun radiation and the daily maximum temperature probably caused local melting around the fibre near the surface, while leaving the deeper-buried nodes unaffected. Indeed, much better coupling and better waveform similitudes between DAS and node data were achieved by teams able to use the snowmobiles to pull sleds with metal keels that could dig a trench in the firn and deploy the cable inside it at a fixed depth (e.g. 30

cm for Agnew et al., 2025). In our case, blue ice and crevasses prevented such deployment procedures. Further experiments are needed to optimise the deployment strategy of optical fibres in the conditions prevalent on coastal Antarctic glaciers (e.g., Agnew et al., 2025; Brisbane et al., 2021; Hudson et al., 2021), as well as to generate power more stably.

5 Examples of data and applications

5.1 A broadband seismic array to monitor global seismicity

The broadband seismic stations, deployed as part of the SEIS-ADELICE project, formed a 19 km-long, linear network capable of recording teleseismic events. Fig. 7 compares the seismic records obtained at rocky outcrops and in icy environments with those obtained at the STS2 sensor of the permanent, vault-installed, Geoscope DRV station. The selected teleseismic event originated in the Vanuatu region and reached the network with a back azimuth of 34.5°, i.e., nearly aligned with the linear profile. The waveforms observed at the different temporary broadband stations are similar in shape and amplitude to each other and to those at the permanent DRV station (Fig. 7a). The predicted seismic

phase arrivals using the IASP91 1D Earth model (Kennett and Engdahl, 1991), particularly the P and S phases, align well with the observed phases on the seismograms (Fig. 7b). As expected, P-waves that arrive at the Earth's surface at a steep angle display homogeneous arrival times across the network. Conversely, surface waves propagating horizontally with a back azimuth parallel to the station alignment display similar waveforms but with progressive delays in arrival times that can be measured between individual wave peaks at AST14, DRV, AST13, AST01, AST02, and AST10 (see Fig. 7c). This gives an apparent phase velocity of 3.7 km/s across the network for Rayleigh waves of 30s dominant period. These results highlight the importance of such temporary seismological deployments on rocky islands and in ice, in the context of investigating and imaging the deep Earth and long-period natural processes (e.g., the POLENET experiment, Accardo et al., 2014).

5.2 Cryoseismic activity: Icequakes and surface crevassing

The dominant cryoseismic activity recorded by stations deployed on and around the Astrolabe Glacier GZ corresponds to so-called 'icequakes', generated by fracturing of the ice surface and the brittle opening of crevasses (Barruol et al., 2013; Fromm et al., 2023; Lombardi et al., 2016; Podolskiy et al., 2016; Osten-Woldenburg, 1990). Icequakes are characterised by short duration (<1 s), impulsive signals with a broad energy spectrum (5-50 Hz), and no clear identifiable seismic phases. Using data from broadband instruments and the 2023 array of seismic nodes, Le Bris et al. (2025) analysed this icequake activity in detail, showing its close connection to ocean tides. These tides cause the entire glacier to flex at its GZ in order to accommodate the relative height difference between the floating and grounded ice, resulting in brittle surface deformation.

Fig. 8 illustrates the characteristics of the icequake signals and their detection. Icequakes are a significant source of seismic activity and are clearly visible on raw seismograms as impulsive events. Fig. 8a shows an example of a one-hour seismogram of the vertical component of the node 01x07, which was deployed in January 2023 (see location Fig. 3b). The STA/LTA algorithm (Allen, 1978) was applied to the continuous data filtered in the [5-40] Hz band, using the short- and long-term average windows STA = 0.5 s and LTA = 5 s, and the ratio STA/LTA allowing to detect the start- and end-time of an event such as trigger_ON = 5 and trigger_OFF = 2. The detected events are indicated by the vertical red dashed lines in Fig. 8b of the zoomed 10 min window and an individual example is shown Fig. 8c. The hourly occurrence of icequakes can then be analysed at each station as an icequake count per hour, in relation to the tide amplitude, such as the example presented in Fig. 8d. Clear periods of seismic quietness can be observed at low tide at this particular site, alongside peaks in icequake activity (with more than 400 events occurring per hour) at high tide on 18 and 19 January, and during rising tides on 20 and 21 January. More details on the icequakes dynamics can be found in Le Bris et al. (2025).

As an example of DAS data analysis, event detection based on STA/LTA (Allen, 1978) using parameters similar to those in Le Bris et al. (2025) (STA = 0.5 s; LTA = 5 s; trigger-on = 5; trigger-off = 2) and filtered in the [5-100] Hz band, was conducted on continuous DAS data from the linear fibre, transformed from strain rate to ground velocity. The results are presented in Fig. 6d for a three-days recording period (16 to 18 January 2024), during which the power was stable, and the fibre was sufficiently sensitive (or sufficiently coupled) to record a number of cryoseismic events. The event detections were performed on all the recording channels and then averaged for each 500 m segment of the fibre. The detection pattern observed along the fibre shows clear daily bursts of seismicity, peaking mostly at high tide or during rising tides. These could be related to tidal processes and surface crevassing (e.g., Barruol et al., 2013; Fromm et al., 2023; Le Bris et al., 2025; Lombardi et al., 2016). However, it is unclear whether the variation in the peak rate of event amplitude is indicative to a true glaciological phenomenon linked to tidal amplitudes. The similarity of the waveforms, durations and pervasiveness of these events compared to those observed at seismic stations suggest they likely correspond to icequakes, but further analysis is required to constrain the type of events, but also to eliminate any potential instrumental artefacts and estimate the impact of the wind-induced ambient noise, which can hinder the detection.

5.3 Cryoseismic activity: Stick-slip events and basal sliding

The second type of cryoseismic event pervasively present in the SEIS-ADELICE recordings at glacier stations is the 'stick-slip' event. These events are well-documented to occur at the base and/or along the lateral boundaries of glaciers to accommodate their horizontal flow over fixed ice or bedrock (e.g., Gräff et al., 2021; Helmstetter et al., 2015; Pirli et al., 2018). In our dataset, these events are characterised by a much smaller amplitude than the icequakes described above, likely due in part to the greater distance from the sources. They display high-frequency (20-100 Hz) signals with well-defined P and S phases, as can be seen in Fig. 9a: P-waves dominating the vertical components and S-waves well visible on the horizontal components few tenths of second later. Reaching the surface at a high incidence angle, they occur repetitively (within minutes), with extremely consistent waveforms. This suggests fixed seismic sources at the ice-bedrock interface that activate regularly with an identical focal mechanism.

Fig. 9 shows an example of a family of stick-slip events recorded in 2023 at seismic nodes deployed on the Astrolabe Glacier GZ (Fig. 3b). Repetitive events are detected by correlating a visually selected signal template with the continuous time series at each seismic node. The methods used to detect icequakes (STA/LTA) and stick-slips (pattern matching) are distinct due to the different characteristics and amplitudes of the signals. In practice, stick-slip detection is performed at a given node throughout its entire recording period. Stick-slip events at other nodes can be retrieved from the cat-

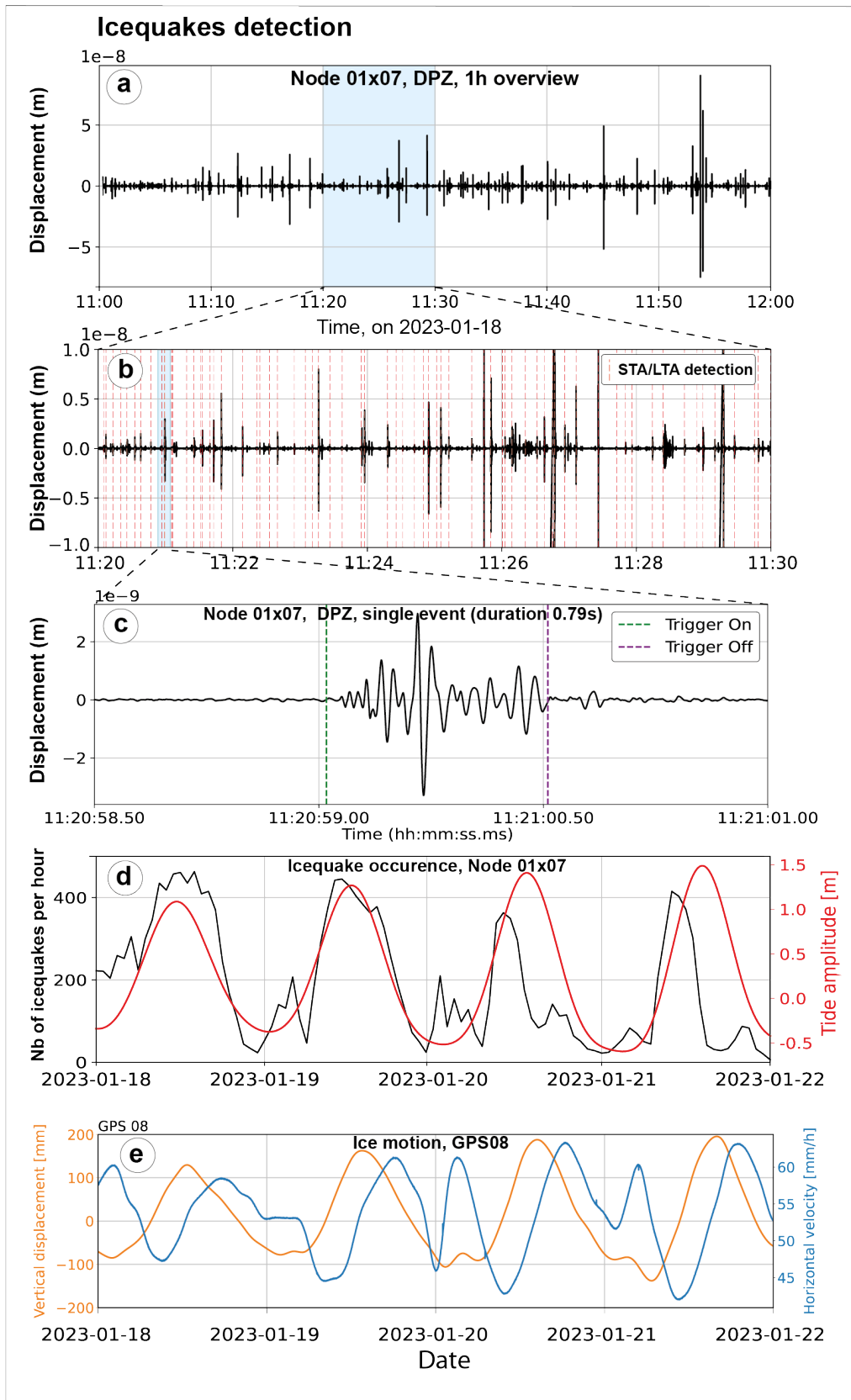


Figure 8 Icequake detection at station 01x07, on Jan. 18, 2023. a) One-hour vertical seismogram (DPZ) at seismic node 01x07 filtered between 10-100 Hz, showing the numerous icequakes appearing as impulsive events. b) Zoom on a 10 min-long window displaying the detected icequakes marked by the red dashed lines. c) 1.5 s-long window showing a single icequake event with the detection trigger on and off (green and purple dashed line, respectively). d) Variation of the number of icequakes detected at station 01x07 (black curve) during the period Jan. 18 to 22, together with the tide amplitude (red curve), as measured at the neighbouring DDU tide gauge. e) Ice motion at GPS08 (located at about 200m NE from node 01x07, see Fig. 1b and 3b). Blue: horizontal ice velocity; Orange: vertical displacement.

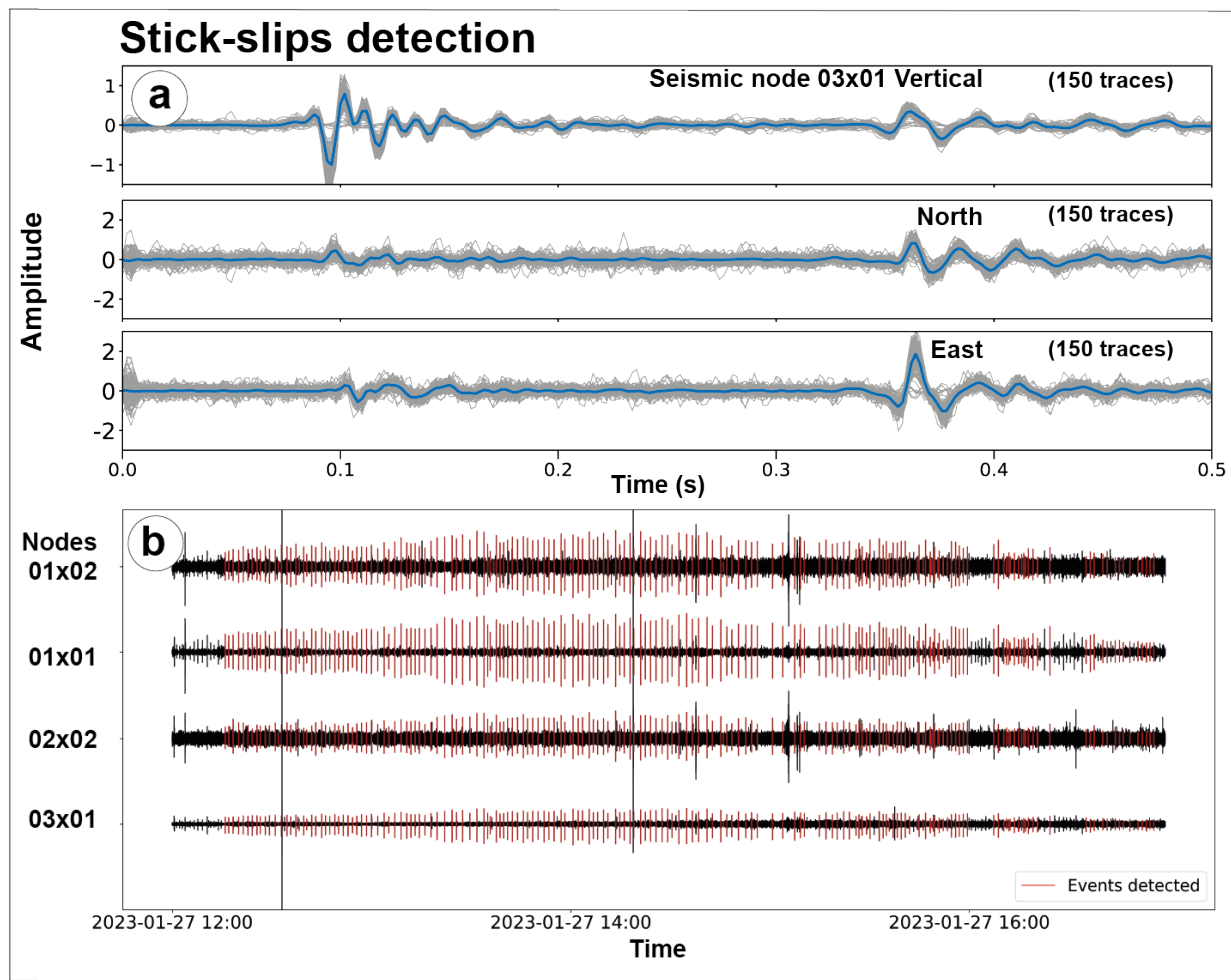


Figure 9 stick-slip detection. a) Example of stacked vertical traces (in blue) of the 150 events (in grey) with the highest correlation coefficients of a stick-slip cluster recorded by the three components of seismic node 03x01 on Jan. 27, 2023. b) Seismograms of vertical components of stations 01x02, 01x01, 02x02, 03x01 over 5 hours on Jan. 27, 2023, showing in red the patterns detected by cross correlation (here, correlations > 0.92) revealing the regular occurrence of stick-slip and their disappearance.

logue of timestamps by selecting a one-second window around each timestamp and can be then located using QuakeMigrate software (Hudson et al., 2020; Winder et al., 2026). Figure 9a shows a stack of 150 waveforms of the detected events recorded at station 03x01 for the three components. Figure 9b shows a five-hour time window presenting the detected patterns at four seismic nodes, with the detected stick-slip waveforms coloured in red. This example illustrates the extremely regular occurrence of repetitive events, with approximately one event occurring every two minutes and lasting several hours before disappearing. Further analysis of the data is required to characterise modulation in amplitude, occurrence throughout the network, and relation to tide phases (Le Bris et al., 2026).

5.4 Imaging the Astrolabe Glacier structure from noise correlation

One of the objectives of dense array deployments is to image the internal structures of the Astrolabe Glacier using noise- and icequake-based surface waves (e.g., Mordret et al., 2018; Pearce et al., 2024; Sergeant et al., 2020; Shapiro et al., 2005; Zigone et al., 2019, 2014). To

demonstrate the feasibility of this approach, we used the ambient noise recorded during the 2023 50-node deployment (green dots on Fig. 3b) to compute the cross-correlation between each station pair. The noise data are pre-processed using a slightly modified version of the workflow proposed by Zigone et al. (2019), with shorter time windows (10 minutes) to improve transient rejection in a more seismically active environment. It involves removal of large amplitude transients like icequakes, or instrumental artifacts using an energy threshold (3 times the mean energy of the day), whitening in a broad frequency band of 0.125–50 Hz, and amplitude clipping at 3.5 times the standard deviation in each window. Following pre-processing, the correlation functions are computed between each pair of stations in the frequency domain and stacked over the whole recording period (excluding 3 noisy days) to enhance the signal-to-noise ratio (SNR). We computed the correlation functions between all the cross-components to obtain the full correlation tensor. Fig. 10 highlights the arrival of Rayleigh waves on the vertical and radial components (ZZ, RR, ZR, RZ) and Love waves on the transverse component (TT), with early P-wave arrivals also visible on some components, such as RR and

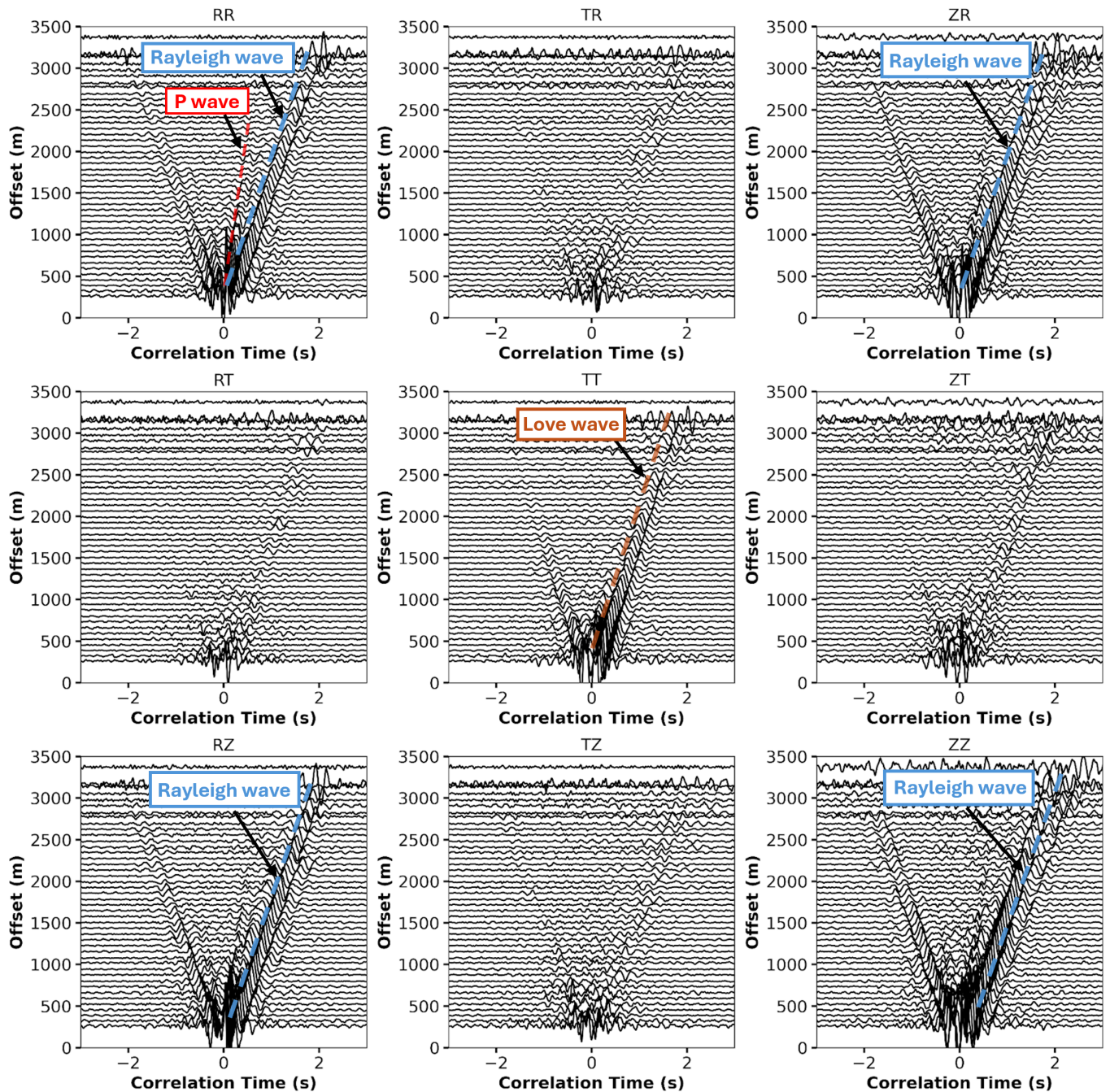


Figure 10 Inter-stations distance in metres (offset) as a function of correlation time in seconds for the nine components of the correlation tensor (components are indicated above the panels) computed using the data from the 50 nodes deployed in Jan. 2023 (green dots on Fig. 3b). The correlations are stacked for each 70 m distance bin and are filtered between 3 and 20 Hz. Clear Rayleigh waves are reconstructed on the RR, RZ, ZR, and ZZ components with an average velocity around 1700 m/s. Faster arrivals, potentially P-waves, are visible on the RR and ZZ components at positive times, with an average velocity of approximately 3700–3800 m/s. Love waves are reconstructed on the TT component with an average velocity of 2000 m/s.

ZZ. Note the slight energy in TR, RT, TZ, and ZT components, which indicates either small errors in sensor orientations, or the presence of seismic anisotropy in the ice (e.g., [Saade et al., 2015](#)). Correlations are not perfectly symmetric around zero lag time, with asymmetries in amplitude and arrival times, particularly for body waves, reflecting variability in source nature and distribution. Although directional effects are observable, surface-wave features remain largely similar between causal and acausal parts. This directionality may introduce small biases in velocity estimates, but the

overall similarity between causal and acausal parts indicates a sufficiently high SNR to allow robust group and phase dispersion measurements. In a dedicated and more thorough analysis, these dispersion measurements will be used to build group and phase velocity maps for each frequency which will then be inverted to build a quasi-3D tomography model of shear wave velocities around the GZ, enabling investigation of spatial and depth velocity variations between the floating and grounded parts of the glacier.

5.5 Glacier motion and seismicity

The permanent GNSS network on the Astrolabe Glacier GZ offers a valuable opportunity to identify clear ice flow patterns and investigate potential links to cryoseismicity. During the various SEIS-ADELICE field deployments, several seismic stations were positioned close to GNSS sites. As an example, we present in Fig. 8e the results obtained at GPS08 and the neighbouring node 01x07 (see Fig. 1 and 3b for locations). This example demonstrates the close relationship between the detected icequakes (Fig. 8d) and the GNSS-derived ice motions (Fig. 8e). From 18 to 21 January 2023, clear peaks in icequake occurrence (culminating at 300–400 events per hour) are observed during high and then mid-rising tides, as indicated by the vertical displacement (orange curve Fig. 8e). The horizontal ice velocity (blue curve) is modulated by the tides, with horizontal accelerations occurring after high tide, suggesting a phase-lagged response to the vertical bending. Depending on the node's location on the glacier, icequake occurrence peaks during rising or falling tides. [Le Bris et al. \(2025\)](#) used this information to propose a model of tide-induced glacier flexure that could explain brittle ice deformation in either the floating or grounded parts of the glacier.

5.6 Calving events from an island station

The installation of station AST14 on Curie Island (see location Fig. 1b and 3a) was motivated by its proximity to the oceanic end of the Astrolabe Glacier's floating tongue. During the site installation on 23 January 2024, we witnessed several calving events in real time, with ice blocks detaching from the glacier terminus. These events were accompanied by clear signals, which were visible on the live seismic record on the field computer. An example of such a local calving event recorded at AST14 is shown in Suppl. Fig. S3. The event lasts several seconds and does not display any identifiable impulsive seismic phase, which is typical of such events (e.g., [Glowacki et al., 2015](#); [Gräff et al., 2025](#); [Podolskiy et al., 2021](#)). It is rich in low frequencies (below 5 Hz), but also contains energy up to (at least) 70 Hz. However, the 200 Hz sampling rate at station AST14 limits the upper frequency investigation of spectrograms to 100 Hz, meaning that higher frequency signals (up to the kHz) that may be present during some calving events (e.g., [Glowacki et al., 2015](#)) could be missed. While the calving of the Astrolabe Glacier appears to be dominated by the frequent detachment of small ice blocks, a few events involving the rotation of large ice blocks have been already witnessed from the DDU base in recent years. These events, similar to the capsize events found in West Antarctica ([Phạm, 2025](#)) could be recorded and retrieved from existing land and OBS data for analysis.

5.7 Anthropogenic signals: example of helicopter noise

In terms of human-made noise, Antarctica is one of the quietest places on Earth. This allows the different sporadic signals caused by human activity to be deciphered. Often related to motor-induced vibrations,

such as aircraft and helicopter noise (e.g., [Eibl et al., 2017](#); [Fichtner et al., 2023](#)), these signals may interfere with natural ones. As an example, we present in Suppl. Fig. S4 (top) a helicopter flyby above the Astrolabe Glacier, as recorded by a seismic node (01x02) on 16 January 2023 (see location Fig. 3b). Prior to the helicopter's arrival, the spectrogram displays a monochromatic fundamental frequency of around 20 Hz and several overtones. The helicopter is an Airbus Helicopters AS350 B3, which has a three-bladed rotor. The base energy line at around 20 Hz corresponds to the rotor's speed of ~400 rotation per minute ($400 \text{ rotation} \times 3 \text{ blades}/60 \text{ s} = 20 \text{ blades per second} = 20 \text{ Hz}$). When passing close to the seismic sensor (at around 04:44:40), the helicopter produced clear Doppler effects, characterised by a progressive decrease of several Hz in the fundamental frequency and of several tens of Hz in the overtones. The magnitude of these effects depends on the helicopter's distance and speed (e.g., [Eibl et al., 2017](#)). An example of a helicopter landing and taking off on the glacier a few hours later on the same day, as recorded by a neighbouring node (04x04) is shown in Suppl. Fig. S4, bottom. After landing at around 04:59, the spectrogram shows a slight decrease in engine rotation and in power sent to the ground, since the blades have no angle of attack with which to push the air downwards. The spectrogram shows maximum energy during the final landing phase and during the take-off (ending around 05:01), when maximum air pressure is directed downwards. Clear Doppler effects are also visible during the helicopter's approach phase. This example illustrates the high level of detail that is hidden within the seismic signals, and the importance of identifying and cataloguing these “events” to prevent the misinterpretation of glaciological signals and processes, such as hydrologically induced tremors (e.g., [Bartholomäus et al., 2015](#); [Lindner et al., 2020](#); [Umlauf et al., 2021](#)).

6 Conclusion

Over a period of five years, the SEIS-ADELICE experiment recorded the cryoseismic activity of the Astrolabe Glacier at various scales using permanent, semi-permanent, and temporary seismic deployments on rock outcrops, on grounded and floating ice, and on the seabed. In this article, we share our field experience of installing and maintaining seismic instruments in challenging conditions. A key strength of this experiment was the deployment of several dense arrays of seismic nodes across the glacier's grounding zone and lateral shear zone. This enables us to characterise the mechanical interaction with daily tides with a high degree of spatial and temporal resolution. PPSD analysis of seismic noise confirms the overall high quality of the seismic dataset, enabling us to explore the signals across various frequency bands, ranging from long periods (several minutes) to high frequencies (several hundred Hz). This noise analysis reveals the presence of unexpected long-period signals peaking at 16 and 50 seconds at stations located on the floating part of the ice tongue. Absent at stations located on grounded ice, these signals could indicate the resonant behaviour of

the partly floating ice tongue. However, further analysis is required to confirm this. Our initial investigations focused on the cryoseismic activity at the glacier GZ evidenced pervasive presence of surface icequakes and basal stick-slip events. The occurrence of surface icequakes clearly demonstrates the significant influence of daily, tide-induced glacier flexure on its brittle behaviour. Basal stick-slip events occur at a small number of fixed sources (whose location, dynamics and mechanisms remain to be investigated) and should constrain the mechanical interaction between ice and bedrock at the grounding zone, and along the lateral shear zones of the glacier. Calving events, which are visible in the data from ocean bottom seismometers (OBS) and island stations close to the glacier terminus show great promise in terms of characterising the calving activity, the processes involved and their seasonal evolution. The entire seismic dataset contains not only the significant local cryoseismic activity, but also the regional and teleseismic events, and continuous ambient noise. This provides the potential to characterise the glacier's structure in detail and to study the underlying solid Earth. The Astrolabe Glacier is a unique target for studying processes associated with outlet glaciers. These preliminary results prove that the deployed instrumentation and proposed methods have successfully recorded the natural processes at play, which may be independent of the glacier size. This approach will be useful for evaluating the long-term impact of climate change on coastal glacier dynamics and the stability of the upstream ice sheet, particularly in relation to warming of the Austral Ocean.

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Data and code availability

The broadband SEIS-ADELICE seismic data are already available at the RESIF data centre (<https://seismology.resif.fr/>) under the FDSN network code ZR (Barruol et al., 2023). OBS and seismic node data are in the process of being archived and distributed at EPOS-Resif but can be provided on request. Seismological data from the Geoscope DRV station can be accessed through the IPGP web services or the Epos-France Seismological Data Centre under the FDSN network code G (Institut de physique du globe de Paris (IPGP) and École et Observatoire des sciences de la Terre de Strasbourg (EOST), 1982). Raw and processed GNSS data acquired on the Astrolabe Glacier GZ are available under a Creative Commons Attribution 4.0 International license in Togaibekov et al. (2024). DAS data are not yet available online, but can be pro-

vided on request (after a retention period ending Jan. 2027). Tide gauge data, managed by the NIVMER/ROSAME project (Calzas et al., 1992), are available at <https://doi.org/10.17183/REFMAR#108>. The Python code to calculate the sun's azimuth to retrieve the geographic North is kindly made available on Github by John Clark Craig (<https://github.com/zemogoravla/simsatool/blob/master/sunpos.py>). Seismic data were processed using ObsPy version 1.4.0 (Beyreuther et al., 2010), available under the ObsPy license at <https://docs.obspy.org/>. Some figures were made with Matplotlib version 3.5.3 (Hunter, 2007), available under the Matplotlib license at <https://matplotlib.org/>.

Competing interests

The authors acknowledge that they have no competing interests.

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