Seismological monitoring of Svalbard's cryosphere: current status and knowledge gaps (CRYOSEIS)

Author names
Andreas Köhler[1], Wojciech Gajek[2], Michal Malinowski[2], Johannes Schweitzer[1], Mariusz Majdanski[2], Wolfram H. Geissler[3], Michal Chamarczuk[2], Andreas Wuestefeld[1]

Institution affiliations
1 NORSAR, Kjeller, Norway
2 Institute of Geophysics Polish Academy of Sciences, Warsaw, Poland
3 Alfred Wegener Institute, Bremerhaven, Germany

Corresponding author: Michal Malinowski, michalm@igf.edu.pl
ORCID number 0000-0002-7190-3683

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1. Introduction

Seismology is the science of studying earthquakes and the material properties in the solid Earth by analyzing observations of elastic waves, which had been radiated by seismic sources and propagated through the Earth. The new research field of environmental seismology studies vibrations and temporal variations in the shallow sub-surface that are caused by non-tectonic sources, such as cryospheric processes or atmospheric forcings (Larose et al. 2015). In particular, seismic signals originating from glaciers and ice sheets have been recently extensively studied in various regions around the globe using either dedicated temporary or permanent seismic stations, making cryoseismology a rapidly developing frontier research topic in Earth Sciences. An excellent overview of the background and existing studies is given in the recent review articles of Podolskiy and Walter 2016 and Aster and Winberry 2017. The popularity of cryoseismology is also recognized in an increasing number of dedicated sessions and workshops at various international conferences and special journal issues devoted to this emerging field (see e.g. special issue of Annals of Glaciology entitled "Progress in Cryoseismology").

While cryoseismological research has a long history at the Polish research station in Hornsund (southern Spitsbergen, Lewandowska and Teisseyre 1964), it was just within the past 5 – 10 years that an increasing number of studies systematically analyzing glacier seismicity have been carried out in Svalbard. In view of these developments and the benefit of using cryoseismology as a tool complementing well-established methods for monitoring the cryosphere and related changes in the Arctic, it is essential to further advance and promote this new field of research in Svalbard. In contrast to popular study regions like Antarctica, Greenland, Alaska and the Alps, relatively few studies have been conducted in Svalbard, and the full potential of cryoseismology has not been explored yet. Moreover, the area of Svalbard has been warming about three times faster than the global estimate over the last 100 years (e.g. Nordli et al. 2014) and accessibility and logistic is much easier compared to other regions in the Arctic or Antarctica, making it a natural laboratory to study changes in the cryosphere induced by climate change. Therefore, this report has the objective to briefly introduce the reader into cryoseismology within a global context, to highlight the recent research activity in Svalbard, and to recommend directions for future research.

2. Overview of existing knowledge

2.1 Cryoseismology

Passive seismic monitoring is a powerful method for better understanding glacial dynamic processes and inferring englacial and subglacial conditions in previously inaccessible areas, complementing traditional glaciological observations from field or remote sensing due to its independence from visibility conditions, spatial extent beyond single observation points (boreholes), and unique high temporal resolution (sub-second scale) also during polar nights. Another key opportunity of using continuous seismic records of permanent stations is the systematic analysis of long-term trends and changes in seasonal patterns of cryo-seismicity or sub-surface structures (e.g. permafrost) over a time period of several years or decades, which allows assessing potential effects of climate change.

Strong cryogenic seismic signals, such as those generated by large iceberg calving at glaciers and icestreams, are observed at ranges up to regional (about 100 – 2000 km) or even teleseismic distances (>2000 km) (Ekström et al. 2003). Local glacier microseismicity (i.e., icequakes), mainly related to brittle ice failure (crevasse opening) and basal processes (e.g. stick-slip motion), is best monitored with stations installed on the ice surface or in shallow boreholes (see Podolskiy and Walter 2016; Aster and Winberry 2017, and references therein). However, in Antarctica, tidal triggering of cryoseismicity not related to calving but representing stick-slip motion events can be also observed at distances up to 300 km (Pirli et al. 2018). Moreover, passive seismic records allow studying the state and evolution of the glacier hydraulic system through monitoring either meltwater-related seismic tremors (Bartholomaus et al. 2015a; Helmstetter et al. 2015; Röösli et al. 2016; Köhler et al. 2019a) or transient signals related to hydro-fracturing and fluid resonance (Stuart et al. 2005). Monitoring of iceberg drift is another application of cryoseismology (e.g. Pirli et al. 2015).

Beside studying seismic signals to better understand source processes, cryoseismology also includes structural investigations of the propagation medium of seismic waves, i.e., it allows inferring properties of the ice or shallow subsurface. Records of the background ambient seismic noise wavefield caused by wind, ocean waves, and flowing water are often used for this purpose by applying methods like seismic noise interferometry or Horizontal-To-Vertical Spectral Ratios (HVSR) (Larose et al. 2015). This approach does not only allow studying the state of the internal structure of glaciers, ice sheets and frozen soil (Overduin et al. 2015; Walter et al. 2015; Diez et al. 2016; Picotti et al. 2017; Preiswerk and Walter 2018; Yan et al. 2018), but also allows time-lapse monitoring of subsurface structures, for example the permafrost active layer (Abbott et al. 2016; James et al. 2017, 2019; Kula et al. 2018; Köhler et al. 2019c) and the subglacial drainage system (Gräff et al. 2019; Zhan 2019).

A challenge in cryoseismology is that processes are mostly observed indirectly through seismic waves recorded at a certain distance from the source. Hence, physical models or calibration with direct observations, i.e., actual source parameters or subsurface quantities, using empirical models is required. Such an approach has shown the potential of seismology to assist and advance glaciological or permafrost research in several cases, for example through the study of deep icequakes to uncover stick-slip motion and basal friction laws (see e.g. Aster and Winberry 2017), through the quantification of calving to better understand mass loss of glaciers (Bartholomaus et al. 2015b; Köhler et al. 2016, 2019b), and through recent experimental studies to improve permafrost active layer monitoring (James et al. 2019).

Seismology is not the only passive, wave propagation-based approach complementing established measurement methods in the cryosphere. For example, infrasound (Asming et al. 2013), hydroacoustic (Glowacki et al. 2015), and water surface waves (Minowa et al. 2019) are well-suitable for monitoring the calving of glaciers. Furthermore, active geophysical methods, such as seismic profiling, ground-penetrating radar (GPR), and electric resistivity tomography (ERT) are well-established methods for ice, snow and permafrost research (Polom et al. 2014; Johansen et al. 2011; Booth et al. 2013; Dow et al. 2013; Church et al. 2019) which can be combined with passive seismology. For example, the glacier's inner structure can be imaged with the highest resolution using a combination of reflection seismic and GPR (King et al. 2008; Church et al. 2019). Those methods can clearly visualize both the bed of the glacier and thermal boundaries between temperate and cold ice. Attempts were made to infer physical basal rock properties using seismic data, e.g. to distinguish between bedrock vs saturated sediments (Dow et al. 2013). Furthermore, refraction seismic can be used to estimate seismic velocities with high precision. Because of seasonal changes in the permafrost active layer, near-surface seismic velocities are changing significantly. Laboratory measurements show (Draebing and Krautblatter 2012) that not only the sediment's but also the low-porosity rock's P-wave velocity increases due to freezing. Such a change can be clearly observed with time-lapse seismic tomography (Hilbich 2010), as water-filled porous rock P-wave velocity will double. This change of near-surface velocities can significantly influence seismological recordings (amplitudes, incidence angles). Moreover, active seismic will result in a 2D or even 3D velocity model of bedrock that is important for precise seismic event localization. To provide such velocity models in areas where active seismic is not permitted or logistically difficult, passive seismology can again come in handy, employing above mentioned ambient noise recordings and seismic interferometry.

State-of-the-art seismological methods and new technologies are expected to further advance cryoseismological research. Automatization of seismic signal detection and classification is mandatory in modern seismology for analyzing the enormous volumes of data obtained from long-term monitoring. Seismic arrays (Schweitzer et al. 2012), which are setups of closely-spaced sensors, allow detection, classification, and location of weak seismic signals and tremors. Detection and classification of various seismic events are nowadays also often performed with machine learning algorithms, which is a rapidly developing field in seismology (Kong et al. 2018; Bergen et al. 2019). Furthermore, developments in seismic measurements using fiber-optic cables (Distributed Acoustic Sensing, DAS) enable time-lapse data acquisition with unprecedented sensor density and spatial sampling down to the meter scale (Jousset et al. 2018, Ajo-Franklin et al. 2019). Such fine sampling, in combination with long fiber length above 10 km, allows for unprecedented resolution on a local scale. Furthermore, DAS systems measure strain (or strain rate), and very-low frequency analysis allows to monitor deformation in sections along the fiber (Jin and Roy 2017), which may be used to measure glacial deformation with high resolution.

2.2 Seismological infrastructure in Svalbard

Seismological monitoring in Svalbard has a long history with the first temporary station being installed in 1911 in Longyearbyen. Subsequently, several analog seismometers were in operation at Kapp Linne (Isfjord Radio, 1958-1963), in Ny-Ålesund (since 1967), Hornsund (since 1978), Barentsburg (since 1979), and Pyramiden (1982-1989). Furthermore, several temporary seismic deployments for tectonic studies were made between 1976 and 1986 in southern Spitsbergen and in 1982 as well as 1986 on Phippsøya, north of Nordaustlandet.

The current network of permanent (digital) seismometers in Svalbard is the backbone of cryoseismological research in the region (Figure 1). It has been continuously extended and upgraded during the past decades, especially during and after the Fourth International Polar Year (2007-2008). For temporary networks deployed for dedicated studies, we refer to Chapter 2.3. Several seismic broadband stations form a sparse seismic network on Spitsbergen with an average interstation distance of about 100 km (Figure 1, Table 1). The small-aperture Spitsbergen seismic array (SPITS) East of Longyearbyen in Adventdalen has an aperture of about 1 km and presently consists of 9 CMG-3T seismometers. It has been operated by NORSAR since 1992 and was upgraded with three-component broadband stations in 2004. Furthermore, single three-component stations are currently in operation. The Kings Bay seismic station (KBS, STS-2 seismometer) in Ny-Ålesund

Table 1: Permanent seismic stations on Spitsbergen. Access to the Norwegian EIDA node being under construction via http://eida.geo.uib.no/.

Name	Location	Network ID	Operators	Comment	Recording since	Sampling rate	Data access
KBS	Ny-Ålesund	IU/GE	AWI, UiB, GSN, GEOFON	Single, three-component	1994	40 Hz; 100 Hz since 2019	IRIS-DMC
HSPB	Hornsund	PL	IG PAS, NORSAR	Single, three-component	09/2007	100 Hz	IRIS-DMC / EIDA-GFZ
BRBA	Barentsburg	NO	KS GS RAS, NORSAR	Single, three-component	2010	80 Hz	EIDA
BRBB	North of Barentsburg	NO	KB GS RAS, NORSAR	Single, three-component	2012	80 Hz	EIDA 2012 only
SPITS	Jansson-haugen, Advent-dalen	NO	NORSAR	Array of 9 stations, since 2004 6 three-component	1992	40 Hz until 2004; 80 Hz since 2004	EIDA

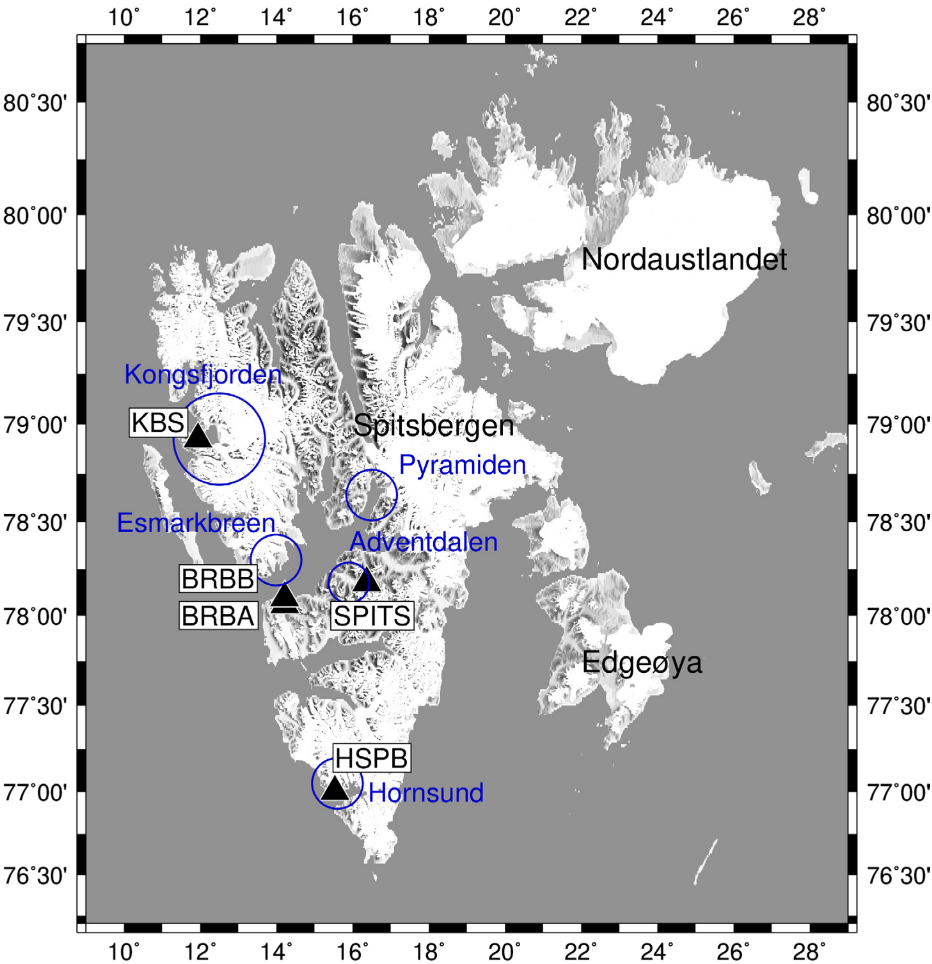


Figure 1: Map of Svalbard showing locations of permanent seismic stations (black triangles, listed in Table 1) and temporary seismic deployments (blue circles, listed in Table 2).

has been in operation as a broadband station of the Global Seismic Network (GSN) and GeoForschungsNetz (GEOFON) seismic network since 1994. After earlier deployments of short-period sensors, for example in 1995 (Górski 2014), an STS-2 broadband seismometer was installed at the Polish research station in Hornsund (HSPB, Figure 2c) in September 2007 by the Institute of Geophysics Polish Academy of Sciences (IGF PAS) and NORSAR (Wilde-Piórko et al. 2009). Since 2010, the Kola Science Centre of the Russian Academy of Sciences has operated a broadband seismometer in Barentsburg (BRBA) in cooperation with NORSAR, and a second seismometer station (BRBB) operated by both partners has

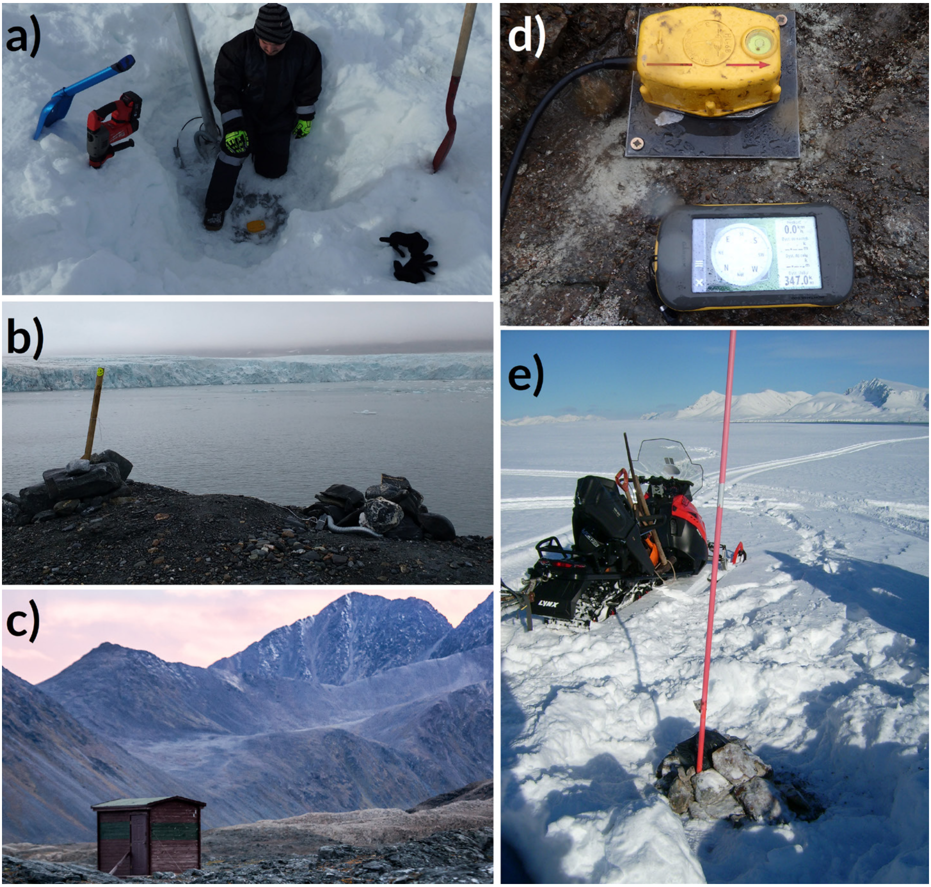


Figure 2: Examples of field installations of seismological equipment. a) on-ice geophone installation in a snow pit (Hansbreen); b) geophone installed like in d), covered with rocks (wind protection) next to the digitizer and power supply. Hansbreen calving front in the background; c) permanent seismological station HSPB next to Polish Polar Station; d) 3-component 4.5 Hz geophone on the metal pad screwed to the rock; e) completed geophone installation deployed on frozen soil close to Ny-Ålesund covered with stones. Photos by courtesy of Wojciech Gajek (a,b,d), Joanna Perchaluk (c), Andreas Köhler (e).

been deployed 4 km north of BRBA in 2012, co-located with a three-site infrasound array. Seismometers are recording with sampling rates of 40 Hz (KBS, SPITS prior to August 2004), 100 Hz (HSPB) and 80 Hz (SPITS after August 2004, BRBA/B). Except for some data gaps during the upgrading and maintenance of seismometers, all stations have been recording continuously since their dates of installation, and data are transferred for analysis to the hosting institutions in near-real-time.

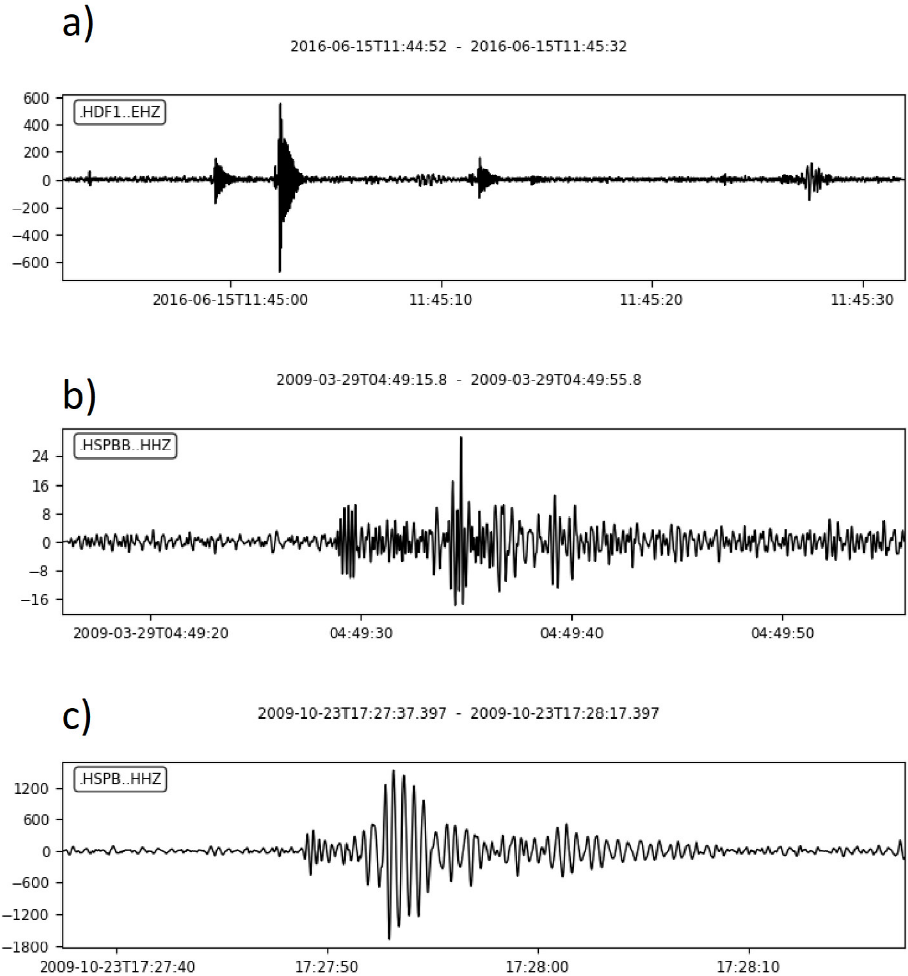
Seismic broadband stations are also located on the island of Hopen since 2007 and Bjørnøya since 1996, both operated by the University of Bergen (UiB). Most recently, on August 2019, NORSAR installed a small aperture seismic array on Bjørnøya. However, due to their distance to glaciated areas, the stations on both islands have not been used for glacier seismological studies, while potential application for permafrost research and monitoring calving at Edgeøya exists. The array deployed on Bjørnøya has been funded through the RCN financed EPOS-Norway infrastructure project, which supplements the European EPOS (European Plate Observing System) infrastructure. More single stations along the coasts of Svalbard and a small aperture seismic array deployment near Hornsund are anticipated using instruments available through EPOS-Norway in 2020.

Seismicity in the Svalbard region is monitored routinely through the automatic processing of SPITS array data by NORSAR (Schweitzer et al. 2012). Due to the high amount of data, only larger events are manually reviewed and re-located by NORSAR analysts, employing also the other seismic stations in the region. However, since the automatic procedure was specifically designed to detect and locate tectonic earthquakes and artificial explosions, the preliminary assigned locations for weak seismic events of a different origin (e.g. icequakes) in the event catalogue can be spurious or biased and give only a rough overview about the spatial-temporal distribution of glacier events.

2.3 Cryoseismological studies in Svalbard

For our review of past cryoseismological studies in Svalbard we distinguish between local studies using mostly temporary sensor deployments, for example, dedicated to monitor calving, icequakes, or tremors at a single glacier, and regional studies utilizing mainly the permanent seismometer network with a focus on detecting and mapping regional glacier seismicity generated by calving and surging. Figure 2 shows field photos of both temporary and permanent installations, while Figure 3 shows examples of cryoseismological signals recorded by such instruments. However, it should be noted that there is an overlap between both approaches, as stations of the permanent network are also used to study local seismicity and sub-surface structures, and temporary stations are used to calibrate, i.e., to constrain the source, of regional seismic event observations. Note also that for logistical reasons and limited station coverage, all local studies as well as regional monitoring efforts so far focused on the main island Spitsbergen.

The first local studies in Svalbard have been carried out at Hornsund by Polish researchers from IG PAS starting already in the ‘60s, particularly focusing on glacier seismicity at Hansbreen. Lewandowska and Teisseyre (1964), Górski (1975), and Czajkowski (1977) investigated ice microtremors and icequakes and their relation to glacier dynamics. This work was continued by IG PAS in the ‘80s and ’90 with a focus on the properties of seismic signals generated by crevassing and glacier motion (Cichowicz 1983; Górski and Teisseyre 1991; Górski 1997, 1999, 2003, 2004). Górski (2014) provides a summary of all findings from past seismic experiments that took place in Hornsund. Recently, IG PAS deployed a new temporary seismic network at Hansbreen (2017-2018) to follow up on previous works and to continue with the long tradition of cryoseismological research in Hornsund (Table 2). The new experiment consisted of two mini-arrays located on both sides of the Hansbreen calving front supplemented by two on-ice stations and was aimed at monitoring seismic activity at the calving front from autumn to spring and calibrating detections of cryogenic events at the nearby HSPB station. The calving front area is also a natural polygon for applying advanced passive seismic processing techniques like the double beamforming technique (Nakata et al. 2016), which allows to identify and separate the



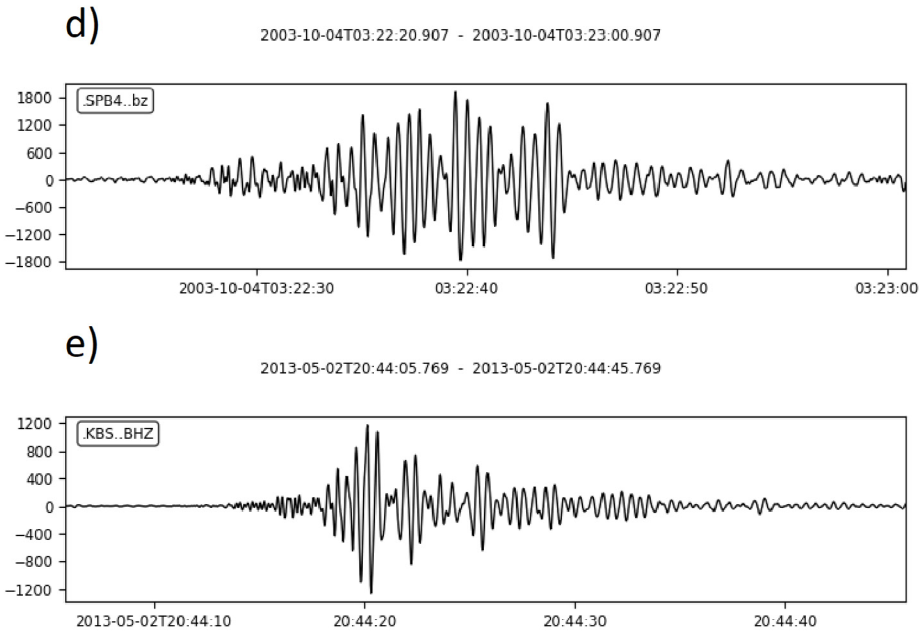


Figure 3: Examples of seismic signals detected on a temporary installation on Holtedalfonna (HDF1) and permanent stations in Svalbard. a) local icequakes, b) a signal of the Nathorstbreen surge, c) calving events at Hansbreen, d) Tunabreen, and e) Kronebreen (Köhler et al. 2015).

specific waves travelling between arrays of sensors and may be used to extract the seismic waves generated, e.g. by calving. Aside from passive seismic studies at Hornsund, also hydroacoustic monitoring of calving at Hansbreen using a single hydrophone temporarily deployed in the fjord has been carried out which allowed distinguishing different types of calving signals (Glowacki et al. 2015).

Another early study has been carried out at Bakaninbreen (SE Spitsbergen) during its surge in 1987 by British researchers presenting for the first time evidence for local seismic emission of a glacier surge in Svalbard (Stuart et al. 2005). Different types of icequakes have been identified on a temporary seismometer network that helped to better understand the progressing of the surge front.

In 2009 and 2010, researchers of the University of Oslo deployed a single-channel geophone at Kronebreen (Kongsfjord, NW Spitsbergen) to record seismic signals generated by calving (Köhler et al. 2012). This pilot study initiates a series of research projects (SEISMOGLAC, NFR grant no. 213359/F20; CalvingSEIS, NFR grant no. 244196/E10)

Table 2: Recent temporary seismic deployments in Svalbard.

Location	Operator	Time period	No. of sensors	Project / Purpose / Comments	Data access, DOIs
Adventdalen	NORSAR	05/2014-09/2014	12	SafeCO2 / SEISVAL	EIDA RESIF, 10.15778/ RESIF.Y22014
Kronebreen, Kongsfjorden	UiO, Uni Kiel	05/2013-09/2013	20	SEISMOGLAC	GIPP GFZ, 10.5880/ GIPP.201303.1 10.2312/ GFZ.b103-17094
Ny Ålesund / Kronebreen / Holtadalfonna	UiO	04/2016-09/2016	24	CalvingSEIS	GIPP GFZ, 10.5880/ GIPP.201604.1 10.2312/ GFZ.b103-19038
Hansbreen	IG PAS	10/2017-04/2018	11	3-seasons long calving front obs.	Unprocessed dataset, to be available from 1.5.2020, 10.5281/ zenodo.3377402
Kongsbreen	UiO, Uni Kiel	04/2018-01/2019	5	Surge and lake drainage obs.	Unprocessed dataset, not openly available yet
Pyramiden / Norden-skiöldbreen	KB GS RAS	2015-??	1	seismic station + infrasound array	unknown
Esmarkbreen	KB GS RAS	06/2012-09/2012	1	Single, three-component	unknown

including local temporary seismic deployments in the Kongsfjord area in 2013 (Kronebreen), 2016 (Kronebreen, Holtedalfonna, and Ny-Ålesund; included hydrophone measurements in Kongsfjord), and 2018/2019 (Kongsvegen) (Figure 1, Table 2) which were carried out in collaboration between the Universities of Oslo and Kiel. These datasets were used to constrain the origin and type of regional glacier seismicity (Köhler et al. 2015), to calibrate and develop methods for seismic quantification of frontal ablation and calving ice loss at Kronebreen (Köhler et al. 2016, 2019b), and to study the sources and seasonal distribution of icequakes and tremors at Holtedalfonna (Köhler et al. 2019a). Outcomes of the CalvingSEIS project were a continuous time series of ice loss at Kronebreen obtained with two different approaches. Seismic calving signals detected at the close station KBS (~15 km from glacier terminus) were calibrated with satellite remote sensing observations of frontal ablation to produce weekly ablation rate estimates between 2001 and 2015 (Köhler et al. 2016). The second method provides ice volumes for individually-observed calving events using calving signals at KBS and was calibrated with LIDAR volume measurements and time-lapse camera images at Kronebreen (Köhler et al. 2019b). While most seismic deployments of UiO were arranged in small-scaled arrays on solid ground, a single on-ice station was installed in a shallow borehole on Holtedalfonna in 2016. This record revealed a complex distribution of icequakes with remarkable correlation with glacier velocity, clear relation to glacier runoff, and evidence for seismic sources at the base of the glacier (Köhler et al. 2019a).

The Kola Branch of the Geophysical Service of the Russian Academy of Sciences (KB

GS RAS) in Apatity, Russia, conducted several studies combining seismic and infrasonic measurement of signals of glacial origin. The seismic station BRBB in Barentsburg was complemented by an infrasound station and a temporary station at the northern bank of Isfjorden which allowed detecting and locating glacier seismic events from Esmarkbreen and Nansenbreen (Asming et al. 2013; Vinogradov et al. 2015). Recently, KB GS RAS has started operating a seismic-infrasound station in Pyramiden with a special focus on monitoring signals originating from Nordenskiölbreen (Vinogradov et al. 2016).

Several studies were carried out focusing on regionally-observed glacier seismicity. Köhler et al. (2015) for the first time systematically detected and located cryogenic seismic signals on Spitsbergen. Clusters of seismic events were identified at several tidewater glaciers which showed a clear seasonal variability and were found to be mainly caused by calving. Based on these findings, regional calving event observations at KBS and SPITS were used to estimate frontal ablation rates at Kronebreen (Köhler et al. 2016). Furthermore, exceptional temporal patterns related to surges were observed for two glaciers (Köhler et al. 2015). Increasing seismic activity at Tunabreen in central Spitsbergen was a result of higher calving activity after the surge in 2003. The initial phase of the recent surge of Nathorstbreen in winter 2009 went along with icequake emissions related to ice failure when the change in back-stress up-glacier led to a sudden increase in basal shear stress and started a dynamic instability (Nuth et al. 2019). Analysis of the seismicity helped to constrain the timing of that process.

Different automatic techniques have been suggested to detect and map regional glacier seismicity in Svalbard using long-term seismological observations. While Köhler et al. (2015, 2016) used a combination of single station STA/LTA triggers (KBS, HSPB), waveform polarization, and array analysis (SPITS), Asming and Fedorov (2015) developed a three-component station detector and locator (HSPB) based on a STA-LTA trigger, P-S phase association, and joint polarization analysis. Gajek et al. (2017) also employed single station detection motivated by the presence of weak seismic events that are difficult to record due to the sparse seismological network in Svalbard. They developed an automatic procedure to distinguish between glacial and non-glacial signals using a fuzzy logic algorithm based on the signal frequency and energy flow analysis. The method was applied to HSPB and KBS to study glacier seismicity providing multi-annual catalogs of monthly-binned cryogenic events for Hornsund and Kongsfjorden regions.

A common finding of all long-term cryoseismological studies (Köhler et al. 2015, 2016; Gajek et al. 2017) is an increase in glacier-related seismicity mainly due to calving activity in recent years (Figure 4), for example a doubling of the number of seismic events in the Hornsund area over the years 2013-2014 (Gajek et al. 2017). Furthermore, those studies showed that the seasonal event distribution shows a time lag of about one month with respect to air temperatures, which suggests a relation between calving activity and fjord-water temperatures. The increase in the number of calving events in the Kongsfjorden

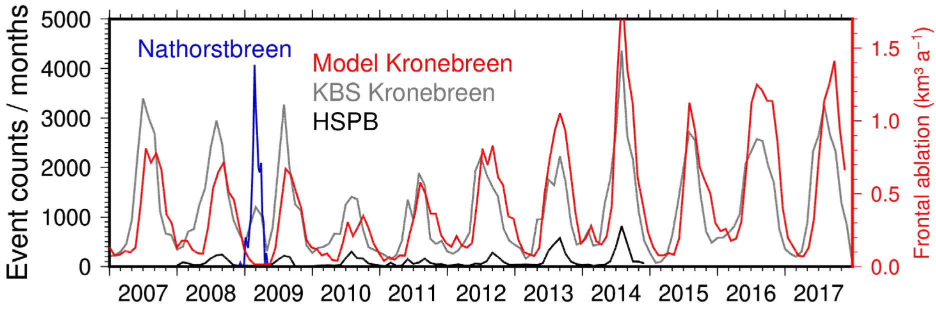


Figure 4: Example of the temporal distribution of cryoseismicity in Svalbard. Detections were made at KBS (Köhler et al. 2019b) and HSPB (Gajek et al. 2017) and include dominantly calving events (in summer/fall), except for surge signals originating from Nathorstbreen in 2009 (blue). An empirical model calibrated with satellite remote sensing observations of frontal ablation is used to estimate ice loss at Kronebreen from seismic data (red).

area since 2013 (Köhler et al. 2016, 2019b) is mainly related to the dramatic retreat of Kronebreen.

Pioneering research focusing on sub-surface structures in the cryosphere using ambient seismic noise has been conducted in the Kongsfjord region within the framework of the CalvingSEIS project and at the Hornsund research station. The potential of the single station HVSR method for monitoring seasonal permafrost active layer variability was explored in Hornsund (Kula et al. 2018) and Ny-Ålesund (Köhler et al. 2019c) with promising results. The HVSR technique will require further studies for calibrating measurements to permafrost parameters and for optimization of the best-suitable seismic network. The method has also been used to infer the (1D) internal seismic velocity structure of Holtedalfonna which allowed modeling of synthetic icequake signals (Köhler et al. 2019a). Results of seismic noise interferometry for active permafrost layer studies (James et al. 2017, 2019) are not yet available in Svalbard. However, a temporary seismic network was deployed in Adventdalen by NORSAR together with French colleagues in 2014 for monitoring a CO2 storage experiment (SafeCO2 project). The goal was to detect microseismicity and to use seismic noise interferometry to investigate the potential of measuring changes in the sub-surface as a result of the CO2 injection. Data are freely available and can be reused in future studies focusing on permafrost for example (Table 2).

Apart from the passive methods, active seismic methods have been successfully used to study the permafrost structure and properties in Svalbard. Rossi et al. (2018) performed a comprehensive test of active seismic methods over a pingo system in Adventdalen. In 2017-18 two active seismic measurements were performed by IG PAS at Hornsund. Initial results (Marciniak et al. 2019ab) show the successful application of active seismic methods

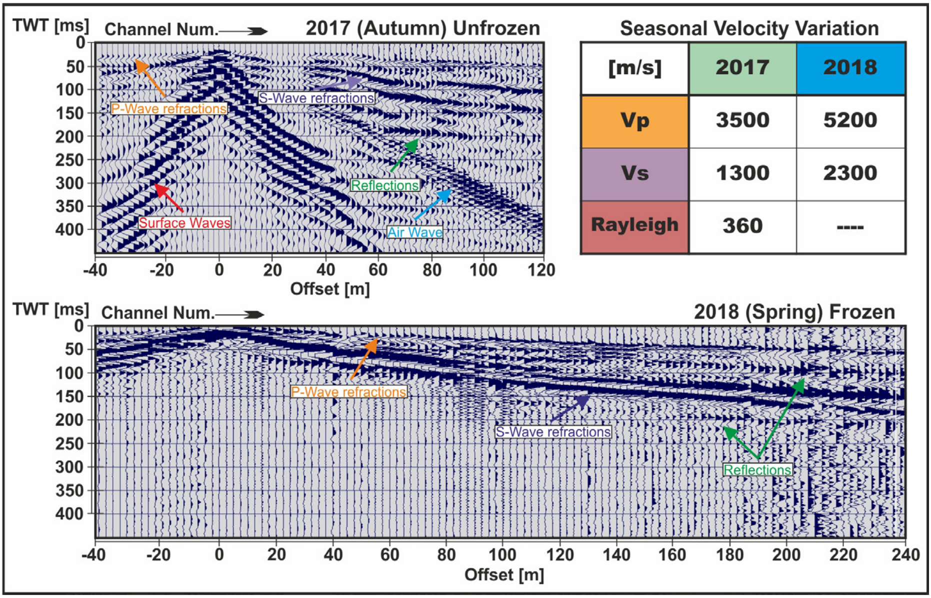


Figure 5: Active seismic wavefield recorded in Hornsund during two seasons: unfrozen (Autumn 2017) and frozen (Spring 2018). Note the significant change in apparent velocities and recorded wavefield due to freezing of the permafrost active layer (Marciniak et al. 2019b).

in the form of surface wave analysis (MASW) for near-surface S-wave velocity structure, refraction seismic tomography for time-lapse P-wave velocity variations (Figure 5), and reflection seismic imaging for geological structures and continuity of permafrost. Those seismic results have been combined with shallow borehole temperature profiles, GPR and ERT images showing clear compatibility.

3. Unanswered questions

3.1 Regional spatial-temporal distribution of glacier seismicity

What is the event distribution beyond the already monitored areas and how can we improve locations of detected events?

There is relatively good knowledge about glacier seismic sources in the Kongsfjord region, Hornsund area, and parts of central Spitsbergen where dedicated studies have been carried out in recent years thanks to the vicinity to permanent seismic stations and other research infrastructure, and the availability of direct observations of glacier dynamic processes (see section 2.3). However, due to lacking station coverage, the spatial-temporal distribution of regional glacier seismicity is still unresolved for large parts of Svalbard, especially in the East of Spitsbergen and the other islands of the archipelago. Of special interest are the tidewater glaciers along the East coast of Spitsbergen and the ice caps of Nordaustlandet, where for example surges have occurred recently and are expected to happen in the future. Using the existing network for mapping sources of glacier seismicity is challenging since larger distances reduce the sensitivity to detect weak seismic signals, i.e., they affect the achievable completeness of event observations. Furthermore, the spatial resolution for discriminating between individual glaciers and tectonic earthquakes suffers from insufficient station coverage. While the ability to use the existing seismic network to study the East of Svalbard is limited, there is still some potential to identify strong events originating from glaciers or ice caps in that region. This has to be further assessed in dedicated studies using, for example, direct and independent observations of strong glacier dynamic events such as glacier surges or large iceberg calving, obtained from satellite remote sensing data. In addition to the seismic network limitation, seismic event locations are biased by unknown structural features in the Earth's crust affecting seismic wave propagation. To obtain reliable location estimates for glacier seismicity, structural investigations on the upper crust are needed by e.g. applying standard seismological methods.

How can we use glacier seismicity to monitor calving and surging?

It is known from previous studies that regional glacier seismicity in Svalbard is dominated by calving (see section 2.3). Calving monitoring with the high temporal resolution is essential but often lacking in glaciological research to better understand the mass loss of glaciers. Furthermore, since glacier seismicity has also shown to be suitable for observing glacier surges in Svalbard, more studies are required to evaluate how efficient this method is for detecting and monitoring future surges in near real-time. For example, it is not yet well-understood which (size) and how surges (mechanisms) generate regionally observable seismicity. It would be also essential for early warning purposes (e.g. for quickly restricting access to active glaciers) to automatize surge detection in seismic records and to define a detection threshold.

How can we produce continuous long-term cryogenic seismic event bulletins?

While dedicated studies have produced catalogues of glacier seismic events for past time periods in particular regions in Svalbard using the entire station network (see section 2.3), there is currently no automatic, real-time system for specifically detecting regional and local glacier seismicity in operation, mainly because those projects had time-limited funding and were not conducted at institutions with a long-term monitoring mandate and suitable infrastructure. Research programs and infrastructures are needed to implement and guarantee continuous, long-term monitoring of glacier seismicity in Svalbard and to produce glacier seismic event bulletins/catalogs usable for glaciological research. These efforts would be based on the outcomes of the already completed projects and would benefit very much from an extension of the current permanent seismic network as well as the deployment of more temporary networks to identify dominant sources of seismicity.

3.2 Seismic observations vs. source and sub-surface parameters

How can observations be transferred into information useful in interdisciplinarity studies?

Detection, classification, and location of glacier seismic signals, as well as measuring seismic velocity variations with ambient noise, can help to identify trends and relative changes in the seasonality of glacier activity and subsurface properties. While this information is already very valuable for glaciological and permafrost research due to its high temporal resolution and the continuous long-term record, actual quantification methods based on seismic measurements are still lacking for many processes. Seismic observables such as event counts, signal properties, seismic velocity changes have to be transferred into physical, glaciological and permafrost-related parameters or quantities. This can be achieved either by developing empirical or physicals models.

How can quantifying dynamic ice loss from seismic observations be extended and improved?

Calibration using satellite and terrestrial remote sensing has already been used for quantifying frontal ablation and the contribution of calving at Kronebreen directly from seismic data, but the empirical models developed are only valid for this particular glacier. Long-term, continuous, and high-temporal resolution records (frontal ablation, dynamic ice loss, sub-marine melting) are not yet available for many glaciers but are necessary to better understand fine-scale processes and key climatic-dynamic feedbacks between calving, climate, terminus evolution, and marine conditions. Field measurements of seismic calving signals simultaneously with the corresponding ice loss volumes at multiple tidewater glaciers in Svalbard are lacking but needed to develop a more general quantification method. Furthermore, there is currently no seismic source model available to simulate seismic signals for the dominant calving style in Svalbard. Developing a physical model would, therefore, offer an alternative to using empirical models for ice loss quantification.

How can seismic observations be used to better understand mechanisms and processes inside or at the base of glaciers?

Icequake signals and tremors can be analyzed using standards seismological methods to for example infer source mechanisms to study not yet well-understood sub-glacier processes such as stick-slip and basal sliding (friction laws). This approach provides high temporal resolution and hence insight that cannot be achieved by other techniques (GNSS, remote sensing). Such methods have been successfully applied for example in Antarctica and on Alpine glaciers, however, not yet in Svalbard due to the lack of suitable (temporary) on-ice seismic networks with good spatial coverage deployed in dedicated field campaigns. Similar, for quantifying discharge using observations of seismic meltwater tremors, methods previously applied on Greenland and Alaska should be adapted. To better understand source processes of seismic signals, integrated approaches are required on glaciers combining passive seismic measurements with e.g. borehole measurements (drill cores, downhole pressure, temperature, and deformation sensors, etc.), in-situ GNSS tracking of glacier flow, remote sensing, and other (active) geophysical methods.

How can seismology contribute to improving permafrost monitoring?

Ground temperature measurements in boreholes close to most research stations/ settlements in Svalbard are commonly used to monitor the effects of climate change on permafrost (Christiansen et al. 2019). They offer sufficient temporal resolution (hourly sampling) but the spatial coverage of these points measurements is naturally limited. In addition, regular (manual) probing of the permafrost active layer thickness on spatial grids is performed (CALM sites) but is only possible in fine-grained soils. Simultaneous seismic measurements at these sites are lacking but are key for developing passive methods for permafrost monitoring applicable in arbitrary areas. One important variable to observe with a wider spatial extent is, for example, the timing of the active-layer freeze-back in autumn since later re-freezing in the season promotes permafrost degeneration (Christiansen et al. 2019). This is of particular significance in the lowlands of Svalbard where the degradation can result in subsidence, landslides, and will affect the local ecosystems and hydrology. In particular, calibration studies are required to relate seasonal changes and long-term trends in the permafrost to seismic velocity changes measured from ambient seismic noise. Furthermore, since permafrost is a new application of ambient noise-based methods, a best-practice for these experiments has not been established yet. In contrast to the HVSR methods, ambient noise interferometry for permafrost monitoring as done in Alaska has not yet been performed in Svalbard.

3.3 Best practice in the field and potential of new technologies

What is the best practice for temporary seismic deployments in Svalbard?

Deployment and maintenance of passive seismic networks in the Arctic environment are challenging due to harsh weather conditions, polar night, and remote locations (Figure 2). There are issues related to the continuous, real-time transfer of large data volumes (lacking mobile network), power supply during winter (limited battery capacity, no solar cells) and instrument coupling to the ground during melt season. Regular maintenance is not always feasible due to remote installations or inaccessibility during certain seasons of the year. Experiences gained during recent field measurements have to be compiled in guidelines and recommendations for future seismic experiments in glacier and permafrost studies. This includes finding and evaluating cost-effective and robust solutions for on-ice and in-ice borehole seismic installations. Borehole instrumentations add the vertical dimension to seismic networks, enhancing the information content of seismological data and providing better insight into the analysis of basal seismicity. However, deployment (drilling, placement) and operation are challenging in moving and deforming ice compared to common seismic borehole installations.

Especially for permafrost monitoring, finding suitable solutions for stable sensor installation during thawed conditions is critical. Questions that have to be addressed in test studies are where the instruments are best placed (surface, within permafrost, borehole), how to keep the sensors from tilting and losing coupling, and what kind of sensors should be used.

Can new technologies improve cryo-seismological measurements?

Advanced and new technologies have to be tested in the field such as DAS recording systems. Also, on-ice seismic arrays can be deployed for detecting and locating weak icequakes and tremors and observing crevassing and its correlation with ice flow, as already exploited in the Alps (e.g. Lindner et al. 2019) and Antarctica (e.g. Smith et al. 2017), but not yet in Svalbard. It is important to determine the common standard and best practices of instrument deployment and optimal layouts of seismic network and array for different applications and purposes in Svalbard (icequake detection, location, structural imaging, noise interferometry, etc.).

Which methods should be combined in the field?

Integrated approaches are essential to advance cryoseismological research (see section 3.2). Different methods complement each other; for example, while active methods have a higher depth resolution (e.g. to measure the thickness of permafrost, the active layer, or glaciers), passive methods allow time-lapse monitoring with high resolution and borehole measurements guarantee high precision but sample a very limited area. Integrated approaches proved to be effective in, e.g. Alpine applications (Gräff et al. 2019), however, the potential of combining passive seismic measurements with active or borehole geophysical measurements is still to be explored in Svalbard.

4. Recommendations for the future

Based on previous cryoseismological studies carried out in Svalbard and in view of the existing knowledge gaps, we provide the following recommendations for related future research and for improving as well as better exploiting the existing research infrastructure. They are also aligned with the previous and current priorities stated in the SESS reports (Christiansen et al. 2019, Schuler et al. 2020):

1. The permanent seismic station network in Svalbard should be extended with long-term deployments to improve detectability and location of glacier seismicity, especially along the east coast of Spitsbergen and in Nordaustlandet. This can be accomplished by deploying single-stations at existing meteorological observation sites or other SIOS monitoring infrastructure, for instance at the depot at Oxford peninsula, in close vicinity to Austfonna and Vestfonna with ongoing glacier monitoring and occurrence of several surges. We also recommend upgrading current single stations to seismic arrays, for example in Hornsund and Ny-Ålesund, where the necessary infrastructure (power supply, internet connection, whole year maintenance possibilities) is already available without additional environmental impact, and which would result in a considerably improved detection capability in combination with the existing SPITS array.

2. Existing and routinely recorded seismic data volumes should be used to extend regional seismic glacier monitoring to so far unstudied regions and unconsidered time periods by implementing a continuous automatic near-real-time event detection system. This system should be based on template events from locally identified sources (calving events, surges, etc.), may adopt machine-learning and advanced seismic array methods to distinguish for example between tectonic and glacier seismicity, and should deliver a sharable, routinely updated bulletin of glacier seismic events in Svalbard findable in the SIOS data access point which allows extracting information about variability of activity (trends and seasonality) in a form usable also for non-seismologists. This effort will benefit from making available legacy seismic datasets.

3. To improve the location of glacier seismicity, structural investigation on crustal scales should be performed which will benefit from network extensions (see point 2) and temporal seismic deployments for structural and/or cryoseismological studies.

4. Multi-disciplinary, integrated field campaigns should be carried out combining passive and active seismic and other geophysical methods with direct observations of cryosphere processes such as calving, meltwater discharge, sub-glacier dynamics, and permafrost thaw depths. These experiments are mandatory to infer physical

cryospheric parameters and quantities from seismic measurements as well as to develop seismic source models. In particular, we recommend to (i) extend the calving quantification method developed for Kronebreen to other tidewater glaciers, (ii) to deploy temporary, purpose-built seismic networks close to existing and to-be-established permafrost observation sites (e.g. Ny-Ålesund, Adventdalen, Barentsburg, Hornsund, Kapp Linné) to calibrate seismic methods, e.g. to monitor the freeze-back in areas not being represented by the existing sites (Christiansen et al. 2019), and (iii) to combine on-ice seismic networks with glacier in-situ measurements to study subglacial drainage and basal processes. These efforts would benefit from establishing a multidisciplinary instrument pool (including seismometers, drilling equipment, borehole sensors, GNSS, etc.) that can also be used for urgent deployments (e.g. an ongoing glacier surge) (Schuler et al. 2020).

5. New technologies and methods have been successfully applied in seismology in recent years such as fiber-optic cables (DAS), seismic noise interferometry, and machine learning. These approaches should be used in Svalbard for cryoseismological research. DAS measurements on glaciers will not only allow analyzing seismicity with high spatial resolution but also inferring slow, aseismic glacier deformation. Noise interferometry has a huge potential for monitoring changes in the permafrost active layer. Machine learning can assist in analyzing large seismic data volumes.

5. Data availability

Table 1 lists information about all permanent seismic broadband stations in Svalbard. There is unrestricted data access to all raw seismic records. All metadata including links to landing sites can be found in the SIOS data access point (referenced there as “seismological station records“). While these datasets might currently be mainly useful for seismologists, we recommend in this report to produce data products useful for cryosphere research in general. We anticipate that the outcomes of future studies will be integrated into the SIOS data access point.

Continuous seismic waveform data are available through different data centres. The most common access is through ORFEUS EIDA nodes (Datacentres of the European Integrated Data Archive, https://www.orfeus-eu.org/data/eida/nodes). Data can be accessed via web-interfaces (ORFEUS or data centres of individual nodes, e.g. GFZ, GEOFON) or different application programming interfaces (e.g. ObsPy). In Table 1, “EIDA” refers to the common Norwegian EIDA node hosted at the University of Bergen, while “IRIS-DMC” means that data are available through the IRIS (Incorporated Research Institutions for Seismology) data centre. The Norwegian EIDA node is under construction within the EPOS-Norway project. Note, that not all seismic datasets have DOIs yet, but European efforts are underway to complete the missing identifiers (see https://www.orfeus-eu.org/data/eida/networks). In Svalbard, only KBS has a registered DOI (https://doi.org/10.7914/SN/IU) today.

Table 2 gives an overview of recent seismic datasets recorded during temporary measurements in Svalbard. Data access status is either open, free on request, or not (yet) available.

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