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Glacial Earthquakes in Disko Bay, Greenland

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Abstract

The occurrence of earthquakes at outlet glaciers in Greenland has been contributed to massive ice calving events. This was a discovery made in 2003, when researchers realized that glacial earthquakes did not fit into global earthquake catalogues. The origin, characteristics and source mechanism of glacial earthquakes have been found to be radically different from tectonic earthquakes, explaining why this type of non-tectonic seismicity is of great scientific interest.

This thesis investigates local-scale earthquakes at Ilulissat Isbræ (2016-2018) in order to characterize them and perform a comparative analysis of global and local glacial earthquakes, focusing on key characteristics such as location, magnitude, depth etc. The purpose of this is to improve the understanding of glacial earthquakes and how they differentiate from tectonic earthquakes. A total of 67 seismic events have been analyzed, resulting in 33 glacial- and 34 tectonic earthquakes. Some earthquakes show classic traits of being either glacial or tectonic, while others are ambiguous.

Of all investigated parameters, hypocenter depth (an average glacial hypocenter depth of ∼11.5 km and ∼22.2 km for tectonic) and low-frequency content, 0.01-0.03 Hz, were found to be the most significant when trying to distinguish between glacial and tectonic earthquakes. The characteristic tight clustering of glacial earthquakes close to the glacier is easily recognized in the data. However, it is accompanied by a tendency of southern displacement relative to the glacier.

Seasonality was found to account for both types of earthquakes, in contrast to the literature, which might be explained by misinterpretations of events. Based on calculations, a strong seasonality at Ilulissat Isbræ shows that glacial earthquakes during the summer are ∼9 times more likely than winter glacial earthquakes.

Lastly, it was concluded that there are clear differences between glacial and tectonic earthquakes at Ilulissat Isbræ, which are seen in all investigated parameters, though some parameters, such as frequency and hypocenter depth, showed clearer differences than others.

Keywords: *Earthquake Seismology, glacial earthquakes, geophysics, Disko Bay, Greenland*

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1. Introduction

Seismology is a field of research within geophysics, where seismic wave energy is investigated in order to obtain knowledge about the Earth. As scientists were working towards making a global earthquake catalogue, they discovered that certain seismic events did not fit into the common catalogue. This led to the discovery of a new type of non-tectonic seismicity - specified in 2003 - that is the focus of this thesis (Ekström, Nettles & Abers, 2003). They were termed 'glacial earthquakes' and are characterized by a significant low-frequency component. They are geographically restricted to the edges of ice sheets in arctic regions, specifically marine terminating outlet glaciers (Ekström et al., 2003; Ekström, Nettles & Tsai, 2006; Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012).

Glacial earthquakes are seismic events connected to moving glaciers, the presence of which making Greenland one of the most studied areas in the world for this type of earthquake (Ekström et al., 2006; Meredith Nettles & Ekström, 2010). The majority of previous research on glacial earthquakes has been done by a research group at Columbia University in New York, led by Meredith Nettles and Göran Ekström. They developed a global glacial earthquake catalogue, with the majority of the seismic events occurring in Greenland and Antarctica.

Due to the quite recent discovery of glacial earthquakes, there is still a lot to be learned about them. This thesis seeks to investigate and characterise seismic events that are possibly connected to Ilulissat Isbræ in Disko Bay, Western Greenland. Ilulissat Isbræ is one of the largest and most active outlet glaciers in the world, which is also why it is of certain interest to look at this particular glacier (Ekström et al., 2003; Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012).

The aim of this study is to characterize local seismic data provided by GEUS[1] in light of previous work on glacial earthquakes done by other researchers on a regional and global scale. The data set contains both tectonic and glacial earthquakes that occurred between 2016 and 2018 and, as such an important part of this thesis is the process of locating and distinguishing between the two types of earthquakes. A comparative approach will focus on the key characteristics of glacial earthquakes for multiple parameters, such as geographic epicenter location, hypocenter

[1] Geological Survey of Denmark and Greenland, Øster Voldgade 10, 1350 Copenhagen.

depth and magnitude. Finally, each parameter is discussed in connection with the local scale glacial earthquakes seen at Ilulissat Isbræ.

This thesis will take its starting point with an **Introduction to glacial earthquakes** and their scientific discovery along with some **Background knowledge** of the topic and the area of interest. Hereafter, the **Data** used for analysis, as well as the **Methods** used in this project to obtain the **Results**, will be presented. This will serve as the foundation for the **Discussion**, which includes an in-depth discussion of different aspects of the results. Finally, a **Conclusion** will be drawn, based on the discussion of the results of this thesis.

This thesis is accompanied by several appendices; **Appendix I** includes a table of ambiguous seismic events; **Appendix II** includes general information regarding SEISAN, e.g. analysis commands; **Appendix III** includes a geological map of Greenland; **Appendix IV** includes information regarding the Raspberry Shake Stations; **Appendix V** contains the full data set in a table; **Appendix VI** includes seismograms from a glacial earthquake on July 21st 2018.

1.1 Background knowledge and previous work

Glacial earthquakes were discovered after the detection of seismic events that did not fit into the standard earthquake catalogue. They were quickly noted to only occur at high latitudes with the majority of the collected data being from Greenland, and minor data from Antarctica and Canada (Meredith Nettles & Ekström, 2010). At first, glacial earthquakes were thought to be high-frequency quakes with low magnitudes, $M_W < 3$, however, this has today proven to be the opposite of the actual characteristics.

The majority of the research on glacial earthquakes has been executed by a relatively small group of researchers, who have conducted their research on some of the largest glacial earthquakes globally, and they have found a number of general characteristics. Glacial earthquakes have a general magnitude between M_w 4.6 and 5.2, and are typically 'slow earthquakes' characterized by a long period of > 30 seconds, typically between 30 and 60 seconds (Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012). The duration of the collapse and calving of the ice margin into the formation of icebergs is most often between 30 and 150 s (Meredith Nettles & Ekström, 2010). The long source duration of glacial earthquakes results in depletion of high-frequency energy (Ekström et al., 2003; Meredith Nettles & Ekström, 2010).

Glacial earthquakes show seasonality with the highest frequency of quakes in the late summer and the lowest frequency during the winter months (Ekström et al., 2006). Table 1 summaries the general characteristics that have been found and agreed upon by the majority of researchers. These are the characteristics that will be reviewed in this thesis in connection with local scale earthquakes. For comparison between previous results and the findings of this thesis, it must be kept in mind that the former studies worked with data on a global scale and the work in this thesis is done on a local to regional scale. Therefore, it is likely that other mechanisms and parameters play a part in the behaviour of the data of this thesis compared to that of other studies.

Characteristics of glacial earthquakes	
Long period	> 30 s
Seasonality	Majority in late summer
Source duration	30 – 150 s
Frequency content	Significant low-frequency component
Magnitude, M_w	4.6 to 5.2

Table 1: Table values from the following sources (Amundson et al., 2008; Ekström et al., 2003, 2006; Meredith Nettles & Ekström, 2010; Tsai, Rice, & Fahnestock, 2008; Veitch & Nettles, 2012)

Another important thing to mention is that the magnitude of the earthquakes in the dataset is different than the majority of earlier published studies. The data in this thesis is comprised of smaller glacial earthquakes with magnitudes only measurable locally and regionally. Therefore, the findings of this thesis cannot be compared directly to e.g. results by Meredith Nettles, Göran Ekström, Victor Tsai etc., who focused on glacial earthquakes that can be measured globally. There is definitely some overlap and similarities between a lot of parameters, but they also differ from one another. For instance, there are no final conclusions as to whether the mechanism behind larger and smaller glacial earthquakes is the same.

A major difference is the frequency content that is analysed in this thesis compared to other studies. When e.g. Nettles is analysing global glacial earthquakes, it involves moment magnitude, M_W, from which a broader part of the frequency spectrum is analysed. In this thesis, local magnitude, M_L, which is using only the higher frequencies (than e.g. Nettles et al. 2010) to calculate the magnitude, is used for calculations. Looking at the entire energy spectrum of the glacial earthquakes, and not only the higher frequencies, means that all the energy of the glacial earthquake is used for the magnitude calculation. This affects the final calculated magnitude and can explain why the magnitudes that are found in this thesis are lower than reported in literature.

Another important note is that Nettles' data from Greenland is only available until 2013, which is before the period of interest in this thesis (Olsen & Nettles, 2017; Veitch & Nettles, 2012).

The period of interest in this thesis is based on when the best data was available from GEUS, where 2016 to 2018 was the best possible trade off. Due to this time gap, direct comparison cannot be made to Nettles' results.

1.2 Glacial earthquakes source of origin

Glacial earthquakes are unlike tectonic earthquakes, which are onset by stress release from tension between tectonic plates (Kearey, Klepeis, & Vine, 2009). Instead, glacial earthquakes originate from non-tectonic mechanisms at the calving front of marine terminating outlet glaciers. Outlet glaciers are located along the coasts of Greenland, where inland glaciers terminate, and such outlet glaciers serve as drainage area of ice masses from the interior parts of the Greenland ice sheet. This realization occurred after scientists worked to improve the location method of glacial earthquakes, and noticed that glacial earthquakes clustered closely along the coast and specifically around major outlet glaciers in Greenland (Ekström et al., 2006; Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012).

The mechanism behind glacial earthquakes is still not fully understood, despite several hypotheses proposed through time. It was initially believed that glacial earthquakes were the result of ice masses ($\sim 10 km^3$) sliding downslope over a distance of 1 to 10 meters. The forces acting while accelerating and deaccelerating were thought to cause the transmission of seismic waves into the solid earth (Ekström et al., 2003, 2006; Meredith Nettles & Ekström, 2010). The model explaining these forces is known as the Centroid Single Force model (also known as 'landslide model') by Kawakatsu. It was originally modelled to explain the forces acting on the solid earth during a landslide, taking both mass and sliding distance into account. Due to similarities in e.g. surface waves and frequency content, the model was later thought to apply to glacial earthquakes as well (Kawakatsu, 1989; Meredith Nettles & Ekström, 2010; Tsai & Ekström, 2007).

It was later discovered that this hypothesis was incorrect and that glacial earthquakes are more likely explained as capsizing due to gravitational instability of newly formed icebergs (km^3 scale) at the glacier calving front. This is possible e.g. when icebergs are more narrow in the glacier along-flow direction compared to the height of the iceberg (Joughin et al., 2008; M. Nettles et al., 2008; Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012). Ice loss events or calving events are therefore generally agreed upon to be the seismogenic source of glacial earthquakes, though their exact implication and the mechanism of calving is yet to be fully understood. Therefore, no fully explanatory model of the mechanism behind glacial earthquakes has been agreed upon (Meredith Nettles & Ekström, 2010; Tsai et al., 2008).

An important distinction must be made between the terms '*glacial calving event'* and '*glacial earthquakes*'. These terms are not synonyms, while they do relate to one another. Glacial calving events, or simply calving events, are the physical process leading to the formation of icebergs, due to a glacier/ice sheet becoming unstable and collapsing/calving. This results in the formation of km^3-size icebergs, possibly exerting large forces on the surrounding area.

The number of calving events will always equal or exceed the number of glacial earthquakes, since not all calving events lead to glacial earthquakes. It is therefore important to state that a calving event at Ilulissat Isbræ is not equal to the occurrence of a glacial earthquake. Glacial earthquakes, on the other hand, are occurrences where ground-shaking is measured due to a calving event. Looking at table 1 again, it shows the characteristics of glacial earthquakes and not calving characteristics.

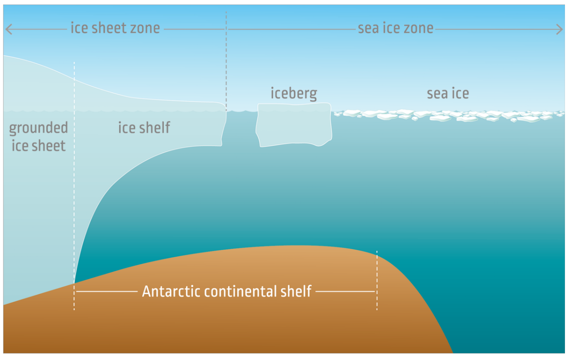


Figure 1: Figure showcases the difference between grounded and non-grounded ice. Grounded ice sheet is physically attached to the basement rock while ice shelves (and ice tongues) are floating with no connection to the basement rock. Borrowed figure from[2].

Scientists proposed a hypothesis regarding the relationship between glacial earthquakes and whether they occur at grounded or non-grounded glaciers. A glacier is grounded when the glacier baseline is close or attached to solid basement rock, whereas a non-grounded glacier is a floating ice shelf with no direct attachment to the basement rock. The hypothesis proposed by Nettles and Ekström (2010), claimed that glacial earthquakes only occur when the glacier calving front is grounded or near grounded (Amundson et al., 2008; Joughin et al., 2008; Meredith Nettles & Ekström, 2010). This hypothesis was further validated by a study in 2012 that looked into 15 different outlet glaciers in Greenland. These outlet glaciers are all known to have large and fairly frequent ice calving events, but all appeared to be 'silent' i.e. produce no glacial earthquakes. This strengthened the hypothesis further, ultimately claiming that the occurrence of glacial earthquakes is only possible when the glacier front/ice margin is within few kilometres of the grounding line and therefore grounded or nearly-grounded (Veitch & Nettles, 2012).

[2] https://theconversation.com/cold-and-calculating-what-the-two-different-types-of-ice-do-to-sea-levels-59996

It must be noted that the above hypothesis is still somewhat speculative, with more research having been executed for larger glacial earthquakes compared to the size of glacial earthquakes examined in this thesis. Glacial calving events as a seismogenic source might, with current knowledge, explain the occurrence of glacial earthquakes, but other theories cannot be disregarded. A study from 1998 found that the Ilulissat Isbræ had a floating ice tongue during the winter, but was grounded in the late summer, explaining the number of earthquakes at certain times during the year (Sohn, Jezek, & Veen, 1998). The ice tongue began a process of ongoing thinning and collapse at the start of the millennium, where the majority of the floating glacier tongue fully disintegrated around 2003. It is hypothesized that the intrusion of warmer ocean waters into Disko Bay contributed to this disintegration (Khan et al., 2010; Khazendar et al., 2019).

1.3 Ilulissat Isbræ

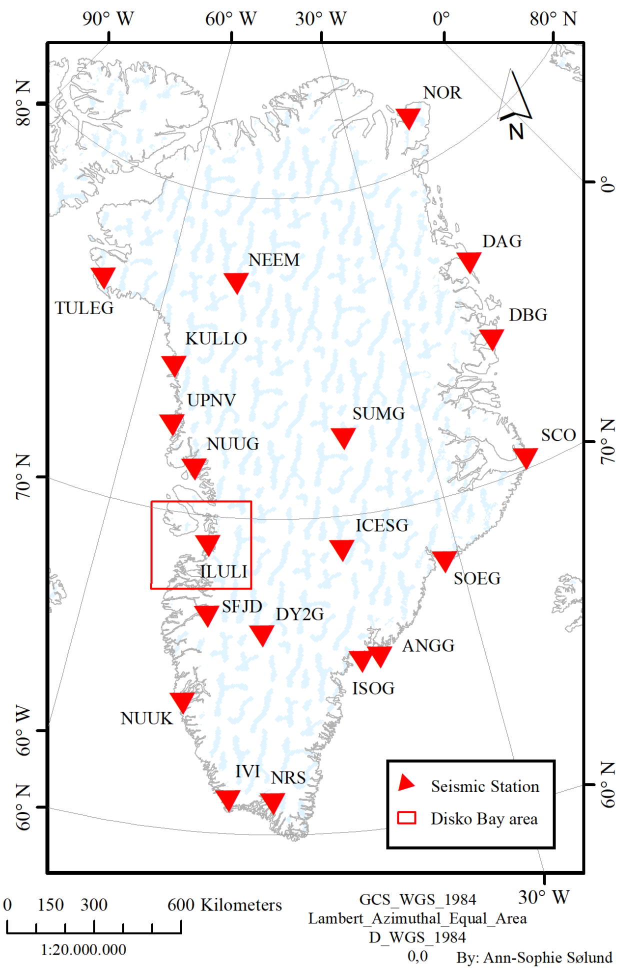


Figure 2: Overview figure of Greenland, showing Disko Bay within the red rectangle on the west coast of Greenland.

Located along the west coast of Greenland, *Ilulissat Isbræ* is one of the largest and most active outlet glaciers in the world ("UNESCO World Heritage Centre - Publications," n.d.), and drains ~6.5% of the Greenland ice sheet (Joughin, Abdalati, & Fahnestock, 2004; Khan et al., 2010; Svensson et al., 2019). The glacier outlet is located just south of the village Ilulissat in Disko Bay (figure 2). Ilulissat is historically also known as 'Jakobshavn' after the founder of the village, and therefore an old Danish name of the glacier is *Jakobshavn Isbræ,* where isbræ is an old Danish name for a glacier. The glacier can also be known by its Greenlandic name *Sermeq Kujalleq.*

The glacier's proximity to Ilulissat - the third largest municipality in Greenland - and the glacier outlet into the fjord (marine-terminating) is the reason why the area is better known as Ilulissat Ice Fjord (Schultz-Lorentzen, Friis, & Rasmussen, 2016). Due to its uniqueness, Ilulissat Isbræ is a UNESCO World Heritage Site. Its existence, therefore, has a special natural and cultural significance and must be taken extra care of ("UNESCO World Heritage Centre - Publications," n.d.). This is why Ilulissat Isbræ has been, and still is, subject to extensive research and will continue to be in the future.

Ilulissat Isbræ is classified as an outlet glacier, meaning that it drains the interior the Greenland Ice Sheet and transports ice towards the coast at a rapid speed of up to 40m/day near the outlet (Das et al., 2008; Svensson et al., 2019). This means that all material within the drainage area will eventually be transported into the ocean via Ilulissat Isbræ. This material will be a mixture of meltwater runoff and icebergs (Das et al., 2008). Being one of the most active outlet glaciers in the world, it accounted for 65% of all glacial earthquakes in Greenland in the 1990s (Veitch & Nettles, 2012). Glaciers are dynamic features, and while the size of Ilulissat Isbræ is constantly changing, it has been reported to have a current thickness of $\sim 900m$, with a glacier front that is between 6 and 7 km long (Amundson et al., 2008; Sohn et al., 1998; Svensson et al., 2019).

Annual and interannual fluctuations are common for all glaciers, including Ilulissat Isbræ. A study from 1998 found that the annual fluctuations of the Ilulissat Isbræ terminus were ∼5km (2.5 km around a central position of the glacier margin). These fluctuations occur at a rather constant velocity throughout the year (Sohn et al., 1998). They also found that the summer calving flux (May-August) is around 6 times higher than the winter calving rate (rest of the year) (Sohn et al., 1998). This difference in summer and winter calving rate will be addressed in section 5.2.1.

The fluctuations of the glacier front are affected by many factors. Amongst these are ocean currents, temperature, precipitation, pressure of ice pushing from the upstream glacier, ice-ocean contact, meltwater, whether the glacier is grounded or not, tide etc. Each of these plays a role in the breakage of the glacier ice, and their relations are very complex and yet to be fully understood (Svensson et al., 2019).

2. Data

This thesis is based on seismic data from Disko Bay in western Greenland, provided by The Geological Survey of Denmark and Greenland (GEUS). The geographic area of interest is between latitudes 71 and 68 and longitudes -53 to -47. These coordinates correspond to all of the Disko Bay area seen on figure 2 within the red square. All earthquakes recorded in the area that occurred during 2016 through 2018 with a minimum local magnitude $M_L > 2$ have been included. However, explosions are excluded from the data set.

A requirement of the data is that events must be recorded at a minimum of three stations in Greenland; earthquakes recorded at less than three stations are not possible to locate correctly. This requirement is set in order to ensure a proper analysis and interpretation of each seismic event at a local scale.

A total of 68 events have been extracted from GEUS database. Due to the physical access limitation to the University of Copenhagen during the Corona pandemic, one seismic event has been fully excluded from the dataset due to unsatisfactory analysis result, while a few other events have been included, however, with a note of only 'rough' analysis. These are found in Appendix I. This leaves a total of 67 seismic events included in this thesis.

The main data analysis is performed in the two computer programmes ArcMap, a Geographic Information System (GIS) software program, and SEISAN[3], a seismic analysis software. Statistical analyses have been performed in Microsoft Excel.

[3] https://seisan.info

3. Methods

This section includes a presentation of the methods used in order to obtain the data on which this thesis is based. The analysis program, SEISAN, will be introduced; both in terms of what data one can obtain from the programme, but also briefly how the programme is used. Then, a presentation of the application of filters on seismic data and how they affect data. The pre-defined crustal model is addressed along with comments on how the seismic stations are spatially distributed across Greenland. Finally, the method and formula used for magnitude calculation will be presented.

3.1 Data analysis and phase picking

Data is processed in the seismic analysis program SEISAN at University of Copenhagen, which contains basic information regarding each seismic event, allowing for further analysis. All parameters from an example of a tectonic earthquake on June 27th, 2017, are seen in figure 3 below.

2016	627	0431	33.8GR		69.092	-49.837	2.6	DNK	5	1.5	2.4LDNK	1
Year	Date (month-day)	Time (hour-minute)	seconds	Location model indicator	Latitude	Longitude	Depth (km)	Hypocenter Reporting Agency	# of stations	Total RMS of time residuals	Local magnitude measurement	Type line

Figure 3: The structure of the Nordic format used in SEISAN[4]

To analyze data extracted from GEUS' database, seismic phases of primary (P) and secondary (S) waves, are picked manually for each seismic event. This is a key part of the earthquake location analysis since the temporal relationship between the P- and S-wave first arrivals is used to find the distance from a given station to the epicenter of an earthquake.

The phase picking is done for multiple channels and stations for all seismic events in the period of interest. From these phase picks, SEISAN calculates a presumed epicenter location,

[4] Nordic format: https://seis.geus.net/software/seisan/node242.html

depth to hypocenter etc. See Appendix II for more information regarding phase picking in SEISAN. An example of analysis of a tectonic earthquake on June 27th, 2016, is seen in figure 4.

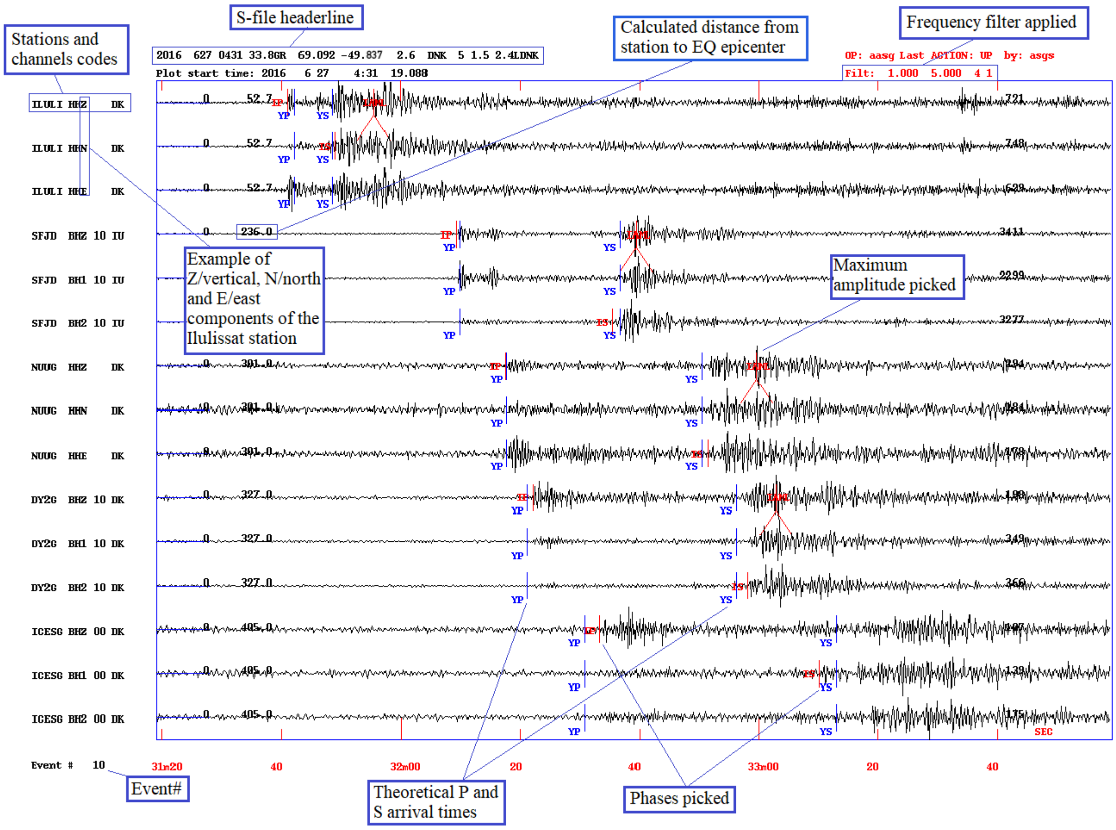


Figure 4: Analysis in SEISAN is done in an interactive mode where one can work with the data directly on the screen. Text boxes indicates the most important features and where to find them. Please **note** that all stations have three components where the P phase is picked on the vertical component, while the S phase is picked on either the N-S or E-W component. The blue vertical lines and letters indicate theoretical arrival times, calculated by SEISAN based on picked (red lines/letters) phase arrivals. The theorecial phase arrivals are adjusted automatically whenever new phases are picked. **Note** also the applied filter (here 1-5Hz) in the upper right corner.

Phase picking

The seismic phases and arrival times are picked manually for each component, station and event. All arrivals are marked as either impulsive (*I*) or emergent (E) and are followed by the seismic phase: P (primary wave) or S (secondary wave). "IS" therefore indicates an impulsive S phase arrival, while "ES" is an emergent S phase arrival etc. Surface waves are marked ESg, at the time of maximum ground roll.

The actual distinction between the S phase and the surface waves is not known due to them arriving simultaneously at a local scale. The exact time of the first arrivals becomes increasingly difficult to determine precisely with increasing distance (see figure 5). The glacial earthquake below (June 26th, 2017, 10:35) is an example of the first arrival becoming increasingly hard to determine with increasing distance. The two stations, ILULI and ICESG, are located at an epicentral distance of 40.0 km and 426 km, respectively, from the supposed epicenter, and the difference in seismic signal appearance is clear. The signal at the proximal ILULI station is much sharper and clear compared to the distal ICESG.

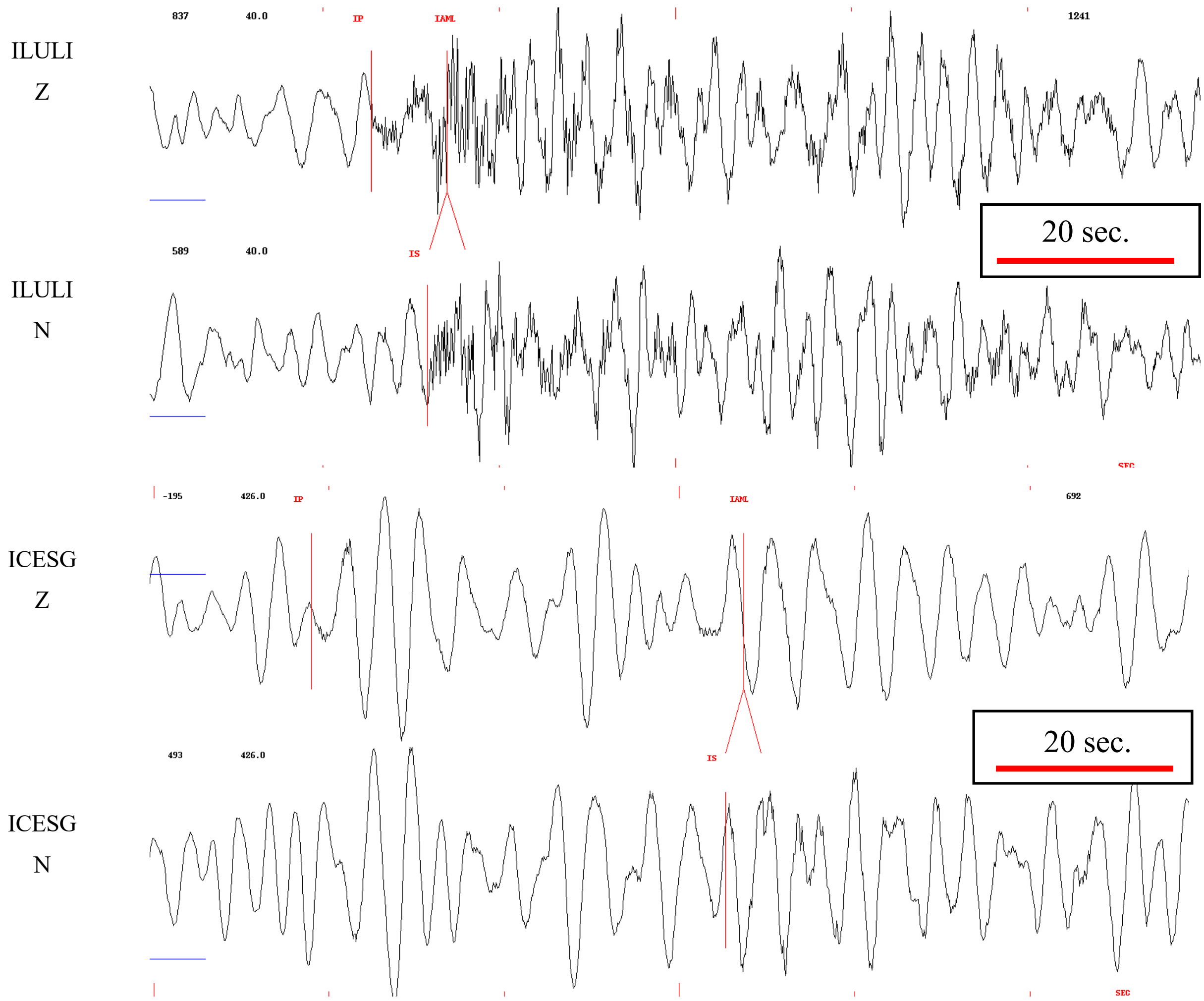


Figure 5: Ilulissat (ILULI) is the top seismogram and Ice South Station (ICESG) at the bottom are located at 40.0 km and 426km (epicentral distance) away respectively from the supposed epicenter. Two channels: a Z/vertical and a horizontal are seen for both seismic stations. Both seismograms are unfiltered and the factor 10 difference in distance to the supposed epicenter shows very clear in the recorded signal. The ILULI station measured a very detailed signal with an abrupt arrival of the signal, which is much less clear at the ICESG station. **Note**, figure 7 shows station locations in Greenland.

3.2 Filtering of seismic signal

The application of frequency filters on a seismic signal is important in terms of final result. As a result of previous work by multiple researchers, certain frequencies have shown to be characteristic of glacial earthquakes. These frequencies have been the starting point of selected frequency filters, which have been modified to be applicable and suitable for both tectonic and glacial events, in accordance with the scope of this thesis. The main frequency filters used are *0.01-0.03Hz, 1-5Hz, 2-4Hz, 3-8Hz* and *5-9.9Hz.*

As also noted by Amundson et al. (2008), the majority of the energy in the seismic signal is at approximately 4 Hz, and therefore the 1-5 Hz filter is especially useful for the data analysis and is the most frequently used filter. The low-frequency component that comprises a significant amount of the energy of glacial earthquakes is also noted by multiple researchers (Amundson et al., 2008; Ekström et al., 2006; Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012). Therefore, a 0.01 to 0.03 Hz filter (reference based on personal communication between Trine Dahl-Jensen and Meredith Nettles) is used specifically for glacial events when looking at longer time spans for a selected number of glacial earthquakes. This will be evident later in section 5.1.3.

The application of a frequency filter always attenuates some frequencies while amplifying others. In other words, filters will always equal loss of signal due to exclusion of frequencies. Therefore, selection of filter and filter type is very important. If a filter is applied for analysis, then the default filter type used is a bandpass filter. The parameters used in the bandpass filters are low-cut and high-cut for parameter one and two respectively. Each parameter being a selected Butterworth corner frequency serving as the lower and upper corner frequency[5].

Careful consideration is needed when applying frequency filters, since only frequencies between the low-cut and high-cut frequencies are analyzed and shown in the filtered seismogram. If one selects a part of frequency spectra with only limited energy, the seismogram will not be representative of the seismic event.

The effect of filters is seen in figure 6 (next page), which is an example of a tectonic earthquake seismogram, recorded on June 26th, 2016, at 08.00. The figure showcases the unfiltered and filtered signal for the same seismic event, station and timespan. In the unfiltered seismogram (*a*), abrupt

[5] https://seis.geus.net/software/seisan/node103.html#5555

changes in both amplitude and frequency are easily recognized. This unfiltered seismogram includes the full frequency spectrum of the earthquake, i.e. all energy.

This is in contrast to (*b*) that only features the part of the energy between 1 and 5 Hz, which includes the main part of the seismic energy. All signal and noise outside the span of the applied frequency filter is attenuated. From the unfiltered data, (*a*), P and S wave arrivals are easily distinguishable, and therefore filter application is not strictly necessary in order to correctly mark the first arrivals of both the P and S phases. This earthquake is interpreted as being a typical tectonic earthquake, due to the abrupt frequency change at the arrival of both the P and S/surface wave phases, which is especially distinct when looking at the filtered signal, (*b*). The appearance of a glacial seismogram will be discussed later.

a) Unfiltered b) Filtered: 1-5Hz

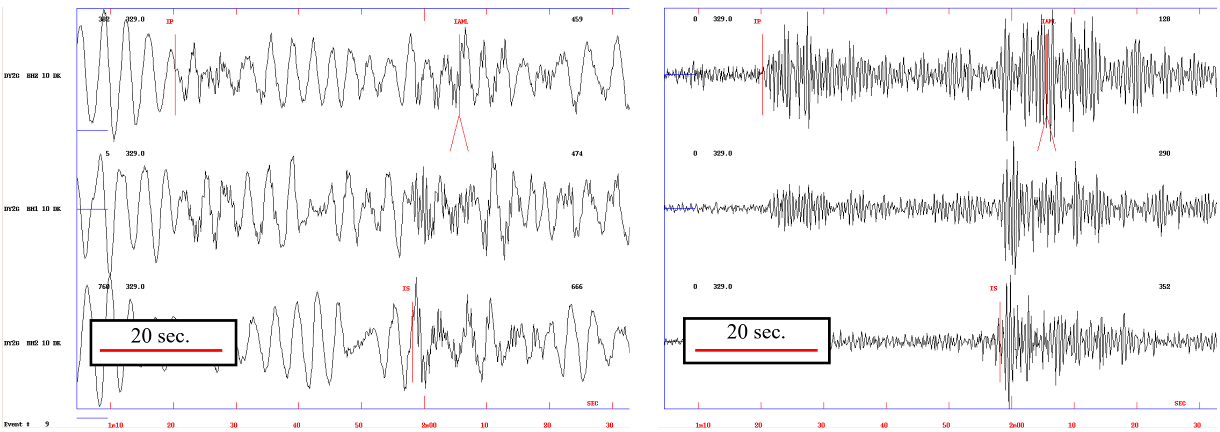


Figure 6a-b: The left seismogram is unfiltered (*a*) and the right seismogram (*b*) is filtered showing only frequencies between 1 and 5 Hz. Both seismograms shows the same tectonic earthquake and time frame for the same seismic station (DY2G). The *y* axis shows the three channels at the DY2G station (Z/vertical, North-South and East-West). The *x* axis shows time in seconds and minutes. **Note** how both P and S arrivals are easily recognized on both the unfiltered and filtered seismogram despite being dramatically different in appearance. It is a classic trait of tectonic earthquakes, that the phases are easily distinguishable.

3.3 Crustal model

P_v (*km/s*)	Depth (*km*)	
6.20	*0.0*	
8.20	*36.0*	*Moho*
8.50	*80.0*	

Table 2: A simple crustal model is defined for all of Greenland. P_v is the seismic P wave velocity, which is defined in a block-like structure, meaning that a constant velocity is defined for each 'layer' of the model. Moho depth is marked at 36 km.

The crustal model used is a simple Greenland-wide seismic model (table 2) containing three seismic homogenous layers, each with constant seismic P wave velocity. The model assumes a stepwise velocity increase with depth, which is geologically common. The modelled layers are defined as blocks with a given constant depth and velocity. This is a simplification of the reality, but deemed realistic for the purpose of this thesis.

Due to the model being very simple, it evidently has its limitations. It is used for all of Greenland and is based on an average crustal composition that might not apply for all regions locally. A potential flaw of the model is that it does not take ice into account, which has a considerably lower seismic P wave velocity 3.4 to 3.9 km/s (depending on anisotropy) compared to solid rocks. The ice thickness at the Ilulissat Isbræ is however less than 1 km thick, and therefore ice has been disregarded in the model (Kearey, Brooks, & Hill, 2002; Kohnen, 1974).

The geology in Disko Bay is predominantly Paleoproterozoic magmatic and/or metamorphic basement rock. Based on GEUS' geological maps (See Appendix III), the most common geology in Disko Bay is orthogneiss with areas dominated by granodiorite (Garde, Connelly, Krawiec, Piazolo, & Thrane, 2002; "Greenland Portal," n.d.; Henriksen, 2008). According to Kearey et al. (2002), the seismic P wave velocity of this type of geology will be somewhere between 5.5 to 8.5 km/s depending on geology, mineralogy and depth. The seismic velocity of the crustal model is in accordance with the subsurface geology, and it is as such deemed that the crustal model is plausible for Disko Bay, when only considering the crystalline basement rock.

3.4 Seismic stations in Greenland

The analysis in this thesis is based on measurements from seismic stations in Greenland (see figure 7). All stations are equipped with STS-2 broadband seismographs that are able to measure a broad spectrum of frequencies, a function that is useful in earthquake seismology. The seismic stations are distributed somewhat evenly across Greenland; however, the majority of stations are located along the coast, with a slightly higher density of seismic stations in the South compared to North. Looking at the distribution of seismic stations relative to Disko Bay, the most proximal stations are located along the West coast.

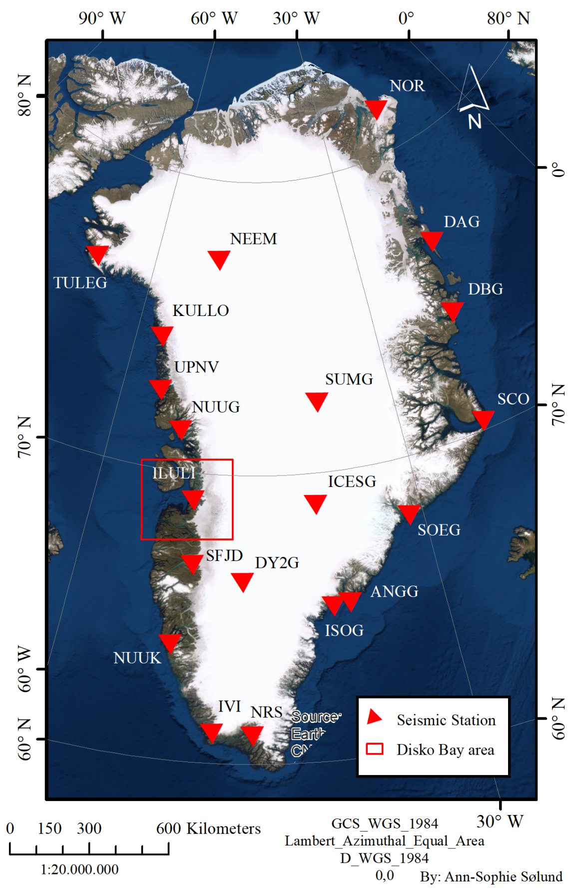


Figure 7: Map of Greenland (scale 1:20.000.000), with red triangles marking location of all seismic stations in Greenland. Red square indicates location of Disko Bay. **Note** UMMG is not featured on the map, but is located just North of Disko Bay.

The most commonly used seismic stations are the following GLISN[6] stations: ILULI (Ilulissat), UMMG (Uummannaq), SFJD (Kangerlussuaq), NUUG (Nuugaatsiaq), DY2G (Dye-2 Raven Camp), ICESG (Ice South Station), UPNV (Upernavik), NUUK (Nuuk), SUMG (Summit), ISOG (Isortoq), RF95F and R2310 (Both Raspberry Shake stations located on islands in the Southern part of Disko Bay (GEUS, n.d.), see Appendix IV. Four seismic stations are located in the interior part of Greenland (NEEM, SUMG, ICESG and DY2G), of which especially the three latter (SUMG, ICESG and DY2G) are of great importance for this thesis, due to their geographical placement relatively close to Disko Bay.

Considering the geometry of the seismic stations around Greenland, larger location errors are expected in an East-West direction compared to North-South. The majority of seismic stations

[6] Greenland Ice Sheet Monitoring Network.

(except the Raspberry Shake stations, which only consist of vertical components) are equipped with three components: vertical (Z), North-South (N) and East-West (E). The seismic stations measure both P and S wave arrivals, which are needed when locating earthquakes. Due to differences in seismic velocity, the separation between the P and the S phase arrival will increase with distance. This relationship can be utilized to locate earthquakes by the method of triangulation (Kearey et al., 2009).

3.5 Measure of magnitude

Magnitude scales are used to infer scientific objectivity and comparability when looking at earthquakes, and to help ensure quantitative comparison of earthquake sizes. Previous global glacial earthquakes studies by Nettles et al. (2010) have found a general glacial magnitude at $\sim 4.6 \leq M_w \leq 5.2$, which is generally agreed upon (Ekström et al., 2006; Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012).

The lower-magnitude boundary is most likely biased by a lower detection limit of the equipment used to detect seismic energy, and while several attempts to find controls on the upper limit of magnitudes have been done, glacier thickness has been suggested as the strongest control on glacial magnitude (Meredith Nettles & Ekström, 2010).

The magnitude measured in this thesis is local magnitude, M_L, calculated from a specified Greenland formula, which has been built into SEISAN. The formula applies to both tectonic and glacial earthquakes, and is based on a simple method approximation from which the amplitude of an earthquake can be determined by measuring the maximum amplitude of the largest phase, L_g. The formula is seen below (Gregersen, 1999)

$$M_L = 2.50 + 2.5\log(D) + \log\left(\frac{A}{T}\right) + path\ correction$$

Where,

A : vertical ground amplitude in nm
T : period in s
D : epicentral distance in degrees

Ground amplitude, A, and period, T, are defined based on manually picked maximum amplitudes of the largest phase on the seismogram, L_g, in SEISAN (Gregersen, 1982). The epicentral distance, D, is found from the earthquake location that is also determined in SEISAN, and is measured, in degrees along the surface of the earth, between the epicenter and the seismic station where the seismic waves are recorded (Kearey et al., 2009). The magnitude of each earthquake is obtained by measuring the amplitude manually in SEISAN for multiple stations individually in order to limit "… *amplitude biases caused by radiation pattern, directivity and abnormal path properties*" (Lay & Wallace, 1995). A Wood Anderson frequency filter is applied to the data before the manual pick of maximum amplitude.

4. Results

This section will contain a presentation of results found from the analysis of data used in this thesis. Representative data will be presented in this section, while the full data set can be found in Appendix V and will only be referred to. The central data table contains all major results, i.e.: geographic location, location errors, magnitude, RMS, number of stations, hypocenter depth, depth error and the earthquake type interpretation. All data is displayed in overview maps in order to show the spatial data distribution along with some of the above parameters.

4.1 Locating earthquakes

Data analysis and interpretation resulted in 33 of the total 67 earthquake events being classified as glacial earthquakes, meaning a total of 34 tectonic earthquakes. The first ten seismic events in 2016 are seen in table 3 (next page), while the full list of seismic events can be found Appendix V.

The table shows the different parameters of interest for each seismic event. The interpretation of earthquake type is noted in the far-right column of the table; note how only three of the first ten earthquakes in 2016 have been classified as glacial. This result is not surprising and will be addressed in further details in the discussion.

Date	Location (lat., long.)	Lat. error *(km)*	Long. er-ror *(km)*	Mag. (M_L)	RMS	#Stations	Depth (*km*)	Non-fixed depth *(km)*	Depth error (km)	Type
29-02-2016_17.49	69.074 , -50.316	7.8	31.4	1.9	1.1	5	15.6	-	13.4	Tectonic
13-05-2016_03.25	69.496 , -52.773	7.6	25.0	2.7	0.5	4	31.6	-	5.7	Tectonic
13-05-2016_06.51	69.010 , -50.280	13.7	43.6	1.6	0.8	4	8.5	-	32.4	Tectonic
19-05-2016_08.28	69.148 , -51.080	3.1	16.8	2.0	0.6	5	0.0F	5.3		Glacial
23-06-2016_14.34	68.974 , -50.271	14.1	44.1	2.0	1.2	6	0.0	-	40.8	Tectonic
25-06-2016_07.15	69.112 , -50.558	5.7	21.6	2.2	0.7	5	18.0	-	8.3	Tectonic
26-06-2016_06.50	69.111 , -49.569	7.6	18.6	2.8	1.2	7	0.0F	0.0		Glacial
26-06-2016_07.01	68.195 , -52.271	10.1	58.3	2.1	2.0	6	0.0F	0.0		Glacial
26-06-2016_08.00	69.099 , -49.879	10.0	34.3	2.2	1.4	5	0.0	-	23.7	Tectonic
27-06-2016_04.31	69.092 , -49.837	10.8	37-5	2.4	1.5		2.6	-	24.9	Tectonic

Table 3: Table column description left to right: Date (ddmmyyyy_hh:mm), location (latitude, longitude), latitude error (km), longitude error (km), magnitude (local M_L), RMS (summed), Number of stations used for locating, calculated depth to hypocentre (F marks fixed hypocenter depth), non-fixed depth (only applies to glacial earthquakes), depth error (km) (only applies to tectonic earthquakes), interpreted type of earthquake. The table features the first ten events in the data set (of the total 67 events). The full table for all 67 events is seen in Appendix V.

To investigate the spatial data distribution, all seismic events are presented in figure 8. According to previous studies, there is a clear correlation between glacial earthquakes and outlet glaciers. This is also evident in figure 8, where the majority of data is located close to the Ilulissat Isbræ.

This trend appears to relate both to tectonic and glacial events, which is surprising. One could argue for a slightly tighter cluster of glacial earthquakes compared to tectonic earthquakes. According to theory, it should only account for glacial earthquakes since tectonic earthquakes are not dependent on glacier activity. This is also why no tectonic earthquakes are considered geographical outliers (Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012).

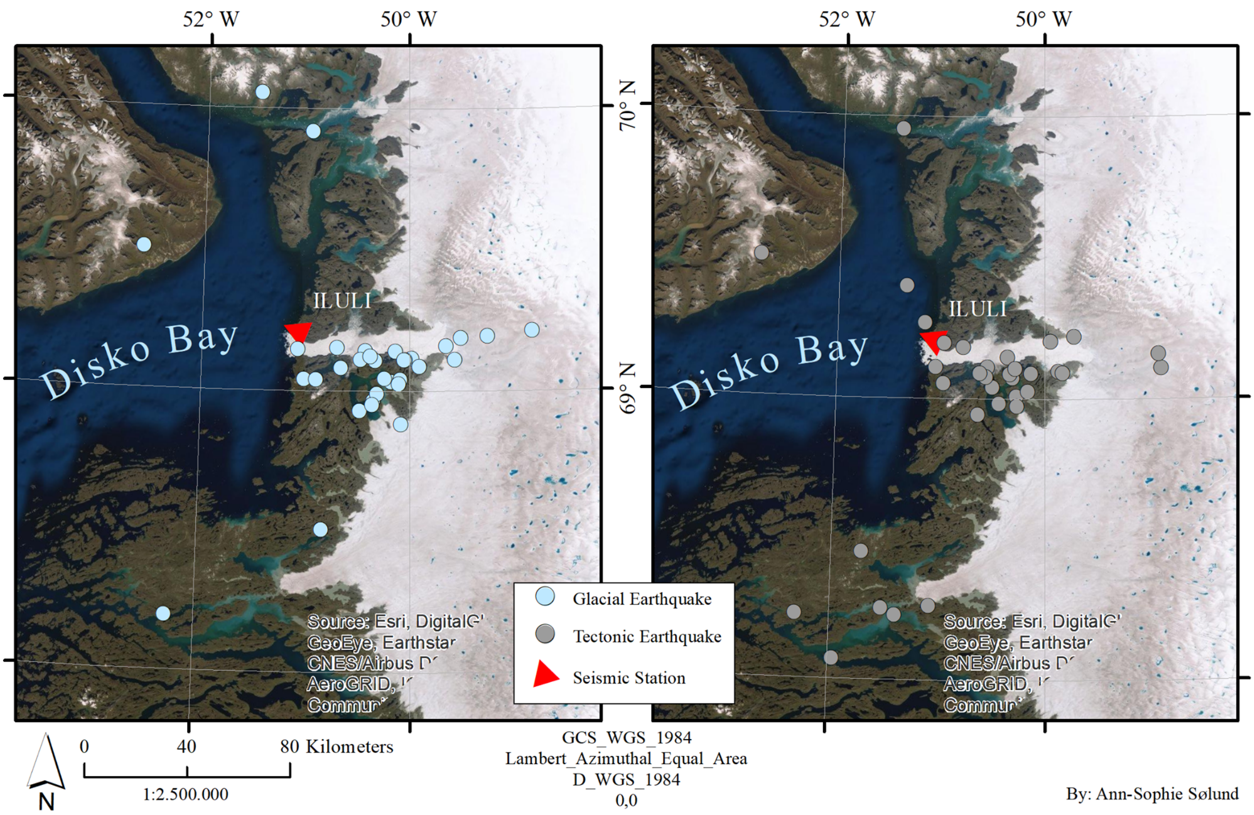


Figure 8: Two overview maps of Disko Bay with Ilulissat Isbræ in the central part of the map. The left map shows the interpreted location of glacial earthquakes (blue circles), while the right map shows the interpreted location of tectonic earthquakes (grey circles). The calving front of Ilulissat Isbræ is located in the eastern part of the "glacial channel". See figure 25 for current glacial calving front location.

There are five glacial outliers that are isolated from the cluster at Ilulissat Isbræ. These events occurred on June 26th 2016, September 20th 2016, August 10th 2017, February 10th 2018 and July 21st 2018. Of the five (glacial) outliers, four are located close to other smaller outlet glaciers North, Eqip Sermia and Kangilernata Sermia, and South, Akuliarutsip Sermia, of Ilulissat (NunaGIS, n.d.). These are likely glacial earthquakes that did not occur at Ilulissat Isbræ, but rather at one of the aforementioned smaller glaciers. The last remaining glacial earthquake (September 20th 2016) is located on Disko Island (island in the upper left corner of the map), far from any glacier. The location and nature of this earthquake are as such difficult to interpret, and it is therefore very likely that this event is a tectonic earthquake.

From figure 8, it appears that all glacial earthquakes surprisingly, but consistently, are located south of the glacier, when disregarding outliers far from the glacier. A systematic error in the pre-defined crustal model could explain this pattern, if e.g. the pre-defined crustal model is not fully representative for this specific area. It could be caused by an over- or under-estimation of the seismic velocities of rock and/or ice. Ice has been disregarded in the crustal model and is therefore also a potential source of a systematic error. However, the ice cover is less than 1 km thick at Ilulissat Isbræ. The actual significance of adding ice to the crustal model might therefore be limited (Kearey et al., 2002; Kohnen, 1974).

Another reason might be the spatial distribution of the seismic stations. For the majority of the station network there are several hundreds of kilometers between each seismic station. Furthermore, the geometry of the stations is uneven with more stations located North and South compared to East and West of Ilulissat. This must be taken into account when looking at the interpreted geographic locations of both glacial and tectonic earthquakes, and one must not be too trusting of the actual 'point location' of each quake. However, before one can fully assess possible reasons behind the apparent affinity for glacial earthquake locations south of the Ilulissat Isbræ, one would have to address the abovementioned parameters in much greater detail, which is outside the scope of this thesis. Therefore, the above interpreted locations must be considered somewhat plausible for the remainder of this thesis. One must, however, consider the location uncertainties.

Some seismic events were easily classified as either tectonic or glacial, while others were more ambiguous and showed traits of both types. Eventually all events were interpreted as one of the two types, with a comment on which events were interpreted with high confidence and which were with low confidence. Therefore, four 'categories' of data have been defined, of which two are the main categories: tectonic and glacial earthquakes. These events are marked as typical tectonic (grey) or clearly glacial (light blue) in figure 8 and 9. The events that are interpreted as either tectonic or glacial, but with less confidence due to ambiguity, are colored yellow and dark blue, respectively, in figure 8. All seismic events have been analyzed as either tectonic or glacial. Therefore, the only purpose of this extra subdivision of data is to make sure that if odd results and interpretations are found, then it might be explained by the interpretation having been made with low confidence.

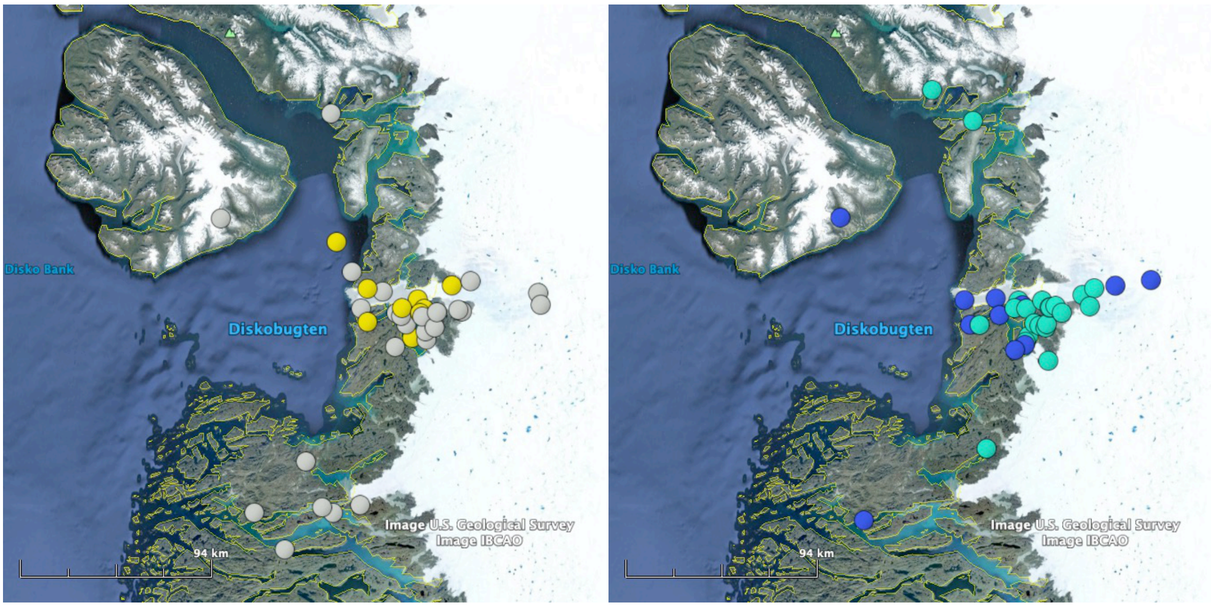


Figure 9: Map indicating the location of tectonic earthquakes (grey), questionable tectonic earthquakes (yellow), glacial earthquakes (light blue) and questionable glacial earthquakes (dark blue). **Note** how the geographic location can be very indicative of possible misinterpreted glacial earthquakes. This is e.g. the two dark blue circles on the North and South side of Disko Bay. These are likely candidates of being tectonic earthquakes. Scale can be found in the lower left corner. Image from Google Earth.

From figure 9 it is evident that the distribution of the lesser confident location interpretations of tectonic earthquakes is more or less random, aside for all questionable events being located rather close to the glacier. None of them are located at greater distances than approximately 70 km to the glacier front. This could indicate that the reason for the doubtful tectonic interpretation might be reasonable. Looking at the glacial earthquakes, none of the lesser confident interpretations are located very close to the glacier front. Instead they are located at rather great distances (not considering uncertainties of the data). Therefore, it would be sensible to question whether these are actual glacial earthquakes. Besides the nine possible tectonic events (yellow in figure 9), and the eleven possible glacial events (dark blue figure 9), only a total of nine events have been marked as very unconfident interpretations. These will be discussed further later, and it can be found in Appendix I.

4.2 Interpretation and localisation uncertainties

Uncertainty is connected to all types of data analysis, and the geographic location of earthquakes is no exception. It is especially important to consider when analysing glacial earthquakes because they, unlike tectonic earthquakes, are restricted to glaciers. Therefore, the location of an earthquake is one of the parameters that one must keep in mind when interpreting data. For all seismic events shown in figure 8, there is a latitudinal and longitudinal error, which are the two parameters comprising the geographic uncertainty. These are, in SEISAN, calculated as a latitude error and longitude error in kilometres, which together gives the uncertainty ellipse for each seis mic event.

The majority of the seismic stations in Greenland are located in a North-South direction compared to East-West direction when locating earthquakes in Disko Bay. The general trend is therefore a greater longitudinal error compared to latitudinal error due to the spatial geometry of seismic stations in Greenland. This is also evident from table 4, where the average longitudinal error is approximately four times larger than the latitudinal error. Furthermore, it appears that the glacial earthquakes in general have a smaller latitude and longitude error compared to the tectonic earthquakes. It means that their geographic locations are in general more accurate than that of the tectonic earthquakes. This result is very positive, as the location of these events are the main focus of this thesis.

	Average latitude error (*km*)	**Average longitude error (*km*)**
Glacial earthquakes	8.9	33.5
Tectonic earthquakes	10.3	48.5

Table 4: Average latitudinal and longitudinal error of glacial and tectonic earthquakes in kilometres. The longitudinal error is larger for both types of earthquakes, due to the geometry of the seismic stations in Greenland.

Looking at a map, latitudes are the horizontal lines parallel to the equator. Therefore, a latitude error is a North-South oriented misplacement of epicentres, when looking at the error simply, and vice versa for longitudes which result in an East-West oriented error. In reality, the location errors are not that simple due to more factors playing a part. The aforementioned uncertainty ellipse can therefore be oblique in regards to the orientation of the graticules[7], and the errors are thereby not directly North-South or East-West oriented.

[7] Graticules comprises both latitudes and longitudes.

However, the possible misplacement caused by the longitude error will be oriented somewhat East-West, which is important when looking at Ilulissat Isbræ. The glacier channel of Ilulissat Isbræ is oriented more or less directly East-West, and therefore an average longitude error of 33.5 km in an East-West direction has quite the impact on the epicentre location. The length of the glacial channel is around 50 km, and the location method is as such quite rough in terms of accurately locating epicentres. The visual representation of the uncertainties is seen in figures 10 and 11 below.

SEISAN is programmed to function with Google Earth, where the latitude/longitude error calculated in SEISAN can be displayed in Google Earth. The figures below show the seismic stations used for locating the earthquakes as triangles with lines from the station to the calculated epicentres. Generally, the more stations used, the more accurate location and less of an uncertainty.

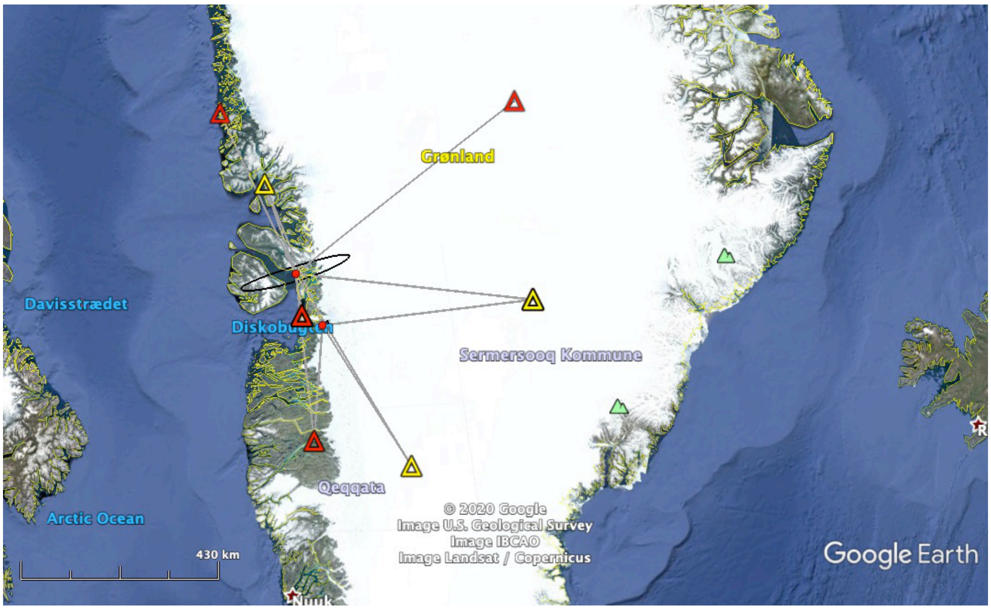


Figure 10: Overview map of the seismic stations (triangles) used for locating two earthquakes: one tectonic earthquake on July 26th 2016, and one glacial on July 10th 2016. The tectonic earthquake has a large uncertainty, and its ellipse of uncertainty can be seen on the map. The glacial earthquake is less uncertain, and the ellipse can only be seen on a larger scale map (figure 11). Scale can be found in the lower left corner, and North is up. Image from Google Earth.

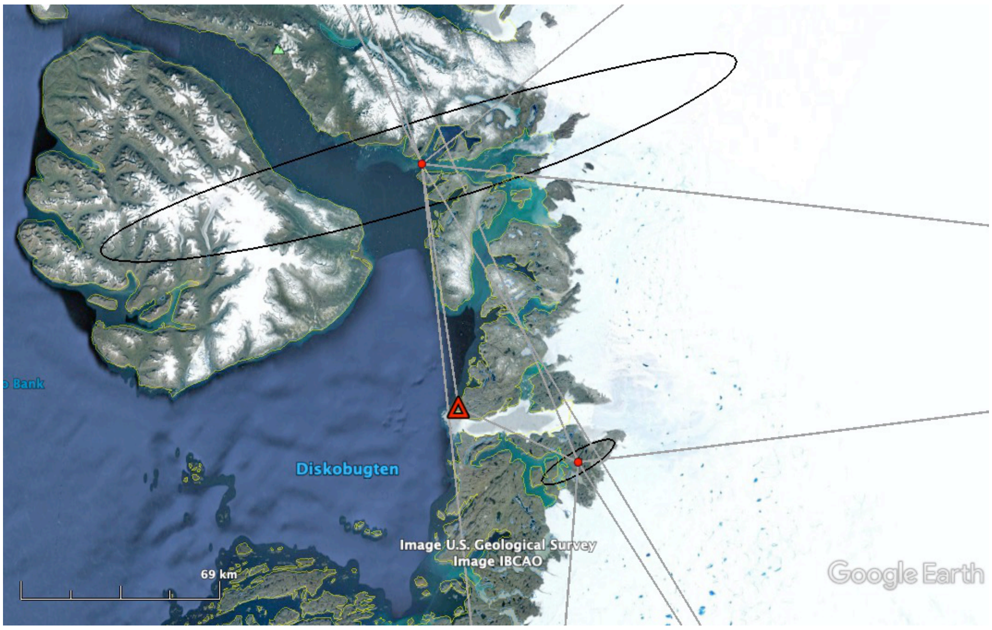


Figure 11: The two events in the data set with the largest (tectonic earthquakes on July 26th 2016) and smallest (glacial earthquake on July 10th 2016) uncertainty is shown as an NE-SW oriented ellipse. Scale can be found in the lower left corner. North is up. Image from Google Earth.

The overview map shows a somewhat even station geometry, utilizing the seismic stations located on the ice sheet in the interior part of Greenland. Looking at a larger scale, figure 11, two earthquakes are featured: one tectonic (larger ellipse) and one glacial (smaller ellipse). The error in kilometres are in SEISAN calculated as being 4.6 km in latitude error and 12.4 km in longitude error for the glacial earthquake. For the tectonic earthquake, the error is much higher and has been calculated to be 18.4 km in latitude error and 108.2 km in longitude error, which is a major uncertainty. It means that the epicenter of this particular tectonic earthquake can possibly be located in most parts of Disko Bay.

Both ellipses are oriented in a somewhat NE-SW orientation, which is present in the majority of the full dataset and is caused by the seismic station geometry. The two earthquakes in figures 10 and 11 have been selected due to them having the largest and smallest uncertainty of the entire dataset. They therefore show the potential upper and lower error margin within the data.

From the tectonic earthquake, it is obvious that this event can be located in most parts of Disko Bay, but most likely in the Northern part of the bay due to lesser latitudinal error. The interpretation of this event is based on recordings from seven stations, which should decrease the uncertainty. However, with a total RMS of 3.1, which is higher than the general accepted RMS in this thesis (< 2.0), this interpretation is most likely flawed, based on the RMS alone[8].

When looking at the glacial earthquake, it has a much smaller ellipse locating the glacial earthquake rather close to the glacier calving front regardless of where within the uncertainty ellipse the actual epicenter might be. Especially when considering that all the glacial earthquakes are located South of the glacier, as it was established in the previous section. In fact, it might be that the ellipse and the glacial earthquake would precisely locate the calving front if the alleged systematic error is disregarded.

To further specify the uncertainty of the data, two additional glacial earthquakes have been selected and shown in figures 12 and 13. These occurred on September 3rd 2017 (eastern located event) and on October 31st 2017 (western located event), and they are both glacial earthquakes. The event on September 3rd 2017 is the glacial event with the highest geographic error (both high latitude and longitude error). The latitude error was calculated as 14.3 km and the longitude error at 48.4 km. Looking at figure 13, it is evident that the uncertainty ellipse is quite large, as it is roughly the same size as the area in which all glacial earthquakes are located within. This is if looking at the 'swarm' of glacial earthquakes that cluster around Ilulissat as a whole (see figures 8 and 9).

The glacial earthquake on September 3rd 2017 is, however, the most uncertain glacial event analysed, and is as such defined as the upper limit of uncertainty of the glacial data in this thesis. To address the question of 'average uncertainty' the glacial event that occurred on October 31st 2017 has been chosen (western event in figures 12 and 13). The latitude and longitude error of this event was found to be 9.9 km and 28.3 km, respectively. This size of error is rather close to the average glacial error margin specified in table 4, and this event therefore is a great way of visualizing the uncertainty of the location interpretation. The size of the uncertainty ellipse is around half the size of the uncertain ellipse of the event on September 3rd 2017.

[8] The analysis process was cut short due to the Corona pandemic, therefore it wasn't possible lower the RMS with the time frame given.

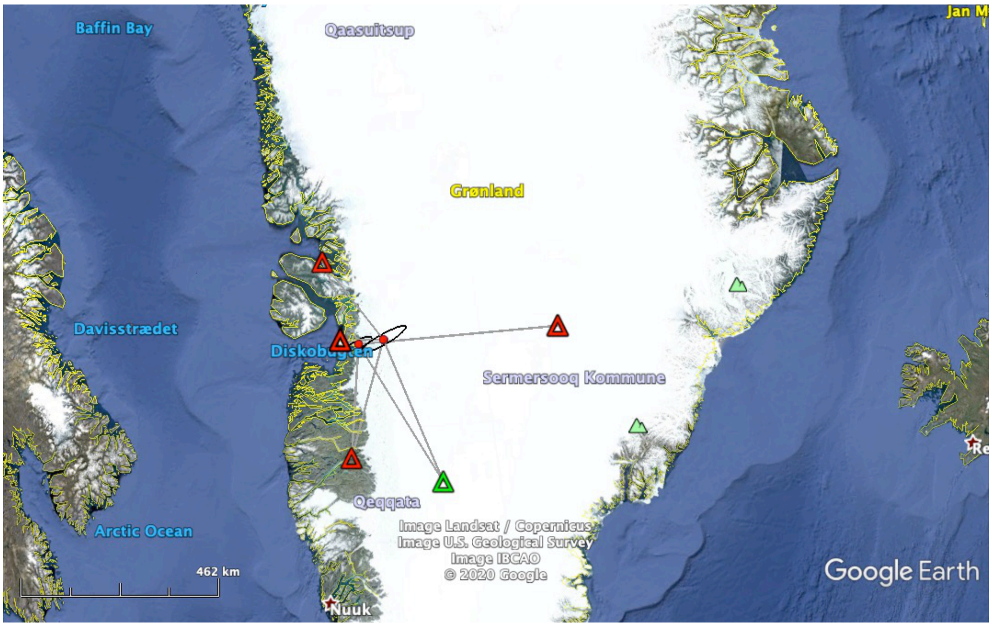


Figure 12: Overview map of the seismic stations (triangles) used for locating two glacial earthquakes: September 3rd 2017 (eastern located event) and October 31st 2017 (western located event). These events are the glacial earthquake with the largest uncertainty, and a glacial earthquake that have an uncertainty close to the overall glacial average latitude and longitude error. Scale can be found in the lower left corner. North is up. Image from Google Earth.

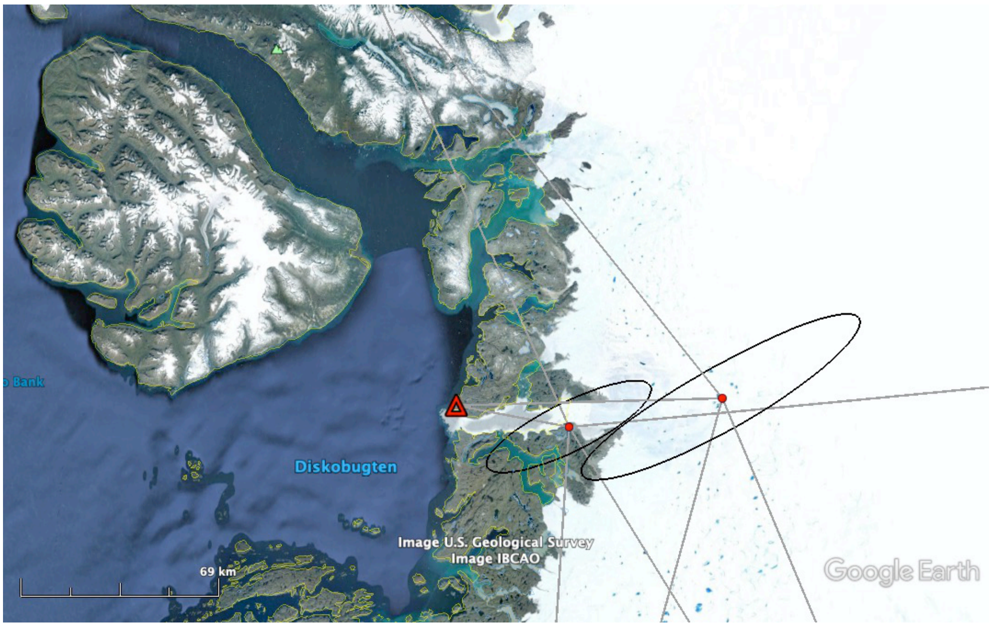


Figure 13: Two glacial earthquakes one (eastern located) being the glacial earthquake with the largest latitude and longitude error, and one (western located) being close to the average latitude and longitude error. The uncertainty is shown as an ellipse. Scale can be found in the lower left corner. North is up. Image from Google Earth.

4.3 Annual data distribution

From the analysis in SEISAN, the 67 seismic events have been interpreted as either glacial or tectonic. To understand the temporal distribution of data, three graphs, figures 14a (2016), 14b (2017) and 14c (2018), have been made to show the annual distribution of glacial and tectonic earthquakes separately. These all show a seasonal pattern in number of occurrences of glacial and tectonic earthquakes, with a peak of glacial earthquakes during the summer and no to few glacial earthquakes the rest of the year. Surprisingly, the same trend seems to account for tectonic earthquakes as well, though the numbers should be randomly distributed during the year (Kearey et al., 2009). It is mostly the summer of 2016 that appears to have an abnormal high number of tectonic earthquakes. This result could be caused by events that were difficult to interpret. Of the total 67 events, especially nine events were ambiguous. The specification of these can be found in Appendix I. This varying seasonality of tectonic earthquakes will be discussed in section 5.2, but could indicate a subjective over-interpretation or inclination towards defining seismic events as tectonic.

During the three-year period, a couple of months stand out and appear to have abnormal glacial earthquake activity. In July 2017 there were no glacial earthquakes recorded. While this is perfectly possible, it is a striking difference from the four and six glacial earthquakes that occurred in June and August, respectively. All years, except for 2018, have no glacial earthquakes recorded before May, which is at the onset of the summer period. The one event that stands out is in February 2018. While this is early for glacial earthquakes to occur, it is feasible that the retreat-advancement pattern of the Ilulissat Isbræ was slightly abnormal in 2018. Glacial earthquakes have been contributed to periods of glacier retreat. This was also the case in 2007, where Ilulissat Isbræ went through a period of glacier front retreat as early as February (Meredith Nettles & Ekström, 2010).

Figure 14a:

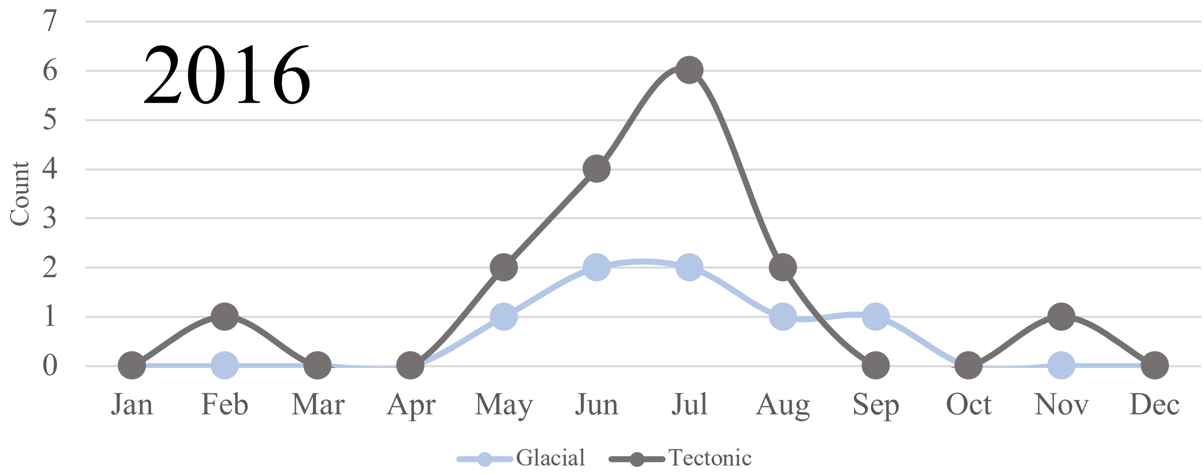


Figure 14b:

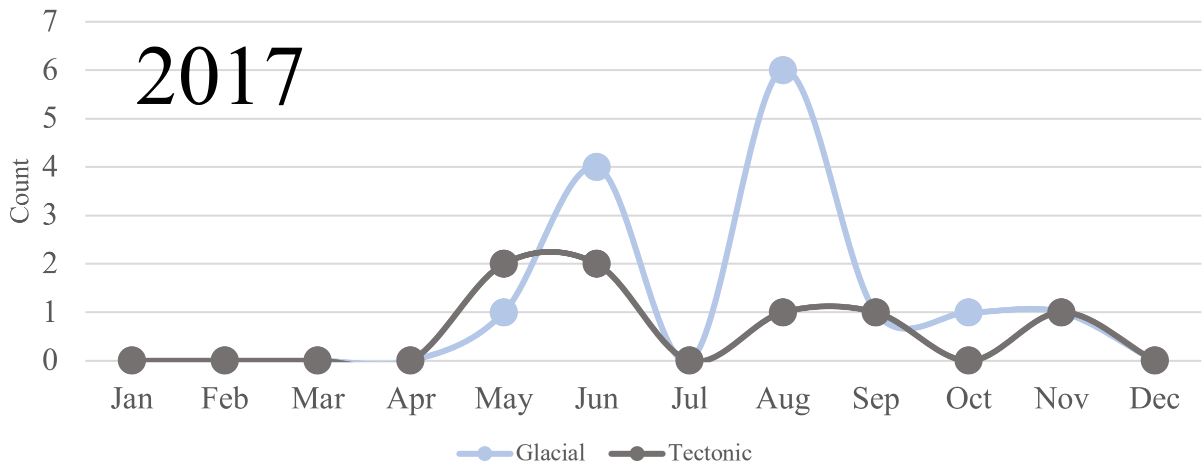


Figure 14c:

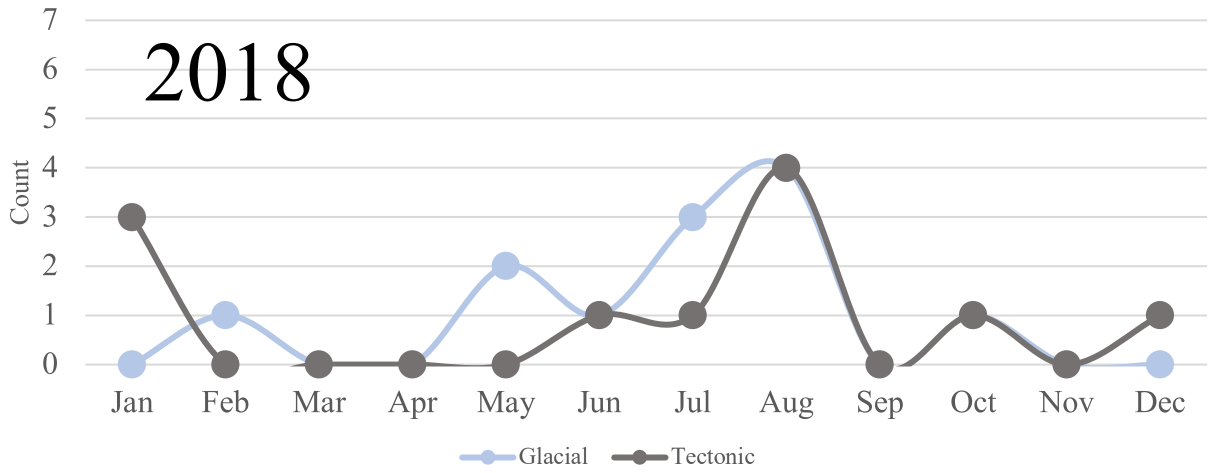


Figure 14 a-c: Monthly occurrence of tectonic (grey) and glacial earthquakes (blue) during the period of interest, 2016 to 2018. Note the seasonal pattern of especially glacial earthquakes, which also seems to account for tectonic earthquakes.

4.4 Earthquake analysis

Prior to the seismic data analysis in SEISAN, the data contained no geographical reference. The order of the seismic stations (along the *y* axis in figure 4) is therefore completely random, and it is only when the first phase arrivals are marked that SEISAN organises the stations based on increasing distance between the epicenter and seismic station. The method of analysis is a continuous back-and-forth adjustment of first arrival times of both the P and S phase until a satisfactory location and RMS value (< 2.0, if possible) is achieved. For most events, a first estimate of phase arrival can be picked with some confidence, while some events require a fair amount of adjustment of possible first-arrival times of the seismic phases.

During the analysis the overarching questions is the question of "*tectonic or glacial earthquake?"*. For the majority of seismic events it is easier to accurately pick phases for a tectonic earthquake compared to a glacial earthquake. The reason for this will be discussed later in this section. In regards to the more challenging glacial earthquakes, a reverse method is used to interpret their geographic location. The approach is here to pick an approximate time of maximum amplitude of the surface waves. The maximum amplitude is located at roughly the same time, relative to P and S arrival, throughout an event when looking at multiple stations. From this, the theoretical first arrival of P and S can then be estimated.

In order to address the similarities and differences between tectonic and glacial earthquakes, a number of seismic events have been chosen. They each represent their type of earthquake and are considered a typical glacial or typical tectonic earthquake, based on seismograms. An overview of the seismic events is found in table 5, which lists parameters of the six chosen seismic events. All parameters, except the date of event, are the result of the seismic interpretation.

Table 5 – Overview table					
Date	**Location (lat., long.)**	**Local Magnitude, M_L**	**Total RMS**	**Depth (km)**	**Type**
27-06-2016_04.31	69.092 , -49.837	2.4	1.5	2.6	Tectonic
30-08-2016_09.08	68.264 , -51.082	2.9	2.8	0.0	Tectonic
28-07-2018_03.45	68.254 , -51.526	3.0	1.4	27.7	Tectonic
03-06-2017_23.06	69.117 , -49.981	2.2	1.4	0.0F	Glacial
14-08-2018_12.23	69.111 , -50.053	2.3	1.4	0.0F	Glacial
23-08-2018_03.17	69.188 , -49.508	2.2	1.5	0.0F	Glacial

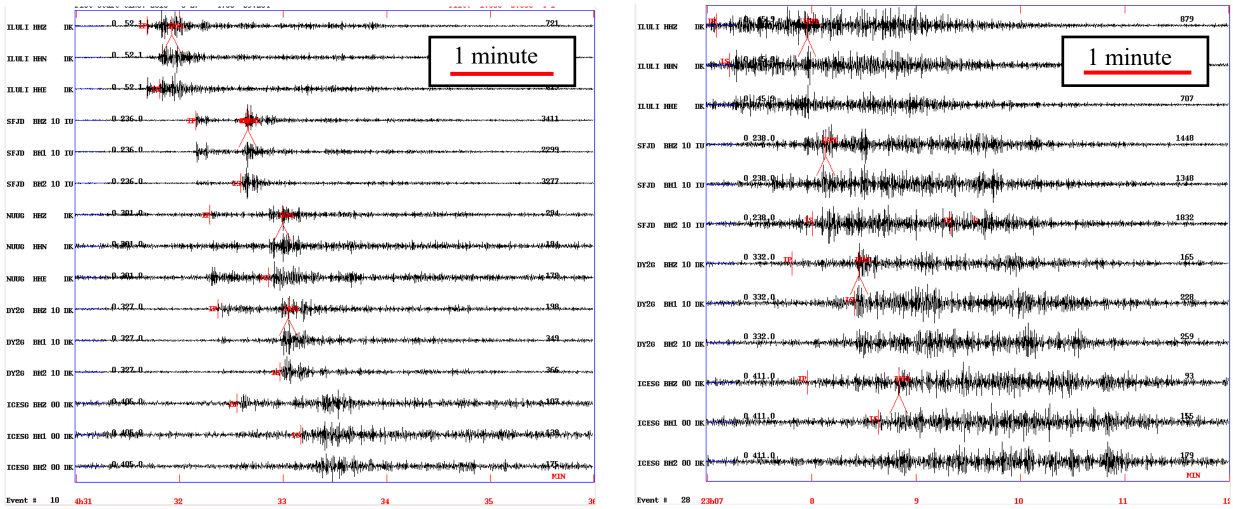
Table 5: Three tectonic and three glacial earthquakes have been chosen. All events are considered 'typical' of their type and chosen based on being representative in terms of both date, location, magnitude, and depth.

The examination of the difference in duration between tectonic and glacial earthquakes is clear in figure 15 below, where the difference is two to three minutes. In a tectonic earthquake the seismic signal appears like a short 'pulse', where first arrivals and seismic phases appear well defined, abrupt and are fairly easy to identify.

This is in contrast to glacial earthquakes, where seismic phases seem almost inseparable and with a shaking duration that is considerably longer (Amundson et al., 2008; Kearey et al., 2009). The shape of a glacial earthquake seismogram has previously been described as "*emergent, cigar-shaped envelopes…*" that "*… reflect the gradual growth and decay of ocean waves during calving events and that the peaks reflect the detachment and overturning of individual icebergs*"

(Amundson et al., 2008). This description seems quite fitting for the majority of the glacial seismograms analyzed in this thesis. Looking at the wave train[9] the signal for a tectonic earthquake looks like "steps", whereas the glacial earthquake is "smoother" when comparing the signal from station to station (down the *y* axis). For some events it is easy to determine whether they are glacial or tectonic, but some appear to have similarities with both types. Both scenarios will be discussed further below.

Tectonic earthquake | Glacial earthquake



Duration: 1 minute | Duration: 3-4 minutes

Figure 15: Both seismograms feature events (left: tectonic earthquake on June 27th 2016, right: glacial earthquake on June 3rd 2017) filtered at 1-5 Hz. Time along the *x* axis and stations with increaseing distance down the *y* axis. P and S arrivals have been identified for boths events and are marked with IP/EP for P phase, and IS/ES for S phase, dependent on the first arrival being immediate (I) or emergent (E). **Note** how the duration of the glacial earthquakes is around 3-4 minutes, whereas it is only around 1 minute for the tectonic earthquake.

To describe the seismic event in figure 15 in greater detail, figure 16 contains the same two events along with four additional seismic events, all of which considered 'typical' of their type of earthquake. They are all used in order to address general characteristics of both tectonic and glacial earthquakes. The seismograms below are all from different events, but since they all have epicenters in Disko Bay, the overall distance in kilometers from any event to a particular station should be approximately the same. To eliminate effects caused by different distances from epicenter, each row in the figure shows seismograms from the same station, at roughly the same distance from

[9] Full length signal of waves, is often referred to as "wave train".

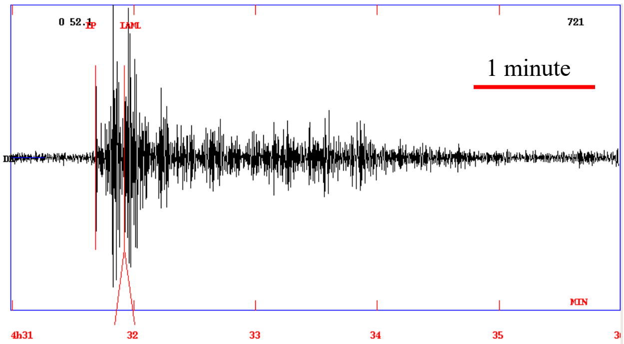
their respective epicenters. The distance is seen as a number in the upper left corner of the seismogram. For the top left event (on June 27th 2016) the distance is 52.1 km.

Figure 16a-f: – Phase arrivals on the vertical component of different seismic stations.

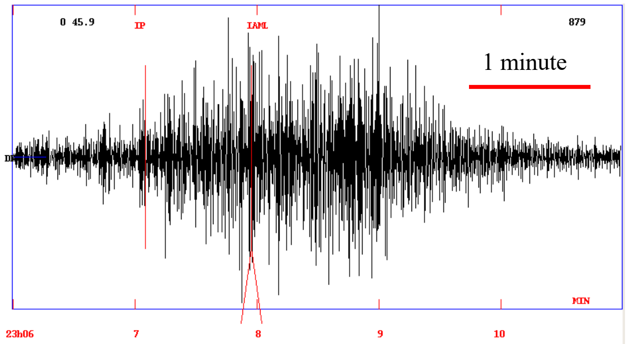
Tectonic earthquakes	***Glacial earthquakes***

ILULI - Ilulissat seismic station

a)

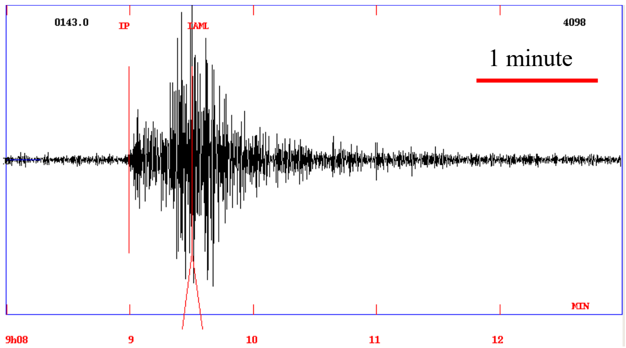


b)

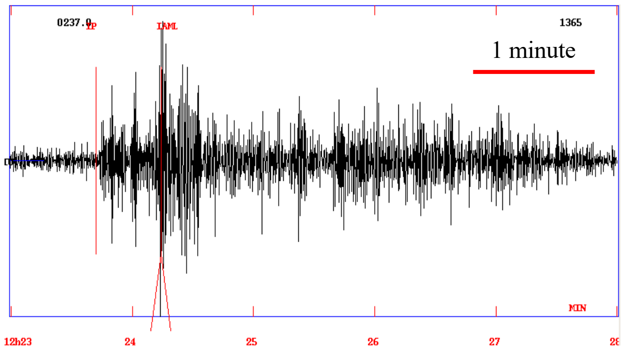


SFJD - Kangerlussuaq seismic station

c)

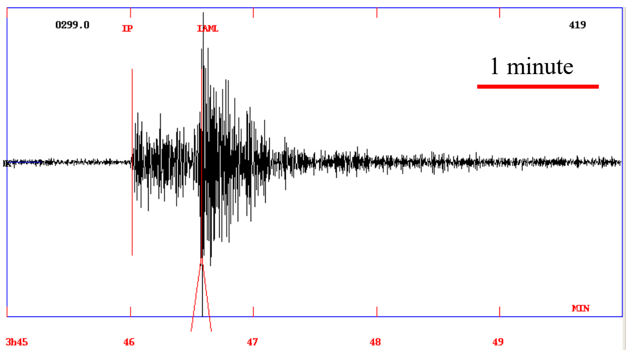


d)



DY2G - Dye-2 Raven Camp seismic station

e)



f)

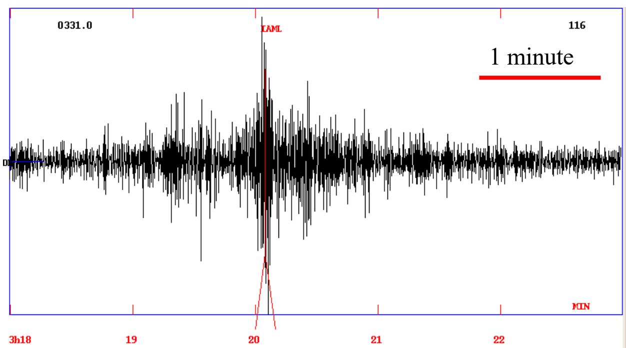


Figure 16a-f: All seismograms show the vertical component (Z) of three stations (ILULI/Ilulissat, SFJD/Kangerlussuaq and DY2G/Dye-2 Raven Camp). Each row shows a tectonic (left) and a glacial (right) earthquake at one of the three stations. The red line marked IP marks the P phase arrival, while the red line marked by IAML indicates the maximum amplitude of the surface waves. The S phase arrival is not marked in the figure, but can be spottet shortly before the arrival of the surface waves where there is a large amplitude increase. The total length of each seismogram is five minutes (*x* axis).

The tectonic earthquakes, 16a, 16c and 16e, are all characterized by an abrupt change from no/minimal amplitude to the arrival of the P wave, resulting in a relatively large amplitude change. When comparing the P wave arrival of a tectonic earthquake to that of a glacial earthquake, 16b, 16d and 16f, the situation is quite different. In the examples, 16b, 16d and 16f, there is always a pre-existing amplitude variation before the P wave arrival. Glacial earthquakes are, unlike tectonic, not onset by an instantaneous rupture motion, but are slower as the ice begins to crack open and tremors increase. Furthermore, it has been argued that ocean waves also have an influence on the seismogram (Amundson et al., 2008), making it harder to determine P wave arrivals of glacial earthquakes compared to a tectonic earthquake, since shaking is present before the actual glacial earthquake. An example is the glacial earthquake 16f, where a P wave arrival has not been identified due to no clear P wave arrival.

For both types of earthquakes, there is a tendency of minor amplitude decrease in between the arrival of the P and S phase arrival. In general, tectonic earthquakes have two clear phase-arrivals (P and S) with maximum amplitude of that phase shortly after the first arrival, followed by a gradual decrease in amplitude with time. This is different from glacial earthquakes, which can behave like tectonic ones (example in figure 16f), except for a somewhat temporal gradual decrease of amplitude. However, most glacial earthquakes look more chaotic along the lines of the seismogram, as seen in figure 16b. This shows how it can be harder to distinguish the seismic phases with confidence for glacial earthquakes.

4.4.1 Temporal and spatial data distribution

All examples above occurred in June through August, which is the time of year with the highest frequency of glacial earthquakes (Ekström et al., 2006; Meredith Nettles & Ekström, 2010). From individual analysis of each event it has been interpreted that the events on June 27th 2016, August 30th 2016 and July 28th 2018 are tectonic, while the events occurring on June 3rd 2017, August 18th 2018 and August 23rd 2018 are glacial.

In the overview map of Disko Bay (Figure 17), it is seen that all three glacial earthquakes are located within short distance of the calving front of Ilulissat Isbræ (see calving front location in figure 25). This strengthens the interpretation of them being glacial earthquakes. Looking at the tectonic earthquakes, two (on August 30th 2016 and on July 28th 2017) are located far away from Ilulissat Isbræ, while one (on June 27th 2016) is located very close to the calving ice front. This is assuming the location of the earthquake is decently accurate given all previously discussed uncertainties. This could be an indication of it being glacial when only basing off location, but when considering all other features of this event it is highly unlikely that it is a glacial earthquake. This is therefore an example of a tectonic earthquake that occurred close to a glacier but is not glacial.

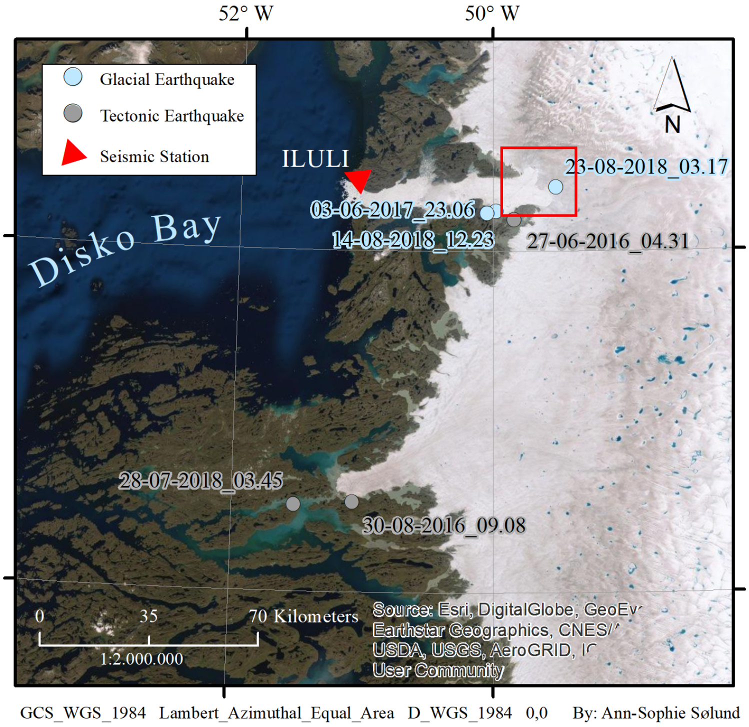


Figure 17: Map of Disko Bay, with ILULI seismic station marked by a red triangle, light blue circles indicates glacial earthquakes and grey circles indicate tectonic earthquakes. The red square indicates the approximate current location of the calving ice front of Ilulissat Isbræ. **Note** how all glacial earthquakes are clustered closely around in the glacier front, while there is no correlation between the location of tectonic epicentres and the glacier front.

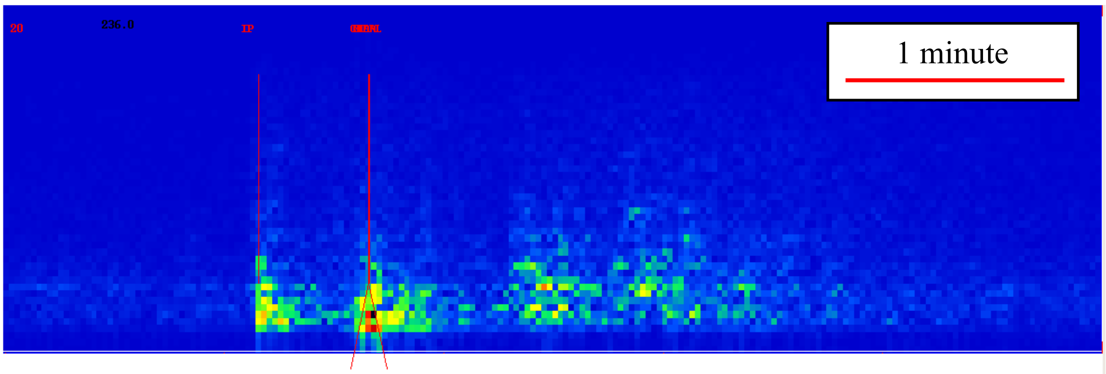
The location of a tectonic earthquake close to the glacier front is not utterly surprising. The tectonic earthquake has no direct link to the glacier and should be independent of the glacier. The possibility of onset of a glacial earthquake due to a tectonic earthquake is not understood and will not be further addressed. Looking at the data for the event on June 27th 2016, there are no tectonic earthquakes occurring at the same time or close to that time. However, since only seismic events with a magnitude $M_L > 2$ have been included in this thesis, it is not impossible that it could happen. Due to limitations in data and access to it, it is not possible to address this in further detail.

4.5 Seismic events with traits of both tectonic and glacial earthquakes

Though all seismic events in this thesis are being characterized as either glacial or tectonic, it is not always simple to interpret the source of a seismic event. Some events have characteristics of both types and are therefore difficult to interpret as one or the other. In order to address the ambiguous earthquakes, examples of both types will be presented in order to make a clear distinction between glacial and tectonic earthquakes. Two seismic events were analysed in figures 18a (June 27th 2016) and 18b (August 14th 2018). They were classified as a tectonic and a glacial, respectively.

An approach to interpret earthquakes, besides looking at the seismogram as in the previous section, is performing a spectral analysis. For this thesis, this is done in SEISAN using single trace mode and looking at the vertical component (Brune, 1970). The results are seen in figures 18a and 18b, which are very different from each other. The purpose of the analysis is to analyse the frequency content in the seismic signal, which is seen in terms of colours depending of the amount of energy at a certain frequency. Colours ranging from low (blue) to high frequency content (red).

a) Tectonic earthquake, vertical component, SFJD station.



b) Glacial earthquake, vertical component, SFJD station.

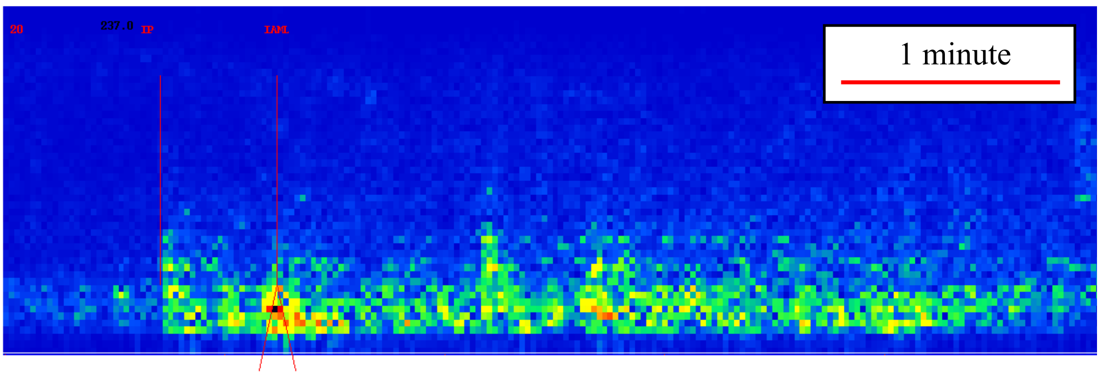


Figure 18a-b: A spectral analysis of a) a tectonic and b) a glacial earthquake at Disko Bay. The blue background serves as neutral background indicating low energy. Colours ranging from green to orange/red is indicative of high energy at a certain frequency ranging from 0 to 20 Hz on the *y* axis. Time is seen along the *x* axis. P and S wave arrivals are marked with red lines and letters IP (P wave) S/surface wave arrival as IAML.

Comparing the two examples, the difference between them is clear. Along the *x* axis of the tectonic earthquake (18a), two well-defined clusters of energy are seen. The clusters vary in frequency from 1 to ∼5 Hz and coincide with the arrival of the P and the S/surface waves. This is not surprising since the frequency interval from 1-5 Hz has previously been noted to contain the majority of the frequency content of both tectonic and glacial earthquakes. Furthermore, the seismic energy during an earthquake is at its highest at the first arrivals of a phase and then ceases gradually with time, which is also seen in seismograms.

Looking at (18b) there are no well-defined clusters of energy, which is not surprising considering it being a glacial earthquake. The frequency content here is also mainly focused around 1 to ∼5 Hz, but with little energy going up to around 7 Hz. Unlike the tectonic earthquake, which occurred fast and well-defined, the glacial earthquake shows a long ‘cloud-like’ structure of energy lasting for a long time after the actual glacial earthquake. Literature claims elevated seismic activity up to several hours after a glacial earthquake, therefore a ‘cloud’ of energy is expected (Amundson et al., 2008). Note that while the two examples above are stereotypical of their specific type of earthquake, most earthquakes lie in between, both in terms of seismograms and spectral analysis.

It is a general trend that the majority of glacial earthquakes will have somewhat separated phase arrivals that are easy to identify in the spectral analysis, but they can appear more inseparable when looking at the seismogram. An example of this is the tectonic earthquake that occurred on November 2nd 2016 (figure 19). When only considering the seismogram, the duration of the event appeared longer than most tectonic earthquakes and separation between the arrival of the difference seismic phase separation is not clear, which therefore could indicate it being a glacial earthquake, despite the event happening in November.

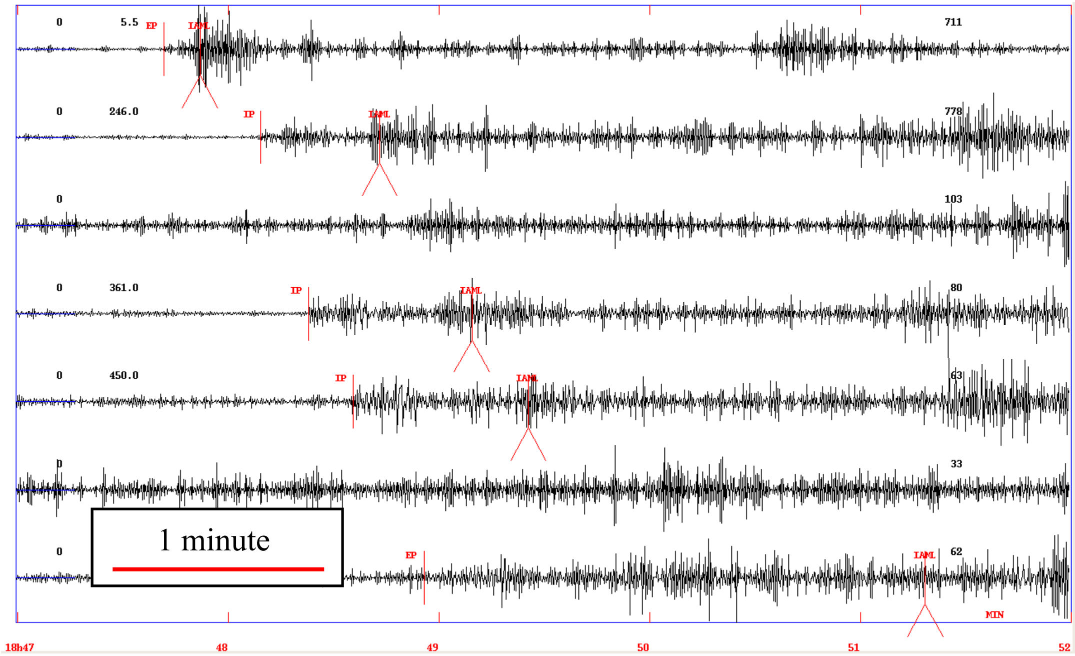


Figure 19: Multi-trace seismogram of a tectonic earthquake on November 2nd 2016, showing seismograms of the vertical component from seven seismic stations in Greenland (Listed from top to bottom: ILULI, SFJD, NUUG, DY2G, ICESG, NUUK and SUMG). The seismic signal is filtered for frequencies 2-4 Hz. P wave arrivals have been identified and marked as IP/EP and S wave arrivals as IS/ES, dependent on the first arrival being immediate (I) or emergent (E).

Note how these events shows similarity to both the tectonic and glacial earthquakes seen in figure 15 (in section 4.4), while having been interpreted as a tectonic earthquake. The doubt arises especially when looking at multiple stations at once in figure 19, which shows that the signal is affected by quite a lot of noise that needs to be disregarded in order to analyse the seismic signal of the earthquake. Especially the stations NUUG and NUUK are influenced by noise. This can be due to many things both human and non-human induced, e.g. a large truck driving by the seismic station or a landslide. For instance, the NUUK station is known to have been misfunctioning during some of the period of interest. These stations are therefore not the primary stations used for the seismic interpretation, but they will of course be checked if they are in agreement with other stations.

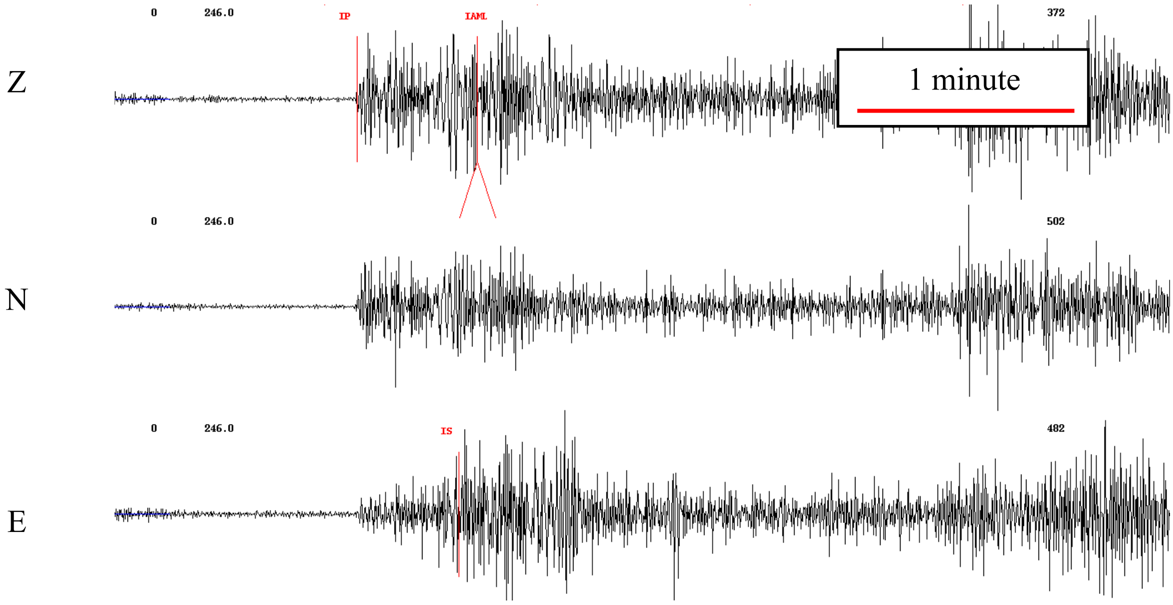


Figure 20: Seismogram of the seismic event on November 2nd 2016 showing all three components at the SFJD station.

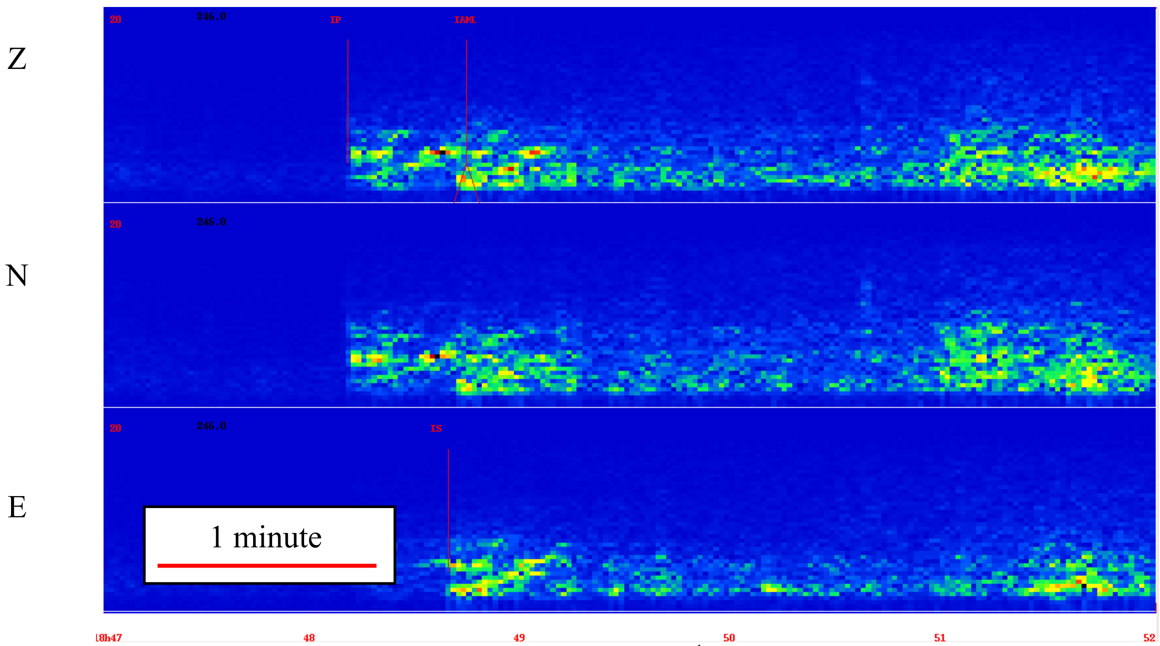


Figure 21: Spectral analysis showing event on November 2nd 2016, recorded at the SFJD station. All three components are shown. The blue background serves as neutral background indicating low energy. Colours ranging from green to orange/red is indicative of high energy at a certain frequency ranging from 0 to 20 Hz on the *y* axis. Time is seen along the *x* axis. P and S wave arrivals are marked with red lines and letters IP (P wave) S/surface wave arrival as IAML.

Looking in greater detail at the SFJD station seismogram, figure 20, there is a distinction between P and S wave arrival despite the noise. Furthermore, when looking at the spectral analysis, figure 21 above, from the same station and components as above, there is also a slight separation of the P and S phase. The spectral analysis points the attention towards another peak of energy that occurred around the time 18:51. This peak of energy is also seen on the seismogram (figures 19 and 20), but it is difficult to identify. In the spectral analysis, however, it seems that there are almost no energy between the two peaks. When comparing this to the first overview seismogram (figure 19), it is clear that these lie parallel to each other, i.e. occurred at the same velocity. They are therefore described as two tectonic earthquakes occurring right after one another.

Between the onset of the two tectonic earthquakes, only three minutes passed. The second earthquake has unfortunately not been analysed in further details other than recognizing its existence[10]. The above paragraphs are the exact reason why it is important to remember that all interpretations of seismic events in this thesis are indeed interpretations. They are not facts, though the majority of the seismic events have been analysed with confidence. It is therefore important to emphasize that both their classification, location, magnitude, depth etc. are all interpretations and are likely to vary even if same methods, as in this thesis, are applied.

[10] Due to the Corona pandemic there was not time to process this as the computer lab.

5. Discussion

The following section consists of a discussion that focuses on glacial hypocentre depth, magnitude, frequency content, and lastly seasonality and glacial earthquake/calving rates. All of the above are characteristic features of glacial earthquakes and are useful when differentiating glacial earthquakes from tectonic earthquakes. These features will be discussed in light of previous work by other researchers.

5.1 Characteristic glacial earthquake parameters

5.1.1 Magnitude

Analysis of magnitude measurements

From the data, the average magnitude is found to be ~ 2.2 M_L, which is considerably lower than the magnitude found in literature (Amundson et al., 2008; Ekström et al., 2003, 2006; Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012). As mentioned before, previous research has focused on globally measurable glacial earthquakes and measured moment magnitude, M_w. This thesis focuses on local and regional glacial earthquakes and therefore a suitable magnitude scale is a local magnitude, M_L. For this reason, one cannot compare the two types of magnitudes directly to one another.

The results of this thesis are based on 33 glacial earthquakes, with magnitudes ranging from 1.6 to 2.8 M_L. This is a very limited number of seismic events to base the magnitude calculation on. The majority of the data, see figure 22, has a magnitude between 1.8 and 2.3 M_L. Though it was claimed in the Data section that this thesis only includes earthquakes with magnitudes $M_L > 2$ it appears from the results that some magnitudes are $M_L < 2$. This is explained by interpretations obtained from this thesis differing from the interpretations by GEUS. Before the data was analyzed for the purpose of this thesis, GEUS had already done some analysis of the data. When the data was extracted from GEUS' database, a magnitude of $M_L > 2$ was set as a data requirement. However, when later analyzed for the purpose of this thesis, some earthquakes were analyzed having a lower magnitude than when analyzed by GEUS.

To showcase the data distribution, a histogram is seen in figure 22. The histogram shows the magnitude distribution of all glacial earthquakes analyzed in this thesis. From the histogram it is clear that most glacial earthquakes cluster between magnitudes of 1.8 and 2.3, with an average glacial magnitude of ~2.1 M_L. The histogram shows only few outliers outside the main data cluster.

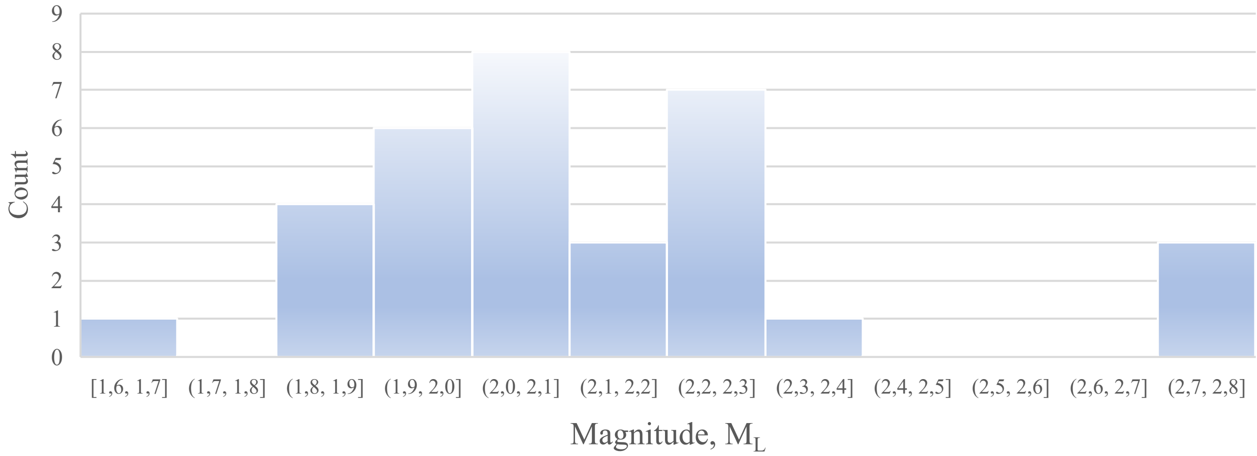


Figure 22: Glacial magnitude distribution using a local magnitude.

The apparent outlying earthquakes ($M_L < 1.8$ and $M_L > 2.4$) all occurred during the typical peak months of glacial earthquakes and were all interpreted to have epicenters close to the glacier margin. Furthermore, all but one (which had a hypocenter depth of 5.3 km) located the hypocenter automatically at the surface without manually 'fixing' hypocenter depth at 0.0 km. They are therefore considered typical glacial earthquakes, and not deemed outliers due to them possibly being tectonic. They must instead be indicative of the uncertainty of the magnitude calculation.

Despite using a different magnitude scale than the majority of the literature, it appears that there is agreement between the magnitudes measured at the 33 glacial earthquakes. Another important consideration, when looking at figure 22, is that the upper magnitude limit of glacial earthquakes is controlled by glacier thickness (Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012). If the glacier thickness is the most important control on the upper limit of glacial earthquake magnitudes, then the maximum glacial magnitude is glacier-specific. As earlier mentioned, the thickness of Ilulissat Isbræ is $\sim 900\ m$, and when looking at the magnitude distribution, figure 22, the sudden cut-off of magnitudes at 2.3 M_L could be caused by the glacier thickness. This would, however, mean that the glacial earthquakes with magnitudes around 2.7 – 2.8 M_L are misinterpreted. Either that or they might not be glacial earthquakes.

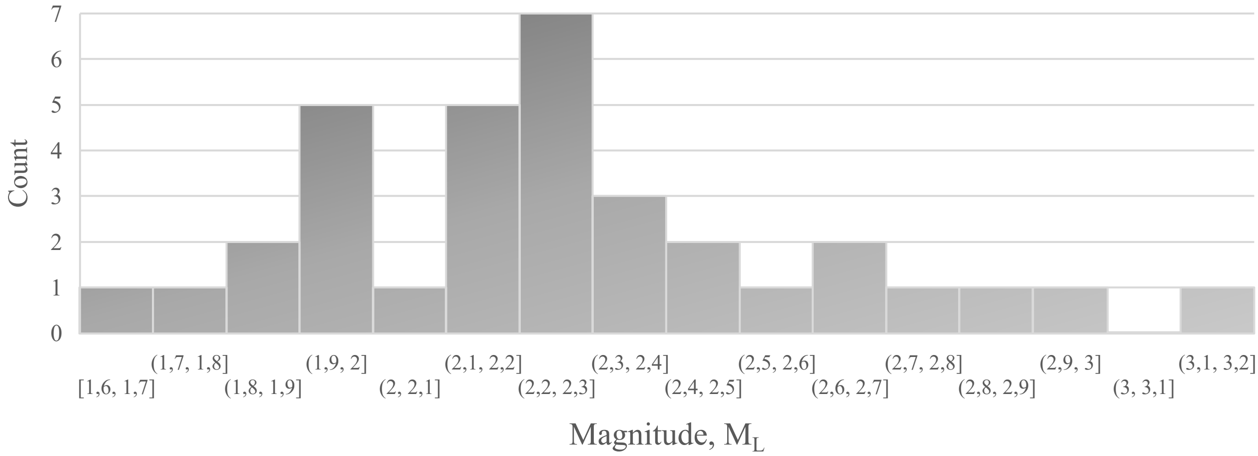


Figure 23: Tectonic magnitude distribution using a local magnitude.

Tectonic earthquakes show a wider range of magnitudes compared to glacial earthquakes. As seen in figure 23, they range from 1.6 M_L to 3.2 M_L. The wider range is expected since tectonic earthquakes technically can have magnitudes from 1 and 10 on the moment magnitude scale (Kearey et al., 2009; Lay & Wallace, 1995). Of course, high magnitudes only occur in tectonically active areas, which Disko Bay is not considered as being. The tectonic earthquakes are also focused around magnitudes $1.8 \leq M_L \leq 2.5$, with an average magnitude of tectonic earthquakes of ~2.3 M_L, only slightly higher than for glacial earthquakes. The outliers (earthquake magnitudes outside $1.8 \leq M_L \leq 2.5$) are few. Since the average of the two types are almost the same, it means that the magnitude in the data in this thesis cannot be used as a parameter to distinguish the two types from one another.

A final interesting feature when comparing glacial and tectonic magnitudes is the range $2.0 \leq M_L \leq 2.1$, which is the most common glacial magnitude, but the least common tectonic magnitude (within the main part). While there is no apparent scientific reason for this difference, it could be interesting if it turned out to be significant.

Figure 24 shows an overview of Disko Bay, which can be used to examine whether or not the data shows spatial correlation between earthquake magnitude and location. The map depicts larger magnitude earthquakes as larger circles, with a colour distinction between the two types of earthquakes.

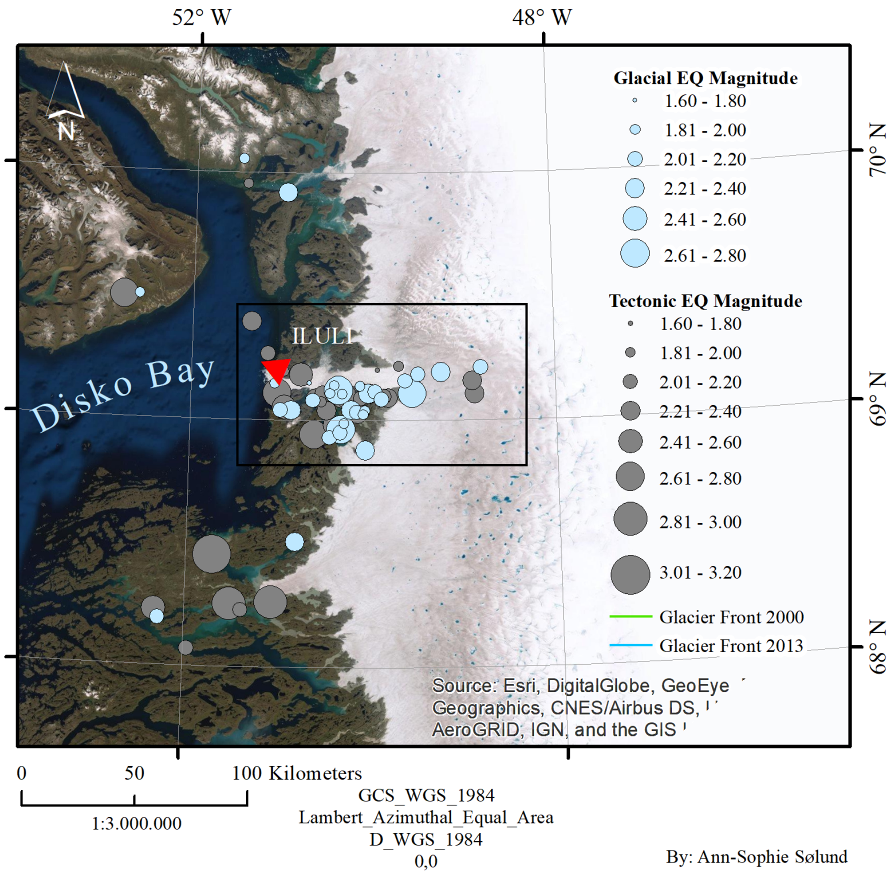


Figure 24: Map of Disko Bay, with the Ilulissat Isbræ located central in the map within the black box. Colored circles defines the two types of earthquakes: Glacial (light blue) and tectonic (grey), and the larger circles refer to larger magnitudes. **Note** that the glacier front is not depicted on the map, due to limited time in GIS due to Corona the legend was not changed in time. I can be found on figure 25.

Besides the tight clustering around Ilulissat Isbræ, there is no apparent correlation between epicenter location of neither tectonic nor glacial earthquakes and their magnitudes. This is expected for tectonic earthquakes since they are not restricted to a specific geographic location, contrary to glacial earthquakes. Three of the largest tectonic earthquakes (by magnitude) are clustered in the South-Western part of Disko Bay. This could be an indication of higher tectonic stresses and stress releases in the area. Looking at geological maps of the area, there are indeed a series of extensional faults along the coast of Disko Bay (Henriksen, 2008). See geological map in Appendix III. These events are most likely connected to the tectonic earthquakes in the area, but no specific reason explains why the three large tectonic earthquakes cluster in one particular area.

Looking in greater detail, figure 25, the tectonic earthquakes generally locate close to Ilulissat Isbræ, but not on the actual glacier. This could, however, be due to the possible systematic error as earlier mentioned. Furthermore, there is a rather large location uncertainty, which one also must keep in mind. Looking at the magnitudes of the glacial earthquakes in figure 25, it looks as if there is a tendency of higher magnitude earthquakes closer to the calving front compared to glacial earthquakes that are located further away from the calving front. Though it looks like there is a pattern in the data, it is difficult to draw any conclusions from it, based on the location uncertainty discussed in section 4.2.

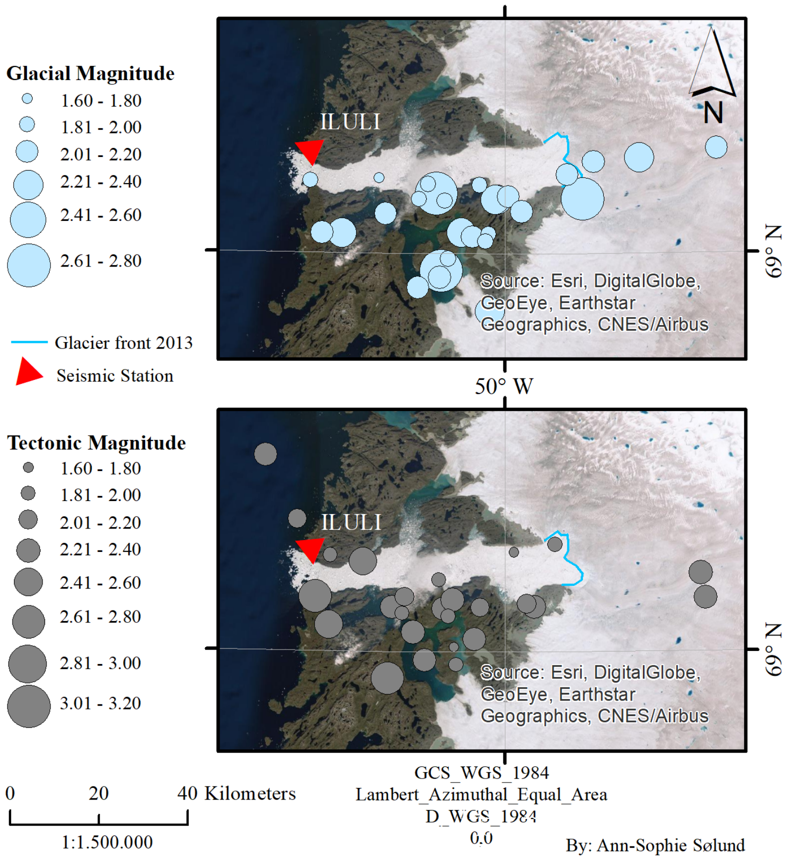


Figure 25: Overview showing location and magnitude, M_L, of all earthquakes. Note same circle size refers to different magnitudes for glacial and tectonic earthquakes.

The calving front position in 2013 is depicted on the map (figure 25), which was the most recent calving front position available[11]. Based on the development of the shape of the glacial calving front over the last couple of years, it seems that the glacier front becomes more shaped like the number '3' with time. The current shape is probably similar to the one in 2013, but with a more profound 3-shape.

As also seen in figure 8, figure 25 shows interpreted epicenter locations of all analyzed earthquakes in this thesis. If only considering earthquakes in proximity to the glacier, there is a slight

[11] GIS online database, search "Ilulissat". PROMICE shapefiles did not download correctly and could not be used.

difference in the location geometry. Comparing the spatial geometry of the glacial earthquake locations to that of tectonic earthquakes, glacial earthquakes are located more along-flow and asymmetrically compared to tectonic earthquakes. This is when considering the entire 'swarm' of glacial/tectonic earthquake as a whole.

The geometry of the tectonic earthquakes is more symmetric (circular) than that of the glacial earthquakes (linear). The geometry of glacial earthquakes has been addressed by several scientists who looked into other large outlet glaciers in Greenland (Kangerlussuaq glacier, Helheim glacier and King Oscar glacier) (Tsai & Ekström, 2007; Veitch & Nettles, 2012). The results of this thesis are in agreement with their findings of larger spreading of epicenter locations along-flow than across-flow direction. The data shows only slight asymmetry compared to their data that showed a clear asymmetric epicenter distribution. This is partly explained by their data being collected during 18 years compared to the 3 years of data used in this thesis. Though the time frame of the data is much shorter than other studies, it is interesting that the glacial earthquake data indeed does show location asymmetry over a period of just three years.

5.1.2 Hypocenter Depth

The seismic data interpretation showed a variety of hypocenter depths of the 67 seismic events included in this thesis. Some glacial earthquakes naturally occur at the surface of the Earth, while others, unless 'fixed in depth', do not, when analyzing them in SEISAN. Fixing the earthquake hypocenter depth is a method of controlling the depth at which an earthquake occurs, though it should be at the surface for glacial earthquakes. Previous researchers have fixed the hypocenter depth differently depending on the study, methods and data available. A general depth fix is between 0 and 10 km, which seems to be agreed upon by multiple researchers (Tsai & Ekström, 2007; Veitch & Nettles, 2012).

In this thesis, it is deemed sensible to fix the hypocenter at 0.0 km depth due to glaciers being the source of glacial earthquakes. However, due to uncertainties caused by a coarse data resolution (long distances between seismic stations), one must not look at the interpreted depths as final depths. It is merely a pointer to a general depth of earthquakes.

The depth calculation done in SEISAN is quite uncertain, as adjustment of arrival time of the seismic phases by just a few seconds will affect both location and depth; sometimes it is a matter of great difference when doing even minor adjustments due to the high velocity of seismic waves and the long distances between seismic stations. The un-fixed depth of the glacial earthquakes varies between 0 km and 58.4 km, and the average hypocenter depth was found to be ~11.5

km. The standard deviation of all 33 glacial earthquakes was found to be 15.1 km. This indicates a large spread of data and thereby a probable high uncertainty of the depth analysis.

SEISAN also automatically calculates a depth error in kilometers for all earthquakes, but since the depth was fixed to 0.0 km for all glacial earthquakes, this cannot be calculated for glacial earthquakes. The large depth uncertainty is also the result of coarse data resolution, which also explains why it is not possible to figure out precisely at what depth the hypocenter of glacial earthquakes actually were. The actual hypocenter depth, and whether is systematic, could be very interesting to analyze. Speculations center around whether the hypocenter is found at the surface, within or at the base of the glacier thickness. It is unfortunately not possible to address this with the data provided for this thesis. Though it could be an interesting debate, it would demand a 3D model of the glacier in order to address this properly. This could be addressed by placing a series of seismographs right on and around the glacier.

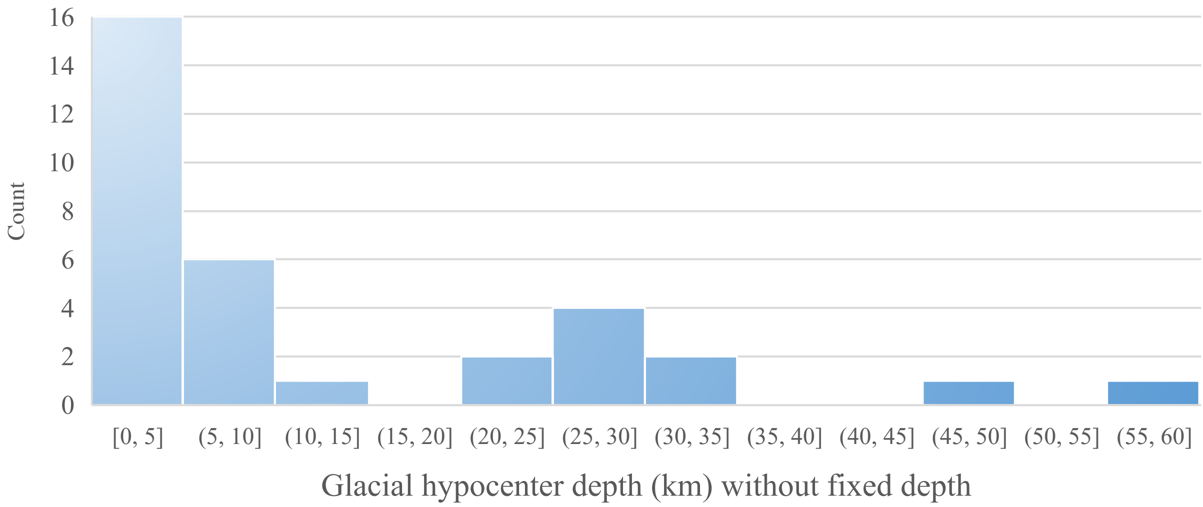


Figure 26: Hypocenter depth of glacial earthquakes.

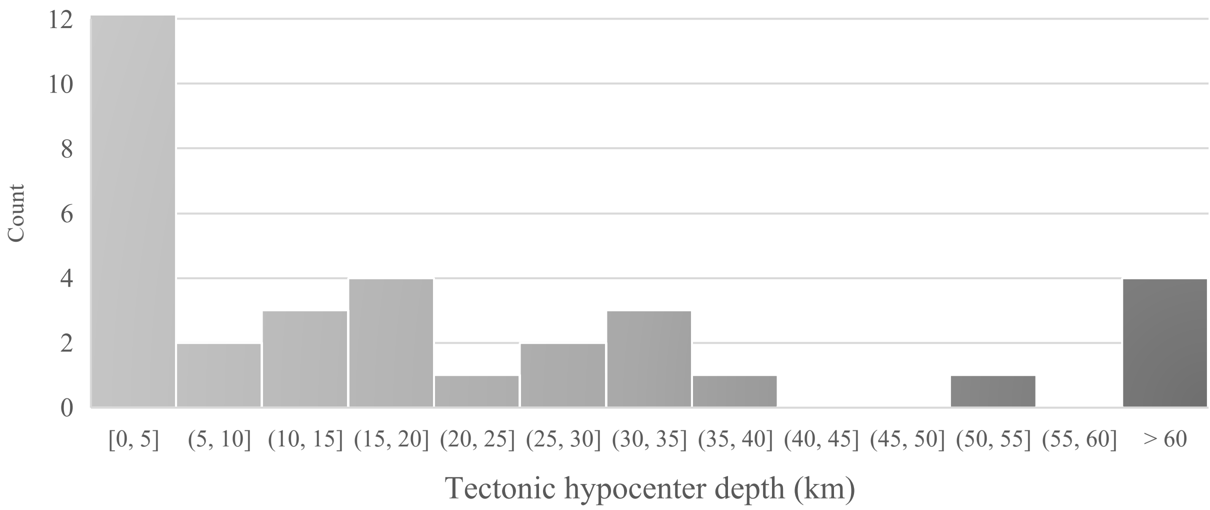


Figure 27: Hypocenter depth of tectonic earthquakes.

As seen in figure 26, almost half (48.5%) of the glacial earthquakes occurred within 5 km from the surface without being fixed in depth. Furthermore, 36.4% of the glacial earthquakes have been interpreted to have hypocenters at the surface of the Earth without being fixed in depth. This is quite a large percentage of the glacial earthquakes that naturally locate their hypocenter at the surface compared to tectonic earthquakes.

Of the tectonic earthquakes, 35.3% occurred within the top five kilometers of the surface, figure 27, but only 26.5% locates an un-fixed hypocenter at the surface of the Earth. It is evident that for both types of earthquakes the majority of data is shallow seismic events, with more glacial earthquakes having hypocenters at very shallow depths. Statistical analysis showed a tectonic average hypocenter depth of ~22.2 km, and a standard deviation of 28.9 km. This is a doubling of both average hypocenter depth and standard deviation for tectonic earthquakes compared to glacial earthquakes. The glacial earthquakes showed an average hypocenter depth of ~11.5 km, and a standard deviation of 15.1 km. This result seems fitting since it is very likely that the glacial average depth is considerably more shallow than the tectonic. Additionally, the average depth error of tectonic earthquakes was found to be ~22.2 km. The depth error cannot be calculated for glacial earthquakes, however, the following is known from results in this thesis: *1)* The average hypocenter depth of glacial earthquakes is half that of tectonic earthquakes, and *2)* The geographic location uncertainty of glacial earthquakes is lower than that of tectonic earthquakes. Therefore, it is considered likely that a supposed depth error of glacial earthquakes would be somewhere between half the depth error of tectonic earthquakes and the actual depth error of tectonic earthquakes if assuming a connection between the geographical error and the depth error. Therefore a possible glacial depth error is between 11.1 km and 22.4 km. If estimating a glacial hypocenter depth error of 15 km, this yield that 70% of all interpreted glacial earthquakes potentially occur at the surface.

Comparison of the depth distribution of glacial (figure 26) and tectonic (figure 27) earthquakes indicate that most of the seismic events occur within the upper five km of the crust. These shallow events are especially important to pay attention to. If only considering the hypocenter depth, there is a potential risk of them being misclassified due to their depth fitting into both categories of earthquakes. Seismic events are very different in terms of how 'stereotypical' they are. It is therefore likely to think that some of the deepest located glacial earthquakes could potentially be tectonic earthquakes based on hypocenter depth.

The two deepest glacial earthquakes occurred on June 3rd 2017 (03-06-2017_23.06) and on July 21st 2018 (21-07-2018_01.33) and were interpreted to occur at depths of 45.4 km and 58.4 km, respectively. The event on June 3rd 2017 is analyzed in section 4.4, where it showed multiple traits of being a typical glacial earthquakes, besides the depth. It furthermore is located almost on the glacier front margin of Ilulissat Isbræ. This is a perfect example of the uncertainty of the depth analysis, since this particular event is clearly a glacial earthquake, but locates at great depth. One must therefore not be too trusting in the hypocenter depth analysis or draw any conclusions from it.

Looking at the tectonic earthquake hypocenters in figure 27, four events are apparently located at greater depths than 60 kilometers: 64.1 km, 99.7 km, 93.3 km and 103.5 km. The mid-two events refer to the same earthquake that was recorded twice[12], and therefore there are in fact only three events with very deep hypocenters. This, as for the glacial earthquakes, is most likely affected by the large uncertainty of the depth analysis. Regardless of the absolute depth in kilometers, these three tectonic earthquakes did most likely occur deep within the earth, and probably deeper than most other earthquakes in the data set.

Another interesting aspect to investigate is the possible correlation between geographic location and hypocenter depth. Figure 28 showcases both types of earthquakes with larger circles referring to greater hypocenter depths. The distribution of the deep and shallow tectonic earthquakes appears, as expected, to be random. The two very deep earthquake east of the glacier are the two previously mentioned tectonic earthquakes that occurred at a depth of 99.7 km and 93.3 km and refer to the same earthquake. These are therefore to be seen as one deep earthquake.

Looking at the glacial earthquakes, there is a large glacial earthquake located quite far from Ilulissat Isbræ, but rather close to a smaller outlet glacier, Akuliarutsip Sermia, south of Disko Bay. This event is the same event (July 21st 2018) that stood out earlier due to its hypocenter depth (58.4 km). The earthquake is an example of a seismic event that is hard to determine whether to be glacial or tectonic.

However, when looking at the seismogram, it does look like a typical glacial earthquake, with a long duration and rather inseparable phase arrivals. On the other hand, it is located at great depth and quite far away from a glacier. It is therefore likely that there is a general misinterpretations of the first arrivals of this event. The seismograms of both multiple stations and from the SFJD station can be seen in Appendix VI. At the time of occurrence of this earthquake, the seismic station at Ilulissat was out of order, i.e. no recordings from ILULI, which could also contribute to it being more difficult to locate, since the Ilulissat station is the only station located in Disko Bay.

[12] The two events were supposed to be merged in SEISAN, but due to limited access to the computer lab at University during the Corona pandemic, this was not possible.

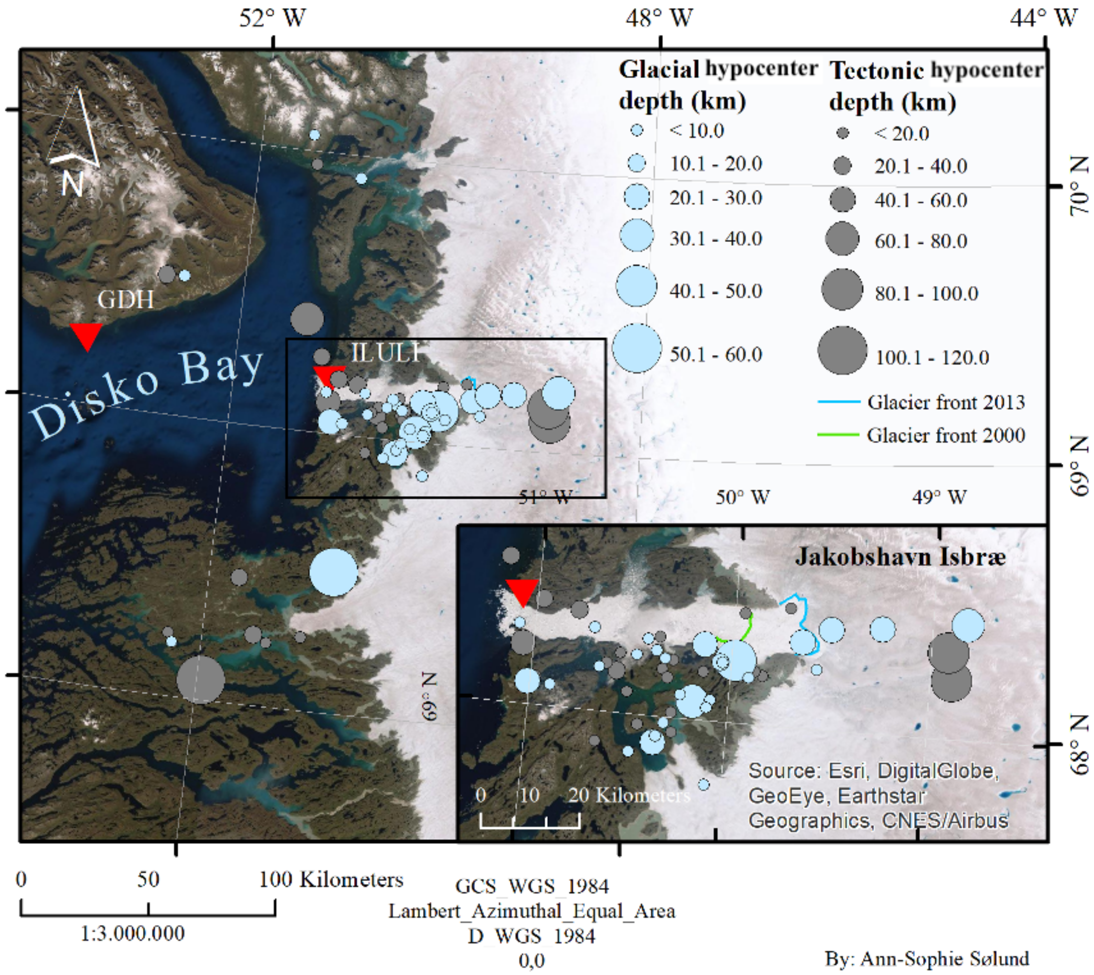


Figure 28: Overview map showing hypocenter depth of glacial earthquakes (light blue) and tectonic earthquakes (grey). Larger circles indicates deeper hypocenters. **Note** same size circle indicates a double depth for tectonic earthquakes compared to glacial earthquakes.

When looking closely at the distribution of earthquakes at the glacier, figure 28, there is no strong correlation between location and hypocenter depth in regards to the tectonic earthquakes. Looking at the glacial earthquake distribution, there are a couple of deep glacial earthquakes close to the glacier front. This is a surprising tendency since it could be feasible to think that the glacial earthquakes located closest to the glacial front would also be located at a shallow depth; if this was the case then they might be the most accurate glacial earthquake interpretations.

Since this is not the case, and when considering all uncertainties, this trend might be deemed pure coincidence. Looking at the western end of the glacier outlet, the majority of the glacial earthquakes appear to occur at shallow depths of less than 10 km. These are the glacial earthquakes that are of interest, since they automatically occur at shallow depths. When considering the average location error previously discussed, it is very likely that these earthquakes are located on the glacier calving front, though it is not possible to address this in depth with the data available.

5.1.3 Low frequency content of glacial earthquakes

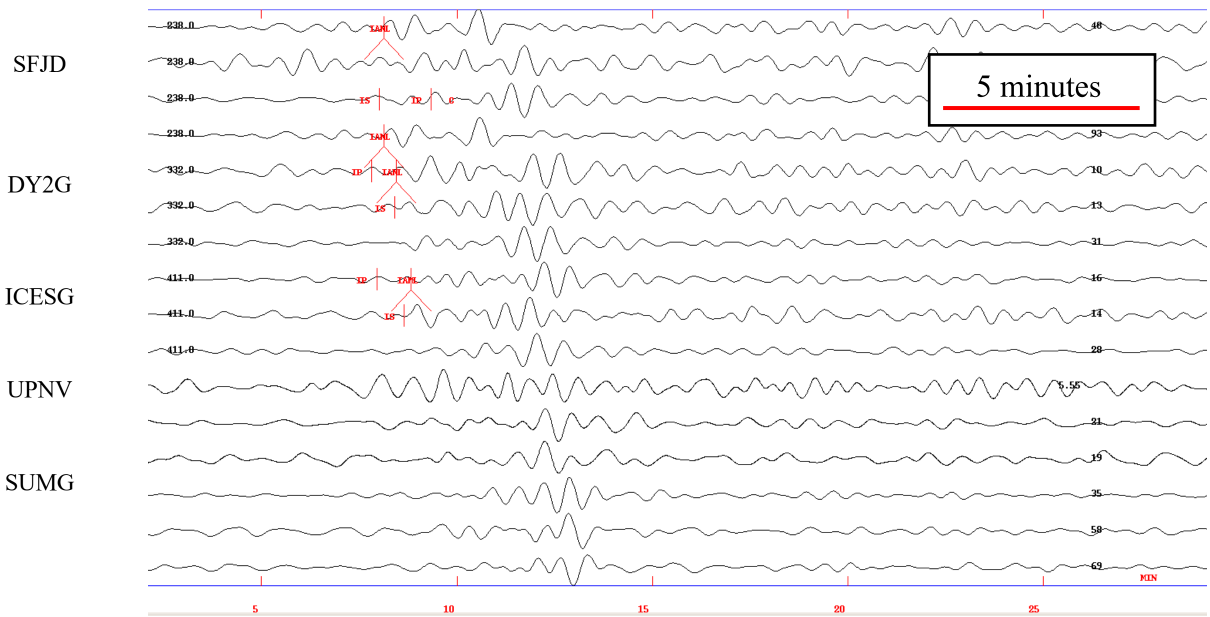
A key feature of glacial earthquakes is the low-frequency component of the signal. These low frequency energies were part of the reason glacial earthquakes remained undetected for a long while. Therefore, the frequency content of an earthquake is used to distinguish between glacial and tectonic earthquakes.

The glacial earthquakes analyzed in this section are the same as in section 4.4. They are now analyzed in terms of frequencies defined by a band pass that is filtered between 0.01 and 0.03 Hz. The dates of the events are as follows: June 3rd 2017, August 14th 2018 and August 23rd 2018.

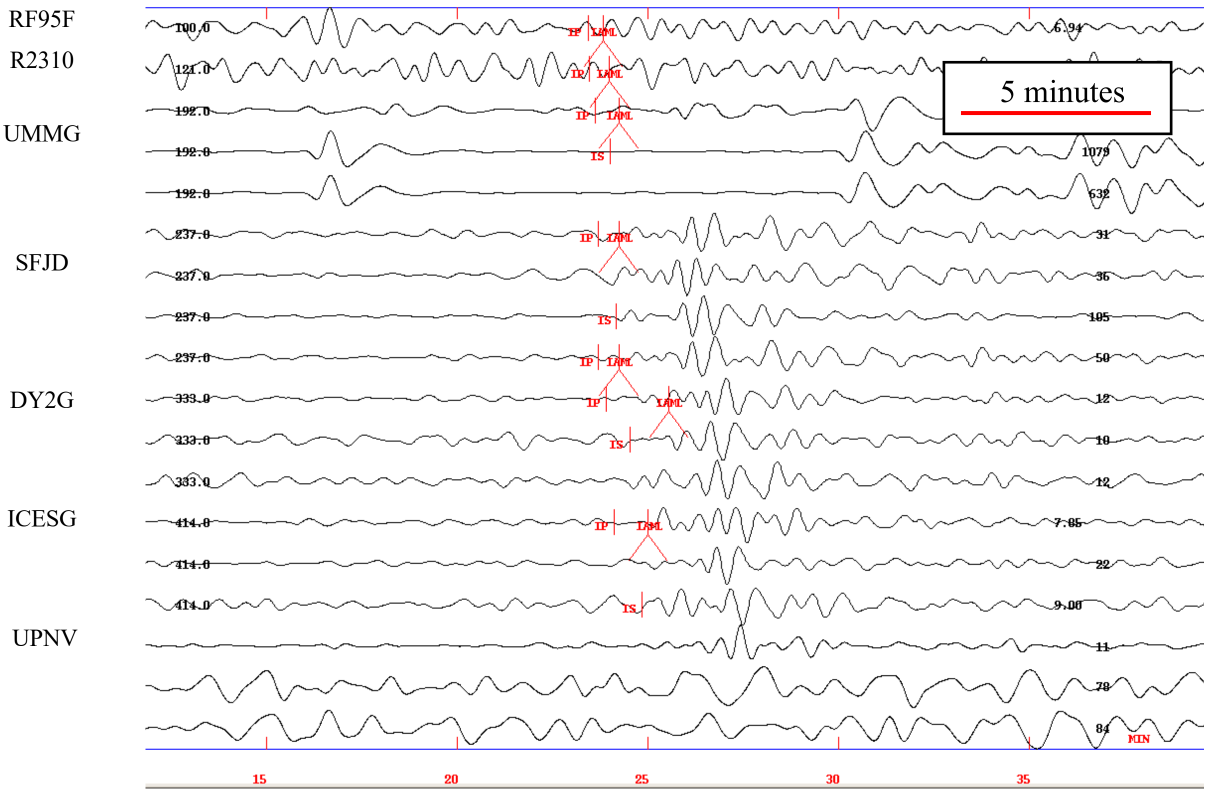
In order to analyze low frequencies, a longer time span of seismograms is needed due to the wave period of low frequencies being longer. Therefore, datafiles of 90 minutes have been extracted from GEUS' database. This is done in order to amplify the low frequency content of the seismic signal, while attenuating high frequencies. For all examples shown in figure 29, seismic stations are seen on the *y* axis, with time displayed along the *x* axis. The low frequency energy seen in figure 29 is characteristic of glacial earthquakes, and it can be used to determine whether a seismic event is glacial or not.

Figure 29 – Low frequency content of glacial earthquakes.

a) June 3rd 2017.



b) August 14th 2018.



c) August 23rd 2018.

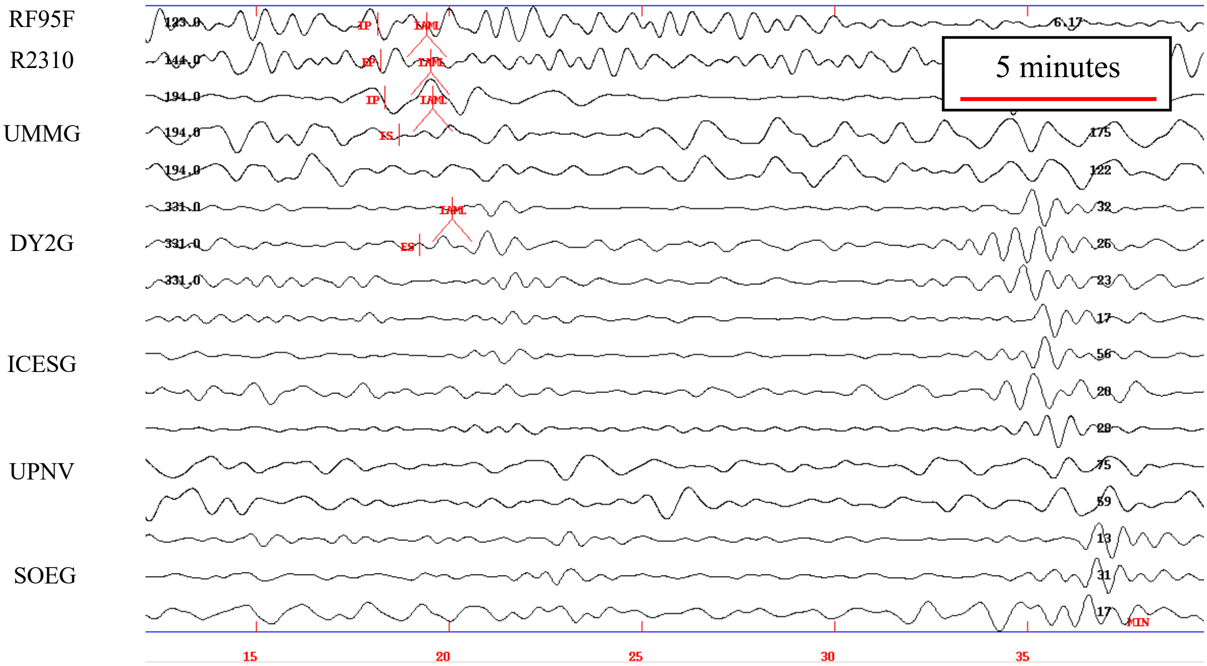


Figure 29a-c: The seismograms of three glacial earthquakes shows seismic stations (and station channels) along the *y* axis, and time in hours and minutes along the *x* axis. The time span of all seismograms is 30 minutes, and a 5 minutes scale-bar has been inserted. Red lines marked IP(impulsive P)/EP(emergent P) marks the P phase arrival. The S phase arrival is marked with IS(impulsive S)/ES(emergent S), while the red line marked by IAML indicates the maximum amplitude of the surface waves. The seismic signal is filtered for low-frequencies at 0.01-0.03Hz in order to showcase the characteristic low-frequency signal in glacial earthquakes. **Note** the distant-earthquake on the seismogram from August 23rd 2018.

For the events on June 3rd 2017 and on August 14th 2018, the low frequency energy is very prominent and stands out clearly on both seismograms. For both of these earthquakes, the main part of the seismic signal is recorded over a duration of five minutes. Hereafter, it appears that there is an elevated amount of shaking or energy for a period of time after the glacial earthquake.

This trend of elevated "glacio-seismic" activity has previously been noted by other researchers (Amundson et al., 2008). When looking at the glacial earthquake on August 23rd 2018, it differs from the two previous examples. In this event, the low frequency content is not as prominent as the previous discussed events. This could lead to an ambiguity as to whether or not this is a glacial earthquake. It must, however, be noted that the time of occurrence (August) and the location of the epicenter (on the glacier front) yields confidence in this to be a glacial earthquake. This is therefore an example of the complexity of glacial earthquakes and their seismic signals.

To showcase the difference between the low frequency content of tectonic and glacial earthquakes, a seismogram filtered at 0.01-0.03 Hz is seen in figure 30. This event on June 27th 2016 only shows a distinct signal for the most proximal stations to the epicenter (DY2G and ICESG). For seismic stations at greater distances there is no significant low frequency signal due to less energy of low-frequency waves.

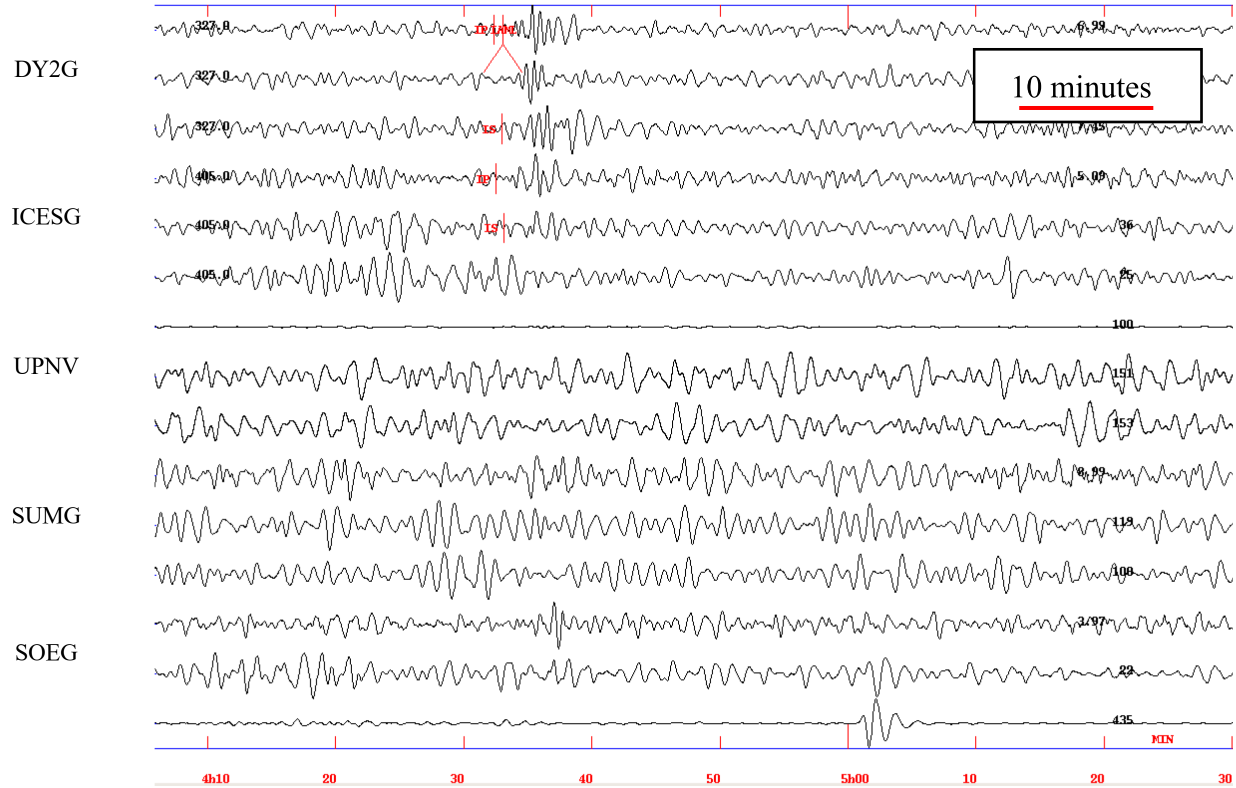


Figure 30: Tectonic earthquake filtered for 0.01-0.03 Hz. **Note** that the tectonic earthquake can only be seen on the two most proximal stations.

From the comparison of the glacial and tectonic earthquakes, it is evident that there is a clear difference in terms of the signal seen in seismograms, when looking only at the low frequencies. This is in agreement with literature and seems to be an efficient way to distinguish between glacial and tectonic earthquakes. Compared to the previous sections regarding hypocenter depth and magnitude, it seems that they are less accurate parameters to analyze with the given data, and no firm conclusions came from either parameters. On the other hand, when looking at the low-frequency content of the seismic signal, it appears to be the most effective parameter to analyze, when trying to distinguish between the two types of earthquakes. If possible, it would be beneficial to have the 90 minutes seismograms for all 67 seismic events included in this thesis. This was, however, not possible to have due to long extraction time from GEUS' database. Therefore, only a few representative seismograms were analyzed.

5.2 Seasonality and temporal changes in calving rate

The seasonality of glacial earthquakes is considered the result of increasing temperatures during the summer months. This increase in temperature leads to an increase in melt water, which is transported down through the ice to the ice-bedrock interface, where it consequently lowers the effective friction at the base of the glacier (Das et al., 2008). This is believed to be a plausible reason for the higher number of glacial earthquakes during the late summer, since only a few glacial earthquakes occur during cold winter months (Ekström et al., 2006; Meredith Nettles & Ekström, 2010; Tsai et al., 2008). This does not imply that an earthquake occurring in late summer excludes the possibility of it being tectonic. If an earthquake in general fits the characteristics of a glacial earthquake, and furthermore occurs in the late summer, the confidence in the interpretation of it being glacial is increased. Aside from the aforementioned higher temperatures during summer leading to an increase in glacial melting, there is also another possible reason for glacial earthquake seasonality. A study at the Helheim Glacier in East Greenland found interesting changes in calving style during the year. They observed a tendency of more tabular and wider icebergs forming at calving events during the winter months. These icebergs are more gravitationally stable, and thereby more likely to remain standing upright after calving. The calving events of this type have been referred to as ‘silent’.

Scientists have noticed what appears to be a direct correlation between the seasonality of glacial earthquakes and glacier retreat and advancement patterns. They have concluded that glacial earthquakes are most often associated with glacier retreat, which occurs mostly during the summer months when temperatures are rising (Ekström et al., 2006; Meredith Nettles & Ekström, 2010; Veitch & Nettles, 2012). Though glacial retreat, and glacial earthquakes, are most common during the summer months, periods of glacial advancement during the summer are possible. The general pattern, however, is a net retreat during the summer and net advance of the calving front during the winter months (Veitch & Nettles, 2012).

5.2.1 Calving and glacial earthquake rate studies

A study by Sohn et al. (1998) of seasonal changes in calving rate at Ilulissat Isbræ concluded that the summer calving rate (May-August) was around six times higher than the winter calving rate (September-April). The study focused on calving rate and ice loss rather than the number of glacial earthquakes, which is slightly different from the focus of this thesis. Since the data in this thesis includes only glacial earthquakes, the actual number of calving events is unknown and supposedly higher since it is highly likely that not all calving events result in a measurable glacial earthquake. Especially because this thesis only includes seismic events with magnitudes $M_L > 2$. For this reason, all potential glacial earthquakes, calvings and/or shakings with lower magnitude are not included.

All things considered, the study by Sohn et al. (1998) reported a summer calving rate 'about 6 times higher' than the winter rate. To compare this to the data in this thesis, a 'glacial earthquake rate' has been calculated using the same method as Sohn et al. (1998). This is different from a calving rate, but somewhat comparable to the 'glacial calving rate' found by Sohn et al. (1998).

The results by Sohn et al. (1998) show a lower calving rate compared to

a)

Total number of earthquakes during 2016 to 2018			
	Glacial Earthquakes	Summer	Winter
January	0		0
Febuary	1		1
March	0		0
April	0		0
May	4	4	
June	7	7	
July	5	5	
August	11	11	
September	2		2
October	2		2
November	1		1
December	0		0
SUM:	33	27	6
Seasonally average per month		6,75	0,75
Probability for a summer GEQ		**9**	

Figure 31a-b: Supposed 'Summer' and 'Winter' months are colored orange and blue respectively inspired by the seasonal division made by Sohn et al. (1998). Numbers in column "Glacial Earthquakes" (GEQ) stems from a) data in this thesis (years 2016-2018) found in Appendix V and b) merged catalogue by Nettles et al. Columns "Summer" and "Winter" included numbers of the respective months in the respective season only. The red histograms show seasonality as the accumulated glacial earthquake count for each month (2016-2018). **Note** both a) and b) show clear seasonality with the majority of glacial earthquakes during the summer. **Note** GEQ is the abbreviation used for Glacial Earthquake.

b)

Total number of GEQ at Ilulissat Isbræ 1993 to 2013			
	Glacial Earthquakes	Summer	Winter
January	2		2
Febuary	3		3
March	2		2
April	3		3
May	9	9	
June	15	15	
July	16	16	
August	10	10	
September	7		7
October	0		0
November	2		2
December	2		2
SUM:	71	50	21
Seasonally average per month		12,5	2,625
Probability for a summer GEQ		**4,76**	

the analysis from this thesis, which showed nine times more glacial events during the summer months than the winter months. The results are seen in figures 31A for the data in this thesis (2016-2018) and 31B for a merged catalogue of data by multiple researchers (1993-2013) (Olsen & Nettles, 2017; Tsai & Ekström, 2007; Veitch & Nettles, 2012). The merged catalogue contains data from 1993 to 2013 and can therefore be used to compare to the data in this thesis in order to set it into a temporal context. Though there is no temporal overlap between the two data sets, they can still be compared to examine if there is a temporal change in calving rate at Ilulissat.

Table 6 shows the summarized results that have been made using data from multiple researchers over the years in order to see how they compare in terms of glacial earthquake/calving rate. The calving rate found by Sohn et al. (1998) seems to be in congruence with the results of this thesis. It is important to keep the temporal aspect in mind, as there is more than 20 years between the two studies, and it would therefore not be surprising if the calving rate at Ilulissat Isbræ has changed, especially when considering climate change. This thesis and Sohn et al. (1998) both show a clear difference between the number of glacial earthquakes during the summer compared to the winter.

Table 6

My results Ilulissat Isbræ (*2016-2018*)	*Sohn et al.* Ilulissat Isbræ (*1998*)	*Merged catalogue* Ilulissat Isbræ (*1993 - 2013*)	*Merged catalogue* Greenland (*1993 - 2013*)
9	~6	4.76	1.84

Table 6: Multiple different data sets have been used to calculate the summer versus winter glacial earthquake rate at Ilulissat glacier: this study, Sohn et al., Olsen & Nettles, Tsai & Ekström and Veitch & Nettles. The two columns on the right are made from the same merged catalogue (data set consisting of data from multiple researchers) and are merely included to show differences in calving rate on a longer time scale and for all of Greenland. **Note** how the calving rate for all of Greenland is remarkable smaller than any of the 'only Ilulissat' calving rates.

The merged catalogue data also focused on glacial earthquakes rather than ice calving events in the period from 1993 to 2013. Using the same partitioning of summer and winter months, a glacial earthquake during the summer is 4.8 times more likely than a winter-glacial earthquake, when looking at Ilulissat Isbræ for the period between 1993 to 2013. This number is 1.8, when looking for all researched outlet glaciers in Greenland for the same time period. Both numbers are considerably lower than both this thesis and the study by Sohn et al. (1998). It can thereby be concluded that the Ilulissat Isbræ show considerable stronger seasonality than the average Greenlandic outlet glacier. This could be linked to higher glacier activity as Ilulissat Isbræ due to it being one of the most active outlet glaciers in the world ("UNESCO World Heritage Centre - Publications," n.d.).

The results in this thesis showed that glacial earthquakes occurred nine times more often during the summer months compared to the rest of the year. This is considerably higher than any of the other calculations and could be explained by several reasons. One immediate reason is subjective interpretation of data. If more inclined towards defining a summer-earthquake as glacial compared to other researchers, it could explain the high number. Subjectivity is, however, not considered to account for such difference.

Another thing to evaluate is the 'data time frame' and 'number of seismic events included in the data'. These are important factors when looking at the glacial earthquake rate during the summer compared to winter. Longer time spans of datasets will result in a broader and more general earthquake/calving rate over a long time period, whereas e.g. the data in this thesis has a limited time span and therefore is more specific to the time period of interest. It is also likely that Ilulissat Isbræ is more active today in terms of glacial earthquakes compared to e.g. 20 years ago.

Finally, the number of seismic events in the data set is also an important factor. This thesis only includes 33 glacial earthquakes, which is a limited number of events to base sound conclusions on. Here, the addition or subtraction of even one glacial earthquake has a rather large effect on the glacial earthquake/calving rate. Since the number of glacial earthquakes in Disko Bay are natural occurrences and are the result of rising temperatures, one cannot ensure more glacial earthquakes per any unit of time. This leaves 'longer time spans of research' as the only option of having more seismic events to base conclusions upon. The above is of course not considering the connection between global warming and glacial earthquakes, which will be addressed later.

5.2.2. Seasonality of glacial earthquakes

To address the question of seasonality of both tectonic and glacial earthquakes, figure 32 shows an overview of all earthquakes from 2016 to 2018. From the figure it is clear that the majority of earthquakes happened in the summer with almost no earthquakes in spring or winter. Note that the histogram shows no distinction between tectonic and glacial earthquakes; it simply states the number of any type of earthquake at Ilulissat Isbræ.

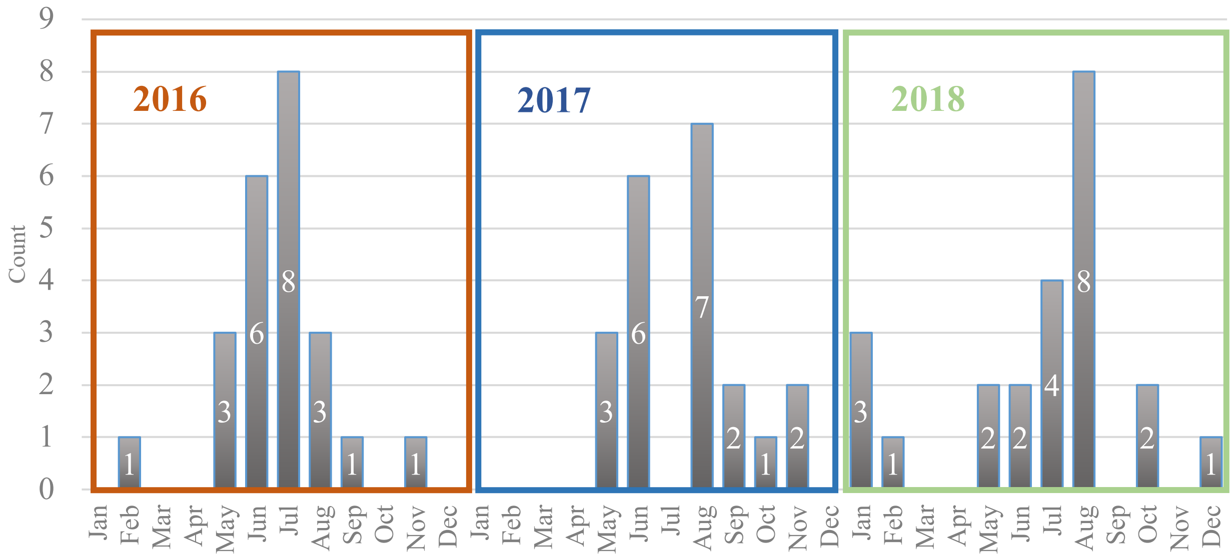


Figure 32: Overview of the number seismic events per month from 2016 to 2018. Each box – red, blue, green – frames one year. The months of every year are seen along the *x* axis, starting with January 2016 on the left and endning in December 2018 on the right. Number of seismic events are seen along the *y* axis. **Note** the apparent seasonality in the data, regardless of type of earthquake.

Seasonality is quantified above with a clear overload of seismic events during the summer months. This fits well with the nine times higher summer glacial earthquake rate discussed in the previous section. This is despite the previous section only taking glacial earthquakes into account while the figure above looks at both types of earthquakes. The pattern in figure 32 is rather surprising, since half of the seismic events are tectonic earthquakes and should not be seasonally affected. Comparing the graph in figure 33 with figures 14a-c, it appears that it is especially the high number of tectonic earthquakes in July 2016 (14a) and partly August 2018 (14c) that affects the apparent seasonal pattern when looking at the monthly average of tectonic earthquakes in figure 32. The explanation for the seasonality of tectonic earthquakes might therefore be explained by July 2016 and August 2018 being months of high tectonic activity in Disko Bay.

Despite both types being more frequent during the summer and late summer, seasonality is more contributed to glacial earthquakes than to tectonic earthquakes, as glacial earthquakes outnumber the tectonic earthquakes in the summer. This is evident from figure 33, where splitting the data into glacial and tectonic earthquakes does not change the pattern dramatically. This was also expected, due to knowledge from previous sections about the seasonal pattern of earthquakes.

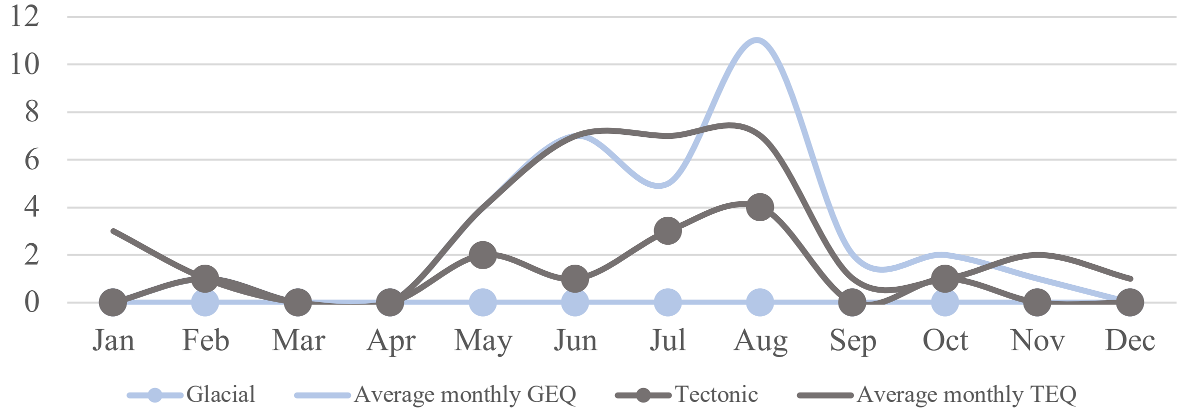


Figure 33: Annual variation in number of glacial (blue) and tectonic (grey) earthquakes. Solid lines with circles show the average monthly number of glacial (GEQ) and tectonic (TEQ) per month, for the period 2016 to 2018. The lines without circles show a summed monthly number of earthquakes for 2016-2018.

The tendency of more earthquakes occurring during the summer months is highly unexpected, and should not be the case. To examine tectonic earthquake seasonality, a portion of the seismic events have been extracted, because they were ambiguous and difficult to interpret as either tectonic or glacial. Nine events have been extracted from the total 67 seismic events and can be seen in Appendix I. These events could potentially be very significant in terms of the general seasonal pattern, since they comprise a decent portion of the total data set. Dividing the ambiguous events into which month and year they occurred in helps clarify if they are significant and thereby bias the seasonal pattern.

Of the nine events, five were interpreted as glacial (occurred in May, June, July and August), and four as tectonic (occurred in January, July and August). All glacial events adhere to the typical seasonal pattern and must be considered as glacial earthquakes. Of the four tectonic earthquakes, three occurred during the summer months (one occurred in July 2016, one in August 2017 and one in August 2018). The tectonic events are spread nicely over the three-year period of interest, but do occur during the summer, which could potentially mean that they are glacial. This is, however, a very limited reason to base any conclusion upon.

When looking at the seismograms, there is no clear either tectonic or glacial interpretation. No significant pattern of doubtful interpretation of the tectonic events, and therefore no particular reason why these tectonic events would bias seasonality due to them being wrongfully defined as tectonic earthquakes. It must be kept in mind that the period of time that the data covers is three years; the high number of tectonic earthquakes during the summer might therefore be explained by there simply being more tectonic activity during the period of interest.

5.3 Glacier climate sensitivity

When discussing glacial earthquakes, it is sensible to discuss them in connection with climate change. Glaciers are very dynamic features and undergo large changes annually in terms of glacier growth and decay. As a result of recent studies of the Greenland ice sheet, researchers found that glaciers respond quickly to changes in climate (Ekström et al., 2006). They typically advance during the winter and retreat during the summer half of the year, i.e. this is the most common period of glacial earthquakes.

The increase of atmospheric as well as oceanic temperatures is a general concern in regards to glacial earthquakes, which are becoming more frequent due to the warming of the climate. This leads to increase in glacial melting, thinning and speed-up. Looking at Ilulissat Isbræ, it was found to undergo thickening from the early 1990s until 1997, and then thinning rapidly with a peak rate of ∼15 m/yr (Joughin et al., 2004). This speed-up meant an increase of mean glacier velocity of 5.7 km/yr in 1992, which in 2003 had risen to a maximum of 12.6km/yr (Joughin et al., 2004). Periods of glacier 'slow-down' and 'speed-up' are found to correspond to periods of respectively glacier thickening and thinning. Therefore, a general thickening of the Ilulissat Isbræ occurred between 1992 and 1997, which was replaced by a period of thinning from 1997.

This supports Sohn et al. (1998), who found a ∼6 times higher summer to winter calving rate, since the glacier was in a period of thinning in 1998. The rapid thinning continued until 2016, where each consecutive year had an annual net-retreat of the glacier front. This resulted in a total surface elevation drop of ∼160 m compared to the 2003-level of the glacier front. The long period of retreat and thinning of Ilulissat Isbræ is believed to have contributed to what is equivalent to ∼0.9mm to the global mean sea-level rise between 2000 and 2010 (Khazendar et al., 2019). The consecutive thinning of the ice sheet until 2003 also explains the collapse and disintegration of the floating ice tongue at Ilulissat Isbræ in 2003, and is the reason for the high glacio-activity of the glacier.

Finally, in 2016 the glacier began to thicken. According to a study by NASA from 2016 until 2018, they documented a three-year continuous advance of the Ilulissat Isbræ glacier front. This change in advance-retreat pattern was contributed to the decrease in temperature of arctic ocean currents[13]. This theory was agreed upon by other researchers, who found that the ocean temperature in the upper 250 m of the water column had cooled to the 1980s temperature level (Khazendar et al., 2019).

As per 2019, the Ilulissat Isbræ is currently re-advancing, slowing and thickening. Therefore, it might explain a possibly lower than usual number of earthquakes included in the data set. The retreat and advance of the glacier front and the position of the grounding line of Ilulissat Isbræ are likely important controls on both the number of calvings and glacial earthquakes measured.

6. Conclusion

In this thesis, multiple characteristic parameters of glacial earthquakes have been investigated and interpreted in order to address 67 earthquakes in Disko Bay. As the result of seismic analysis, 33 seismic events were interpreted as glacial earthquakes, leaving 34 being interpreted as tectonic earthquakes. The focus of this thesis is the glacial earthquakes at Ilulissat Isbræ, which turned out to be the main glacier of the glacial earthquakes in this thesis; only a few occurred at other smaller outlet glaciers in Disko Bay. The location analysis showed a tight cluster of especially glacial earthquakes close to Ilulissat Isbræ, while the tectonic earthquakes were randomly distributed across a wider area.

It was found that there is a tendency of southern placement of all seismic events in regards to the glacier. This possible displacement might be explained by a flawed crustal model or the geometry of seismic stations in Greenland. Ilulissat Isbræ is known to be one of the most active marine terminating outlet glaciers in the world, accounting for a large amount of the glacial earthquakes in Greenland. Of all seismic events at Ilulissat Isbræ, both typical and atypical earthquakes have been analyzed and it can be concluded that the difference between glacial and tectonic earthquakes can be very clear, but there are also ambiguous earthquakes showing traits of both types of earthquakes (glacial and tectonic). Therefore, this thesis looked into different earthquakes parameters such as: location, magnitude, hypocenter depth and seasonality.

[13] https://climate.nasa.gov/news/2882/jakobshavn-glacier-grows-for-third-straight-year/

The average glacial magnitude, $\sim 2.1\ M_L$, in this thesis is considerably lower than what is stated in literature ($4.6\ to\ 5.2\ M_W$). This is reasoned by a difference in magnitude scale used in this thesis, M_L, compared to other studies, M_W. The lower magnitude of glacial earthquakes is therefore expected. Comparing the glacial to the tectonic average magnitude, $2.3\ M_L$, it is found that the magnitude range is broader for tectonic earthquakes; however, the majority of the earthquake have magnitudes between 1.8 and $2.4\ M_L$, which is also the typical interval of glacial earthquakes. Looking at the relationship between earthquake epicenter locations and magnitude, there appears to be no solid spatial correlation. Glacial and tectonic earthquakes are therefore very similar in terms of magnitude, and it is therefore not considered a determining factor when distinguishing between the two types of earthquakes.

The glacial hypocenter depth is defined as 0.0 km due to glaciers being the seismogenic source of glacial earthquakes. From the results, approximately half of all glacial earthquakes in this thesis had hypocenters within five kilometers of the surface. The average hypocenter depth of glacial earthquakes was found to be 11.5 km, while being 22.2 km for tectonic earthquakes. The doubled average depth of tectonic earthquakes is expected seeing that they are not, unlike glacial earthquakes, depth-restricted. This is supported by 70% of all glacial earthquakes having hypocenters within 15 km of the surface. 15 km are furthermore the estimated depth uncertainty of glacial earthquakes. Therefore, the surficial nature of glacial earthquakes is an undeniable characteristic. Despite the results of the depth analysis, no firm conclusions can be made due to the high uncertainty of the depth analysis.

A more characteristic parameter used to distinguish tectonic earthquakes from glacial earthquakes is the low-frequency content of the seismic signal. The low frequencies, 0.01-0.03 Hz, are found to be much more profound for glacial earthquakes compared to tectonic earthquakes.

According to the results, both tectonic and glacial earthquakes show seasonality, even though the tectonic earthquakes should be randomly distributed during the course of a year. The apparent seasonality of tectonic earthquakes might be explained by misclassification or coincidentally high tectonic activity during the summers of especially 2016 and 2018.

Looking into the seasonal calving rate of a study Sohn et al. (1998), it showed a ~ 6 times higher calving flux during the summer compared to winter. This was a ~ 9 times higher glacial earthquake rate compared to the data in this thesis. Though the two studies, this thesis and Sohn et al. (1998), did not look into the exact same parameter, the results are in congruence with one another when considering the temporal separation of the two studies. For a more direct approach, the data in this thesis was compared with merged data from Greenland from 1993 to 2013. Here, the glacial earthquake rate during the summer was ~ 1.84 higher than the winter rate, when looking at data from all of Greenland, and ∼4.76 higher when looking at Ilulissat Isbræ in the same period. This solidified that Ilulissat Isbræ shows strong seasonality.

Lastly, based on all sub-discussions of glacial earthquake characteristics, it is concluded that the results of previous work are in general in congruence with the findings in this thesis, in terms of earthquake location, hypocenter depth, frequency content, as well as seasonality of glacial earthquakes. When trying to compare glacial earthquakes to tectonic earthquakes, the parameters that were the most characteristic of glacial earthquakes are: the proximal epicenter location to glaciers, the earthquake duration, seismic phase separation or lack hereof, shallow hypocenter depth and the low-frequency content. These are therefore deemed mostly effective, when trying to distinguish between the two types of earthquakes.

7. Further studies

Due to glacial earthquakes still not being fully understood, there is a variety of possible research that would be interesting to investigate in further detail. One possibility is to look at newer data from Disko Bay, since more seismic stations have been installed in the Disko Bay in order to increase the spatial resolution of seismic data in Greenland. The new seismic stations have been installed after 2018 and are currently in operation[14].

Another possible further study could be an investigation of whether the hypocenter of glacial earthquakes occur at the surface, within or at the base of the glacier. This question was brought to attention by William Colgan and would most likely demand a 3D model of Ilulissat Isbræ, meaning that seismographs would have to be installed all around, and on, the glacier in order to be able to evaluate such question. The main limitation in this thesis is therefore the low seismic station density in Greenland. It could therefore be interesting to see how a higher seismic station density would change the results of this thesis.

Lastly, it could be interesting to investigate the possible relation between supraglacial lake drainage events and glacial earthquakes, and whether there is a temporal correlation between the two. It could be done by comparing known glacial earthquakes to known drainage events, but due to the limitations of this thesis it was sadly cut out of the scope. It is, however, a really interesting possible correlation that would be of great interest for future research.

[14] Reference is conversations with Trine Dahl-Jensen

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Appendices

Appendix I – Ambiguous seismic events

Nine events proved to be very difficult to interpret. These were spread out through the whole period of interest. Their date, location, magnitude etc. can be found in the table below:

Date	Location	Lat. error (km)	Long. Error (km)	Mag. (M_L)	RMS	#Sta-tions	Depth (km)	Non-fixed depth (km)	Depth error (km)	Type
19-05-2016_08.28	69.148 , -51.080	3.10	16.80	2.0	0.60	5	0.0F	5.30	-	Glacial
26-06-2016_06.50	69.111 , -49.569	7.60	18.60	2.8	1.20	7	0.0F	0.00	-	Glacial
26-06-2016_07.01	68.195 , -52.271	10.10	58.30	2.1	2.00	6	0.0F	0.00	-	Glacial
29-07-2016_08.57	68.452 , -51.716	1.40	14.20	3.2	0.10	3	31.30	-	5.50	Tectonic
20-09-2016_03.34	69.501 , -52.602	8.70	36.20	2.0	1.30	5	0.0F	1.50	-	Glacial
13-08-2017_11.57	69.399 , -51.347	15.70	80.00	2.3	1.40	5	64.10	-	21.50	Tectonic
25-01-2018_18.00	69.148 , -50.366	14.70	59.70	1.9	2.10	5	19.80	-	22.60	Tectonic
10-08-2018_10.28	69.089 , -50.341	8.10	34.40	2.3	1.30	7	18.80		17.30	Tectonic
29-08-2018_08.30	69.154 , -50.701	5.00	24.80	1.6	0.90	4	0.0F	0.00	-	Glacial

Table column description left to right: Date (ddmmyyyy_hh:mm), location (latitude, longitude), latitude error (km), longitude error (km), magnitude (local M_L), RMS (summed), Number of stations used for locating, calculated depth to hypocentre (F marks fixed hypocenter depth), non-fixed depth (only applies to glacial earthquakes), depth error (km) (only applies to tectonic earthquakes), interpreted type of earthquake.

Appendix II – SEISAN

The SEISAN software is built simply and consists of a Linux command window from which one can plot any event, pick phases, determine amplitude, locate it etc. All interpretation is made in the programme "eev" within SEISAN, are done via single or double digit (letter or number) commands, which yields for easy manoeuvring of the software.

Link: https://seis.geus.net/software/seisan/node56.html

Main commands are used. These are seen below:

?	See list of EEV commands	*z,x,v,b,n,m*	Change between frequency filters
enter	Move forward to next event	*0…9*	Phase picking
b	One event back	*0*	Phase picking: ground roll
f	Move forward to next event (when in plot mode)	*r*	Redraw / e.g. update screen to new filter setting
t	Toggle between single and multi-trace view	*d*	Delete phase pick
e	Edit event / S-file	*po*	Plot event in default multi trace mode
22	e.g. Go to event #22	*l*	Locate
tt	Show only header line of an event	*I*	On/off theoretic "arrival time"
w	Check waveform files to an event	*q*	Quit program
o + p + o	"Options" >"Picked" >"OK", a way to sort for only 'picked' stations	*W*	See all stations

Most common phase picks, and their keyboard keys (1…0)

1: IP (Impulsive P phase)
2: EP (Emergent P phase)
7: IS (Impulsive S phase)
8: ES (Emergent S phase)
0: ESg (Surface ground roll)

<u>Tips n' tricks for locating earthquakes:</u>

- Use as low-frequency filters as possible, if phase picking without applying filter is possible this is favorable.

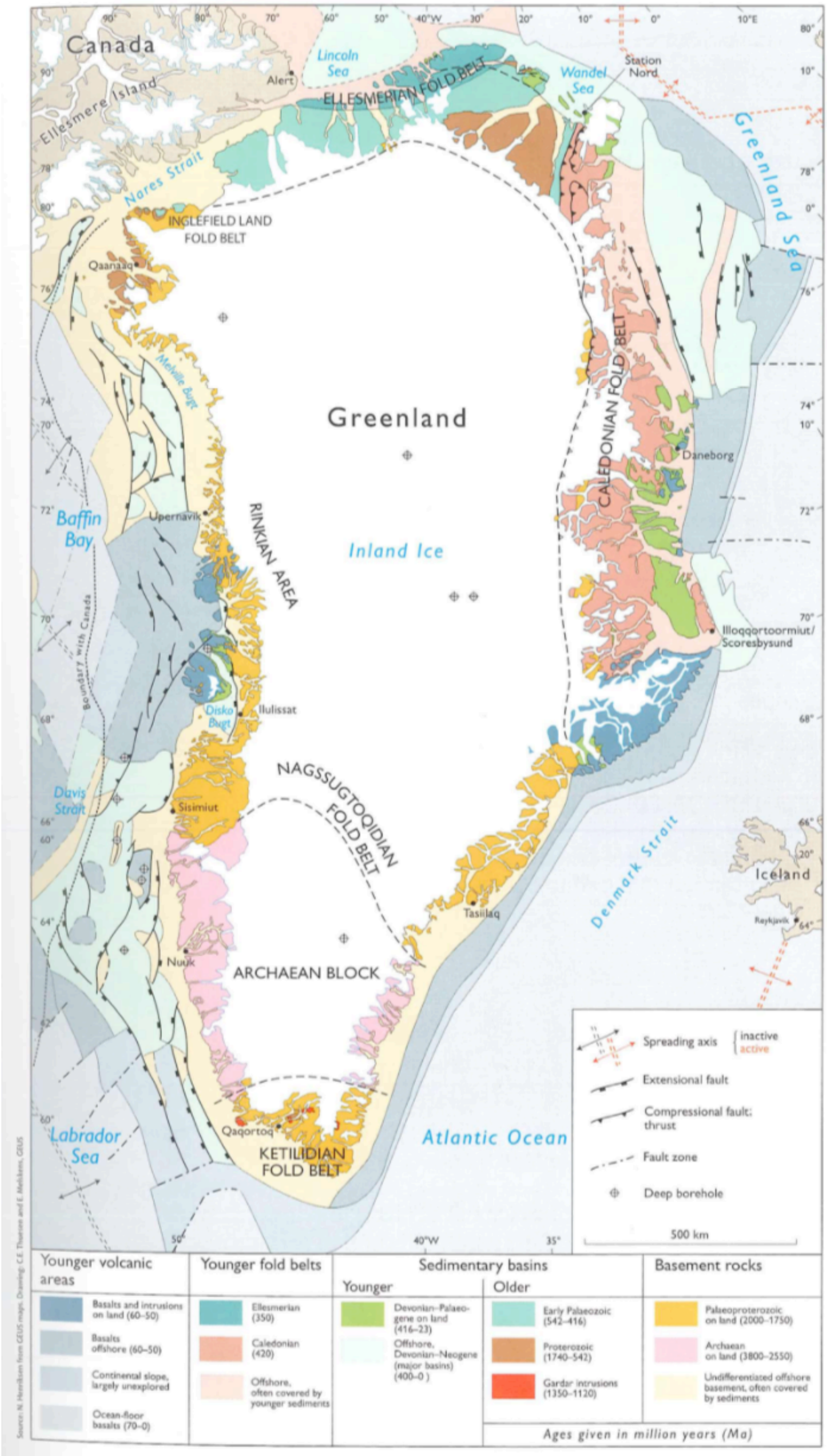
- To get an approximate location of an event that is hard to locate, try picking the surface wave ”0” phase (ESg, surface waves) where the maximum amplitude is situated. This helps with approximating the theoretical first arrival of P and S phase. Then the correct arrival might be picked from this theoretical run times.
- Change of weights (0 (100%), 1(75%), 2(50%), 3(25%) and 4(0%)) if you have comfort in a certain phase arrival, and it does not match the theoretical run times.
- Use "*y*" to toggle for a specific station, and "*t*" for toggle a certain channel of a station.
- If a certain feature is interesting but not a phase arrival then it can defined as either E or I, which are marks without weight.
- A summed root-mean-sq. of less than 2.0 is acceptable, sometimes this is hard to achieve with glacial earthquakes.
- When SEISAN has calculated a location, look at root-mean-sq. for each station/phase, if one stand out then consider looking at that particular station/channel again.
- Fix or unfix the depth of an earthquake by the command "*fix*".

For picking the correct amplitude:

- Use Wood-Anderson filter (and read it from the max amplitude after the S wave arrival).
- Max. amplitude is measured within one oscillation, but sometimes a slight "crank/bend" in the sinuous form is allowed.
- '*A*' measure automatic amplitude, beware not always correct.
- A local magnitude scale, IAML, is used.
- The maximum amplitude is often located at roughly the same location in the wave train.
- Amplitude is measured within the high frequency part of the signal, and should not be mistaken for a high amplitude background signal. A way of checking this is looking at signal from before the onset of the event. This way one can see what background signal is affecting the signal from the event. This signal is typically low frequency, and will comprise part of the signal. Hence, when measuring max. amplitude make sure to:
    - Do it in the high-frequency area
    - Avoid measuring at times of interference of the low-frequency signal. Hence, measure max. amplitude at times that are least affected by other signal, these are the top and bottom of each oscillation where there is minimal constructive or destructive interference.
- If amplitude is difficult to measure ground roll motion instead of counts (SEISAN default). This is done by choosing a certain channel, then select '*v*' filter (press '*v*'), then '*g*' (ground motion), select the window of data for this operation, and then '*d*' (displacement).
- Amplitude measurements from different stations (during same event) should be somewhat close, within approximately 0.5 magnitude. Beware of possible systematics in terms of e.g. compass-direction dependent magnitudes, if e.g. stations south of the quake is always higher or lower than other directions.

Appendix III – Geological map Greenland

From: Henriksen, N. (2008). *Geological History of Greenland Four billion years of Earth evolution*. Geological Survey of Denmark and Greenland.

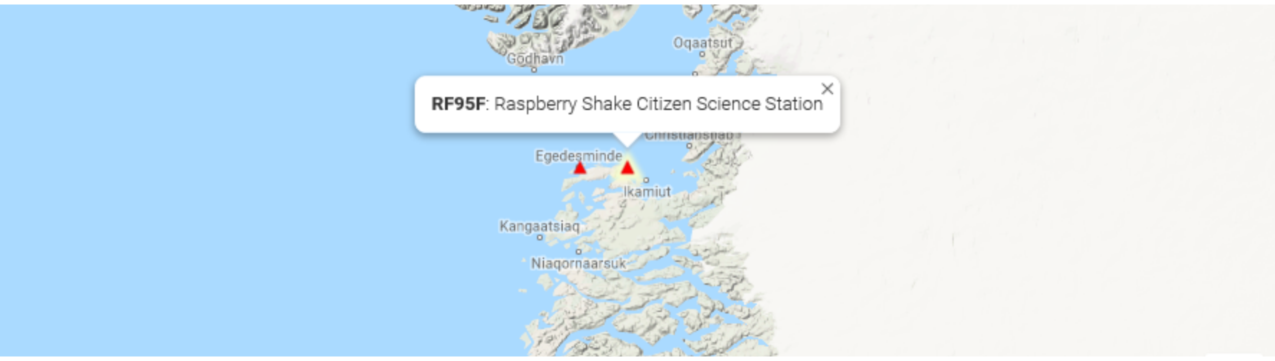


Appendix IV – Raspberry Shake Stations

Two seismic stations are not provided from GEUS, but are on the figure below. These are RF95F and R2310, which both are Raspberry Shake Citizen Science Stations located on islands in the southern part of Disko Bay.

Link: https://www.fdsn.org/networks/detail/AM/

Name	*Station*	*Latitude*	*Longitude*
R2310	Raspberry Shake Citizen Science Station	68.702703	-52.845382
RF95F	Raspberry Shake Citizen Science Station	68.702703	-52.12379



Appendix V – Data set

Date	Location	Lat. error *(km)*	Long. Error *(km)*	Mag. (M_L)	RMS	#Stations	Depth *(km)*	Non-fixed depth *(km)*	Depth error (km)	Type
29-02-2016_17.49	69.074 , -50.316	7.8	31.4	1.9	1.1	5	15.6	-	13.4	Tectonic
13-05-2016_03.25	69.496 , -52.773	7.6	25.0	2.7	0.5	4	31.6	-	5.7	Tectonic
13-05-2016_06.51	69.010 , -50.280	13.7	43.6	1.6	0.8	4	8.5	-	32.4	Tectonic
19-05-2016_08.28	69.148 , -51.080	3.1	16.8	2.0	0.6	5	0.0F	5.3	-	Glacial*
23-06-2016_14.34	68.974 , -50.271	14.1	44.1	2.0	1.2	6	0.0	-	40.8	Tectonic
25-06-2016_07.15	69.112 , -50.558	5.7	21.6	2.2	0.7	5	18.0	-	8.3	Tectonic*
26-06-2016_06.50	69.111 , -49.569	7.6	18.6	2.8	1.2	7	0.0F	0.0	-	Glacial
26-06-2016_07.01	68.195 , -52.271	10.1	58.3	2.1	2.0	6	0.0F	0.0	-	Glacial*
26-06-2016_08.00	69.099 , -49.879	10.0	34.3	2.2	1.4	5	0.0	-	23.7	Tectonic
27-06-2016_04.31	69.092 , -49.837	10.8	37.5	2.4	1.5		2.6	-	24.9	Tectonic
08-07-2016_16.33	69.034 , -50.179	12.10	32.40	2.2	190	6	0.0F	30.20	-	Glacial
08-07-2016_17.13	69.184 , -50.789	9.70	40.60	2.5	1.40	6	32.80	-	9.10	Tectonic

Table column description left to right: Date (ddmmyyyy_hh:mm), location (latitude, longitude), latitude error (km), longitude error (km), magnitude (local M_L), RMS (summed), Number of stations used for locating, calculated depth to hypocentre (F marks fixed hypocenter depth), non-fixed depth (only applies to glacial earthquakes), depth error (km) (only applies to tectonic earthquakes), interpreted type of earthquake. Events marked with * indicate a higher level of uncertainty of the interpretation.

Date	Location	Lat. error *(km)*	Long. Error *(km)*	Mag. (M_L)	RMS	#Stations	Depth *(km)*	Non-fixed depth *(km)*	Depth error (km)	Type
10-07-2016_04.36	69.040 , -50.091	4.60	12.40	2.0	0.70	5	0.0F	7.30	-	Glacial
26-07-2016_10.18	68.230 , -51.399	7.90	58.40	2.2	1.40	6	0.00	-	17.80	Tectonic
26-07-2016_14.27	69.954 , -51.416	18.40	108.20	2.0	3.10	7	0.00	-	41.00	Tectonic
29-07-2016_08.57	68.452 , -51.716	1.40	14.20	3.2	0.10	3	31.30	-	5.50	Tectonic
29-07-2016_09.12	68.228 , -52.317	8.00	59.70	2.6	1.30	6	12.60	-	15.30	Tectonic
30-07-2016_15.25	69.026 , -50.169	9.30	34.60	2.3	1.30	5	2.70	-	21.20	Tectonic
13-08-2016_08.34	68.983 , -50.443	5.80	23.60	2.4	0.80	5	2.80	-	13.10	Tectonic*
28-08-2016_00.37	69.025 , -50.107	14.70	34.30	1.9	2.00	4	0.0F	0.10	-	Glacial
30-08-2016_09.08	68.264 , -51.082	15.10	102.70	2.9	2.80	6	0.00	-	36.90	Tectonic
20-09-2016_03.34	69.501 , -52.602	8.70	36.20	2.0	1.30	5	0.0F	1.50	-	Glacial*
02-11-2016_18.47	69.197 , -50.973	15.40	85.60	2.0	1.50	5	35.10	-	15.30	Tectonic*
11-05-2017_09.38	69.041 , -50.510	4.80	17.50	2.3	0.50	6	4.20	-	12.40	Tectonic

Table column description left to right: Date (ddmmyyyy_hh:mm), location (latitude, longitude), latitude error (km), longitude error (km), magnitude (local M_L), RMS (summed), Number of stations used for locating, calculated depth to hypocentre (F marks fixed hypocenter depth), non-fixed depth (only applies to glacial earthquakes), depth error (km) (only applies to tectonic earthquakes), interpreted type of earthquake. Events marked with * indicate a higher level of uncertainty of the interpretation.

Date	Location	Lat. error (km)	Long. Error (km)	Mag. (M_L)	RMS	#Stations	Depth (km)	Non-fixed depth (km)	Depth error (km)	Type
18-05-2017_03.58	68.945 , -50.647	6.50	28.10	2.7	0.90	5	0.00	-	15.30	Tectonic
27-05-2017_01.25	69.161 , -49.652	10.70	38.50	2.1	1.70	5	0.0F	25.40	-	Glacial
02-06-2017_10.06	69.078 , -50.570	6.70	28.40	2.0	0.90	5	21.30	-	9.10	Tectonic
03-06-2017_23.06	69.117 , -49.981	11.30	21.00	2.2	1.40	4	0.0F	45.40	-	Glacial
03-06-2017_23.38	68.965 , -50.350	6.60	23.00	2.8	1.20	5	0.0F	0.00	-	Glacial
14-06-2017_13.26	68.882 , -50.083	7.10	20.30	2.3	1.10	4	0.0F	9.00	-	Glacial
26-06-2017_10.35	68.990 , -50.314	8.30	22.50	1.9	1.20	4	0.0F	0.00	-	Glacial
30-06-2017_05.05	69.112 , -51.053	13.30	46.70	2.8	0.90	6	53.30	-	19.60	Tectonic
01-08-2017_17.10	69.143 , -50.427	14.00	27.80	2.0	1.70	4	0.0F	0.00	-	Glacial
01-08-2017_22.19	69.044 , -50.241	3.90	10.40	2.3	0.50	4	0.0F	0.00	-	Glacial
09-08-2017_09.52	69.111 , -50.044	10.00	29.60	2.3	2.10	7	0.0F	8.30	-	Glacial
10-08-2017_09.23	69.921 , -50.960	11.30	57.70	2.3	2.10	4	0,0F	2.00	-	Glacial

Table column description left to right: Date (ddmmyyyy_hh:mm), location (latitude, longitude), latitude error (km), longitude error (km), magnitude (local M_L), RMS (summed), Number of stations used for locating, calculated depth to hypocentre (F marks fixed hypocenter depth), non-fixed depth (only applies to glacial earthquakes), depth error (km) (only applies to tectonic earthquakes), interpreted type of earthquake. Events marked with * indicate a higher level of uncertainty of the interpretation.

Date	Location	Lat. error *(km)*	Long. Error *(km)*	Mag. (M_L)	RMS	#Stations	Depth *(km)*	Non-fixed depth *(km)*	Depth error (km)	Type
13-08-2017_11.57	69.399 , -51.347	15.70	80.00	2.3	1.40	5	64.10	-	21.50	Tectonic*
29-08-2017_08.44	69.087 , -49.907	8.00	28.40	2.1	1.10	5	0.0F	9.50	-	Glacial
31-08-2017_21.15	69.082 , -50.660	7.60	36.60	2.1	1.10	4	0.0F	0.00	-	Glacial*
03-09-2017_02.13	69.214 , -48.820	14.30	48.40	2.1	2.00	4	0.0F	30.90	-	Glacial*
21-09-2017_10.03	69.091 , -50.138	8.80	35.60	2.2	1.40	6	12.10	-	16.50	Tectonic
31-10-2017_08.57	69.141 , -50.140	9.90	28.30	2.0	1.80	5	0.0F	26.80	-	Glacial
02-11-2017_07.49	69.111 , -50.476	10.50	47.30	2.0	1.60	5	0.0F	0.00	-	Glacial
10-11-2017_10.16	69.270 , -51.161	8.00	37.60	2.2	1.10	5	25.70	-	6.50	Tectonic
17-01-2018_02.55	69.109 , -48.887	12.10	89.60	2.3	1.10	3	99.70	-	44.60	Tectonic
17-01-2018_02.55	69.160 , -48.911	20.90	85.90	2.3	2.80	6	93.30	-	79.80	Tectonic
25-01-2018_18.00	69.148 , -50.366	14.70	59.70	1.9	2.10	5	1980	-	22.60	Tectonic*
10-02-2018_02.15	70.056 , -51.475	8.90	54.50	1.9	1.80	5	0.0F	0.00	-	Glacial

Table column description left to right: Date (ddmmyyyy_hh:mm), location (latitude, longitude), latitude error (km), longitude error (km), magnitude (local M_L), RMS (summed), Number of stations used for locating, calculated depth to hypocentre (F marks fixed hypocenter depth), non-fixed depth (only applies to glacial earthquakes), depth error (km) (only applies to tectonic earthquakes), interpreted type of earthquake. Events marked with * indicate a higher level of uncertainty of the interpretation.

Date	Location	Lat. error *(km)*	Long. Error *(km)*	Mag. (M_L)	RMS	#Stations	Depth *(km)*	Non-fixed depth *(km)*	Depth error (km)	Type
22-05-2018_21.45	69.042 , -51.014	7.30	35.30	2.1	1.40	6	0.0F	27.00	-	Glacial*
28-05-2018_05.42	69.108 , -50.334	7.00	32.30	1.9	1.40	5	0.0F	0.00	-	Glacial
13-06-2018_03.09	68.070 , -51.961	12.80	49.20	2.1	1.00	5	103.50	-	48.70	Tectonic
14-06-2018_12.58	68.931 , -50.478	5.30	24.90	2.1	1.00	5	0.0F	2.90	-	Glacial*
02-07-2018_19.07	69.196 , -49.252	10.40	60.00	2.4	1.80	7	0.0F	21.00	-	Glacial*
21-07-2018_01.33	68.508 , -50.832	15.00	44.70	2.3	0.70	5	0.0F	58.40	-	Glacial
26-07-2018_03.51	69.123 , -50.380	8.40	38.70	2.8	1.60	6	0.0F	5.30	-	Glacial*
28-07-2018_03.45	68,254 , -51,526	13.40	81.80	3.0	1.40	5	27.70	-	22.00	Tectonic
10-08-2018_10.28	69.089 , -50.341	8.10	34.40	2.3	1.30	7	18.80	-	17.30	Tectonic*
14-08-2018_12.23	69.111 , -50.053	6.60	23.70	2.3	1.40	7	0.0F	11.60	-	Glacial
21-08-2018_02.07	69.054 , -50.976	7.90	35.90	2.5	1.40	8	0.00	-	21.30	Tectonic*
22-08-2018_04.03	69.091 , -50.627	9.20	42.20	2.4	1.40	5	0.00	-	21.40	Tectonic*

Table column description left to right: Date (ddmmyyyy_hh:mm), location (latitude, longitude), latitude error (km), longitude error (km), magnitude (local M_L), RMS (summed), Number of stations used for locating, calculated depth to hypocentre (F marks fixed hypocenter depth), non-fixed depth (only applies to glacial earthquakes), depth error (km) (only applies to tectonic earthquakes), interpreted type of earthquake. Events marked with * indicate a higher level of uncertainty of the interpretation.

Date	**Location**	**Lat. error *(km)***	**Long. Error *(km)***	**Mag. (M_L)**	**RMS**	**#Stations**	**Depth *(km)***	**Non-fixed depth *(km)***	**Depth error (km)**	**Type**
22-08-2018_14.26	69.107 , -50.292	7.90	34.70	2.3	1.20	5	0.00	-	18.40	Tectonic*
23-08-2018_03.17	69.188 , -49.508	9.00	51.10	2.2	1.50	6	0.0F	21.50	-	Glacial
28-08-2018_04.24	68.952 , -50.360	9.20	43.30	2.1	1.40	6	0.0F	28.40	-	Glacial
29-08-2018_08.30	69.154 , -50.701	5.00	24.80	1.6	0.90	4	0.0F	0.00	-	Glacial*
12-10-2018_03.04	69.221 , -49.722	10.10	60.80	2.00	1.30	5	8.10	-	24.10	Tectonic
15-10-2018_01.18	69.041 , -50.899	7.30	23.50	2.3	1.70	7	0.0F	0.00	-	Glacial
16-12-2018_14.05	69.205 , -49.950	7.10	36.60	1.8	0.90	5	11.10	-	15.20	Tectonic*

Table column description left to right: Date (ddmmyyyy_hh:mm), location (latitude, longitude), latitude error (km), longitude error (km), magnitude (local M_L), RMS (summed), Number of stations used for locating, calculated depth to hypocentre (F marks fixed hypocenter depth), non-fixed depth (only applies to glacial earthquakes), depth error (km) (only applies to tectonic earthquakes), interpreted type of earthquake. Events marked with * indicate a higher level of uncertainty of the interpretation.

Appendix VI – Seismograms on July 21st 2018, 01:33