# Annual report for the

# Norwegian National Seismic Network

# 2018

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# 1 Introduction

This annual report for the Norwegian National Seismic Network (NNSN) covers operational aspects for the seismic stations contributing data, presents the seismic activity in the target areas and the associated scientific work carried out under the project. The report is prepared by the University of Bergen with contributions from NORSAR.

The NNSN is supported by the oil industry through the Norwegian Oil and Gas Association and the University of Bergen (UiB).

All data stored in the NNSN database are available to the public via Internet, e-mail or by manual request. The main web-portal for earthquake information is www.skjelv.no. It is possible to search interactively for specific data and then download the data from ftp://ftp.geo.uib.no/pub/seismo/DATA/. Data are processed as soon as possible and updated lists of events recorded by Norwegian stations are available soon after recording. These pages are automatically updated with regular intervals.

# 2 Operation

## 2.1 NNSN

The University of Bergen (UiB) has the main responsibility to run the NNSN and operates at present 35 of the seismic stations that form the NNSN located as seen in Figure 1. The latest station is located in Leirdalen (LEIR), Nordland, and was operational in December 2018. The LEIR station was funded through the EPOS-Norway project. NORSAR operate 3 seismic arrays, which also include broadband instruments, and three single seismometer stations (AKN, JETT and JMIC). In total, NORSAR provides data from 12 broadband stations to the NNSN.

In addition to the NNSN stations, waveform data from selected stations in Finland (University of Helsinki), Denmark (Geological Survey of Denmark and Greenland, GEUS), Sweden (Swedish National Seismic Network at University of Uppsala, SNSN), Island (The Islandic Meteorological Office, IMO) and Great Britain (British Geological Survey, BGS) are transferred in real time and included in the NNSN database. More than 20 stations located in or operated by neighbouring countries are received continuously in Bergen and are used for locating earthquakes, see Figure 1 and Figure 2. Phase data from neighbouring countries and from arrays in Russia (Apatity), Finland (Finess), Sweden (Hagfors) are also included.

Offshore, one station with real-time data is provided from the Ekofisk field by ConocoPhillips and also data from the Grane operated by Equinor are transferred to Bergen and used in locations. The station HSPB is operated jointly between NORSAR and the Geophysical Institute, Polish Academy of Sciences, Warsaw, Poland and the stations BRBA and BRBB, both located in Barentsburg, Svalbard, are a collaboration between NORSAR and the Kola Science Centre, Russian Academy of Sciences, Apatity, Russia.

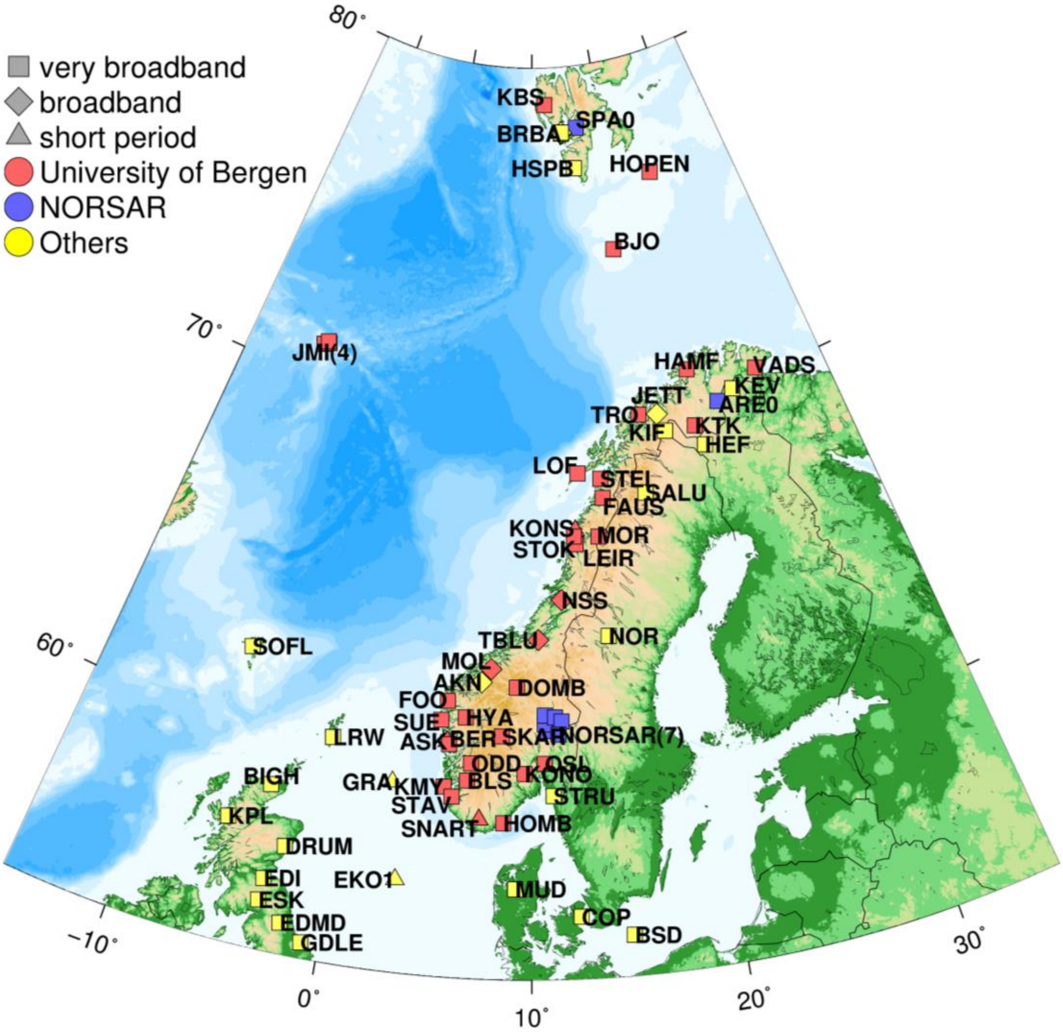



**Figure 1. Stations contributing to the Norwegian National Seismic Network (NNSN). UiB operates 35 stations (red) and NORSAR operates the stations marked in blue, including the three arrays and stations AKN and JMIC. The stations marked in yellow are operated by oil companies or neighbouring countries.**

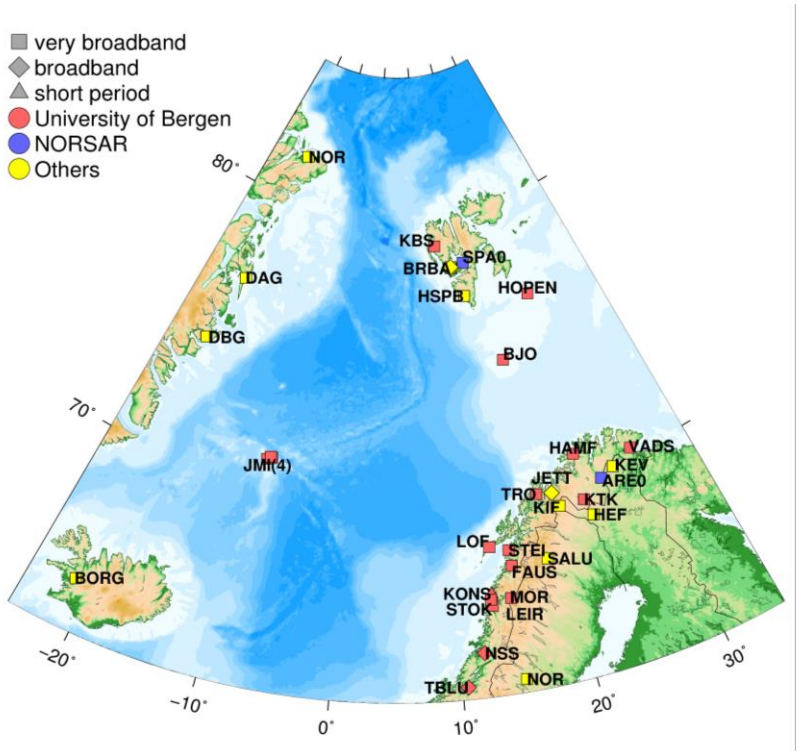



**Figure 2. Location of seismic stations in the artic contributing data to NNSN.**

The seismicity detected by the network is processed at UiB, however NORSAR also integrate their results into the joint database at UiB. At NORSAR the parameters of analyst-reviewed events are converted into parameter files in Nordic format and forwarded via ftp to UiB on a weekly basis. The magnitude threshold is set to about M=1.5 for regional events of potential interest for the NNSN.

Seismic data recorded at stations located on Greenland and Iceland are included in the NNSN real-time processing (Figure 2). These data are important for the location of earthquakes south and west of Jan Mayen and along the entire northern Mid-Atlantic ridge.

UiB is in the process of upgrading the NNSN by changing short period (SP) to broadband (BB) seismometers. The current status of this upgrade is shown in Table 1. As of today the numbers of SP, BB stations and stations with real time transmission are listed in Table 1.

**Table 1. Overview of UiB seismic stations**

| | Short Period | Broadband | Real time |
|---|---|---|---|
| Number of stations | 2 | 33<br>(30 with natural period greater than 100 sec) | 35 |

The operational stability for each station is shown in Table 2. The down time is computed from the amount of data that are missing from the continuous recordings at UiB. This is done as the goal is to obtain as complete continuous data from all stations as possible. The statistics will, therefore, also show when a single component is not working. Also, communication or computing problems at the centre will contribute to the overall downtime. In the case of communication problems, a station may not participate in the earthquake detection process, but the data can be used when it becomes avaiable. Thus, the statistics given allow us to evaluate the data availability when rerunning the earthquake detection not in real-time.

The data completeness for the majority of the stations was above 95%, except for HOMB and TBLU (see technical service overview for details).

**Table 2. Data completeness in % for 2018 for all stations of the NNSN operated by UiB.**

| Station | Data completeness % | | Station | Data completeness % |
|---|---|---|---|---|
| Askøy (ASK) | 95 | | Konsvik (KONS) | 100 |
| Bergen (BER) | 100 | | Leirfjord (LEIR) | 100 (after December) |
| Bjørnøya (BJO) | 98 | | Lofoten (LOF) | 100 |
| Blåsjø (BLS) | 100 | | Mo i Rana (MOR8) | 99 |
| Dombås (DOMB) | 100 | | Molde (MOL) | 99 |
| Fauske (FAUS) | 100 | | Namsos (NSS) | 100 |
| Florø (FOO) | 98 | | Odda (OOD1) | 100 |
| Hammerfest (HAMF) | 100 | | Oslo (OSL) | 100 |
| Homborsund (HOMB) | **92** | | Skarslia (SKAR) | 98 |
| Hopen (HOPEN) | 100 | | Snartemo (SNART) | 99 |
| Høyanger (HYA) | 100 | | Stavanger (STAV) | 98 |
| Jan Mayen (JMI) | 100 | | Steigen (STEI) | 100 |
| Jan Mayen (JNE) | 99 (after August) | | Stokkvågen (STOK) | 100 |
| Jan Mayen (JNW) | 99 (after October) | | Sulen (SUE) | 100 |
| Karmøy (KMY) | 100 | | Blussuvoll (TBLU) | **89** |
| Kautokeino (KTK1) | 100 | | Tromsø (TRO) | 99 |
| Kings Bay (KBS) | 99 | | Vadsø (VADS) | 100 |
| Kongsberg (KONO) | 99 | | | |

## 2.2 NNSN field stations maintenance

The technical changes for each seismic station are listed below. It is mentioned if these changes are carried out by the respective local contact and not by the staff of UiB. When a station stops working, tests are made to locate the problem. Sometimes the reason cannot be found and the cause of the problem will be marked as unknown.

List of station maintenance operations during this reporting period of 2018 were:

Ask (ASK)

26.02.18: Cable to GPS antenna damaged by rodents. The local contact attempted to repair the cable but did not succeed.

06.03.18: Visit. New GPS antenna and cable was installed.

04.07.18: Station down since 01.07.18 due to power loss. Data lost.

19.08.18: Data missing (until 21 Aug), probably again due to power issue.

30.10.18: Visit. Preparing for upgrade.

07.11.18. Visit. The station was upgraded with a Trillium 120QA sensor. The digitizer was not changed. Problem with the network connection. Some data is lost while the seismometer was not connected.

09.11.18: Visit. Network connection fixed.

Bergen (BER)

No visit or technical changes

Bjørnøya (BJO1)

06.02.18: Problem with digitizer. Local personnel restarted the instrumentation since ‘ping’ from Bergen did not work. Some data lost between Feb 2-6.

12.02.18: Station personnel changed the GPS antenna.

Blåsjø (BLS)

No visit or technical changes

Blussuvoll (TBLU)

18.07.18: Power cable reconnected, it had been pulled out by mistake. Data lost due to power loss 26 June to 17 July.

26.11.18: Data loss due to power cut to the sensor. Data lost for Nov 10-25 since contact person was not available during this time.

Dombås (DOMB)

No visit or technical changes.

Fauske (FAUS)

19.07.18: Station and vault inspected by local contact. A small amount of water was removed.

Florø (FOO)

30.07.18: Station down since 00:24. Station ok from 06:10 after power cycling.

03.08.18: Station down. OK after power cycling. No data lost.

| | |
|---|---|
| Hammerfest (HAMF) | No visit or technical changes. |
| Homborsund (HOMB) | 15.05.18: Station down from 01.05.18 due to defective PC. Old PC and digitizer replaced with a Guralp CMG-DM24S3-EAM digitizer. Communication changed from local fibre to a GSM router. Data lost 1-15 May.<br>04.06.18: Digitizer gain changed from 8 to 1.<br>23.07.18: Station down since 21.07.18. Power cycling done, not successful.<br>30.07.18: Power cycling done again, now successful. Data lost 21-30 July.<br>13.08.18: Station down since 09.08.18. Power cycling done. Station ok. Data lost 9-13 August. |
| Hopen (HOPEN) | 15.03.18: GPS antenna replaced by local personnel. GPS error detected 14.03.18. |
| Høyanger (HYA) | No visit or technical changes. |
| Jan Mayen (JMI/) | No major changes. |
| Jan Mayen (JNE/Ulla) | July 18: The old instrument cabin was replaced with a new by local personnel, Figure 3. |

**Figure 3 The old instrument cabin was replaced with a new one.**

23.08.18: Visit from UiB. Upgrade of the site. New Trillium 120 seismometer and Centaur digitizer installed. New digital radio transmission.

**Figure 4 The station JNE after upgrade as seen from two directions: sensor vault (orange), the instrument cabin (white), the GSSN mast and the hemisphere shaped GNSS antenna.**

10.09.18: The Trillium sensor was moved into the bottom of the plastic pipe. Data lost between 06.09.18 to 10.09.18.

**Figure 5. Inside the volt. The trillium sensor (green) is placed at the bottom of the orange plastic tube.**

Jan Mayen (JNW/ Liberg)

09.02.18: Station visited by local personnel. No changes made, some measurements done.

18.07.18: Existing instrument cabin replaced.

**Figure 6. The old instrument cabin is replaced by local personnel.**

23.08.18: Visit from UiB. Upgrade of the site. New Trillium 120 seismometer and Centaur digitizer installed. New digital radio transmission. Due to a missing connecting cable the Trillium sensor was not set into operation.

**Figure 7. The seismic station JNW, located at Liberg, seen from two directions.**

15.10.18: The Trillium sensor was connected and set into operation by local personnel.

Karmøy (KMY)

No visit or technical changes

Kautokeino (KTK)

10.05.18: The station records only noise. The seismometer belongs to the Norwegian broadband pool and was borrowed during a temporary deployment in the region. Several attempts were made to fix the problem both remotely and by local contact. Problem was with the connection box for the seismometer.

20.06.18: Visit 19-20 June. Station was upgraded with a Trillium 120QA sensor and the DM24-EAM digitizer was replaced with an identical unit. The previous sensor was returned to the Norwegian broadband pool.

Kings Bay (KBS)

No visit or technical changes.

Kongsberg (KONO)

No visit or technical changes. USGS plans to move the site to a better location in the mine. This work may be done during winter 2018/19.

Konsvik (KONS)

16.11.18: Timing error since 01.10.18. The problem is most likely situated in the digitizer. There are no spare digitizer at UiB that can be used to replace the one at the station. The installation at KONS will be evaluated for upgrade.

Leirfjord (LEIR)

23.10.18: Visit from UIB. A local contractor has done all the digging at the site prior to the visit from UiB. The construction of the volt, installation of the antenna and mast for the connection cabinet were done during the week. Figure 8 shows the construction of the GSNN mast to the left and the site to the right.

**Figure 8. The site in Leirfjord during construction.**

4-7. 11.18: Visit from UiB and Kartverket. The seismic station was installed and put into operation. Figure 9 shows an overview over the site. The sensor tank to the right, the connection box to the left and the GNSS antenna (marked with arrow).

**Figure 9. The site for LEIR after completion of the area and installation of the antennas and the connection box. The GSNN antenna mast is marked.**

**Figure 10. The Trillium sensor installed inside the volt. The junction box and the digitizer on the wall to the left.**

Lofoten (LOF)

No visit or technical changes.

Mo i Rana (MOR8)

20.07.18: Station down since 14.07.18. Reset power supply for sensor and digitizer. Station ok. Data loss on July 19 and 25.

27.07.18: Station down since 24.07.18. Reset power supply for sensor and digitizer. Station ok.

| | |
|---|---|
| | 03.08.18: Station down since 01.08.18. Reset power supply for sensor and digitizer. Station ok. |
| | 06.08.18: Station down since 05.08.18. Reset power supply for sensor and digitizer. Station ok. |
| Molde (MOL) | 02.10.18: No diskspace available on the local PC. Data lost since 24.09.18. |
| Namsos (NSS) | No visit or technical changes. |
| Odda (ODD1) | 07.06.18: Visit by local contact who brought back SS-1Rranger sensors which were phased out in 2016. |
| Oslo (OSL) | No visit or technical changes. |
| Skarslia (SKAR) | 30.07.18: Visit by local operator. Station has been down since 13.07.18 due to a malfunctioning digitizer after a thunderstorm. Data lost. |
| | 14.08.18: Visit by local operator. The digitizer was replaced. A lightning strike caused digitizer problems and the station has been down since 31.07.18. Data lost. |
| | 17-20.09.18: Visit. Router and digitizer were replaced. |
| | 12.10.18: Visit. Modified electronics enclosure inside vault. Added separate GPS-cable, over-voltage protection and DC-DC converter to get extra layer of protection for digitizer and sensor. |
| Snartemo (SNART) | No visit or technical changes. |
| Stavanger (STAV) | 04.06.18: Station has been down since 28.05.18 due to power loss locally at OD and following power loss to the sensor. Data lost 28 May to 4 June. |
| Steigen (STEI) | No visit or technical changes. |
| Stokkvågen (STOK) | 16:05.18: Station down since 09.05.18 due to communication problems between digitizer and router. No data lost. |
| | 14.06.18: The sensor was moved from the very temporary location in the garage to a better site on a cement slab under the garage. |
| Sulen (SUE) | No visit or technical changes. |
| Tromsø (TRO) | Feb 2018: Data lost between Feb 17-21. Unknown reason. |
| | Summer 2018: Building work at the Tromsø Museum caused noisy data and periods with power loss. No visit or technical changes. |
| Vadsø (VADS) | |
| | Visit by the local contact. No repairs needed. |

## 2.3 The NORSAR stations and arrays

NORSAR is providing data to the NNSN from the following main data streams:

- NOA (southern Norway, array, 7 3C broadband sensors)
- ARCES (Finnmark, array, 1 3C broadband seismic sensor)
- SPITS (Spitsbergen, array, 1 3C broadband sensors)
- JMIC (Jan Mayen, 3C broadband sensor)
- AKN (Åknes, Møre og Romsdal, 3C broadband sensor)
- JETT (Jettan, Troms, 3C broadband sensor)
- I37H0 (Bardufoss, 3C broadband sensor)

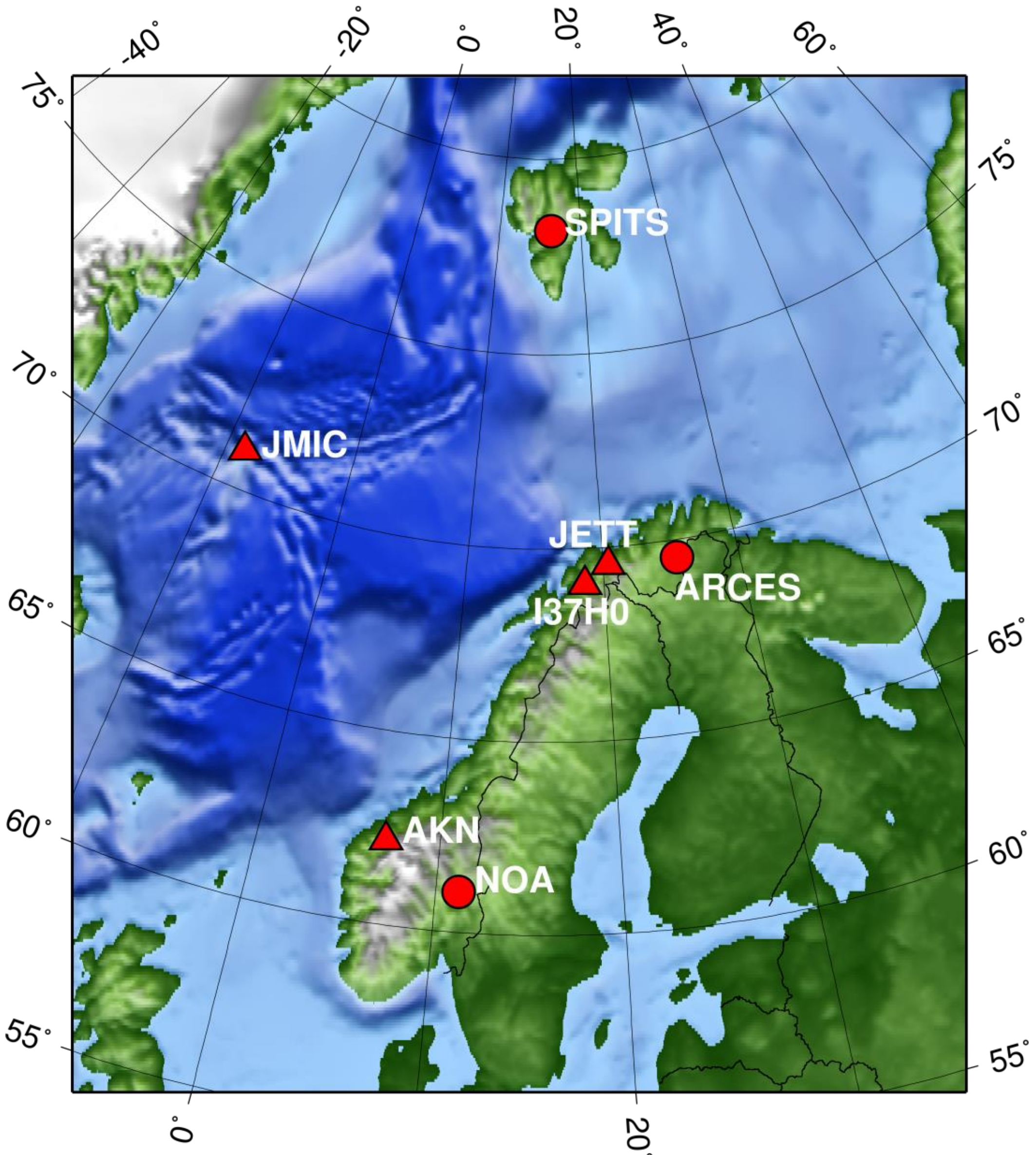



**Figure 11. NORSAR seismic arrays/stations (NOA, ARCES, SPITS, JMIC, AKN, I37H0)**

### 2.3.1 Data availability

All data recorded at NORSAR are continuous. The following table provides a monthly overview on the data availability of 13 main data streams provided by NORSAR to the NNSN.

**Table 3 Systems recording performance (in % of data completeness) for 13 main data streams provided from NORSAR to NNSN.**

| | NAO01 | NBO00 | NB201 | NC204 | NC303 | NC405 | NC602 |
|---|---|---|---|---|---|---|---|
| Jan | 100.00 | 100.00 | 96.92 | 100.00 | 79.95 | 99.99 | 100.00 |
| Feb | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Mar | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Apr | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| May | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Jun | 100.00 | 100.00 | 100.00 | 100.00 | 98.05 | 100.00 | 100.00 |
| Jul | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Aug | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.99 |
| Sep | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Oct | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Nov | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.77 |
| Dec | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

| | ARA0 | JMIC | SPA0 | AKN | JETT | I37H0 |
|---|---|---|---|---|---|---|
| Jan | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Feb | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Mar | 100.00 | 100.00 | 100.00 | 100.00 | 99.99 | 99.99 |
| Apr | 99.97 | 99.98 | 100.00 | 99.82 | 100.00 | 100.00 |
| May | 99.99 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Jun | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Jul | 99.72 | 100.00 | 77.82 | 100.00 | 100.00 | 100.00 |
| Aug | 100.00 | 99.74 | 73.02 | 100.00 | 100.00 | 72.07 |
| Sep | 100.00 | 99.47 | 78.70 | 100.00 | 100.00 | 0.00 |
| Oct | 100.00 | 99.98 | 100.00 | 100.00 | 100.00 | 0.00 |
| Nov | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 28.63 |
| Dec | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 2.87 |

### 2.3.2 Detections

The NORSAR analysis results are based on automatic phase detection and automatic phase associations which produce the automatic bulletin. Based on the automatic bulletin, a manual analysis of the data is prepared, resulting in the reviewed bulletin. The automatic bulletin for northern Europe is created using the Generalized Beam Forming (GBF) method. This bulletin (available at https://www.norsar.no/extranet/bulletins (requires login)) is subsequently screened for local and regional events of interest in Fennoscadia and in Norway, which in turn are reviewed by an analyst. Table 4 gives a summary of the phase detections and events declared by GBF and the analyst.

**Table 4 Phase detections and event summary.**

| | Jan. | Feb. | March | April | May | June |
|---|---|---|---|---|---|---|
| Phase detections | 210353 | 235903 | 230986 | 253192 | 206190 | 230101 |
| Associated phases | 5157 | 7993 | 7125 | 6897 | 5957 | 5380 |
| Un-associated phases | 205196 | 227910 | 223861 | 246295 | 200233 | 224721 |
| Screened GBF events for Fennoscandia/Norway | 488 | 723 | 641 | 626 | 528 | 500 |
| No. of events defined by the analyst | 23 | 36 | 40 | 44 | 56 | 27 |
| | July | Aug. | Sep. | October | Nov. | Dec. |
| Phase detections | 251336 | 284781 | 320654 | 274749 | 255799 | 210764 |
| Associated phases | 5707 | 5265 | 5854 | 4913 | 4223 | 4415 |
| Un-associated phases | 245629 | 279516 | 314800 | 269836 | 251576 | 206349 |
| Screened GBF events for Fennoscandia/Norway | 544 | 509 | 551 | 461 | 403 | 399 |
| No. of events defined by the analyst | 20 | 28 | 48 | 28 | 25 | 17 |

# 3 NNSN achievements and plans

The overall purpose of the NNSN is to provide data both for scientific studies, but equally important for the routine observation of earthquakes. This in principle means that broadband seismometers are desired at all sites. The number of broadband seismometers in the network will be increased to replace the last remaining short period instruments. A general goal for the development has been to achieve standardization in particular with the seismometers and digitizers.

## 3.1 NNSN achievements in 2018

- Major upgrade of the seismic stations JNW and JNE at Jan Mayen through the EPOS-Norway project. These stations are upgraded from single short period sensors to three component broadband sensors. All stations are now transmitting continuous data to Bergen in real time.
- The two NNSN stations at Askøy (ASK) and Kautokeino (KTK) were upgraded with broadband seismometers.
- The new magnitude scale for the areas between Greenland and Svalbard, north/northwest of Jan Mayen is published and taken into use in the daily processing.
- Data from ten sensors at Grane (Equinor) are now received at UiB. Data flow from Oseberg has not yet started. The Grane data is implemented in the daily processing.
- The applications (two rounds) for seismic stations at Svalbard under EPOS-Norway was rejected by Sysselmannen. Planning for alternative sites onshore and offshore Svalbard has started.

- Planning of new seismic stations in the Nordland area under EPOS-Norway is in progress and station LEIR was installed and real time data transferred from November 2018.
- The NNSN web pages have been redeveloped, and became operational in the summer.
- An evaluation of the seismicity in the northern North Sea has been made.
- Work to improve detection based on measuring correlation has been carried out for southern Norway.
- Detailed work on the ML=4.5 North Sea earthquake in June 2017 has been carried out.
- Two seismic stations (Manen and Damen) were deployed close to the mountain Mannen in an attempt to record precursors of the expected main landslide (September).
- The work on attenuation tomography is published.
- An EIDA node for improved data distribution of Norwegian seismic data has been established under EPOS-Norway. The system is functioning and currently tested by the European EIDA group.
- A temporary deployment with 22 broadband stations from the Norwegian broadband pool has been carried out to cover the area roughly between Bergen and Odda with two lines. The data is recorded offline, but will be combined with the NNSN data.

## 3.2 Plans for 2019

- Improved automatic detection will be implemented in spring 2019.
- Continue the work on cross-correlation based detection.
- Continue work on discrimination of explosions.
- Work on identifying anisotropy from teleseismic polarization analysis will be completed.
- A 3-year Postdoc is expected to start at UiB in the summer; research topics will be defined based on candidate and NNSN requirements.
- Stations NSS and MOL will be upgraded.
- Station TBLU will be moved, new site will be built.
- Work on a new station in the Røros area will begin.
- The work on new stations in Nordland with EPOS-Norway funding will continue, we expect to complete 3 more stations before the summer, some of the remaining 3 stations will also be done during this year.
- It is likely that the equipment at Kongsberg will be moved further into the mine.

# 4 Seismicity of Norway and surrounding areas for 2018

The earthquake locations presented have been compiled from all available seismic stations as described above. All phase data are collected by UiB and all located local and regional earthquakes recorded on NNSN stations are presented on the web pages. The largest events are e-mailed to the European-Mediterranean Seismological Centre (EMSC) and the International Seismological Center (ISC) to be published on their respective web pages. Explosion reports from quarries, mines, the Norwegian army, road construction and others are included in the NNSN database as verified local explosions (LE). For felt earthquakes, questionaries are evaluated and if possible a macroseismic map is produced. When all available data is collected and processed, a monthly bulletin is prepared and distributed. A brief overview of the events published in the monthly bulletins is given in this annual report.

Local, regional and teleseismic events that are detected by the UiB network are included. The merging of data between NORSAR and UiB is based on the following principles:

**i)** All local and regional events recorded by NORSAR that are also detected by the NNSN network are included.

**ii)** Local and regional events with local magnitude larger than 1.5 detected by NORSAR and not recorded by the NNSN are included. However, probable explosions from the Kiruna/Malmberget area are not included.

**iii)** All teleseismic events recorded by NORSAR and also detected by the NNSN are included.

**iv)** All teleseismic events with NORSAR magnitude $M_b \geq 5.0$ are included even if not detected by the NNSN.

Data from the British Geological Survey (BGS) and the Geological Survey of Denmark and Greenland (GEUS) are included in the database in Bergen following similar criteria as mentioned above, however only events located in the prime area of interest, 54-85°N and 15°W-35°E, and with magnitude ≥ 2.0 are included. From the Greenland area only earthquakes recorded on NNSN stations are included. Phase data and locations from University of Helsinki and University of Uppsala are included NNSN database to improve NNSN locations for events in the eastern parts of Norway or possibly for larger events elsewhere.

## 4.1 Events recorded by the NNSN

Based on the criteria mentioned above, a total of 7,486 local and regional events were detected by the NNSN during 2018. Of these local and regional events, 23% were large enough to be recorded by several stations and hence could be located reliably, and are not classified as explosions (LP or LE). The numbers of local/regional and teleseismic events, recorded per month in 2018 are shown in Figure 12.

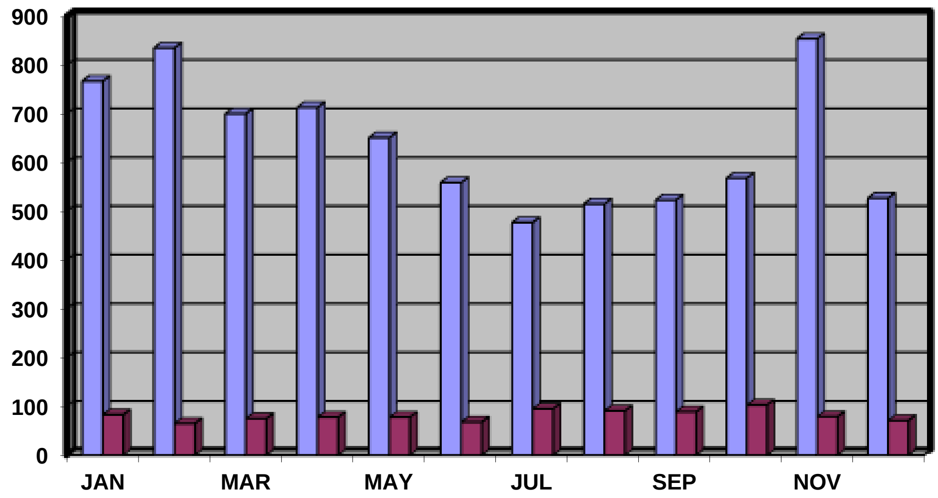



**Figure 12. The number of recorded local/regional (blue) and teleseismic (red) events during 2018. The average number of local and regional events recorded per month is 634 (724 in 2017).**

A total of 944 teleseismic events were recorded in 2018, giving a monthly average of 79 events. In addition to the locations determined at UiB and NORSAR, also preliminary locations published by the USGS (United States Geological Survey) or the EMSC (European Mediterranean Seismological Centre) based on the worldwide network are included for earthquakes registered by NNSN stations.

During the years there has been an increase in the number of local/regional (L/R) events recorded into the NNSN database. A large number of recorded L/R events are believed to be explosions, but improved methods for identifying explosions are used and an increased number of explosions are identified. An increased attempt is also made to identify induced and glacial events. Glacial events are particularly seen in the Svalbard area. As can be seen from Figure 13 the number of teleseismic (D) earthquakes recorded are relative stable while the number of recorded local/regional events shows a general increase from 2014. The local maximum in 2008 for example is due to the M6 earthquake in Storfjorden, Svalbard and its aftershocks.

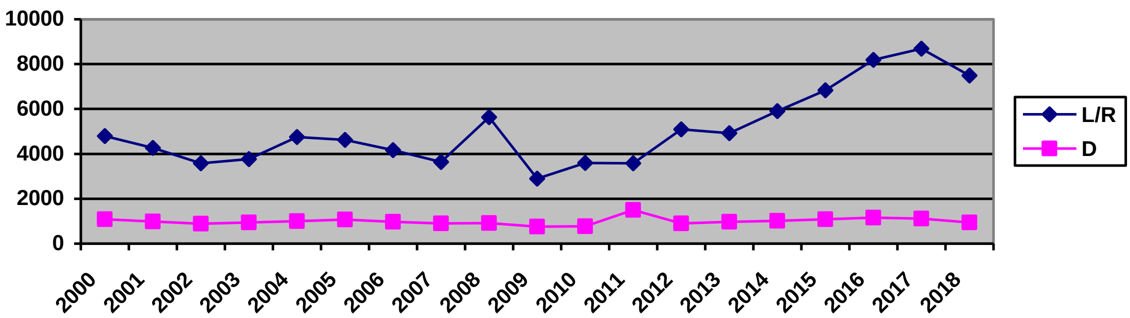



**Figure 13. Number of local/regional (blue) and teleseismic (pink) events recorded in the NNSN database since 2000**

UiB, as an observatory in the global network of seismological observatories, reports local and teleseismic phases to the International Seismological Center (ISC). All events (teleseismic, regional and local) recorded from January to December 2018 with M ≥ 3 are plotted in Figure 14.

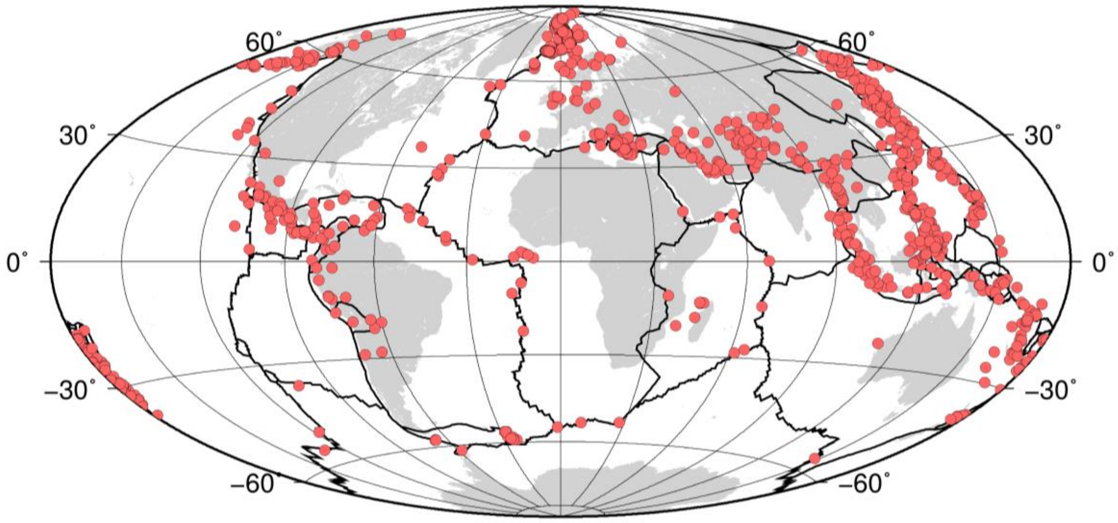



**Figure 14. Epicentre distribution of earthquakes with M≥3.0, located by the NNSN from January to December 2018. Teleseismic events recorded only by NORSAR have M≥5.0.**

Monthly station recording statistics from January to December 2018 are given in Table 6 and 7. These tables show, for each station, local events recorded on more than one station, and recorded teleseismic events. The statistics are based on the analysed data and are taken from the database. Table 6 and 7 show both earthquakes and explosions. Identified or suspected explosions will only be located with a minimum number of stations. Therefore, some stations (e.g. KTK, MOR8) will have a higher number of detections.

The following was observed from Table 6 and 7:

- There is an increase in local events in April and in November at the stations at Jan Mayen. This coincides with a ML=4.4 earthquake 24th April and the MN=5.6 earthquake 9th November and their aftershocks, see Figure 22 upper part.
- A major upgrade was made during June - August 2018 for JNE and JNW stations. Due to technical issues the upgrade was finalized in September for JNE and in October for JNW. From Table 6 this is clearly seen as an increase in detected local and teleseismic earthquakes from the same months.
- TBLU and OSL are recording mostly teleseismic earthquakes, which is as expected due to their location in noisy environment. Stronger local earthquakes will, however, be detected.
- The stations KONS, STOK and MOR8 continue to record a higher number of small earthquakes and explosions in the area. Due to improved methods identifying explosions fewer explosions are located and therefore fewer picks are made at these stations.
- The number of events at stations KTK and VADS varies a lot depending on which station is picked for identified explosion. (For explosions at known mines and quarries only P-wave onsets at two stations are identified.)

- During June-August waveform data from the stations JETT, AKN, BRBA and BRBB were not transferred to Bergen from NORSAR and these stations were not included in the locations during that time period.
- During July-September data are also missing from the SPITS array at Svalbard, probably due to technical problems.

**Table 5. Monthly statistics of events recorded at each station for January-June 2018. Abbreviations are: L = Number of local events recorded at more than one station and D = Number of teleseismic events recorded at the station.**

| | JANUARY | | FEBRUARY | | MARCH | | APRIL | | MAY | | JUNE | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **STATION** | **L** | **D** | **L** | **D** | **L** | **D** | **L** | **D** | **L** | **D** | **L** | **D** |
| **ASK** | 21 | 25 | 16 | 11 | 17 | 14 | 19 | 15 | 25 | 31 | 28 | 14 |
| **BER** | 8 | 37 | 6 | 13 | 7 | 24 | 7 | 15 | 7 | 28 | 9 | 17 |
| **BJO1** | 10 | 26 | 14 | 9 | 20 | 18 | 24 | 14 | 14 | 9 | 17 | 8 |
| **BLS5** | 29 | 43 | 42 | 23 | 43 | 33 | 32 | 21 | 24 | 34 | 17 | 20 |
| **DOMB** | 11 | 62 | 15 | 33 | 14 | 45 | 14 | 34 | 14 | 43 | 4 | 28 |
| **FAUS** | 76 | 68 | 80 | 35 | 73 | 54 | 68 | 36 | 26 | 37 | 54 | 32 |
| **FOO** | 14 | 28 | 11 | 14 | 16 | 23 | 10 | 13 | 14 | 23 | 13 | 16 |
| **HAMF** | 13 | 56 | 15 | 26 | 6 | 38 | 10 | 24 | 9 | 36 | 9 | 23 |
| **HOMB** | 20 | 26 | 38 | 15 | 28 | 21 | 48 | 14 | 26 | 19 | 22 | 17 |
| **HOPEN** | 116 | 47 | 85 | 21 | 112 | 33 | 83 | 22 | 36 | 12 | 67 | 4 |
| **HYA** | 26 | 31 | 23 | 15 | 28 | 29 | 29 | 14 | 31 | 24 | 31 | 21 |
| **JMI** | 9 | 6 | 9 | 4 | 9 | 4 | 27 | 1 | 17 | 4 | 22 | 3 |
| **JMIC** | 8 | 7 | 8 | 5 | 8 | 4 | 28 | 3 | 19 | 2 | 26 | 1 |
| **JNE** | 6 | 1 | 7 | 1 | 6 | 0 | 25 | 0 | 14 | 2 | 12 | 0 |
| **JNW** | 0 | 0 | 0 | 0 | 4 | 0 | 16 | 0 | 14 | 1 | 14 | 0 |
| **KBS** | 169 | 45 | 189 | 23 | 136 | 37 | 135 | 17 | 190 | 23 | 162 | 20 |
| **KMY** | 17 | 24 | 15 | 10 | 21 | 20 | 23 | 13 | 23 | 24 | 22 | 14 |
| **KONO** | 22 | 54 | 34 | 23 | 34 | 38 | 17 | 24 | 23 | 36 | 27 | 23 |
| **KONS** | 73 | 46 | 61 | 16 | 68 | 31 | 92 | 22 | 75 | 23 | 56 | 22 |
| **KTK1** | 139 | 69 | 152 | 40 | 69 | 54 | 99 | 41 | 18 | 17 | 11 | 11 |
| **LEIR** | - | - | - | - | - | - | - | - | - | - | - | - |
| **LOF** | 26 | 44 | 21 | 17 | 24 | 33 | 43 | 25 | 21 | 18 | 21 | 20 |
| **MOL** | 6 | 39 | 6 | 10 | 4 | 20 | 6 | 14 | 10 | 20 | 7 | 14 |
| **MOR8** | 63 | 61 | 50 | 31 | 58 | 46 | 72 | 30 | 54 | 40 | 48 | 32 |
| **NSS** | 63 | 63 | 10 | 27 | 14 | 43 | 16 | 34 | 7 | 36 | 14 | 27 |
| **ODD1** | 18 | 46 | 36 | 21 | 37 | 33 | 20 | 16 | 13 | 24 | 21 | 14 |
| **OSL** | 12 | 48 | 6 | 12 | 6 | 31 | 5 | 16 | 2 | 27 | 6 | 24 |
| **SKAR** | 43 | 63 | 53 | 24 | 54 | 37 | 48 | 25 | 57 | 41 | 55 | 29 |
| **SNART** | 20 | 30 | 42 | 14 | 32 | 24 | 52 | 14 | 33 | 31 | 21 | 16 |
| **STAV** | 9 | 36 | 3 | 8 | 8 | 19 | 6 | 14 | 4 | 23 | 6 | 10 |
| **STEI** | 51 | 63 | 56 | 35 | 54 | 51 | 60 | 34 | 52 | 40 | 52 | 33 |
| **STOK** | 49 | 41 | 43 | 20 | 54 | 31 | 70 | 20 | 41 | 20 | 45 | 26 |
| **SUE** | 18 | 30 | 20 | 11 | 22 | 22 | 25 | 12 | 29 | 22 | 24 | 15 |
| **TBLU** | 3 | 34 | 3 | 12 | 0 | 20 | 2 | 12 | 2 | 21 | 1 | 9 |
| **TRO** | 12 | 67 | 13 | 30 | 12 | 47 | 17 | 32 | 12 | 37 | 12 | 30 |
| **VADS** | 25 | 61 | 53 | 25 | 16 | 42 | 38 | 25 | 31 | 30 | 13 | 21 |
| **AKN** | 22 | 49 | 29 | 30 | 35 | 34 | 25 | 28 | 24 | 38 | 15 | 14 |
| **JETT** | 36 | 65 | 74 | 39 | 41 | 45 | 48 | 40 | 24 | 35 | 20 | 23 |
| **NORSAR** | 7 | 73 | 14 | 48 | 8 | 70 | 9 | 68 | 4 | 67 | 8 | 58 |
| **ARCES** | 132 | 69 | 156 | 42 | 140 | 52 | 98 | 39 | 52 | 46 | 29 | 11 |
| **SPITS** | 190 | 63 | 200 | 34 | 148 | 48 | 140 | 30 | 200 | 32 | 159 | 26 |

**Table 6. Monthly statistics of events recorded at each station for July-December 2018. Abbreviations are: L = Number of local events recorded at more than one station and D = Number of teleseismic events recorded at the station.**

| | JULY | | AUGUST | | SEPT | | OCT | | NOV | | DEC | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **STATION** | **L** | **D** | **L** | **D** | **L** | **D** | **L** | **D** | **L** | **D** | **L** | **D** |
| **ASK** | 19 | 32 | 39 | 28 | 35 | 19 | 41 | 30 | 7 | 13 | 26 | 23 |
| **BER** | 6 | 37 | 26 | 37 | 11 | 20 | 20 | 39 | 8 | 22 | 10 | 34 |
| **BJO1** | 18 | 28 | 16 | 27 | 4 | 10 | 16 | 17 | 9 | 13 | 3 | 9 |
| **BLS5** | 6 | 40 | 35 | 42 | 26 | 26 | 39 | 37 | 31 | 32 | 21 | 28 |
| **DOMB** | 10 | 59 | 31 | 55 | 17 | 37 | 20 | 54 | 16 | 36 | 13 | 37 |
| **FAUS** | 60 | 65 | 49 | 56 | 44 | 45 | 32 | 51 | 35 | 39 | 55 | 43 |
| **FOO** | 12 | 33 | 31 | 34 | 22 | 21 | 34 | 30 | 25 | 14 | 18 | 18 |
| **HAMF** | 10 | 56 | 10 | 44 | 9 | 39 | 9 | 47 | 11 | 30 | 6 | 33 |
| **HOMB** | 21 | 26 | 17 | 27 | 27 | 20 | 24 | 30 | 16 | 19 | 11 | 26 |
| **HOPEN** | 35 | 21 | 62 | 29 | 20 | 12 | 99 | 19 | 31 | 14 | 25 | 14 |
| **HYA** | 24 | 42 | 53 | 46 | 34 | 24 | 48 | 36 | 46 | 20 | 24 | 23 |
| **JMI** | 9 | 9 | 17 | 20 | 25 | 8 | 23 | 7 | 119 | 4 | 25 | 5 |
| **JMIC** | 12 | 10 | 20 | 21 | 22 | 7 | 24 | 11 | 145 | 5 | 27 | 5 |
| **JNE** | 0 | 0 | 1 | 1 | 23 | 6 | 26 | 6 | 136 | 6 | 27 | 5 |
| **JNW** | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 4 | 169 | 7 | 32 | 3 |
| **KBS** | 74 | 37 | 96 | 41 | 89 | 28 | 150 | 34 | 113 | 18 | 79 | 16 |
| **KMY** | 21 | 38 | 27 | 30 | 22 | 14 | 28 | 25 | 25 | 13 | 16 | 17 |
| **KONO** | 30 | 49 | 38 | 39 | 29 | 31 | 36 | 47 | 20 | 32 | 18 | 35 |
| **KONS** | 48 | 38 | 65 | 38 | 71 | 31 | 17 | 13 | 71 | 25 | 45 | 3 |
| **KTK1** | 59 | 64 | 62 | 55 | 46 | 47 | 38 | 53 | 51 | 43 | 47 | 46 |
| **LEIR** | - | - | - | - | - | - | - | - | 2 | 3 | 50 | 41 |
| **LOF** | 11 | 46 | 27 | 44 | 21 | 33 | 17 | 31 | 16 | 19 | 22 | 29 |
| **MOL** | 4 | 34 | 21 | 35 | 11 | 22 | 19 | 35 | 9 | 16 | 6 | 20 |
| **MOR8** | 32 | 45 | 43 | 47 | 55 | 49 | 26 | 50 | 45 | 36 | 47 | 40 |
| **NSS** | 7 | 57 | 14 | 51 | 10 | 40 | 12 | 47 | 12 | 36 | 8 | 39 |
| **ODD1** | 27 | 37 | 33 | 37 | 21 | 21 | 31 | 38 | 33 | 25 | 21 | 31 |
| **OSL** | 3 | 39 | 14 | 39 | 0 | 33 | 10 | 34 | 7 | 28 | 4 | 27 |
| **SKAR** | 35 | 22 | 13 | 25 | 36 | 33 | 69 | 49 | 55 | 37 | 43 | 36 |
| **SNART** | 20 | 35 | 23 | 38 | 28 | 21 | 29 | 32 | 23 | 18 | 13 | 25 |
| **STAV** | 9 | 31 | 13 | 32 | 14 | 14 | 10 | 29 | 4 | 21 | 5 | 19 |
| **STEI** | 49 | 64 | 50 | 53 | 51 | 46 | 40 | 45 | 37 | 35 | 41 | 40 |
| **STOK** | 41 | 40 | 55 | 41 | 60 | 30 | 26 | 36 | 70 | 26 | 53 | 32 |
| **SUE** | 150 | 31 | 42 | 34 | 29 | 13 | 39 | 28 | 38 | 18 | 23 | 18 |
| **TBLU** | 12 | 19 | 5 | 46 | 3 | 20 | 7 | 34 | 0 | 8 | 1 | 22 |
| **TRO** | 21 | 60 | 14 | 54 | 14 | 42 | 10 | 49 | 13 | 34 | 11 | 38 |
| **VADS** | 21 | 54 | 26 | 49 | 16 | 35 | 32 | 46 | 31 | 31 | 32 | 35 |
| **AKN** | 3 | 0 | 17 | 0 | 30 | 36 | 36 | 37 | 40 | 28 | 21 | 29 |
| **JETT** | 3 | 0 | 4 | 0 | 19 | 43 | 24 | 45 | 19 | 30 | 29 | 39 |
| **NORSAR** | 3 | 92 | 14 | 85 | 9 | 80 | 11 | 98 | 10 | 70 | 10 | 69 |
| **ARCES** | 8 | 4 | 14 | 38 | 22 | 44 | 34 | 51 | 63 | 40 | 64 | 45 |
| **SPITS** | 68 | 42 | 73 | 38 | 93 | 25 | 165 | 44 | 133 | 28 | 84 | 37 |

## 4.2 The seismicity of Norway and adjacent areas

This section first gives an overview of the seismicity in the monitoring area before presenting the activity in specific areas in more detail.

The main area of interest is defined as 54-82N and 15W-35 Figure 15. We also show the seismicity for the Arctic region including the Barents Sea defined by coordinates 65-85°N and 25°W-50°E, Figure 18. A total of 3146 recorded events are located inside the NNSN prime area. During analysis and using the explosion filter (Ottemöller, 1995), 38% of these events were identified as confirmed or probable explosions, or induced events. The number of located explosions are decreasing due to improved methods to discriminate between earthquakes and explosions. For identified explosions P-phase is only picked for two stations, and the events are therefore not located. Figure 15 shows all events in the prime area, analysed and located during 2018. Among these, ca 270 are located in the vicinity of Jan Mayen.

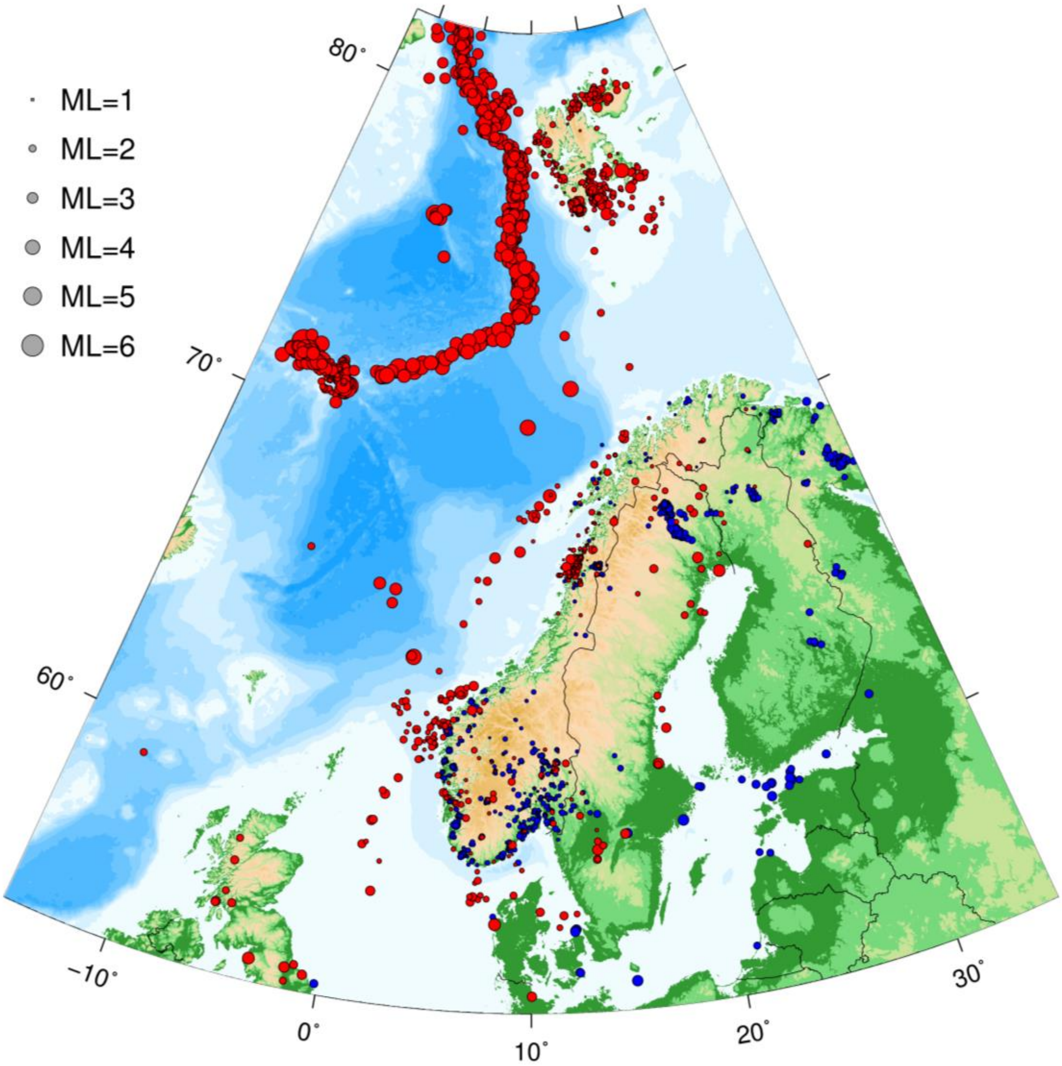



**Figure 15. Epicentre distribution of events analysed and located in 2018. Earthquakes are plotted in red. Probable and confirmed explosions and induced events are plotted in blue.**

Figure 16 shows the location of earthquakes (mining induced events, known and probable explosions removed) located within the prime area with one of the calculated magnitudes above 3. Table 7 lists the same earthquakes with all earthquakes located close to the Mid-Atlantic ridge excluded.

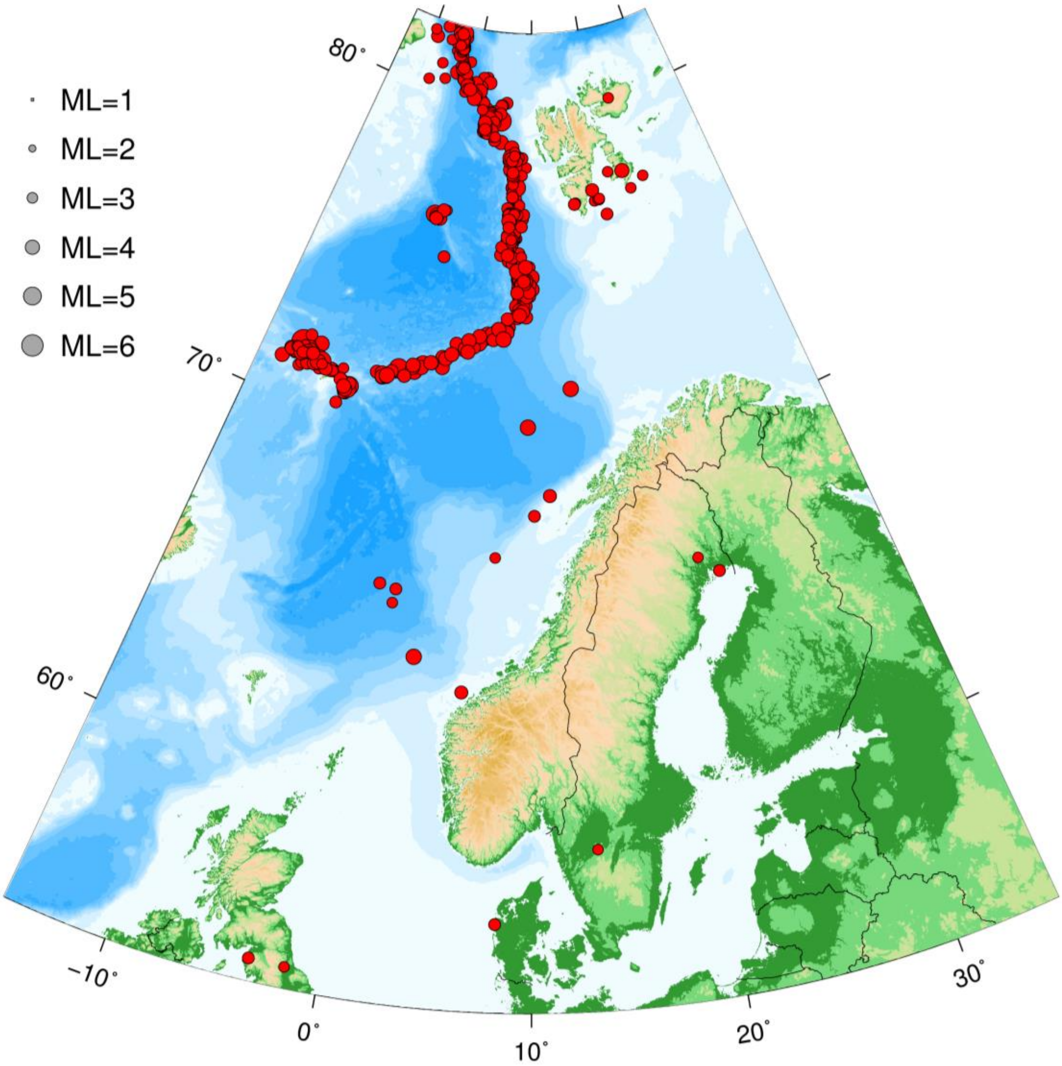



**Figure 16. Epicentre distribution of located events with one of the calculated magnitudes above or equal to 3.0. For station location, see Figure 1.**

**Table 7. Earthquakes located in the vicinity of mainland Norway and in the Svalbard area (grey background) with any reported magnitude above or equal to 3.0 for the time period January through December 2018. In cases where all BER magnitudes are below 3 but the event still is included in the list, NORSAR (NAO), GEUS- Geological Survey of Denmark and Greenland (DNK), University of Uppsala (UPP), University of Helsinki (HEL) or the British Geological Survey (BGS) has reported a magnitude of 3.0 or larger. Abbreviations are: HR = hour (UTC), MM = minutes, Sec = seconds, L = distance identification (L=local, R=regional, D=teleseismic), Latitud = latitude, Longitud = longitude, Depth = focal depth (km), F = fixed depth, AGA = agency (BER=Bergen), NST = number of stations, RMS = root mean square of the travel-time residuals, ML = local magnitude, Mw = moment magnitude and the new MN = mb(Pn,Sn) magnitude.**

| Year | Date | HRMM | Sec | L | Latitud | Longitud | Depth | AGA | NST | RMS | ML BER | MN BER | ML NAO | Mw BER | ML OTHERS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2018 | 1 2 | 2349 | 22.1 | L | 76.982 | 18.907 | 21.3 | BER | 15 | 0.6 | 2.6 | | 3.0 | | |
| 2018 | 2 4 | 0204 | 22.9 | L | 66.219 | 21.882 | 15.0 | BER | 23 | 0.7 | 2.4 | | 3.0 | | 3.1UPP |
| 2018 | 214 | 0411 | 34.4 | L | 65.104 | 0.539 | 11.7 | BER | 41 | 1.0 | 2.5 | | 3.1 | | |
| 2018 | 216 | 2153 | 25.6 | L | 77.134 | 23.265 | 19.7 | BER | 15 | 0.8 | 2.6 | | 3.1 | | |
| 2018 | 220 | 1526 | 10.0 | L | 68.471 | 11.437 | 15.0 | BER | 44 | 0.8 | 2.8 | | 3.6 | | |
| 2018 | 228 | 0733 | 51.3 | L | 54.602 | -3.368 | 3.1 | BER | 26 | 0.4 | 2.9 | | | | 3.3BGS |
| 2018 | 313 | 0613 | 39.8 | L | 76.964 | 18.685 | 15.0 | BER | 14 | 0.7 | 2.5 | | 3.0 | | |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2018 | 419 | 1801 | 23.0 | L | 62.793 | 5.656 | 21.3 | BER | 50 | 0.8 | 3.4 | | 3.6 | | 3.9DNK |
| 2018 | 420 | 0601 | 13.7 | L | 70.454 | 9.725 | 20.5 | BER | 26 | 0.9 | | 4.3 | 3.5 | | |
| 2018 | 430 | 0239 | 31.9 | L | 77.682 | 22.613 | 15.0 | BER | 30 | 1.4 | 3.3 | | 4.1 | | |
| 2018 | 5 4 | 1752 | 20.8 | L | 76.953 | 18.274 | 12.0 | BER | 8 | 0.6 | 2.9 | | 3.0 | | |
| 2018 | 511 | 0710 | 18.9 | L | 76.515 | 19.576 | 15.0 | BER | 12 | 0.7 | 3.2 | | 3.5 | | |
| 2018 | 615 | 1903 | 9.9 | L | 76.979 | 18.830 | 21.1 | BER | 12 | 0.7 | 2.9 | | 3.4 | | |
| 2018 | 623 | 0549 | 15.2 | L | 58.422 | 13.530 | 15.5 | BER | 37 | 0.8 | 3.2 | | 3.7 | | 3.2UPP |
| 2018 | 624 | 0635 | 7.2 | L | 77.395 | 25.181 | 20.3 | BER | 10 | 0.6 | 2.4 | | 3.0 | | |
| 2018 | 627 | 0722 | 36.9 | L | 65.723 | 23.150 | 4.8 | BER | 28 | 0.6 | 2.9 | | | | 3.3UPP |
| 2018 | 811 | 1552 | 50.0 | L | 65.499 | 0.639 | 23.5 | BER | 31 | 0.7 | 2.2 | | 3.5 | | |
| 2018 | 814 | 0416 | 12.5 | L | 67.902 | 10.244 | 13.6 | BER | 27 | 0.6 | 2.7 | | 3.3 | | |
| 2018 | 9 2 | 1303 | 28.3 | L | 65.584 | -0.487 | 10.0 | BER | 27 | 0.7 | 2.3 | | 3.3 | | |
| 2018 | 915 | 1839 | 9.4 | L | 54.578 | -1.643 | 26.1 | BER | 28 | 0.8 | 2.5 | | | | 3.1BGS |
| 2018 | 916 | 0857 | 44.0 | L | 56.406 | 8.182 | 15.0 | BER | 59 | 1.1 | 3.1 | | 3.0 | | 3.5DNK |
| 2018 | 930 | 1012 | 12.0 | L | 76.956 | 15.746 | 4.3 | BER | 13 | 0.9 | 3.1 | | 3.2 | | |
| 2018 | 10 5 | 1616 | 3.0 | L | 76.917 | 15.597 | 7.6 | BER | 12 | 0.5 | 3.0 | | 3.3 | | |
| 2018 | 1012 | 1239 | 10.3 | L | 66.674 | 7.377 | 25.9 | BER | 35 | 0.6 | 2.4 | | 3.1 | 2.5 | |
| 2018 | 1013 | 0833 | 16.4 | L | 77.273 | 18.191 | 15.0 | BER | 23 | 1.2 | 3.0 | | 3.8 | | |
| 2018 | 1018 | 1813 | 10.8 | L | 63.659 | 2.457 | 15.6 | BER | 53 | 0.9 | 3.6 | | 4.4 | 3.6 | |
| 2018 | 1112 | 0947 | 36.2 | L | 71.536 | 13.601 | 14.1 | BER | 49 | 0.9 | 3.6 | | 4.5 | | |
| 2018 | 1118 | 1005 | 8.0 | L | 76.995 | 18.900 | 15.9 | BER | 14 | 1.0 | 2.9 | | 3.2 | | |
| 2018 | 1123 | 1603 | 32.0 | L | 79.868 | 23.013 | 21.7 | BER | 8 | 0.7 | 3.0 | | 3.0 | | |
| 2018 | 1216 | 2149 | 55.0 | L | 77.743 | 20.619 | 19.4 | BER | 8 | 0.6 | 3.1 | | 3.0 | | |

The largest local or regional earthquake in 2018, recorded on Norwegian stations and within the prime area, was an earthquake that occurred on 18 October at 18:13 (UTC) in the area northwest of Stad (Figure 16). The calculated location is 63.659N, 2.457E with magnitude $M_{L(BER)}$=3.6 Seismograms for the earthquake recorded at the closest stations including the two BGS stations LRW and SOFL, and the two temporary stations MANEN and DAMEN, are shown in Figure 17.

An equally large earthquake occurred 12 November 2018 at 09:47 located to Norskehavet northwest of Tromsø.

The largest earthquake of the year occurred in the Jan Mayen fracture zone about 135 km northwest of the island on 9 November 2018 at 01:49 (UTC) with MW=6.8 (GCMT). The event was felt on Jan Mayen and had numerous aftershocks. The moment tensor solution by GCMT was consistent with the orientation of movement along the fracture zone, which is left-lateral strike slip along the NW-SE striking plane. The accelerometer at JMI recorded a maximum acceleration of 0.45 $m/s^2$.

Between February and July 2018, seismic activity was observed along the Greenland Fracture Zone. A total of 13 earthquakes were recorded by NNSN stations and located to the area 75.0-76.6N, 2.5-0.0W. The earthquakes are recorded on the seismic stations at Svalbard and Greenland, but the larger events are also recorded at the Norwegian mainland stations. The largest earthquake in the sequence was recorded on 30 May 2018, with a calculated magnitude $M_{N(BER)}$=5.1.

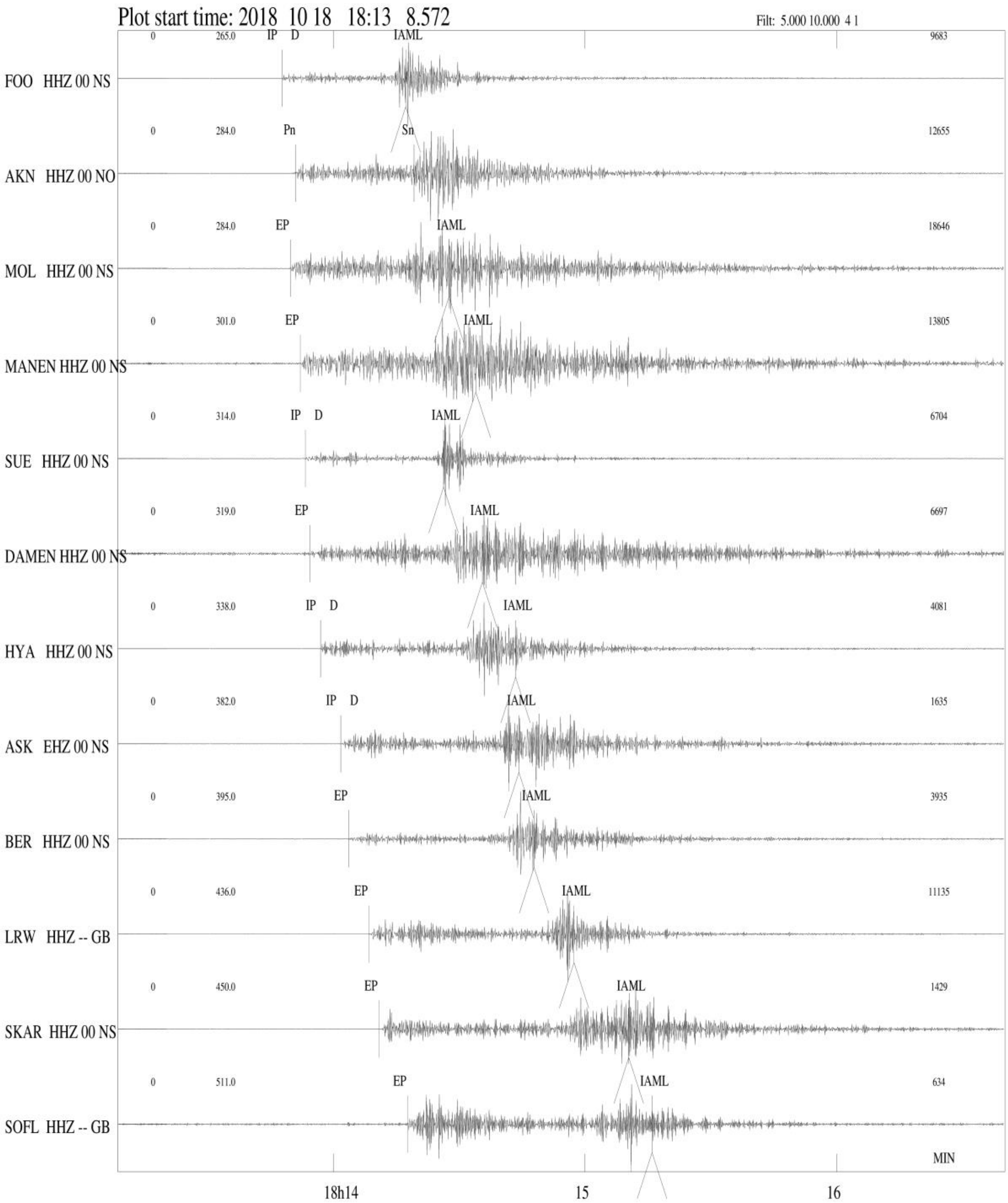



**Figure 17 Seismic traces for the earthquake occurring 18 October 2018 at 18:13 (UTC). The seismograms are filtered between 5-10Hz. The P-phase, some S-phases and amplitude measurements are marked.**

An earthquake located closer to the coast occurred 19 April 2018 at 18:01 (UTC) offshore, west of Molde and Ålesund (Figure 16). This earthquake was felt in the closest populated areas in Møre og Romsdal as can be seen in Figure 30.

We define the arctic area as the region 65-85°N and 25°W-50°E. Most of the activity falls into three areas: Jan Mayen, the Mid-Atlantic ridge and Storfjorden southeast of Svalbard, as can be seen in Figure 18. Since 2014 data from Danish stations on Greenland (see Figure 2) and since June 2017 the BORG station located on Iceland, were included in the daily processing which has increased the location capability for earthquakes south and west of Jan

Mayen, and northwest of Svalbard. The number of earthquakes recorded on enough stations to be located, has increased.

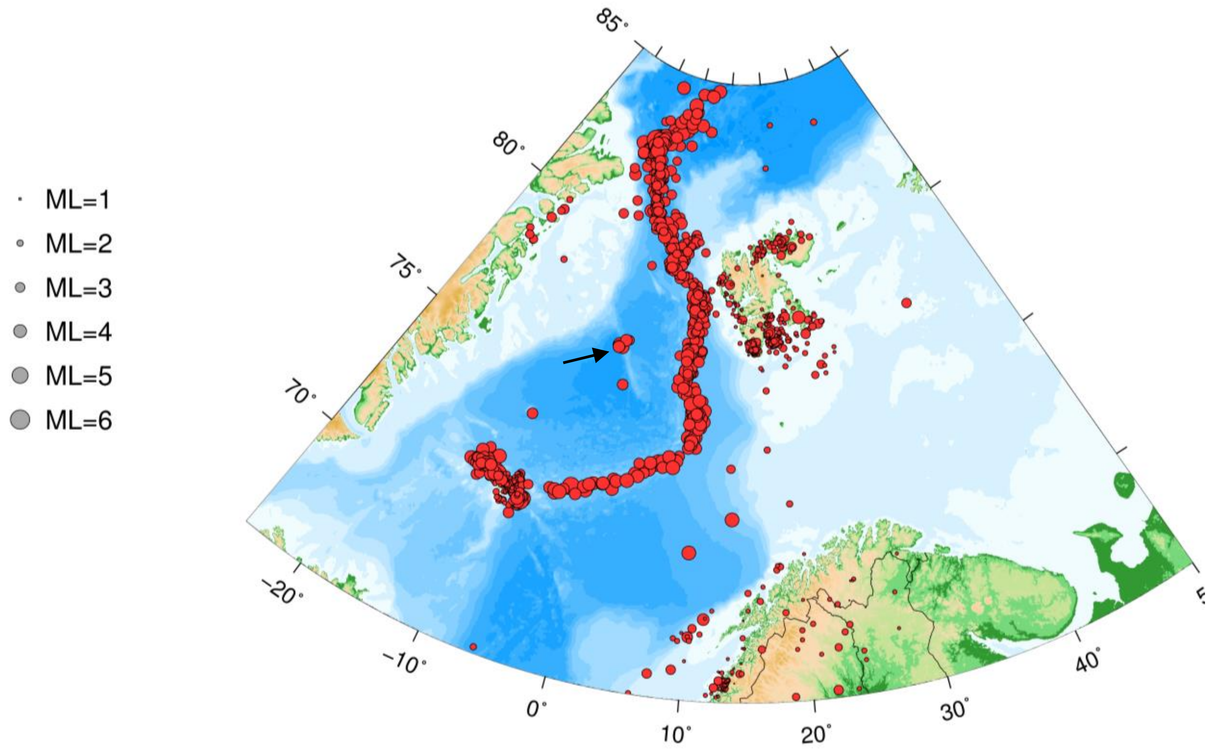



**Figure 18. Seismicity in the Norwegian arctic area during 2018. A total of 1696 located earthquakes.**

From the figure one can notice that the seismic activity to the west of Jan Mayen has increased compared to 2017. The Greenland Fracture Zone (arrow in Figure 18) has clear activity in its northern part.

### 4.2.1 Seismicity in Nordland

Figure 19 shows the seismicity in Nordland with 254 located earthquakes. The area includes known locations of possible earthquake swarm activity such as Meløy (66.8N, 13.5E), Steigen (67.8N, 15.1E) and Stokkvågen (66.3N, 13.1). The Steigen area was more active between 2007 and 2008, then it was relatively quiet until 2015 when 44 earthquakes appeared. In spring 2016 the temporary stations deployed during the NEONOR2 (2013-2016) project were taken down. The decreased station density in the area has resulted in fewer events with low magnitude being located (Figure 20). As part of the EPOS project seven new seismic stations will be installed in the Nordland area. This will improve earthquake detection and reduce the location uncertainty.

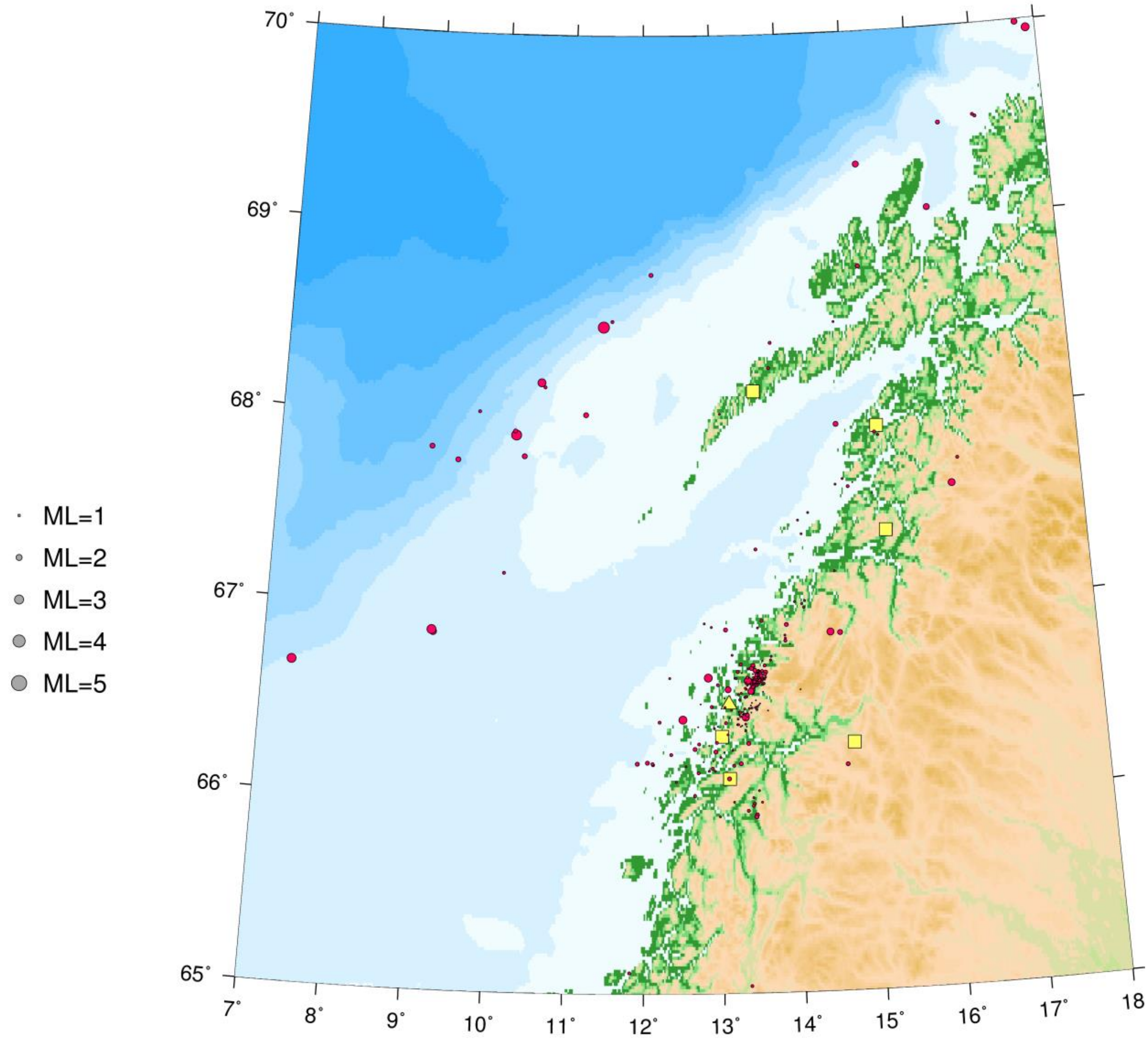



**Figure 19. Seismicity in the Nordland area. Red circles show seismicity for 2018 and yellow triangle is NNSN seismic stations. Only probably earthquakes are included.**

As seen in Figure 19, the most active area onshore is near Jektvik (66.6N,13.5E), west of the Svartisen glacier, with 105 located earthquakes during 2018. The earthquake-activity within this area is now stable after the high in 2015 (Figure 20).

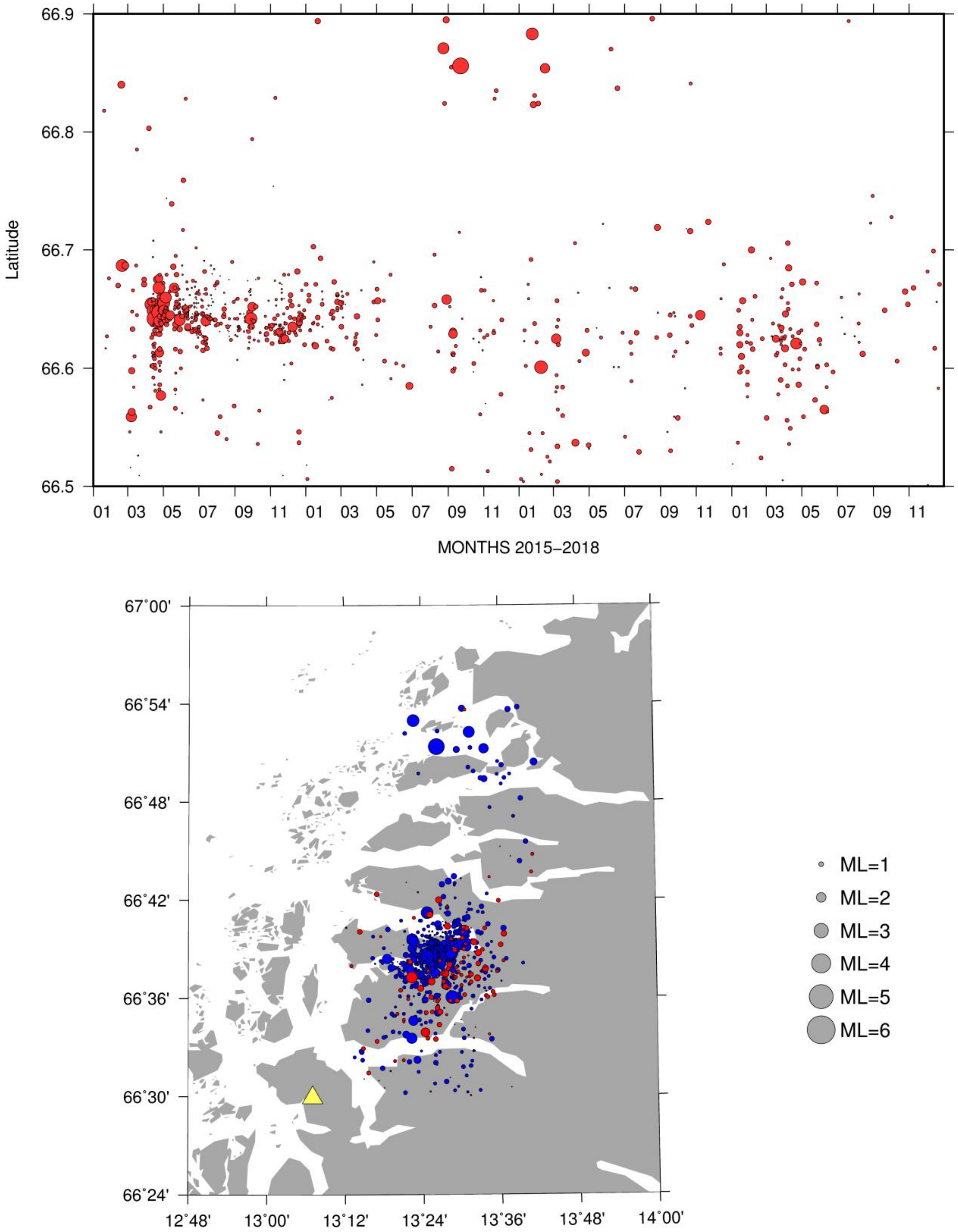



**Figure 20 Time distribution (upper) and location (lower) of the earthquake swarm located in the Jektvik area, southwest of the Svartisen glacier. Earthquakes occurring during 2018 are marked in red and earthquakes recorded in 2015 through 2017 are marked in blue. Note! The events shown are limited by 66.5- 66.9N and 13.2-13.7E, a smaller area than shown on the map. The location of the permanent NNSN station (KONS) are marked with a yellow triangle on the map.**

### 4.2.2 Seismicity in the Jan Mayen area

Jan Mayen is located in an active tectonic area with two major structures, the Mid Atlantic ridge and the Jan Mayen fracture zone, interacting in the vicinity of the island. Due to both tectonic and magmatic activity in the area, the number of recorded earthquakes is higher than in other areas covered by Norwegian seismic stations. NNSN are operating three of the four seismic stations on the island (see Figure 21).

During 2018, a total of 268 earthquakes were located as seen in Figure 21 and of these, 73 had a magnitude equal to or above 3.0. The initial work preparing for the station upgrade was initiated in June 2018 and data from JNE and JNW are missing until the upgrade was finalized and the stations started recording on 13 August 2018. The gap in the located earthquakes is clearly seen on Figure 21.

An increase in located earthquakes was observed at the end of 2018. The earthquakes are located to the northwest of the island, along the Jan Mayen Fracture Zone. The largest earthquake occurred 9 November 2018 at 01:49 (UTC) with magnitude 6.8W(USGS). The epicentre was located approximately 135km from Olonkinbyen. The main shock was followed by 32 located aftershocks.

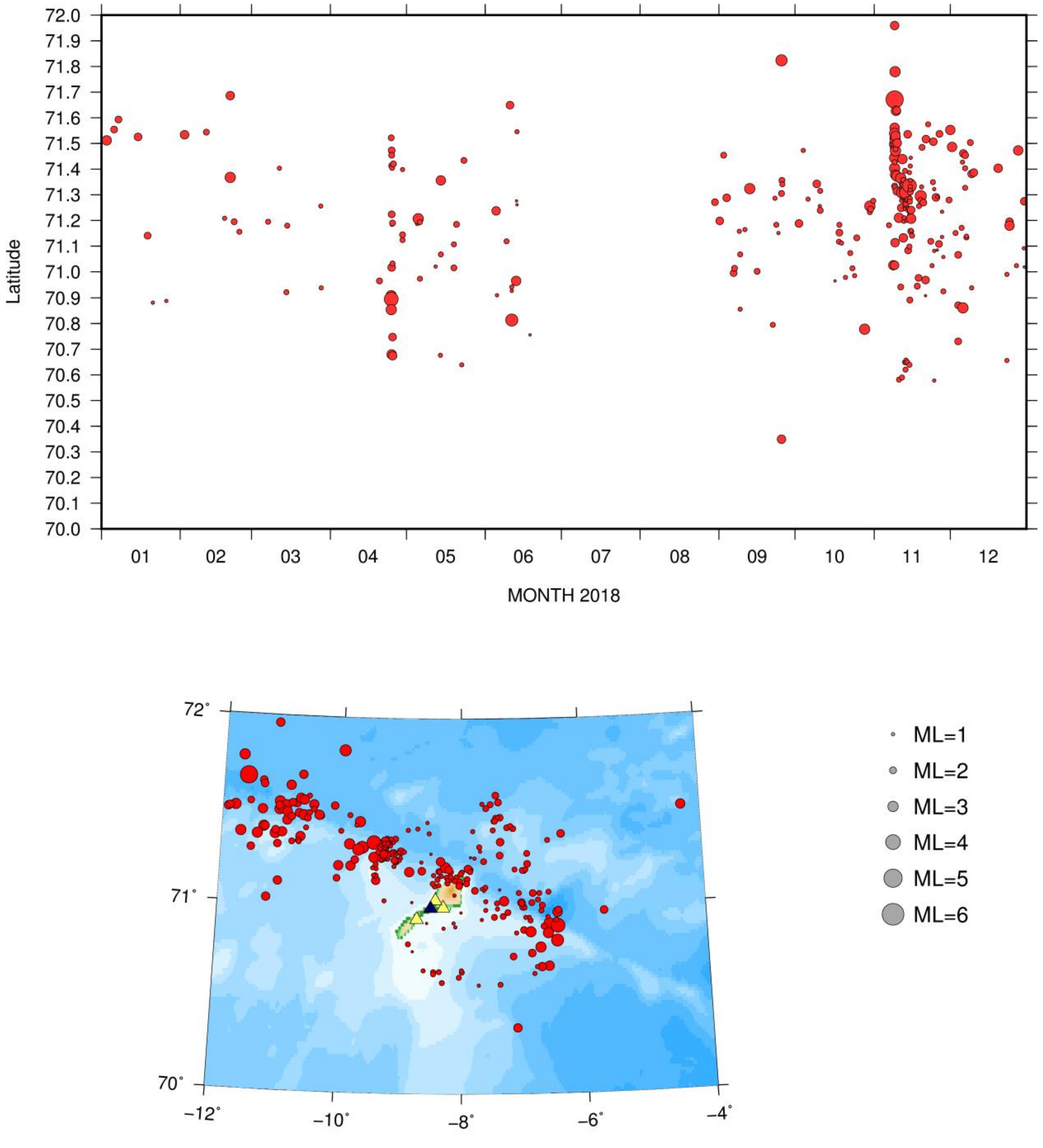



**Figure 21. Earthquakes located in the vicinity of Jan Mayen during 2018. The time distribution is shown in the upper part. The lack of located earthquakes during June–August is due to upgrade of the JNE and JNW stations. The seismic stations operated by NNSN are marked with yellow triangles and the seismic station operated by NORSAR is marked in black.**

The number of recorded earthquakes in the Jan Mayen area has varied over the last years (Figure 22). The number of relatively strong earthquakes (M≥3) shows smaller time variation than for the smaller earthquakes. The increases in 2004 and 2005 were due to the M=6.0 earthquake in 2004 and its aftershocks (Sørensen et al., 2007). The same is true for 2011, where the M=6.0 earthquake on 29 January was followed by a sequence of aftershocks. The 30 August 2012 earthquake (M=6.3) with its fore and aftershocks clearly increases the number of recorded events in 2012 compared with previous years, making it the largest number of recorded events yearly for more than 10 years. For the following years after 2012, the number of located smaller earthquakes has increased slightly, while the number of larger (M≥3.0) earthquakes is relative stable. The slightly lower number in located earthquakes during parts of 2016, 2017 and 2018 is caused by different technical problems and major upgrade (see technical section above).

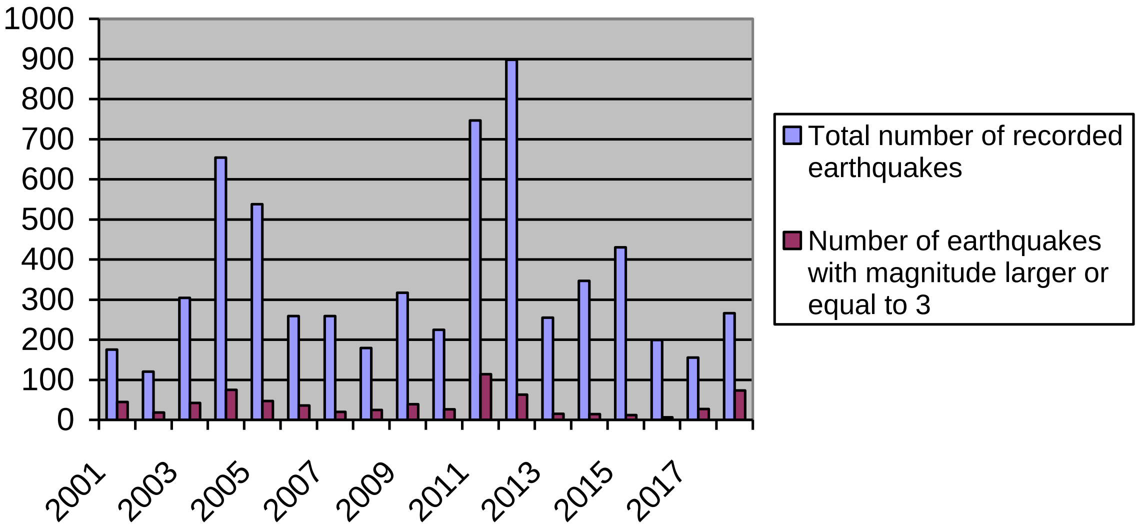



**Figure 22. Yearly distribution of earthquakes located in the Jan Mayen area since 2001. The area is as shown in Figure 21.**

### 4.2.3 Seismicity at Svalbard

The seismicity in the Svalbard area is presented in Figure 23, showing both a map with the seismicity since 2007 and the distribution of events over time. There are several seismically active areas in this region. This report will focus on three main areas: the Storfjorden area including Heer Land (on the northwest side of Storfjorden) and Diskobukta (the area west of Egdeøya), Sørkappland (the area at the very southwest coast of Spitsbergen), and Nordaustlandet. From Figure 23 there is no indication of increased seismic activity in any area or seismic activity in areas which not has been seismic active previously.

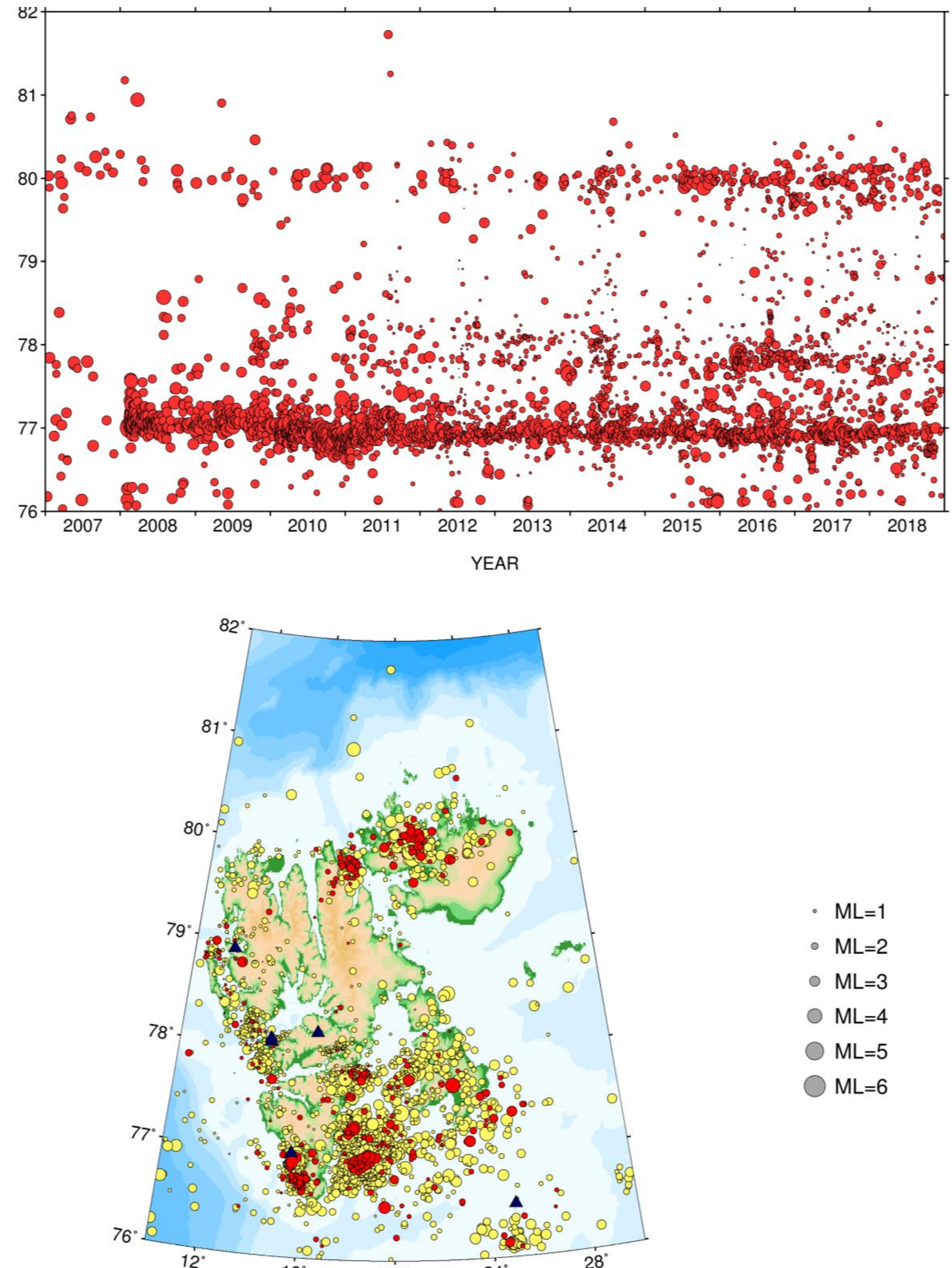



**Figure 23. Seismicity in the Svalbard area. Bottom: Earthquakes occurring in 2018 are plotted in red circles. Yellow circles show seismicity for 2007-2017. The blue triangles give the station locations. Top: Seismicity in the same area is plotted as latitude as function of time.**

## Storfjorden

The Storfjorden area southeast of Svalbard, defined by latitude 76.5-78N and longitude 16-22E, has been more seismically active since the $M_w$=6.0 earthquake on 21st February 2008. The earthquake was the starting point of a prolonged earthquake sequence. The yearly variation in the number of detected earthquakes in Storfjorden area is shown in Figure 23. An increase in the number of located earthquakes is clearly seen in 2008 explained by the M6 earthquake and its aftershocks.

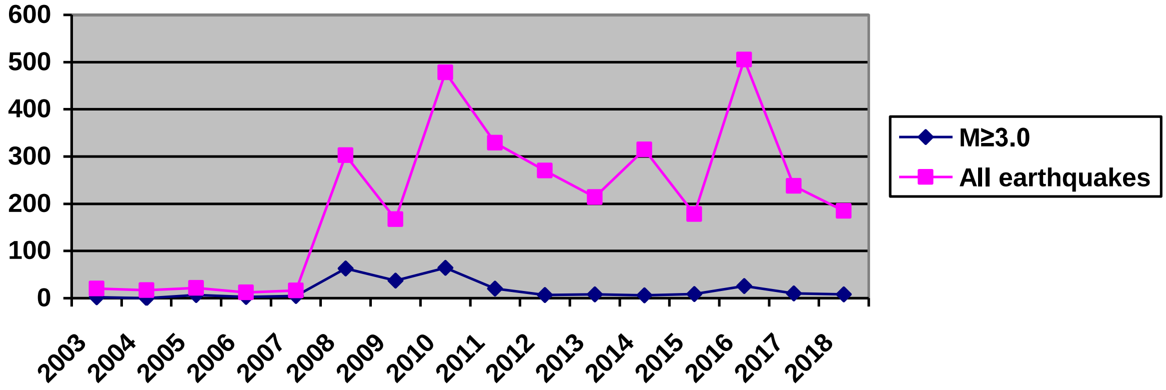



**Figure 24. Yearly number of earthquakes located to the Storfjorden area.**

The total number of events located in the Storfjorden area in 2018 was 185, which presents a decrease from 2017. Figure 23 shows both a map with the seismicity since 2007 and the distribution of events over time. In Diskobukta (77.6-78.1N, 19.3-22.0E), where the seismic activity was relatively high in 2016, the seismicity has decreased significantly but is still higher than the expected normal level.

The largest earthquake in the Storfjorden area during 2018 occurred May 11th at 07:10(UTC) located 76.5N 19.6E, with a magnitude $M_L$=3.2(BER).

## Sørkappland

At Sørkappland, located at the southwestern coast of Spitsbergen (76.4-77.2N, 14-17E), the earthquake activity has increased the last three years, as can be seen from Figure 25.

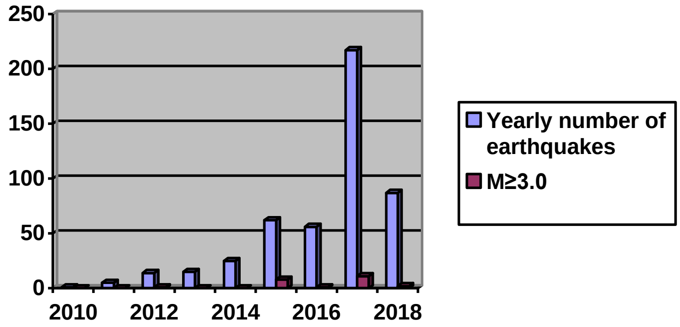
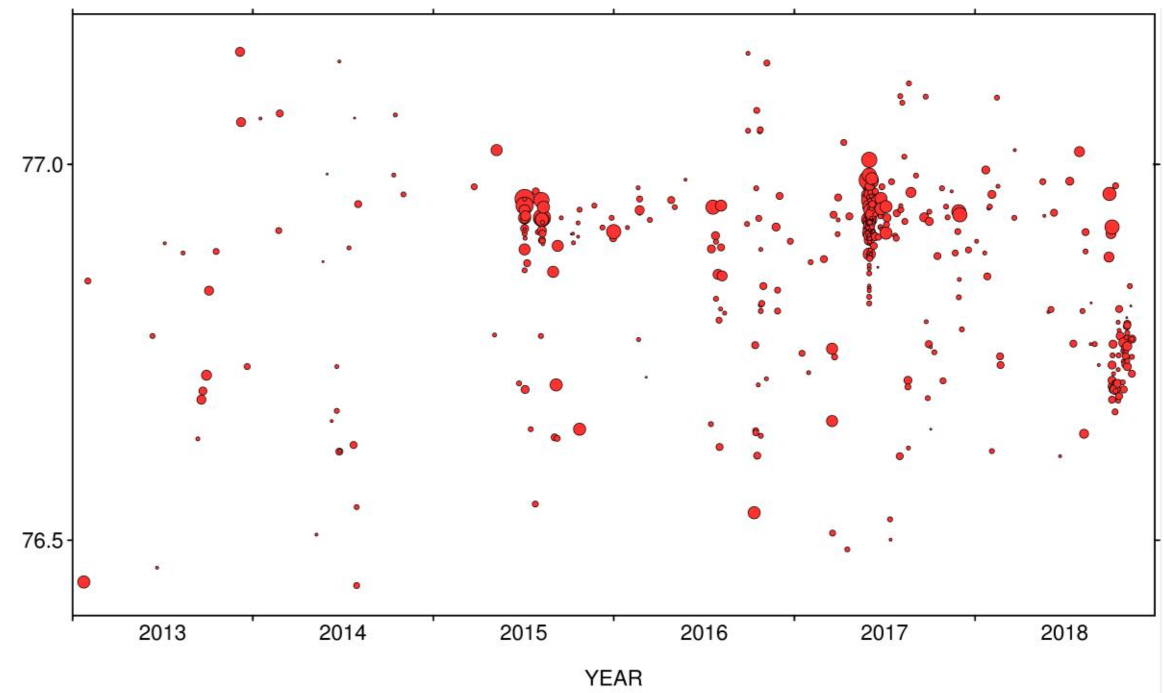



**Figure 25. Yearly number of earthquakes recorded in the Sørkappland area.**

The earthquakes located to the area the last five years are plotted in Figure 26. Digital data from the seismic station at Hornsund, Svalbard (HSPB) was routinely included in the NNSN data prosessing from November 2009, and increased the number of small located earthquakes. The last years there was an increase in earthquakes located to the area with a recorded high in 2017, as can be seen on Figure 25. During 2018, 87 earthquakes were located here and 2 had a magnitude slightly above 3.0. These two earthquakes are located to the Hornsund fjord, see Figure 26.

A majority of the earthquakes recorded in 2018 are located to an area south of the mouth of the Hornsund fjord. There is reasonable uncertainty in the location of the events in this area so it is possible that the earthquakes should be located closer together, defining a new seismic active area.



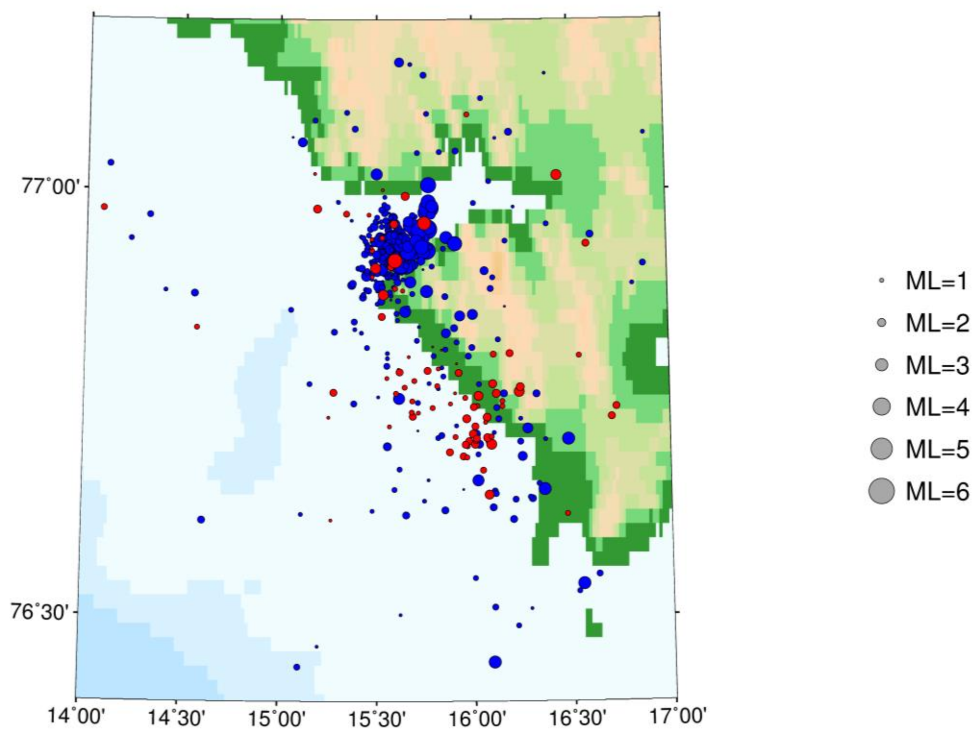
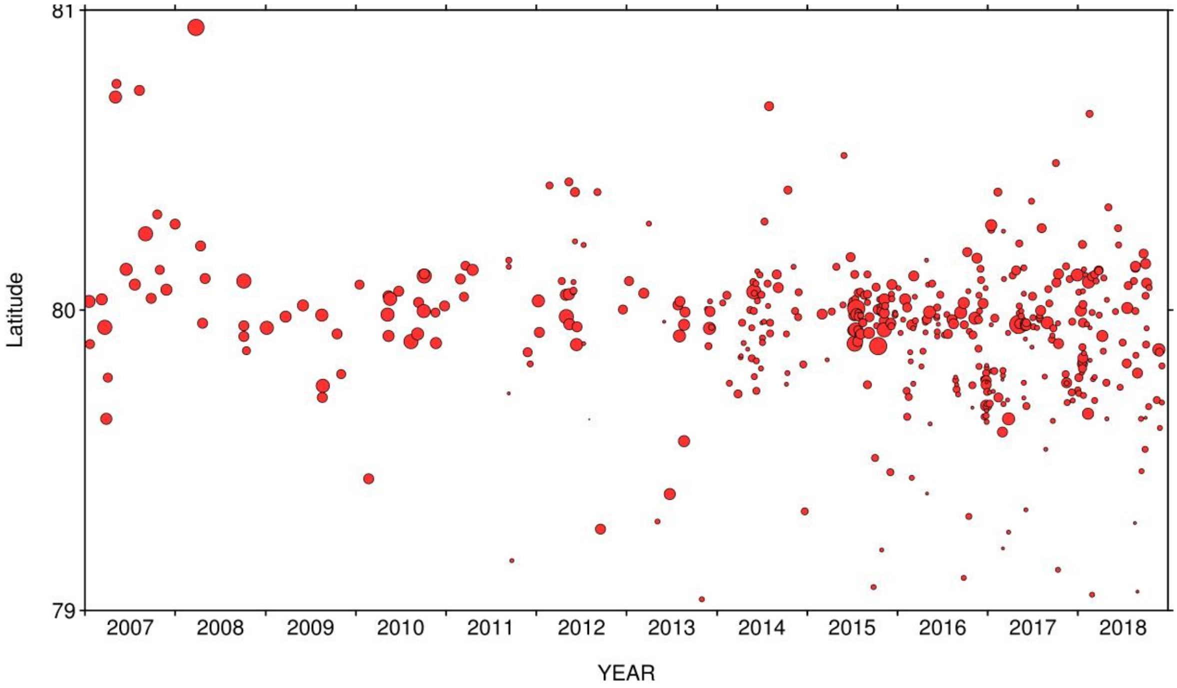




**Figure 26. Earthquakes in the NNSN database since 2013. Earthquakes detected 2013-2017 (blue) and 2018 (red),**

## Nordaustlandet

Nordaustlandet is a well-known seismically active area. Earthquakes located since January 2007 are presented in Figure 27. In 2016, an independent small cluster developed to the west of the regular activity, on the western side of the Hinlopenstretet. During 2018, 78 earthquakes were located at Nordaustlandet. These earthquakes are marked in red in Figure 27. As can be seen from the figure the earthquake activity located onshore west of the Hilopenstretet continues but the seismic activity has not increased.

It should be noted that the location accuracy in this area is rather sensitive to the seismogram interpretation and small changes may change the epicentre by tens of kilometres. However, the separation of this new cluster from the regular pattern is likely to be real.



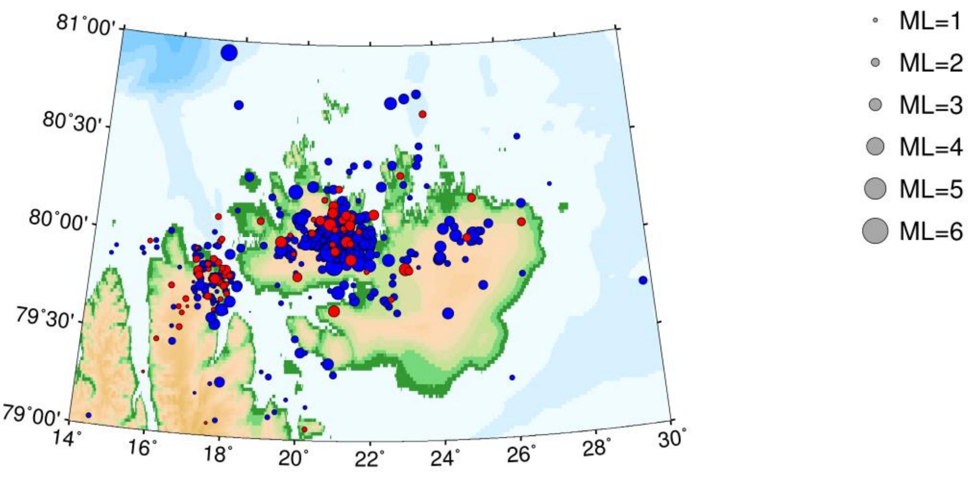




**Figure 27. Earthquakes located at Nordaustlandet during 2018 (red) and between 2007-2017 (blue).**

### 4.2.4 Earthquakes in the southern North Sea

The North Sea area is in this report defined by 54-60N and 1W-5E. During 2018, 10 earthquakes were detected and located in the North Sea, Table 8. The yearly distribution of earthquakes in the area since 2000, is presented in Figure 28. The seismic stations located in the area and contributing data to NNSN are marked by blue triangles. For the location accuracy in the North Sea data from offshore installations are important. A separate triggering algorithm has been tested using Grane data to ensure that also the smaller earthquakes in the area are identified. The detection ability for the NNSN onshore seismic stations are limited to magnitude 2.5 at these distances. All earthquakes located to the area since 2007 and their distribution over time, are presented in Figure 29.

**Table 8. Earthquakes recorded during 2018 and located in the area limited by 54-60N and 1W-5E.**

| Year | Date | HRMM | Sec | L | Latitud | Longitud | Depth | AGA | NST | RMS | ML BER | ML NAO | ML BGS | ML DNK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2018 | 3 3 | 1418 | 33.8 | L | 57.879 | 2.089 | 22.5 | BER | 22 | 0.6 | 1.4 | | | |
| 2018 | 317 | 1637 | 50.2 | L | 59.740 | 1.909 | 27.5 | BER | 28 | 0.4 | 2.3 | | 2.8 | |
| 2018 | 420 | 1814 | 5.6 | L | 57.026 | 1.832 | 13.6 | BER | 32 | 0.7 | 1.8 | | 2.6 | |
| 2018 | 420 | 1936 | 35.2 | L | 59.838 | 1.742 | 23.0 | BER | 13 | 0.7 | 1.9 | | | |
| 2018 | 826 | 2159 | 53.2 | L | 58.279 | 1.080 | 17.7 | BER | 35 | 0.4 | 1.9 | | 2.3 | |
| 2018 | 828 | 0459 | 19.9 | L | 54.468 | -0.765 | 15.0 | BER | 39 | 0.9 | 2.2 | | 2.8 | |
| 2018 | 926 | 1302 | 7.0 | L | 58.974 | 1.383 | 15.0 | BER | 34 | 0.5 | 2.4 | | 2.8 | |
| 2018 | 10 1 | 2015 | 42.1 | L | 58.991 | 1.445 | 15.0 | BER | 18 | 1.0 | 1.7 | | | 2.3 |
| 2018 | 12 3 | 1036 | 0.5 | L | 58.354 | 1.261 | 31.0 | BER | 14 | 0.3 | 1.4 | | | |

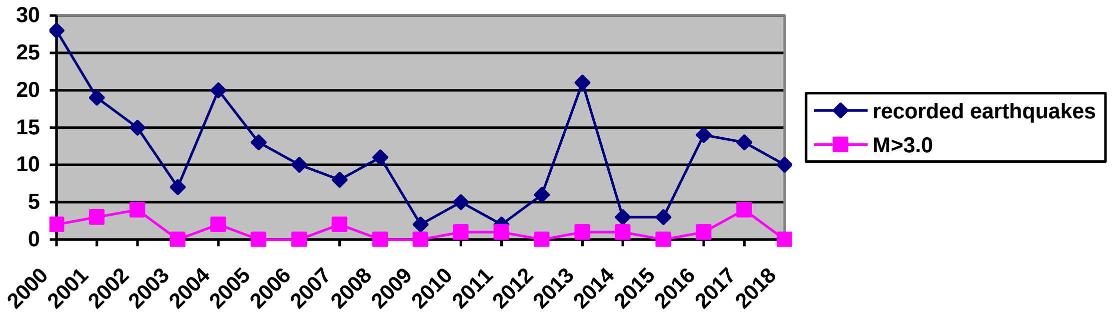
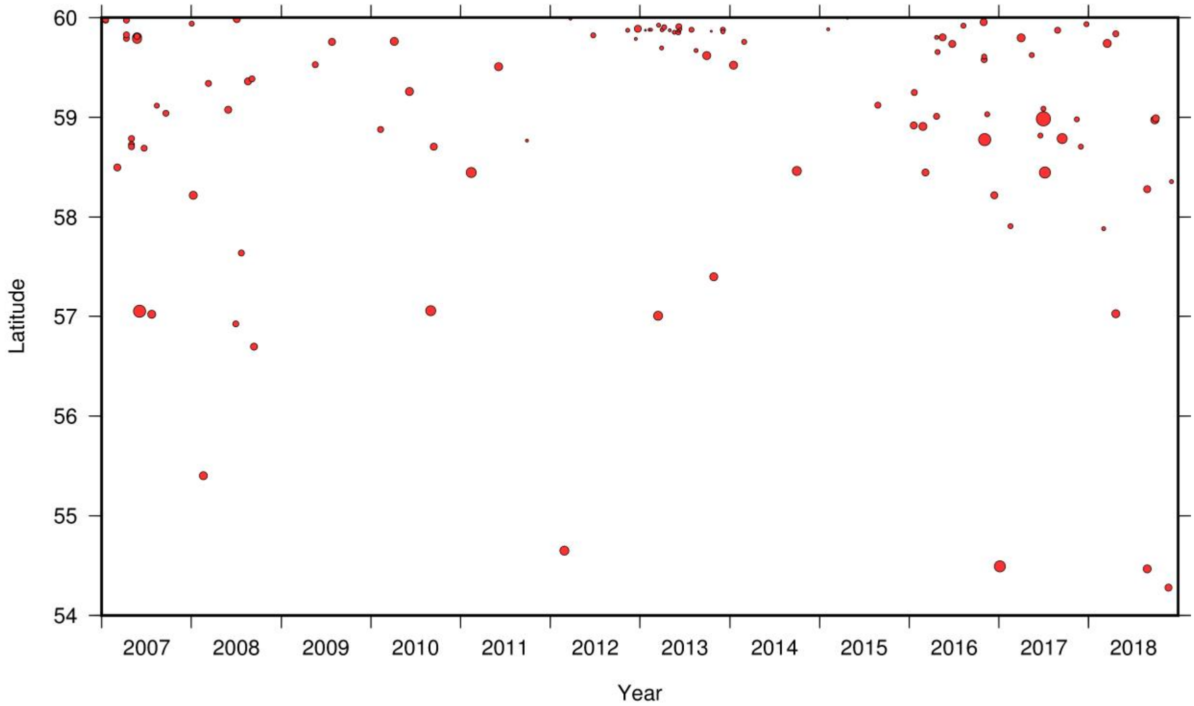



**Figure 28. Number of recorded earthquakes in the area 54-60N, 1W-5E.**



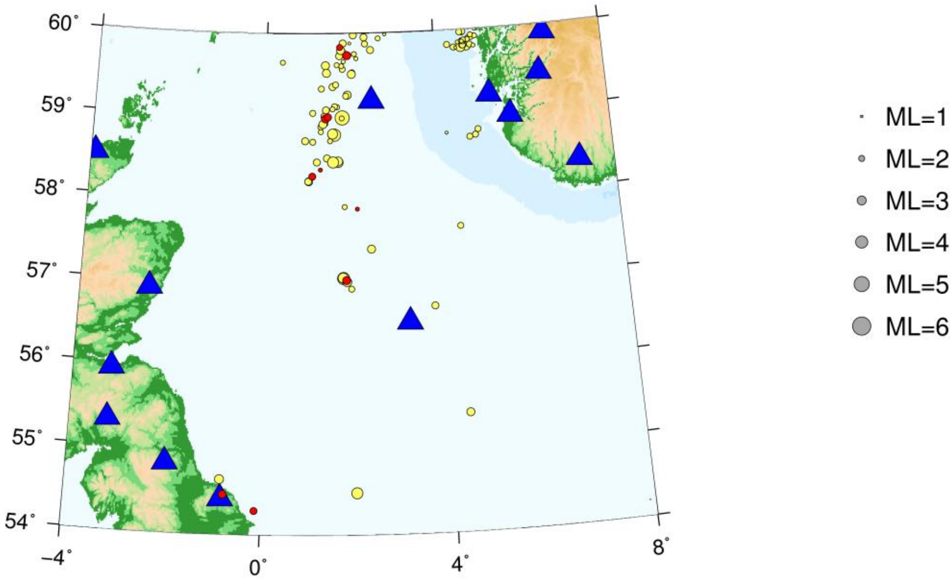




**Figure 29. Time distribution (upper) and location (lower) of the earthquake located within 54-60N and 1W-5E in the southern North Sea (Note that the map is larger than the area used for selection of earthquakes). Earthquakes recorded during 2018 are marked in red, while earthquakes from 2007-2017 are yellow. Seismic stations are marked with blue triangles.**

### 4.2.5 Felt earthquakes

In total, 25 earthquakes were reported felt and located within the target area during 2018 (see Table 9 and Figure 30). For the Jan Mayen Island and the area southwest of the Svartisen glacier, the number of felt earthquakes is expected to be larger than reported.

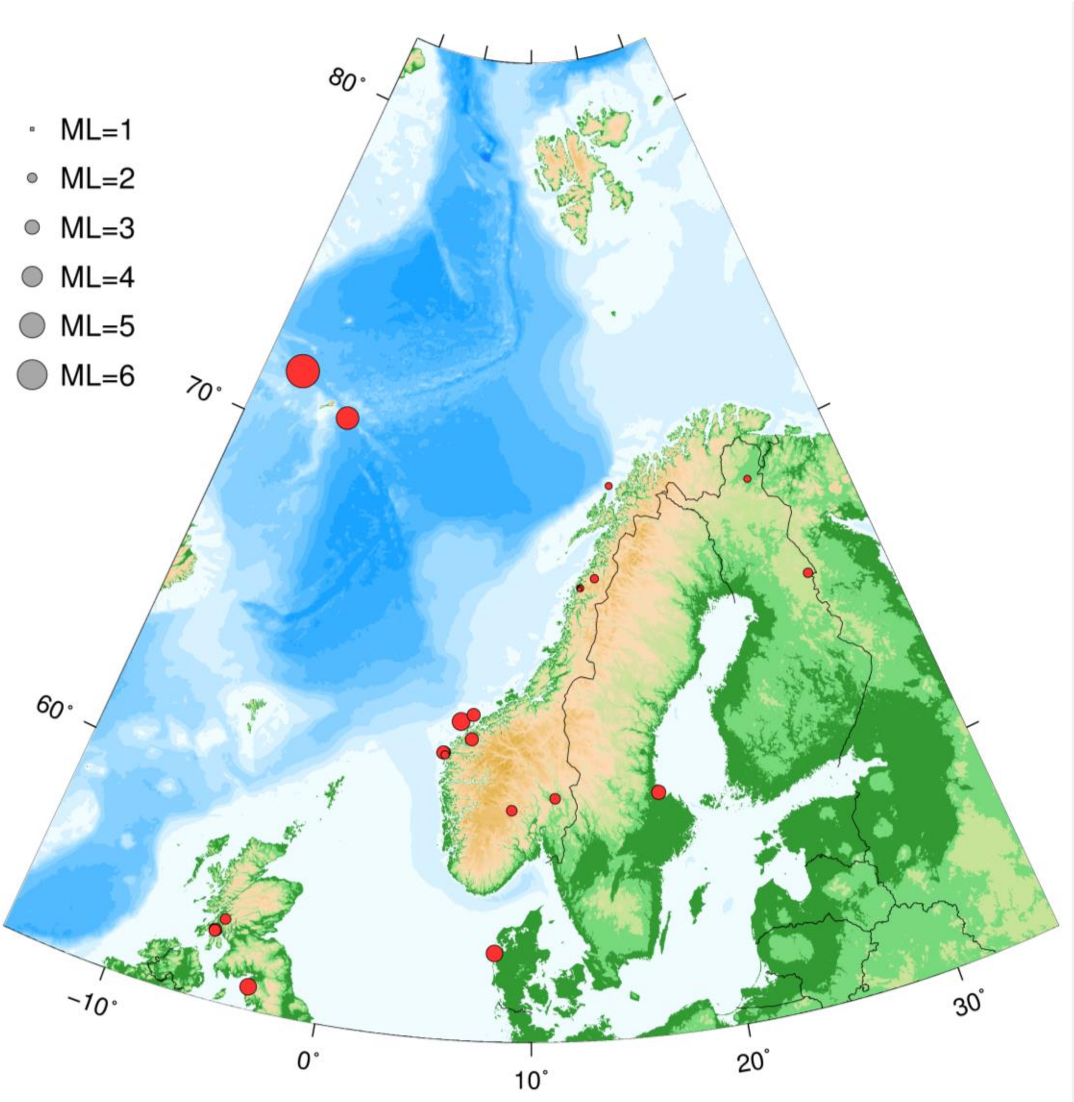



**Figure 30. Location of the 25 earthquakes reported felt during 2018 within the target area.**

Large felt earthquakes are mostly reported to UiB shortly after the origin time, and location information and questionnaires are available for the public on the site www.skjelv.no. Smaller felt earthquakes may be reported by the public to local newspapers or other institutions and then reported to UiB. Depending on the time-delay for these reports to be available at UiB, the information on the web might be accordingly delayed. For any felt earthquake the public has to be made aware of the questionnaire, which is done by informing on web, twitter and when UiB is contacted by media, private persons or other institutions. Earthquakes large enough to be felt and occurring in heavily populated areas increases the number of people using the web reporting the intensities.

**Table 9. Earthquakes reported felt in the BER database in 2018. Abbreviations are: $M_L$ = local magnitude and $M_w$ = moment magnitude, W: questionnaires received on web (Yes/No). The largest felt earthquakes are marked in red. Earthquakes marked in blue are located in Great Britain, Sweden or Finland.**

| Nr | Date | Time (UTC) | Max. Intensity (MMI) | Magnitude (BER) | Instrumental epicentre location | W |
|---|---|---|---|---|---|---|
| 1 | 14.01.18 | 19:30 | | $M_L$=1.4 | 66.62N / 13.54E | N |
| 2 | 14.01.18 | 19:53 | | $M_L$=1.4 | 66.63N / 13.56E | N |
| 3 | 14.01.18 | 19:57 | | $M_L$=1.0 | 66.60N / 13.48E | N |
| 4 | 02.05.18 | 23:21 | III | $M_L$=1.5, $M_L$=2.2(DNK) | 60.69N / 11.36E | N |
| 5 | 17.02.18 | 14:31 | V | $M_L$=4.2, $M_L$=4.6(BGS) | 51.76N / 3.82E | - |
| 6 | 28.02.18 | 07:33 | III | $M_L$=2.9, $M_L$=3.3(BGS) | 54.60N / 3.37E | - |
| 7 | 03.04.18 | 19:14 | IV | $M_L$=2.1, $M_L$=2.1(NAO) | 60.36N / 8.90E | Y |
| 8 | 19.04.18 | 18:01 | V | $M_L$=3.4, $M_L$=3.6(NAO) | 62.79N / 5.66E | Y |
| 9 | 27.04.18 | 03:48 | III | $M_L$=1.4, $M_L$=1.4(NAO) | 69.49N / 16.41E | N |
| 10 | 29.04.18 | 18:19 | III | $M_L$=2.5, $M_L$=2.6(BGS) | 55.89N / 5.55W | - |
| 11 | 01.05.18 | 06:16 | III | $M_L$=2.3, $M_L$= 2.5(BGS) | 55.87N / 5.58W | - |
| 12 | 02.05.18 | 22:59 | III | $M_L$=2.1, $M_L$=2.1(BGS) | 56.23N / 5.23W | - |
| 13 | 18.05.10 | 03:51 | III | $M_L$=1.5 | 61.90N / 4.78E | N |
| 14 | 18.05.18 | 03:52 | III | $M_L$=2.6, $M_L$= 2.7(NAO) | 61.90N / 4.78E | Y |
| 15 | 11.06.18 | 12:36 | IV | $M_L$=3.7, $M_N$=4.6, $M_L$=4.1(NAO), $M_L$=2.6(DNK) | 70.81N / 6.43W | Y |
| 16 | 29.07.18 | 10:01 | - | $M_L$=1.2, $M_L$=1.5(HEL) | 68.85N / 27.49E | - |
| 17 | 31.07.18 | 13:29 | - | $M_L$=1.5, $M_L$=2.0(HEL) | 65.75N / 29.58E | - |
| 18 | 20.08.18 | 07:25 | V | $M_L$=2.7, $M_L$= 2.7(NAO) | 61.88N / 4.75E | Y |
| 19 | 16.09.18 | 08:57 | - | $M_L$=3.1, $M_L$=3.5(DNK) | 56.41N / 8.18E | - |
| 20 | 28.09.18 | 14:06 | III | $M_L$=2.6, $M_L$=2.4(NAO) | 63.00N / 6.40E | Y |
| 21 | 20.10.18 | 11:56 | - | $M_L$=2.4, $M_L$=2.7(NAO), $M_L$=2.8(HEL), $M_L$=2.9(UPP) | 60.66N / 17.29E | - |
| 22 | 09.11.18 | 01:49 | - | $M_N$=5.6, $M_S$=6.5, $M_L$=6.4(NAO), $M_W$=6.8(USGS) | 71.67N / 11.51W | - |
| 23 | 10.12.18 | 17:05 | IV | $M_L$=2.5, $M_W$=2.7, $M_L$=2.5(NAO) | 62.32N / 6.39E | Y |
| 24 | 29.12.18 | 20:50 | III | $M_L$=1.6, $M_W$=1.8 | 66.86N / 14.60E | N |
| 25 | 30.12.18 | 18:11 | III | $M_L$=1.7 | 61.83N / 4.85E | N |

The largest felt earthquake during 2018 occurred on 9 November at 01:49 (UTC). The earthquake is located 135 km north-west of Jan Mayen along the Jan Mayen Fracture Zone and most of the personnel at Jan Mayen woke up.

The largest felt earthquake close to the Norwegian mainland occurred 19 April 2018 at 18:01(UTC) and was located offshore north-west of Ålesund. The earthquake was reported felt from most of Møre og Romsdal and 216 questionnaires were submitted to UiB. A map showing the intensities reported is shown in Figure 31.

The BGS reported that the earthquake on 17 February 2018 at 14:31(UTC) (#5 in Table 9) located to south Wales, is the largest earthquake located on mainland Britain in almost ten years.

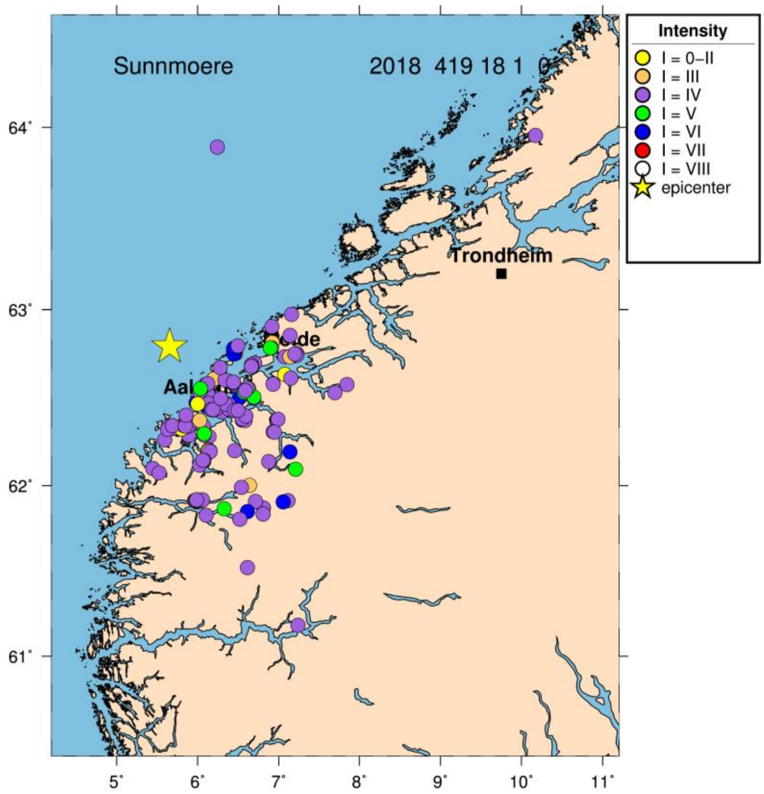



**Figure 31 Location of the 216 reported intensities observations from the earthquake April 19th 2018. The instrumental location is marked with a yellow star. The observation marked offshore is due to an observer giving wrong location for his observation.**

# 5 Scientific studies

This section gives an overview of research work that is carried out under the NNSN project in 2018. The main objective of this work is to improve the understanding of earthquakes and the seismological models in the region, mostly by using data recorded by the NNSN. Results will be used to improve the NNSN monitoring service.

## 5.1 Regional magnitude scale mb(Sn) for the North Atlantic

(by Won-Young Kim and Lars Ottemöller)

A regional Pn wave magnitude scale mb(Pn) for earthquakes that occur along the Northern Mid-Atlantic Ridge (NMAR) was developed by Kim and Ottemöller (2017). The magnitude scale was based on the regional high-frequency Pn waves in the frequency band 0.8 – 8 Hz, and over the distance range 100 – 1,800 km in the Northern Atlantic region. The mb(Pn) was anchored to the moment magnitude MW from the global Centroid Moment Tensor (GCMT) catalog) for earthquakes in the magnitude range from MW 4.5 to 7.0. Kim and Ottemöller (2017) obtained the amplitude distance curve for regional Pn waves whose propagation paths were mostly confined to the oceanic lithosphere. In most of the continental shield regions worldwide, the Sn phase is less well observed due to strong attenuation along its propagation paths that makes it hard to discern onset arrivals, and contamination from preceding P-wave and its coda at short ranges.

However, high-frequency Pn and Sn waves are the prominent phases in the Northern Atlantic region from the earthquakes along NMAR. Observed Sn waves are often as strong as Pn waves on vertical Wood-Anderson (WA) records at regional stations in the region. Sn waves are about 35% of the all peak amplitude measurements from the whole seismograms (476 Sn and 877 Pn observations from 135 earthquakes). Hence, the Northern Atlantic region provides an opportunity to map Sn phase amplitude distance curve for paths across deep ocean basins.

In addition to the mb(Pn) scale, we developed a regional Sn magnitude scale, mb(Sn), for earthquakes that occur along NMAR in the Northern Atlantic region by using high-frequency Sn waves (Figure 31). The Northern Atlantic is an ideal region to analyze the Sn phase, due to fairly good station coverage across deep ocean basins that provide efficient Sn paths and frequent occurrence of earthquakes along NMAR. Sn wave propagating in the oceanic lithosphere with apparent group velocity of 4.3–4.5 km/s is used for mb(Sn), which will complement the mb(Pn) scale developed previously, and enable us to extend the regional magnitude scales that are a continuation of ML scale for mostly Lg waves with group velocity of 3.5 km/s along continental lithospheric paths, and allows us to use all regional phases such as Pn, Sn and Lg in the Northern Atlantic region to assign reliable magnitude.

Routine amplitude measurements by the NNSN were done on Sn in the past, which means that with the new mb(Sn) scale magnitudes can be recomputed.

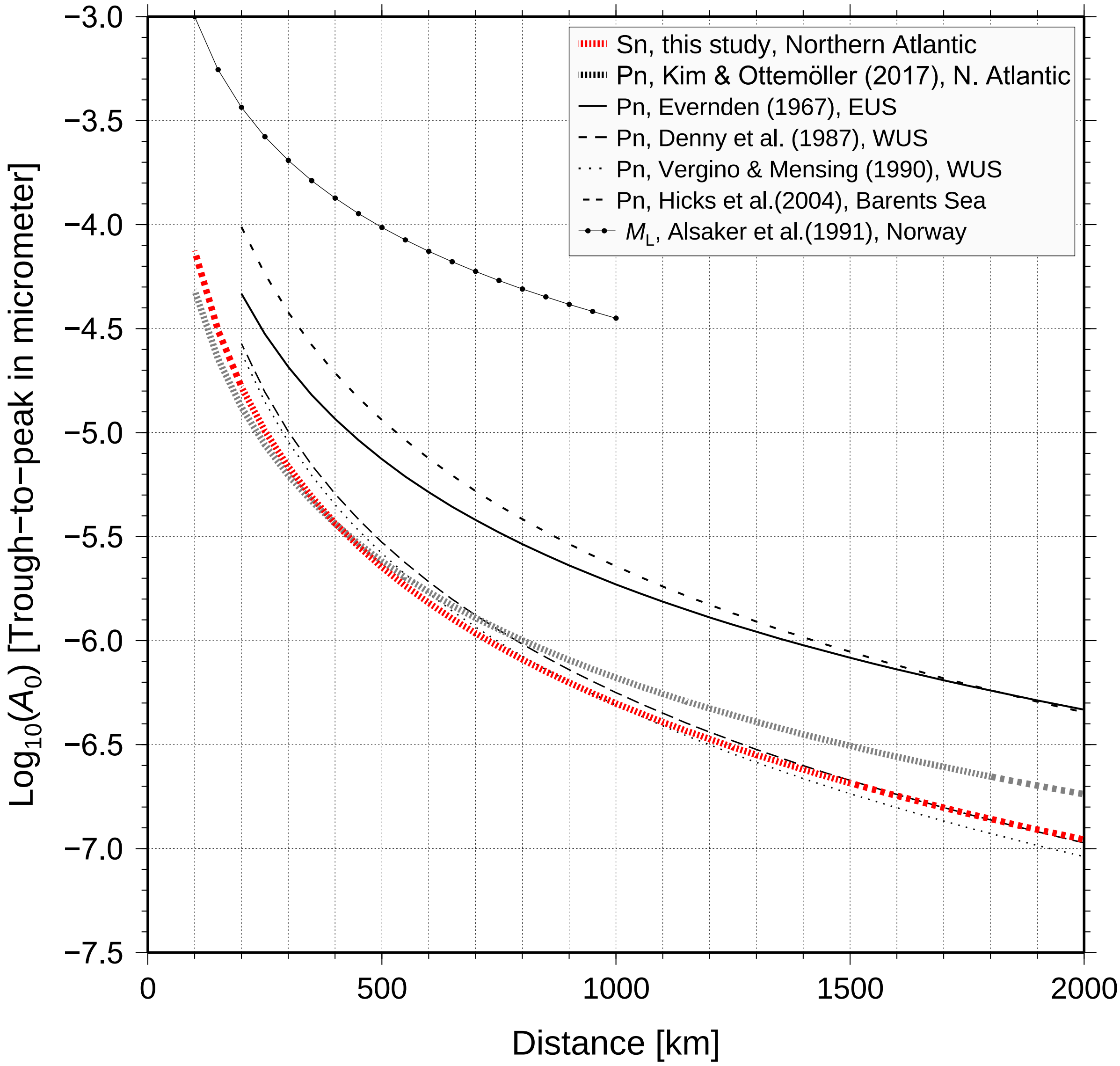



**Figure 32. The amplitude-distance curve, $-\log_{10}(A_0)$, for *Sn* magnitude scale obtained in this study for Northern Atlantic region is plotted with a thick red dashed line (200 to 1500 km). The amplitude-distance curves for various formulae for regional $m_b$(*Pn*) scales are plotted for comparison. The curves are for North Atlantic region, eastern U.S., western U.S., and Barents Sea and are normalized to the maximum trough-to-peak amplitude in micrometers. The amplitude-distance curve for $M_L$ scale used for earthquakes in Norway is plotted for reference.**

## 5.2 Stress drop from empirical Green's function

(by Andrea Demuth, Norunn Tjåland and Lars Ottemöller)

Stress drop is a parameter that is defined by the ratio of fault slip to fault dimension and expresses how much high frequency signal is released by an earthquake of a given magnitude. Larger slip on a smaller fault plane (compared to earthquake of the same seismic moment, but smaller slip on larger fault) results in a higher corner frequency and greater energy release. The general assumption is that earthquakes in intraplate areas such as Norway, earthquakes have a higher stress drop than those in tectonically more active settings. Calculations of stress drop in Norway have been done in the past by measuring the corner frequency from displacement spectra, but for smaller earthquakes this is often not reliable due to insufficient correction for attenuation. An alternative is to make use of Empirical Green's function (EGF) deconvolution where a smaller earthquake is deconvolved from a larger one to obtain the source time function. Both events have to be in the same location and share the same mechanism, such that the smaller one is considered a point source that represents the Green's function. An example of spectra of events suitable for this approach is shown in Figure 33.

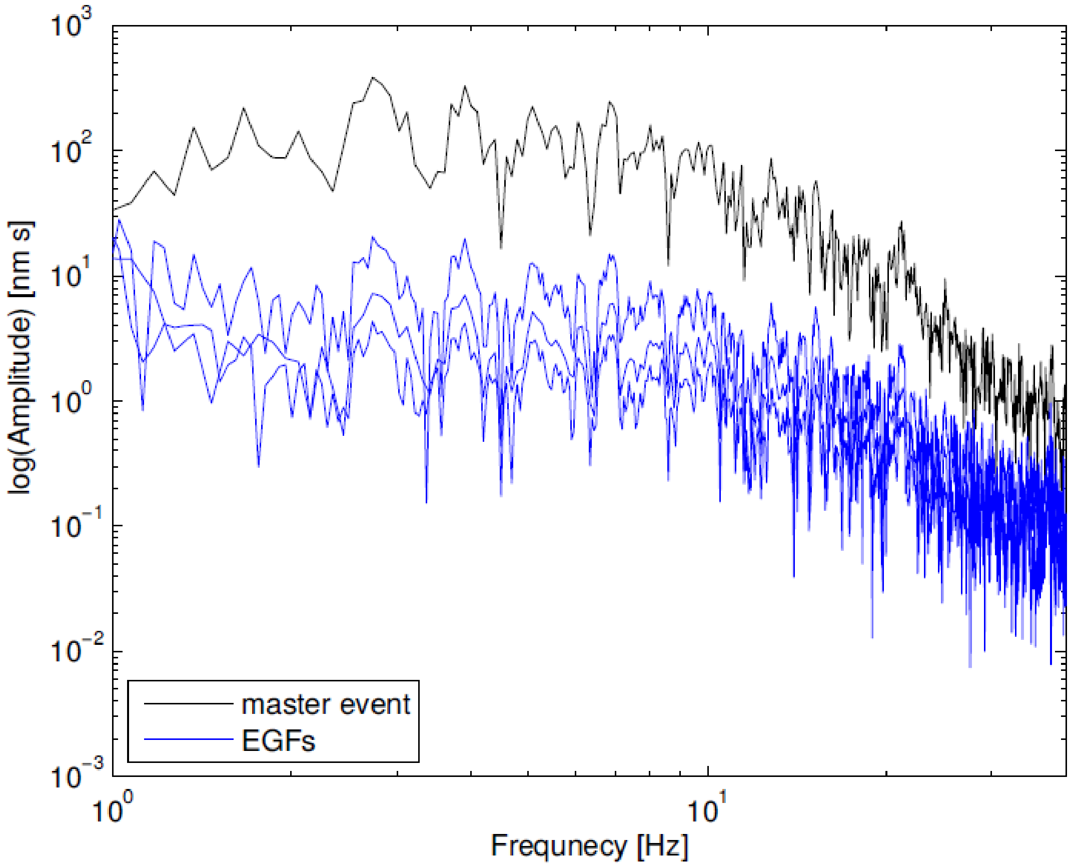



**Figure 33. Amplitude speactra of a larger (master) and three smaller earthquakes that are used for the EGF approach.**

We searched the NNSN catalogue for suitable event pairs for southwestern Norway, Nordland and Svalbard. Stress drop was computed for 107 earthquakes (Figure 34). The total range of stress drop values is from 0.4 to 355 bars for earthquakes for magnitudes from 1.3 to 3.4. The results show that stress drop in the Nordland area is relatively low, which is probably related to the swarm like nature of the seismicity in this region. For southern Norway and Svalbard, we find an increase of stress drop with magnitude. This is observed in some other regions for small earthquakes (M<3), while globally earthquake self-similarity or constant stress drop is found for larger earthquakes in one tectonic setting.

Overall, the results indicate that small earthquakes in Norway can have low stress drop. However, we cannot conclude that this is similar for larger events as we see an indication of increasing stress drop with magnitude. For the 2008 M=6.1 Svalbard earthquake we had previously seen that this event had higher stress drop than the smaller earthquakes in the Storfjorden area. The results have an implication for seismic hazard, which needs to assume that the largest earthquakes in Norway can have a relatively high stress drop.

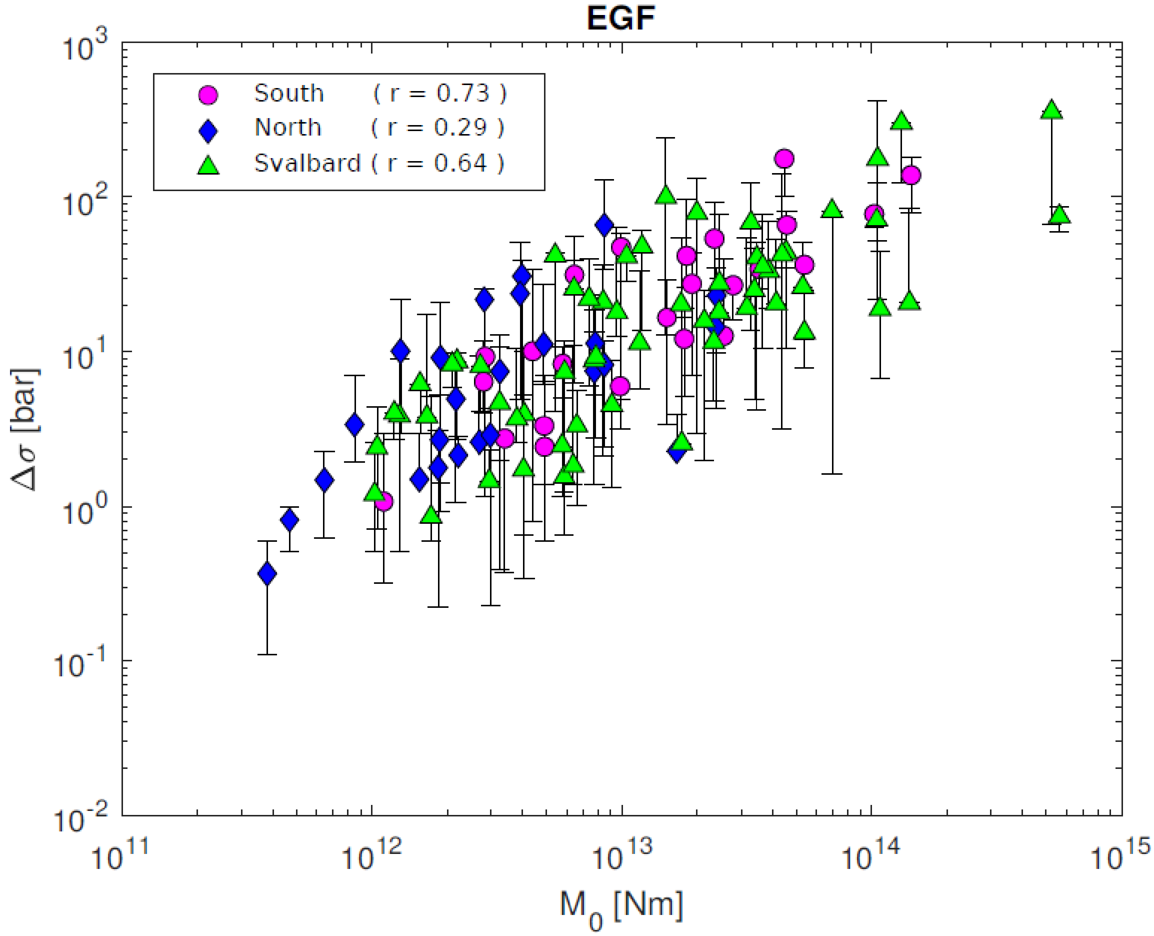



**Figure 34. Stress drop computed for 107 earthquakes using the EGF approach in southwestern norway, Nordland and Svalbard.**

## 5.3 Evaluation of fault plane solutions in the North Sea region

(by Norunn Tjåland and Lars Ottemöller)

The northern North Sea is one of the regions in Norway of relatively high seismicity, and over the years, several larger earthquakes have been registered here. The earthquake activity can be linked to existing faults that are reactivated by stresses of plate tectonic origin or influenced by vertical stresses associated with deglaciation or sediment loading. The aim of this work was to increase the understanding of the tectonic conditions in this specific area through analysis of earthquake locations and focal mechanisms. We have estimated the location uncertainty (Figure 35) and demonstrated the result of applying relative location methods (Figure 36) in areas of moderate seismicity. We have determined and reviewed earthquake focal mechanisms for a total of 70 earthquakes occurring in the northern North Sea region with emphasis on presenting reliable fault plane solutions (Figure 37).

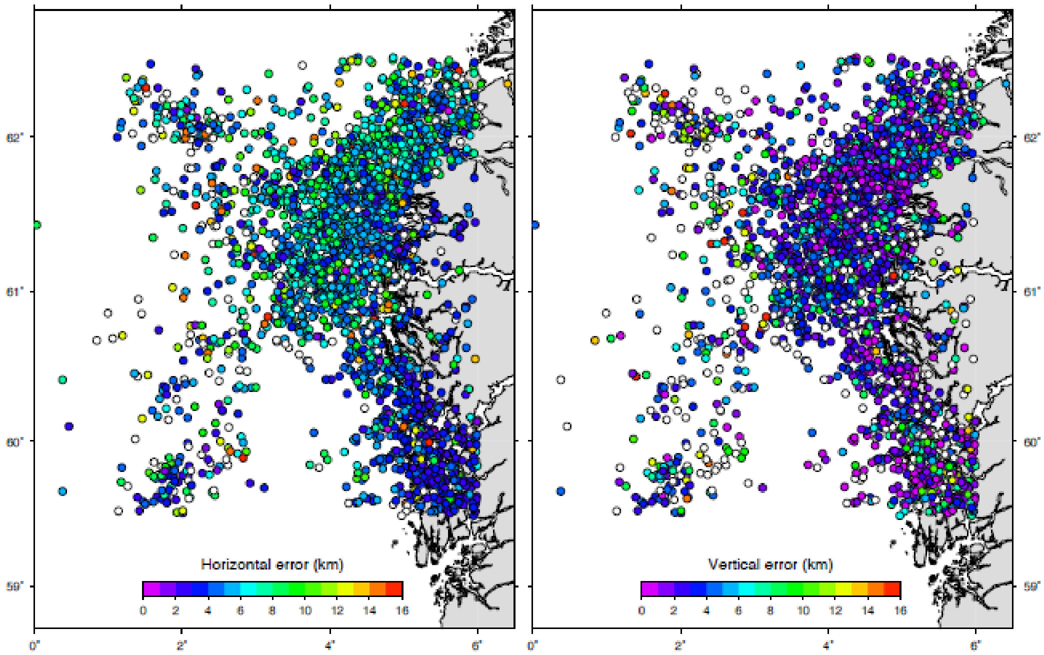



**Figure 35. Estimated location errors by applying a random bootstrap technique where stations are randomly removed and noise is added to the arrival times.**

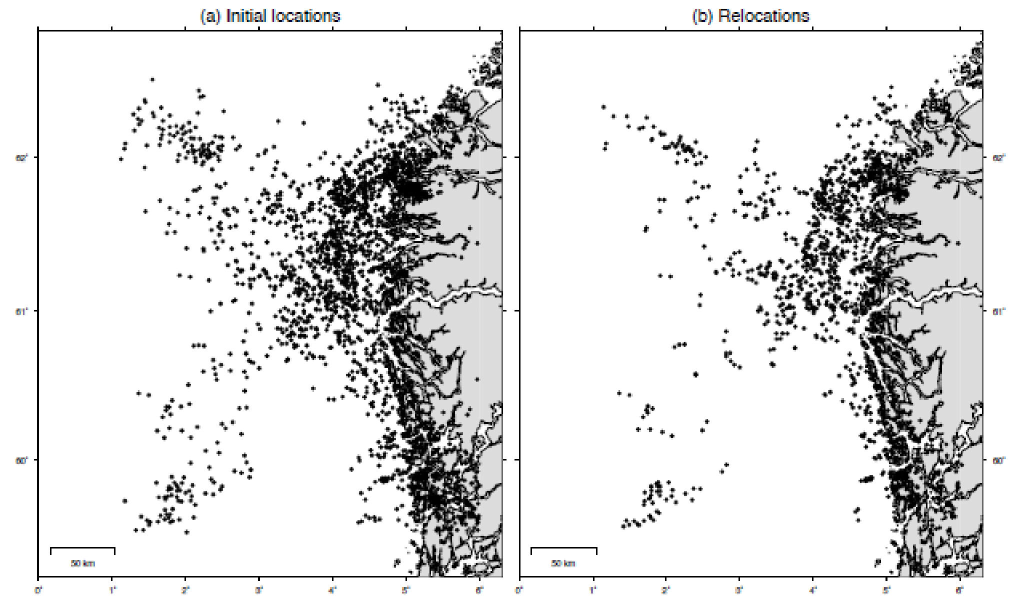



**Figure 36. Comparison of epicenter locations from the NNSN catalogue (left) with locations obtained with double-difference relocation (right).**

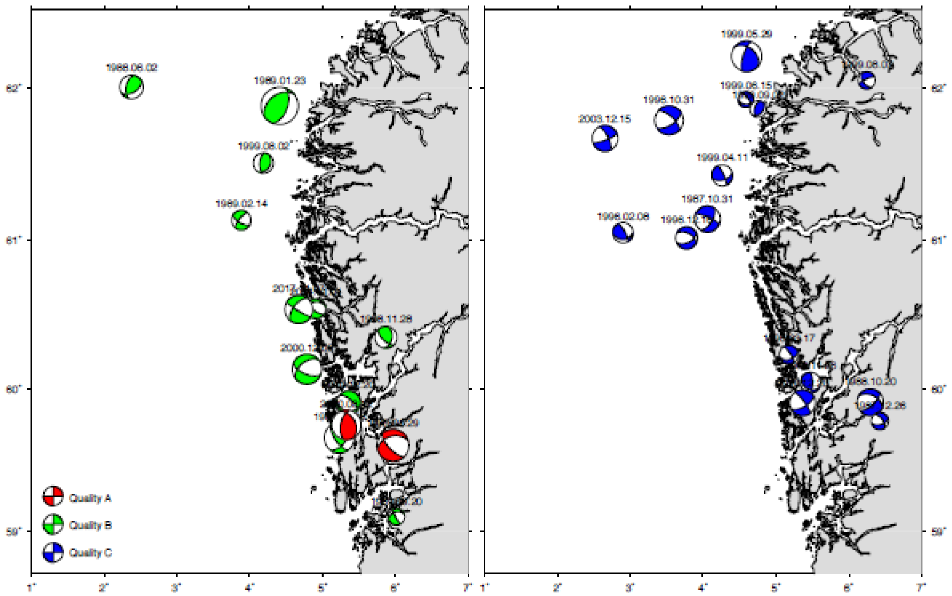



**Figure 37. Result from fault plane solution re-evaluation. Plot on the left gives solutions of quality of A and B, while plot on the right gives C quality solutions. The C solutions should generally not be used for interpretation.**

Earthquake focal mechanisms of small to moderate size earthquakes, occurring during the period from 1982 to 2017, have been determined using P-wave first motion polarities and a grid search method. Well-constrained and robust solutions are of great importance for understanding the tectonic environment and the results indicate that the northern North Sea area is influenced by both extensional and compressional tectonics. The focal mechanisms of some earthquakes also indicate the existence of strike-slip faulting, while there is a tendency of reverse faulting offshore.

The result from our study, also including the fault plane solutions for some recent events, seems to be in agreement with the study of Hicks et al. (2000) that includes fault plane solutions for different parts of Norway. They report a trend of reverse to oblique reverse offshore. In comparison, onshore western Norway, we find mainly oblique solutions, but clustered in the area of normal and strike-slip faulting regime.

We estimated location errors by adding random noise to the arrival times and changing the number of stations to get a sense of the location uncertainty. The results have been compared to the errors derived from the standard location program, which gives slightly larger errors, but shows the similar trend of less accurate locations offshore. It reflects the importance of good station coverage, in particular for controlling hypocenter depth and in obtaining good signal-to-noise ratio. As the locations are not only affected by the seismic network features and observational errors, but also by errors in the velocity model used in the location process we have used a double-difference approach to locate pairs of earthquakes relative to one another in order to reduce the effect of velocity heterogeneities. During the inversion with weighting and re-weighting of the data, almost half the number of events are removed because they have lost linkage to neighboring events due to few observations on common stations, large residuals or large separation distance between earthquakes. The remaining events show a more focused image.

## 5.4 Detection of microseismicity in the North Sea

(by Felix Halpaap and Lars Ottemöller)

The Norwegian National Seismic Network (NNSN) is responsible for earthquake monitoring on the Norwegian mainland and in the surrounding land and marine areas. Analysts at the NNSN process these earthquakes to create, store, and publish a normative catalog of earthquakes in Norway. The NNSN earthquake catalogs from the last 120 years show that earthquakes occur over the whole Nordic region (Figure 38 A), with the tectonically most active areas concentrated offshore Nordland and offshore Western Norway in the North Sea.

The distribution of catalogued earthquakes is, however, biased by the distribution of stations across the region. The network affords the best coverage in the onshore domain, while the coverage worsens in offshore domains such as the North Sea. This is due to the fact that the shortest distance between earthquakes and seismograph stations on land can be up to 300 km for earthquakes in the central North Sea.

In the North Sea, oil and gas production are major economic activities that rely on geologic and tectonic information for efficient and save execution. To better understand tectonic activity in the North Sea, we therefore want to explore the potential of advanced earthquake processing methods that are able to detect small-magnitude earthquakes that were missed by the current processing scheme. To first evaluate the difference in earthquake detectability depending on location, we compare the completeness magnitude for five zones in Western Norway and in the central to northern North Sea (57.5 – 64.0 ºN, -2.0 – 7.0 ºE, Figure 38 B). To detected previously uncatalogued events, we then apply a template-matching algorithm on the continuous seismic data recorded by the NNSN.

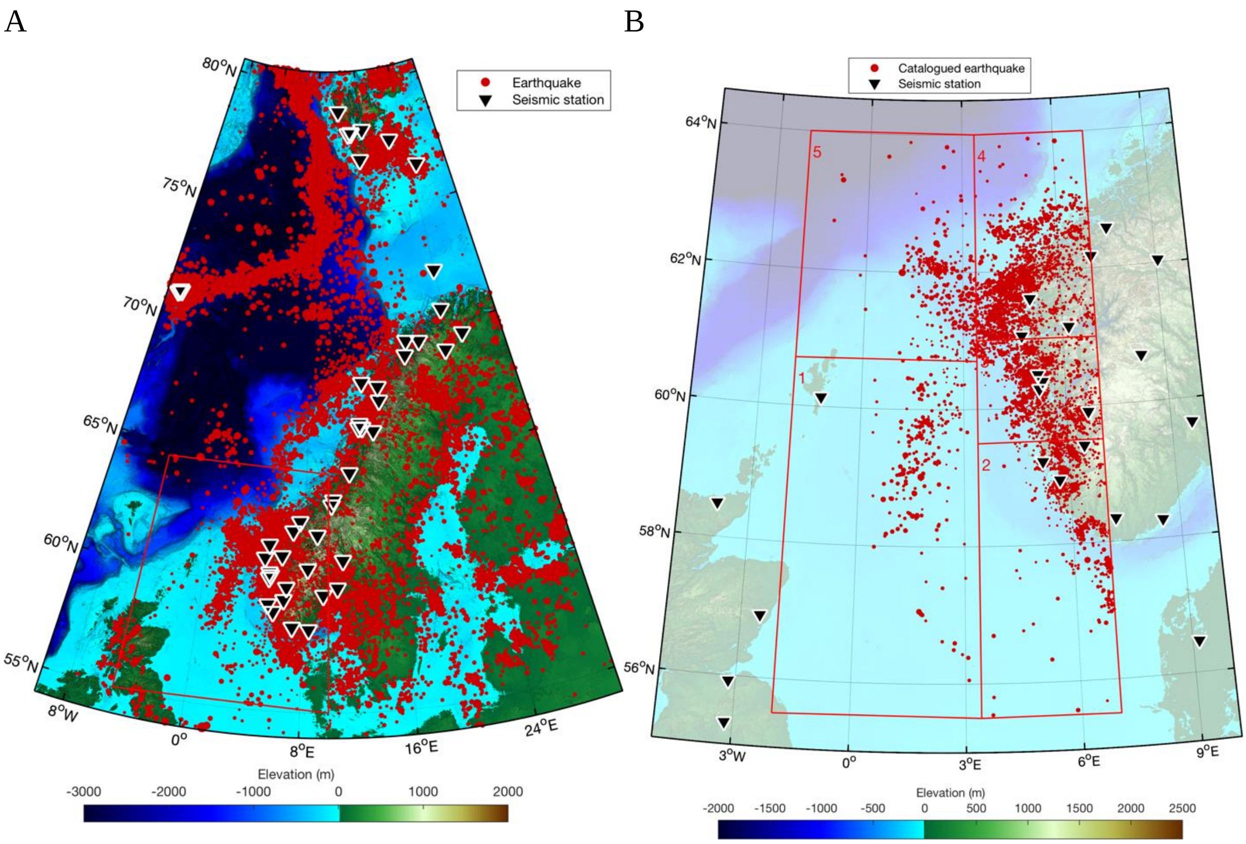



**Figure 38. Seismicity maps of the Nordic region. (A) Map showing all earthquakes recorded by the NNSN between 1900 and 2018 in the Nordic region. A red rectangle marks the position of the northern North Sea are depiced in B. (B) Map showing the northern North Sea with seismicity (red dots, years 1990 – 2018) and seismic stations (inverted triangles). Red lines indicate the individually analyzed seismicity zones (see text and Table 1).**

A template-matching algorithm compares the waveforms of previously recorded earthquakes to find earthquakes with similar waveforms that were not previously detected due to low signal-to-noise ratio (SNR, Chamberlain et al., 2018). Waveforms are similar when earthquakes occur at short distance from one another and with similar focal mechanism. The earthquakes used for comparison through cross-correlation define the templates, which comprise waveforms and associated arrival time picks from a subset of seismic stations and seismometer channels. This subset is chosen according to the noise level at the stations and the azimuthal coverage of earthquakes that these stations can provide.

To compare and improve the earthquake detectability, we defined five seismicity zones that allow us to (a) evaluate the earthquake detectability and catalog completeness, and (b) define earthquake templates with optimal station subsets and template parameters. We define each seismicity zone based on the main tectonically active features, e.g. aiming not to break single seismically active structures in two, and the station distribution, i.e. ensuring that earthquakes are covered by proximal stations and with least azimuthal gap possible.

Figure 39A shows the five seismicity zones that we defined according to the following criteria: (a) Zone boundaries should not break apart seismically active structures, (b) zone boundaries should take the distribution of stations into account such that earthquakes are covered by proximal stations and with least azimuthal gap possible. Criterium (b) may require exceptions to criterium (a) where we split up particularly large seismically active areas to allow a better comparison between regions.

**Table 10. Definition and parameters of seismicity zones of the central - northern North Sea. The number of events given in the table is the combined number of earthquakes and explosions.**

| Zone No. | Seismicity Zone | Latitude | Longitude | Stations (minimum 8 for template creation) | Earthquakes (Events) in zone (1990 – 2018) | Template parameters | Tem plate No. | Mc | $M_{min}$ | Picked Detectio ns (2016 – 2018) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Main Graben zone | 55.5 – 60.7 | -2.0 – 3.4 | ASK, KMY, HYA, FOO, BLS5, SNART, ODD1, SUE, KONO, LRW, BIGH, ESK, EDI, MUD | 254 (254) | 15 s 2.5 – 8 Hz SNR > 1.2 | 178 | 1.6 | 0.8 | 36 |
| 2 | Rogaland | 55.5 – 59.5 | 3.4 – 7.0 | SNART, HOMB, STAV, KMY, BLS5, KONO, ODD1, MUD | 1422 (3469) | 7 s 2.5 – 8 Hz SNR > 1.2 | 677 | 1.2 | -0.7 | 308 |
| 3 | Hordaland | 59.5 – 61.0 | 3.4 – 7.0 | ASK, BER, ODD1, SUE, HYA, KMY, BLS5, KONO, FOO | 3269 (4275) | 7 s 2.5 – 8 Hz SNR > 1.2 | 1805 | 1.0 | -0.9 | 252 |
| 4 | Nordvestlandet | 61.0 – 64.0 | 3.4 – 7.0 | SUE, HYA, MOL, FOO, AKN, ASK, BER, ODD1, DOMB, SKAR | 2488 (2955) | 7 s 2.5 – 8 Hz SNR > 1.2 | 1687 | 1.5 | -0.4 | 205 |
| 5 | Møre basin | 60.7 – 64.0 | -2.0 – 3.4 | MOL, SUE, FOO, AKN, BER, ASK, HYA, SKAR, ODD1, LRW, BIGH, KONO, SOFL | 367 (397) | 15 s 2.5 – 8 Hz SNR > 1.2 | 234 | 2.1 | 0.7 | 22 |
| | TOTAL | | | | 7800 | | 4581 | | | 823 |

In each of the five zones, we estimate the completeness magnitude of the NNSN catalog between 1990 and 2018 by fitting a line to the Gutenberg-Richter distribution in each region. The estimated completeness magnitudes $M_c$ for all zones are shown inTable 10. In the zones (2 – 4) close to the coast, we estimate completeness magnitudes of local magnitude ($M_L$) 1.0 to 1.5. Further offshore, the completeness magnitude can be as high as $M_L$=2.1. It implies that the NNSN currently does not detect all earthquakes above that magnitude, even though earthquakes as small as $M_L$=0.7 can sometimes be detected.

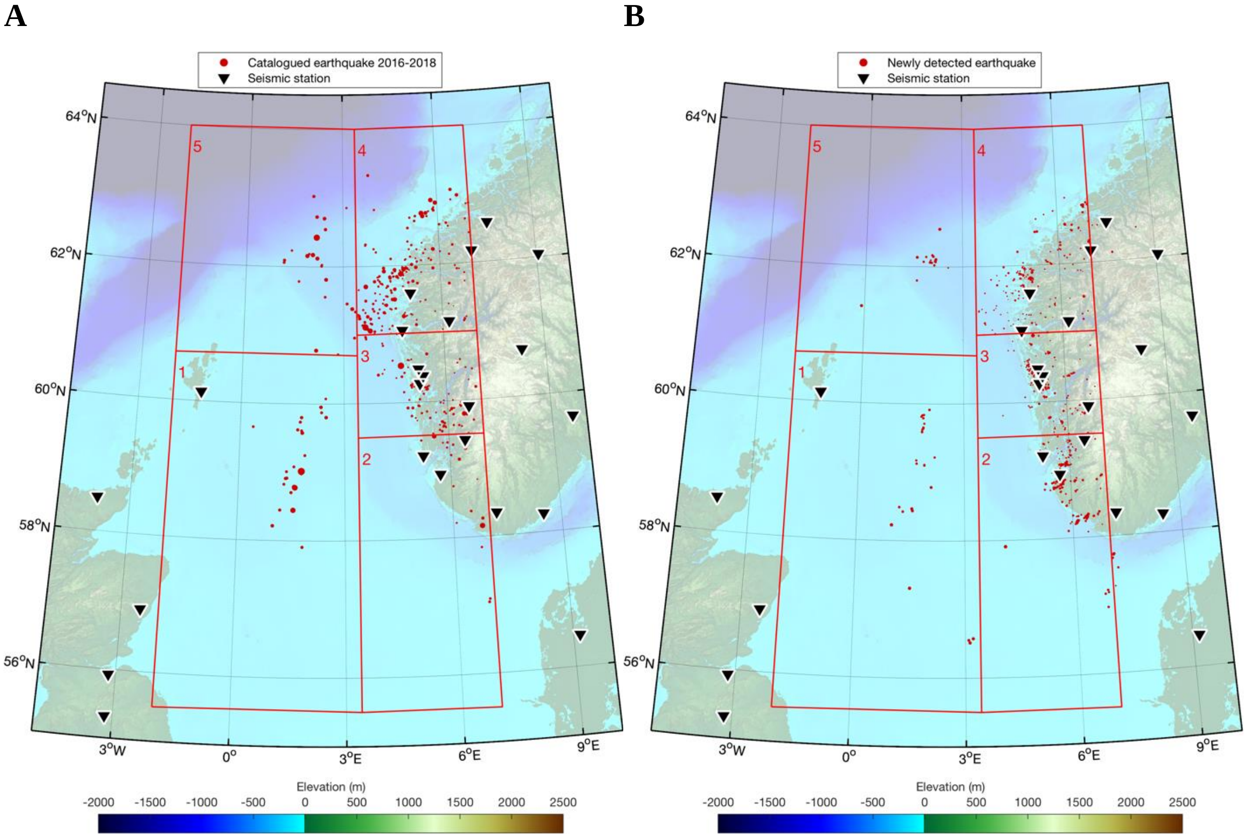



**Figure 39. Seismicity maps of the North Sea for the period 2016 – 2018. (A) Map showing the earthquakes catalogued in the NNSN. (B) Map showing the earthquakes that were newly detected and picked through the application of the template matching software. Note that templates used for detection are chosen from the seismicity covering the period 1990 – 2018.**

To explore whether we can effectively detect additional earthquakes based on waveform similarity in the North Sea region, we run a template-matching algorithm on the continuously recorded data of the NNSN. We use the open-source program EQcorrscan (Chamberlain et al., 2018) and defined templates according to the following criteria: Minimum number of traces with picks: 8; minimum SNR: 1.2, filter band 2.5 Hz – 8 Hz. Additional criteria, including the template length and station subset, depend on the seismicity zone and are listed inTable 10. Here we detect only additional earthquakes in the 2016 – 2018 period, because these data were already available in the required format. Once all data since the onset of continuous recording in the NNSN (2006) are available in this format, the software can be applied to the entire period of continuous data.

Through template-matching, we detect a total number of 823 previously uncatalogued events. Each of these events could be picked from waveform similarity at a minimum number of stations. The minimum number of stations was set to four with a minimum cross correlation coefficient (CCC) of 0.3 and minimum four P-picks. Each event was manually checked to exclude a small number of false positive detections. The number of earthquakes detected with these parameters for each zone are displayed in Table 10. Compared to the currently detectable seismicity rates in the zones, e.g. about 9 earthquakes per year in zone 1, we were able to detect up to 2.5 times more earthquakes per year (i.e., 36 earthquakes in 2.5 years in zone 1). These newly detected earthquakes () complement the dataset of previously catalogued events and fill some gaps in the seismically active structures that could not previously be evaluated.

As we only detected earthquakes in the 2016 – 2018 period, there is a potential to improve the NNSN earthquake catalog by using template matching on the continuous data since 2006, and by including the method into the routine processing at the NNSN. It will allow to lower the detection threshold in particular in the offshore domain and will help us to better understand the tectonically active features in the region.

## 5.5 Building confidence in offshore earthquake location estimates using probabilistic multiple event location techniques

(by Steven Gibbon, Annie Jerkins and Tormod Kværna)

The $M_W$ 4.5 earthquake in the North Sea on June 30, 2017, was unusual among seismic events in the region in that it was large enough to generate clear signals at teleseismic distances. Most North Sea earthquakes are of magnitude 3 or below, generating only signals at regional distances. Regional seismic traveltime estimates are subject to significantly higher uncertainty than teleseismic traveltime estimates (e.g. Myers et al., 2015) and consequently the bias and uncertainty associated with the location of this globally observed event may be considerably lower than for many smaller events that are only observed regionally. The June 30 earthquake was also significant in generating clear teleseismic depth phases, which – in the absence of a dense, local, seismic network – provide the best possible constraints on focal depth. A motivation to analyze this event in greater detail is to provide a reference event for location purposes.

Multiple event re-analysis of earthquake locations for clustered seismicity can improve location estimates for individual events significantly (e.g. Myers et al., 2007; Nooshiri et al., 2017). The *Bayesloc* Bayesian hierarchical probabilistic multiple event location algorithm calculates joint probability distributions for event hypocenters, phase identification labels, phase reading uncertainties and, most significantly, corrections to seismic traveltime predictions. The traveltime prediction corrections are estimated from large numbers of events, many of which are well constrained. They mitigate inaccuracies in the velocity model applied and reduce the location bias for those events with relatively few observations. Significantly, prior constraints can be applied to event locations in Bayesloc when additional information is available. Although this usually applies to Ground Truth explosions, for which the location and origin time are known exactly, we can for example constrain the depth of an event if it is known from independent analysis to lie in a given range.

Figure 40 displays the output from the Bayesloc program (red symbols) for a number of the better observed events in the Central North Sea. A prior constraint was applied to the depth of the June 30 earthquake. The NNSN catalog has been supplemented with additional readings from other stations, including the large aperture NORSAR array and some temporary deployments. A more clustered image of seismicity emerges in the relocated events than in the single-event location estimates (grey symbols) and it appears that most of the largest earthquakes in the period 2000-2018 occur to the west of the oil fields. Many of the largest relocation vectors in Figure 40 are found to be associated with apparent timing or phase pick errors on one or more stations. Uncorrected timing anomalies with significant influence on the single-event location estimates have demonstrably reduced influence on the multiple event location distributions. The ability of Bayesloc to improve the traveltime predictions for all arrivals increases the relative size of the traveltime residuals for the few readings subject to timing errors and makes it easier for them to be ignored in the final location estimates.

In order to build confidence in the Bayesloc location estimates displayed in Figure 40, we perform the same multiple event location calculation but using the Fennoscandia velocity model (Mykkeltveit and Ringdal, 1981). These location estimates are shown as black symbols in Figure 41. We see that the pattern of seismicity is relatively unchanged by the application of the slightly different velocity model. This provides confidence that the joint probability distribution for the departures from the predicted traveltimes compensates adequately for the inadequacies of the 1-D velocity models. As the recording of seismic events in the region continues into the future, most likely with better station coverage and better instrumentation, the quality of the multiple event location distributions is likely to improve continually to provide an ever-sharper image of North Sea seismicity.

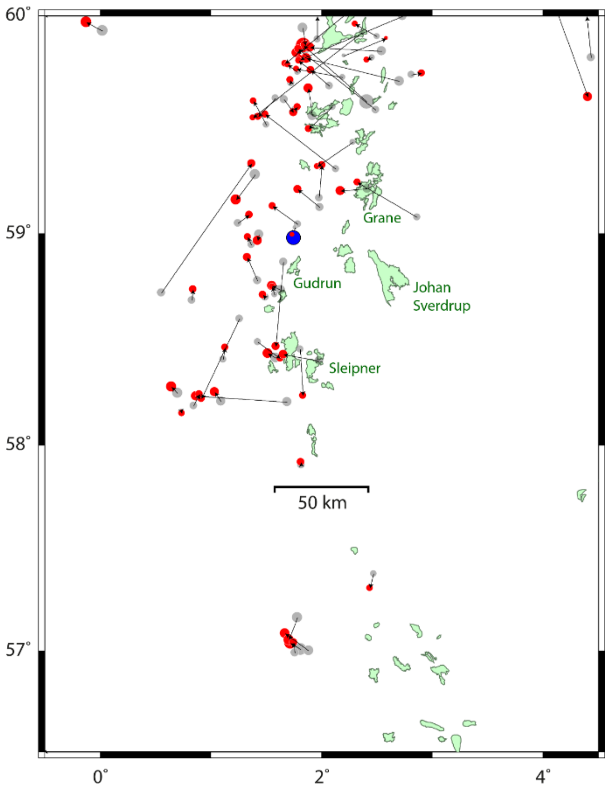



**Figure 40** ***(Left) Selected events from the NNSN bulletin in the period 2000-2018 (grey symbols) and their relocations using the Bayesloc probabilistic multiple event location algorithm (red symbols). Bayesloc generates joint probability distributions both for event hypocenters and for correction terms for traveltime predictions. The largest relocation vectors (the longest lines) can in most cases be associated with timing errors on one or more stations. Green regions indicate the extent of North Sea production fields as indicated by the Norwegian Petroleum Directorate. The location of the 30 June 2017 event is shown by the blue symbol.***

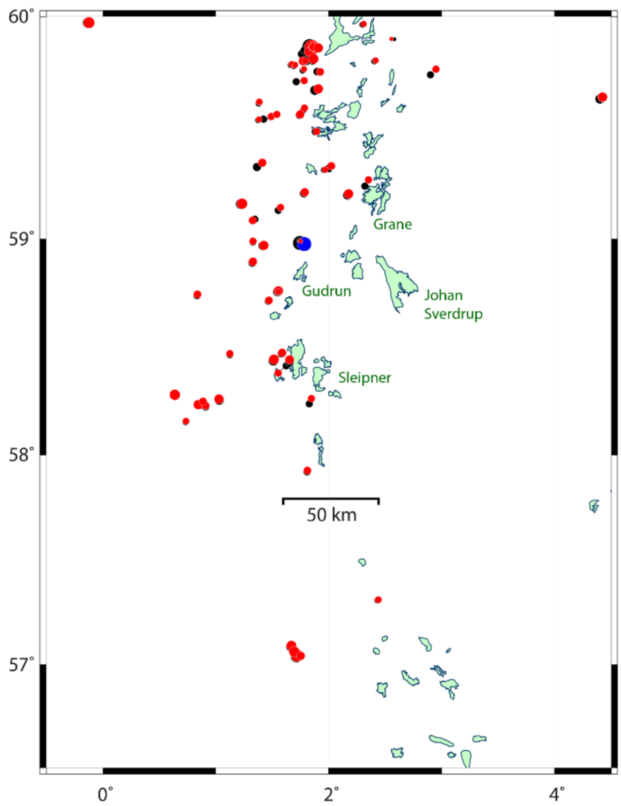



**Figure 41 (Right)The Bayesloc location estimates from Figure 40 (red symbols), obtained using the University of Bergen seismic velocity model, together with the corresponding Bayesloc location estimates using the Fennoscandian velocity model (black symbols).**

# 6 Publications and presentations of NNSN data during 2018

Data collected on Norwegian seismic stations are made available through the Internet and is provided on request to interested parties. Therefore it is difficult to get a comprehensive overview on the use and all publication based on Norwegian data. The following reference list shows publications and presentations of UiB and NORSAR scientists for the reporting period, based on data of NNSN and NORSAR stations.

## 6.1 Master of Science Thesis, UiB

Ellingsen, A. (2018). Seismicity and Crustal Structure in North Greenland, MSc thesis, Dept. of Earth Science, University of Bergen.

Løviknes, K. (2018). Measuring seismic station timing errors from ambient noise, MSc thesis, Dept. of Earth Science, University of Bergen.

## 6.2 Publications

Demuth, A., Ottemöller, L. & Keers, H. (2018) QLg tomography beneath Norway, J. Seismol. https://doi.org/10.1007/s10950-018-9798-x

Kim, W.Y., & Ottemöller, L. (2017). Regional Pn body‐wave magnitude scale mb(Pn) for earthquakes along the northern mid‐ Atlantic Ridge. *Journal of Geophysical Research: Solid Earth*, 122, 10,321−10,340.

Ottemöller, L., M.L. Strømme and B.M. Storheim (2018). Seismic monitoring and data processing at the Norwegian National Seismic Network, in Summary of the Bulletin of the International Seismological Centre 2015 January-June.

## 6.3 Oral presentations

Jeddi, Z., Sørensen, M.B., Voss, P. and INTAROS WP2 team (2018). Seismological Monitoring in the Arctic: A Brief Introduction to INTAROS, *Nordic Seismology Seminar, Kjeller, Norway, 24-26 September 2018.*

Jeddi, Z. (2018). Seismological Observation in the Arctic: Examples of Combining Seismometer and Hydrophone Observations, *UAK research school, Longyearbyen, Svalbard, 2-7 December 2018.*

Jerkins, A., Gibbons,S, Kværna,T., and Schweitzer,J.: Location and Depth Estimation of the North Sea Earthquake 30 June 2017. *EGU General Assembly 2018, Vienna.*

Jerkins, A., Gibbons,S, Kværna,T., and Schweitzer,J.: Location and Depth Estimation of the North Sea Earthquake 30 June 2017. *Nordic seminar, NORSAR.*

Kim, Won-Young and L. Ottemöller. (2018) Regional Body-Wave Magnitude Scale mb(Pn/Sn) for Earthquakes in the North Atlantic Region. *Nordic Seismology Seminar, Kjeller, Norway, 24-26 September 2018.*

Kim, Won-Young and L. Ottemöller. (2018) Regional Body-Wave Magnitude Scale mb(Pn/Sn) for Earthquakes in the North Atlantic Region. *The 36$^{th}$ General Assembly of the European Seismological Commission, Valletta, Malta, 2-7 September 2018.*

Michalek, J., C. Rønnevik, X. Wang, K. Atakan, T. Langeland, T. Kvaerna, H. Pascal Kierulf, and B.-O. Grøtan (2018). EPOS-Norway – Integration of Norwegian geoscientific data into a common e-Infrastucture, EGU General Assembly 2018, Vienna, Austria.

Michalek, J., C. Rønnevik, T. Utheim, Ø. Natvik, L. Ottemöller, U. Baadshaug, J. Magnus Christensen (2018). Building UIB-NORSAR EIDA node - integration of Norwegian seismic data into EPOS. *Nordic Seismology Seminar, Kjeller, Norway, 24-26 September 2018.*

Ottemöller, L. (2018). Monitoring by the Norwegian National Seismic Network. *The 36$^{th}$ General Assembly of the European Seismological Commission, Valletta, Malta, 2-7 September 2018.*

Sørensen, M.B. and Voss, P. (2018). Investigation of macroseismic data for earthquakes in Denmark and Norway, *The 36$^{th}$ General Assembly of the European Seismological Commission, Valletta, Malta, 2-7 September 2018.*

Sørensen, M.B. (2018). What do we know about large historical earthquakes in Norway? *Nordic Seismology Seminar, Kjeller, Norway, 24-26 September 2018.*

Sørensen, M.B. (2018). Kommunikasjon av jordskjelvrisiko i Norge, *The annual meeting of the Norwegian Geophysical Society, Bergen, Norway, 26-27 September 2018.*

Sørensen, M.B. (2018). What do we know about large historical earthquakes in Norway? *"Geofaredagen 2018", Lillestrøm, Norway, 1. November 2018.*

Sørensen, M.B. (2018). Natural Hazards in the Arctic, *lecture at UAK research school, Longyearbyen, Svalbard, 2-7 December 2018.*

Tjåland, N. and L. Ottemöller (2018). Evaluation of Seismicity in the Northern North Sea. *Nordic Seismology Seminar, Kjeller, Norway, 24-26 September 2018.*

## 6.4 Poster presentations

Jerkins, A., Gibbons,S, Kværna,T., and Schweitzer,J. Location of the 30 June 2017 North Sea

Earthquake. *ESC 2018 Malta*.

Schweitzer, J., Y. Konechnaya, A. Fedorov, S. Gibbons and M. Pirli (2017). A New Seismic Bulletin for Svalbard and the European Arctic, *Svalbard Science Conference 2017*, 6 – 8 November 2017

Mäntyniemi, P., Sørensen, M.B., Tatevossian, R.E. and Lund, B. (2018). A new macroseismic map of the Lurøy, Norway earthquake of 31 August 1819, *The 36th General Assembly of the European Seismological Commission, Valletta, Malta, 2-7 September 2018.*

Voss, P.H., Sørensen, M.B. and the INTAROS Team (2018). Earthquake monitoring in the Arctic region – the seismological component of INTAROS, *The 36th General Assembly of the European Seismological Commission, Valletta, Malta, 2-7 September 2018.*

Voss, P.H., Sørensen, M.B., Jeddi, Z. and the INTAROS Team (2018). The status of the seismological component of INTAROS project, *Nordic Seismology Seminar, Kjeller, Norway, 24-26 September 2018.*

## 6.5 Reports

Sørensen, M.B., Voss, P. and INTAROS WP2 team (2018). Report on Present Observing Capacities and Gaps: Land and Cryosphere, Integrated Arctic Observation System – INTAROS- Deliverable 2.7.

Sørensen, M.B., Voss, P. and INTAROS WP2 team (2018). Report on Exploitation of Existing Data: Land and Cryosphere, Integrated Arctic Observation System – INTAROS- Deliverable 2.8.

Jeddi, Z., Sørensen, M.B., Voss, P. and INTAROS WP2 team (2018). Report on Catalogue of Products and Services Based on Land and Terrestrial Cryosphere Data, Integrated Arctic Observation System -INTAROS- Deliverable 2.9.

## 6.6 Popular scientific contributions:

Sørensen, M.B. (2018). Kan «Skjelvet» virkelig ramme oss? «Forskning viser at…» *Article in Dagens Næringsliv, 1. September 2018.*

Sørensen, M.B. (2018). «Skjelvet» - også i Bergen? *Introduction to the pre-opening of «Skjelvet» at Bergen Kino, 28. August 2018.*

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