Progress Report 2015

for

Norwegian National Seismic Network

January 1 to October 31, 2015

Supported by

Norwegian Oil and Gas Association

and

University of Bergen, Department of Earth Science

Prepared by

Department of Earth Science
University of Bergen
Allegaten 41, N-5007 Bergen

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1 Introduction

This annual report describes the operation of the Norwegian National Seismic Network (NNSN) for the first part of 2015. The network is financially supported by the oil industry through the Norwegian Oil and Gas Association and the University of Bergen (UiB). UiB has the main responsibility to run the NNSN. This report covers operational aspects for all seismic stations operated by the Department of Earth Science at the UiB and includes the financial report.

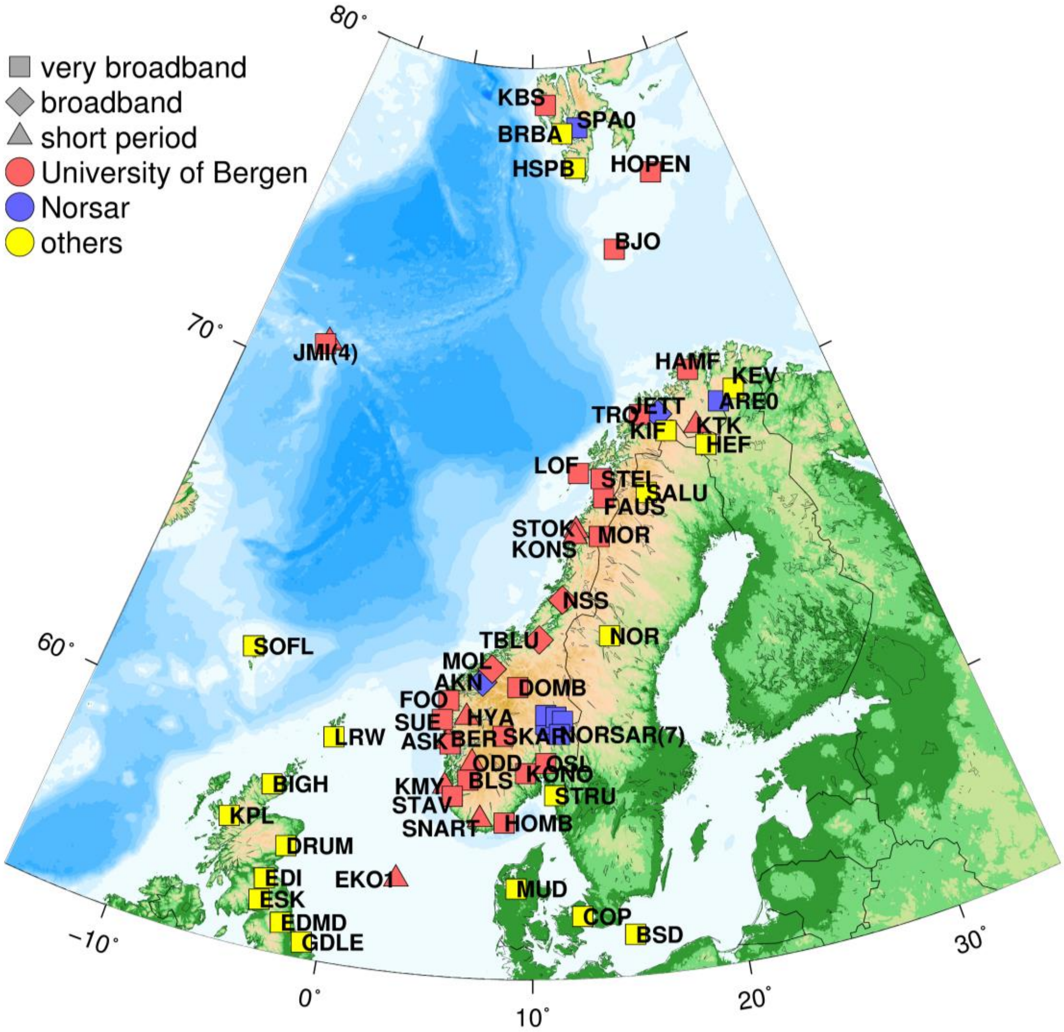

Figure 1. Stations delivering data to the NNSN database. UiB operates 33 stations (red) and NORSAR operates the stations marked in blue, including the three arrays and stations AKN and JMIC.

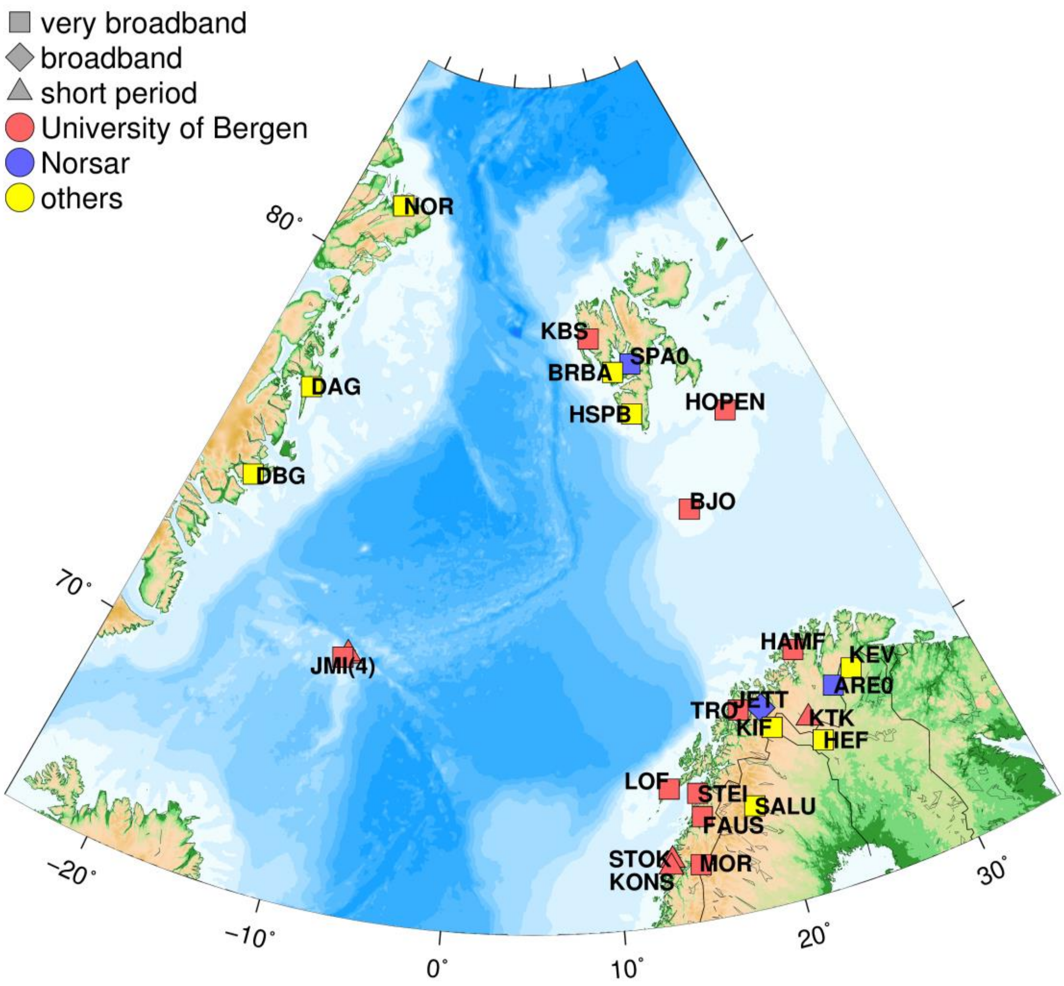

Figure 2. Seismic stations in the arctic area, including the three stations located on Greenland operated by GEUS, Denmark.

2 Operation

In Norway, UiB operates 33 of the seismic stations that form the Norwegian National Seismic Network (NNSN). NORSAR operates 3 seismic arrays, which also include broadband instruments, and three single seismometer stations (JMIC, JETT and AKN) (Figure 1). In total, NORSAR provides data from 14 broadband stations to the NNSN. The station HSPB is operated jointly between NORSAR and the Geophysical Institute, Polish Academy of Sciences, Warsaw, Poland and the stations located in Barentsburg (BRBA and BRBB) are operated jointly between NORSAR and the Kola Regional Seismological Centre of Geophysical Service, Russia. Data from the Danish stations located on the east coast of Greenland are also available (Figure 2) and contribute to the location of earthquakes in the Greenland Sea and Norwegian Sea.

The seismicity detected by the network is processed at UiB, but also NORSAR integrates their results in the joint database at UiB. Seismicity maps for the reporting period are shown in Figure 3 and Figure 4.

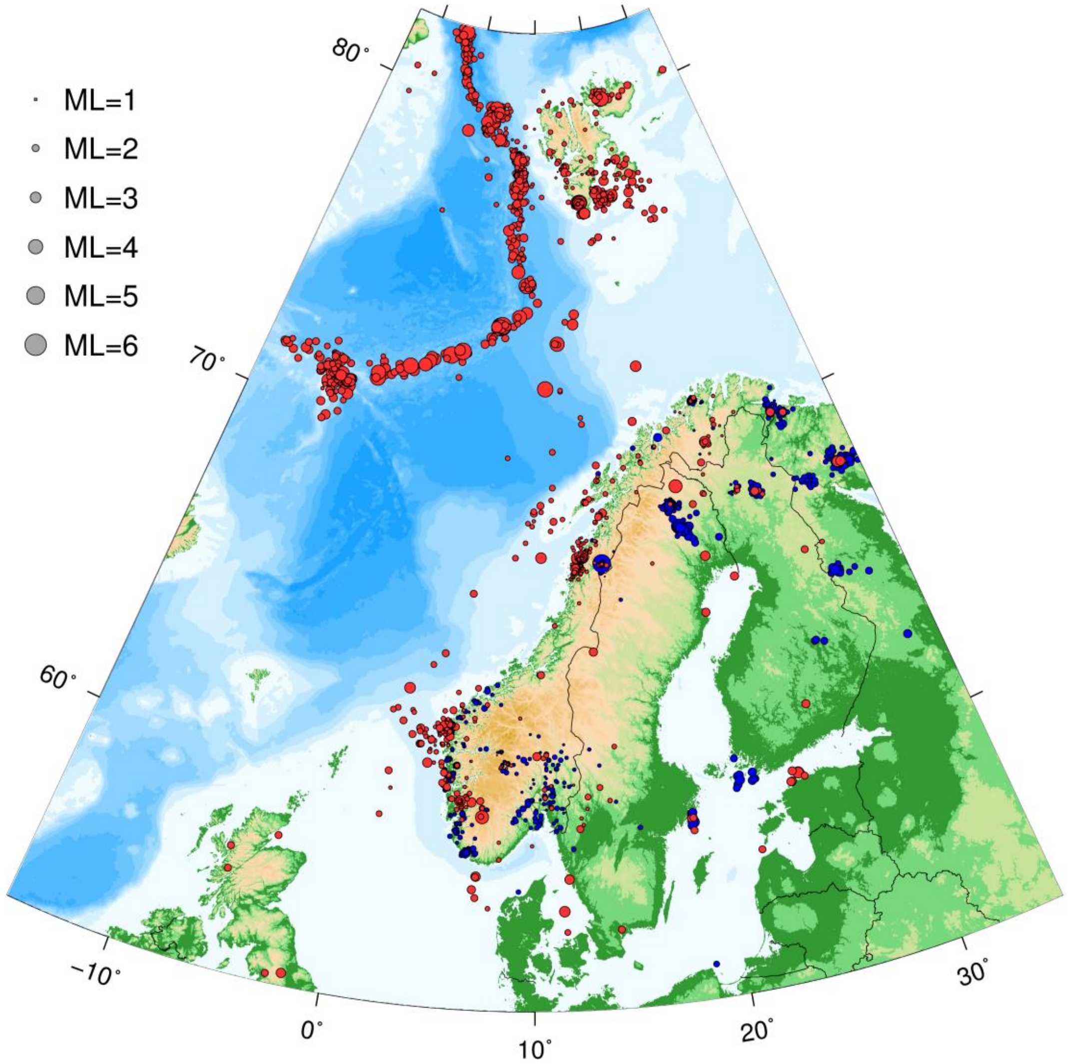

Figure 3. Seismicity map showing earthquakes (red) and explosions (blue) for the period January to October, 2015.

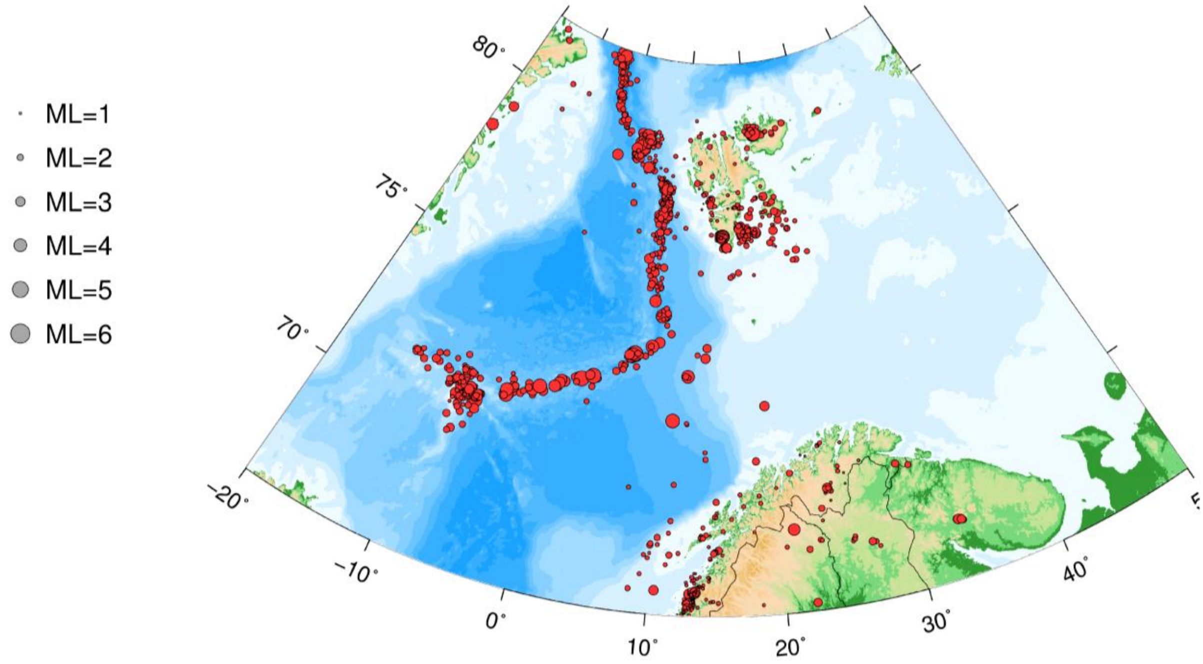

Figure 4. Seismicity in the artic area for the period January to October 2015. Known and probable explosions are excluded.

UiB is in the process of upgrading the NNSN by installing new stations and changing short period (SP) to broadband (BB) seismometers. A further effort is made to install additional high quality digitizers. The current use of seismometers is shown in Figure 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	10	23 (20 with natural period greater than 100 sec)	30 (not real time are 2 short period and 1 broadband stations on Jan Mayen)

The operational stability for each station is shown in Table 2. The downtime is computed from the amount of data that are missing from the continuous recordings at UiB. The statistics will, therefore, also show when a single component is not working. This is done as the goal is to obtain as complete continuous data from all stations as possible. 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 has been transferred. Thus, the statistics given allow us to evaluate the data availability when rerunning the earthquake detection not in real-time.

The downtime for the majority of stations is below 5%. Larger down time were observed for the following stations: MOR8, ODD1, KONS and TBLU (see technical service overview for details). For these four stations, the downtime was due to malfunctioning PCs and also a power break at KONS.

Table 2. Data completeness in % for January to October 2015 for all stations of the NNSN operated by UiB.

Station	Data completeness in %
Askøy (ASK)	95
Bergen (BER)	100
Bjørnøya (BJO)	99
Blåsjø (BLS)	100
Dombås (DOMB)	100
Florø (FOO)	95
Fauske (FAUS)	100
Hammerfest (HAMF)	100
Homborsund (HOMB)	100
Hopen (HOPEN)	98
Høyanger (HYA)	98
Jan Mayen (JMI)	100
Jan Mayen (JNE)	100
Jan Mayen (JNW)	100
Karmøy (KMY)	100
Kautokeino (KTK)	100

Station	Data completeness in %
Kings Bay (KBS)	98
Kongsberg (KONO)	98
Konsvik (KONS)	**88**
Lofoten (LOF)	99
Mo i Rana (MOR8)	**87**
Molde (MOL)	96
Namsos (NSS)	100
Odda (OOD1)	**94**
Oslo (OSL)	100
Skarslia (SKAR)	100
Snartemo (SNART)	99
Stavanger (STAV)	99
Steigen (STEI)	99
Stokkvågen (STOK)	99
Sulen (SUE)	99
Blussuvoll (TBLU)	**62**
Tromsø (TRO)	97

3 Field stations and technical service

The technical changes for each seismic station are listed below. It is noted if these changes are carried out by the respective local contact and not by the technical staff of UiB. When a station stops working, tests are made to locate the problem. The different equipment components can be restarted from Bergen, and this sometimes helps to resolve the issue.

Major changes during this reporting period of 2015 were:

Ask (ASK)

07.01.15: Visit. Malfunctioning digitizer is replaced. The station down from 20. December 2014 and data is lost.

20.01.15: Visit: Station was down due to lightning. Changed digitizer, GPS-antenna, power supply. Industrial-PC phased out. Removed remains from older installations.

22.01.15: Visit. Changed GSM router. Inspection of earth grounding rod and measurement of its resistivity. Checked station coordinates.

26.10.15: Visit. Changed GSM router with ICE version.

Bergen (BER)	03.02.15: In order to test the STS-2 sensor that was phased out at HOPEN in Sept 2014, we swapped the BER STS-2 unit with the one from HOPEN. Testing started Tue Feb 3. 2015 and was completed Thu 5 Feb., when the original BER STS-2 sensor was put into operation again.
Bjørnøya (BJO1)	21.08.15: Visit. Inspection. The digitizer was moved to sensor, GPS antenna installed on nearby pole and mass centered. 08.10.15: Local personel replaced Ethernet Extender unit in sensor box with a spare unit.
Blåsjø (BLS)	No visit or technical changes
Blussuvoll (TBLU)	10.03.15: Visit. PC and power supply replaced. 24.03.15: Visit. Replaced serial cable between sensor and recording equipment. Data lost since February 18. Discussed possible new site with Stjørdal Kommune. 17.08.15: Local contact installed new industrial PC. Data lost since June 24. 21.09.15: PC problem. Local contact installed and tested SMS reset device. Replaced industrial PC with new unit.
Dombås (DOMB)	No visit or technical changes.
Fauske (FAUS)	04.03.15: Local operator. Water, possibly caused by condensation, was removed from the vault. A new lid and gasket were installed to avoid condensation. 13.03.15: Local operator. New cable installed between router and digitizer. 25.05.15: Local operator. Water removed, attempt to install new router which did not work so the old router was reinstalled. Switched back to the original network cable between router and digitizer. 11.06.15: Visit. Changed digitizer and router. 17.06.15. Communication down since 1. june. The router operated by default in 4G, but FAUS is outside 4G area. Parameter settings changed on router. 12.09.15: Replaced lid. Work done by local entrepreneur. 16.10.15: Visit for inspection and maintenance. 30.10.15: Padlock, pressure-proof entry and tube installed by local operator.
Florø (FOO)	11.03.15: Visit. Replaced the digitizer and power supply.
Hammerfest (HAMF)	No visit or technical changes.
Homborsund (HOMB)	No visit or technical changes.

Hopen (HOPEN)	26.08.15: Visit. New vault installed. New installation of seismometer, digitizer and telemetry between building and vault. 21.09.15: Local staff at Hopen finished the backfilling and the remaining el. work. 15.10.15: During October the local staff at Hopen did minor maintenance.
Høyanger (HYA)	No visit or technical changes.
Jan Mayen (JMI)	No visit or technical changes.
JNE	No visit or technical changes.
JNW	No visit or technical changes.
Karmøy (KMY)	No visit or technical changes.
Kautokeino (KTK)	14.07.15: Visit. Replaced the ranger seismometer with a Streckeisen STS-2.5 on loan from Norwegian broadband pool until end of 2016. 24.07.15: Masscentering done by local contact. 31.07.15: Local contact checked the sensor. No mass-centering needed.
Kings Bay (KBS)	No visit or technical changes.
Kongsberg (KONO)	No visit or technical changes.
Konsvik (KONS)	25.03.2015: Station down until April 07. 2015 because of power-loss during the Easter vacation. Data lost. 18.05.2015: PC problem. The local contact absent May 5-12. New PC installed. Data lost between April18- May 18.
Lofoten (LOF)	No visit or technical changes.
Mo i Rana (MOR8)	04.03.15: Station has been down since February 07. 2015 due to a faulty PC. The PC has been replaced. Data has been lost. 21.07.15: Station down from July 19. Resetting of power supply and digitizer done remotely.
Molde (MOL)	17.02.15: Power loss due to lightning. New sensor installed, COM 1 and 2 on the industrial PC was defect, but COM 3 and 4 could be used. Data

lost.

Namsos (NSS)	No visit or technical changes.
Odda (ODD1)	10.09.15: The PC was defect. New PC and modem were shipped to the local contact. Due to holiday the new PC and modem was installed 11th September. Data is lost between august 28 and September 10.
Oslo (OSL)	18.09.15: Visit. Installed new Nanometrics interface cable between digitizer (Güralp DM24-EAM) and sensor (Nanometrics Trillium 120PA). Phased out old cable with two junction boxes.
Skarslia (SKAR)	12.07.15: Visit. Inspection. 08.10.15: Visit. Inspection.
Snartemo (SNART)	No visit or technical changes.
Stavanger (STAV)	05.01.2015: Station down until January 07. 2015 due to power break at OD. Data lost.
Steigen (STEI)	No visit or technical changes.
Stokkvågen (STOK)	No visit or technical changes.
Sulen (SUE)	No visit or technical changes
Tromsø (TRO)	04.04.15: Station has been down until April 14. 2015 due to a defective PC. PC has been replaced by local operator.
Vadsø (VADS)	16.10.2015: Visit. The vault for the new station was constructed. The station location is shown in Figure 10.

4 Research

4.1 UIB: Magnitude scales by Won-Young Kim (Columbia University)

The standard ML magnitude scale in use at UiB was derived from earthquake recordings corresponding to travel paths in continental crust. It has been realized for some time that this method is not applicable to earthquakes along the Mid-Atlantic ridge. The resulting discrepancy between other magnitudes and ML can be as large as a difference of 2 in magnitude. We propose to determine empirical amplitude distance curves for crustal phases, *Pn*, *Pg*, *Sn* and *Lg* waves for earthquakes in Norway including offshore Norwegian Sea and adjacent regions. We will calibrate magnitude scales to the moment magnitude of several reference events in the region. We propose to implement an automatic method to identify observed *Pn* and *Sn* phases based on group velocities and to apply appropriate phase specific amplitude attenuation curves to assign a robust magnitude for earthquakes in mid-Atlantic ridge segments.

Seismicity along the mid-Atlantic ridge segments around Norway may be grouped based upon the Flinn-Engdahl geographic region names. The seismic regions are from north to south: North of Svalbard, Svalbard, Greenland Sea, Norwegian Sea and Jan Mayen regions. Seismic waveform data from these regions recorded at seismic stations in Svalbard, Greenland, and northern Scandinavia indicate that records consist predominantly of *Pn* and *Sn* waves. No *Lg* wave trains are discernable on the paths between mid-Atlantic ridge events and seismic stations on land. Seismic records from the Mw 4.7 event on 19 Nov 2011 north of Svalbard are shown in Figure 5. The records at the nearest station NOR (Δ=249 km, Az=290º) in Greenland show trace of Lg waves with 3.0-3.7 km/s suggesting that a large portion of this path must be continental crust. However, *Sn* waves are the predominant signals on 3-component records at stations in the distance range of 366 km to 864 km.

A dataset of recordings of about 150 earthquakes on seismic stations in the region has been established. From this a detailed characterization of the dominant regional phase types will be made to evaluate which phases are most suitable for magnitude calculation. From these observations, distance correction curves will be produced for the relevant seismic phases and a magnitude scale will be developed to produce magnitudes similar to globally reported moment magnitudes.

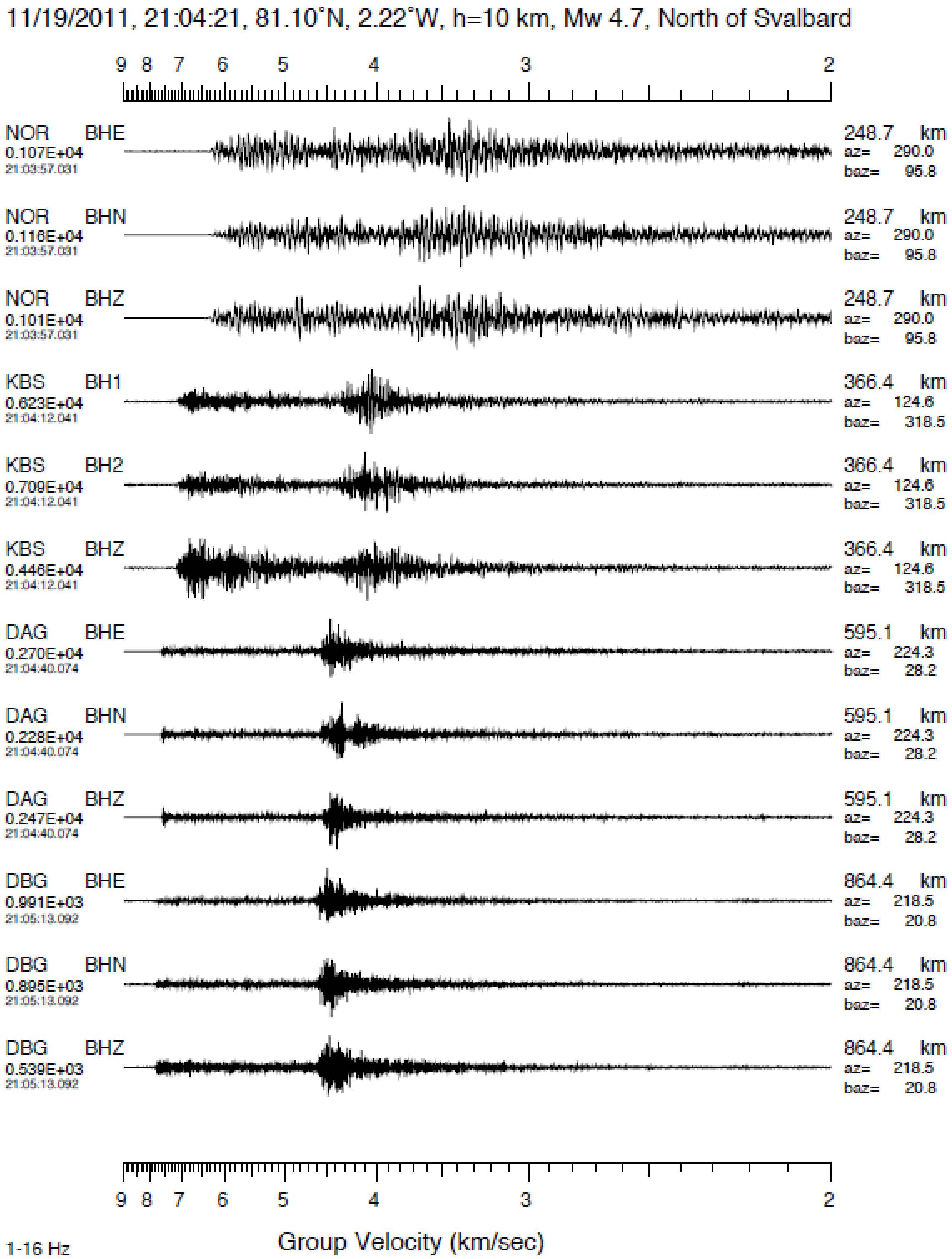

Figure 5. Sample seismograms from earthquake north of Svalbard, filtered 1-16 Hz.

4.2 UIB: Polarization analysis by Luigia Cristiano

Tomographic studies and SKS splitting studies are the most applied techniques to investigate the seismic anisotropy in the Lithosphere. Anisotropy as well as the Lateral Heterogeneity are expected to affect the particle motion (polarization) of seismic waves. There are still few studies investigating the anomalies in the P waves and surface waves polarization characteristics. The study of polarization of seismic waves offers the potential to investigate local and distant heterogeneities and the local anisotropy. The P wave polarization can be described by two parameters: azimuthal and vertical angle, that, in case of isotropic, homogeneous medium are expected to be along the great circle path direction and along the vertical polarization angle.

An automatic determination of the Polarization characteristics is needed to process the data consistently. The polarization parameters of the first teleseismic P-wave are automatically picked and to each pick is associated a quality parameter. The automatic procedure allows to process a number of events characterized by different backazimuth and incidence angle.

The database consists of about 20 year of data recorded by the Norwegian National Seismic Network, with about 1000 teleseismic events that are useful for this work.The polarization analysis is conducted in two frequency bands to investigate the dependence of the measured parameters on frequency as well as on backazimuth and epicentral distance. This would put constraint on the characteristics and location of the source of anomalies. The quality of the measurements is overall high. P-wave polarization analysis on those data revealed a strong dependence of measured parameters on frequency and backazimuth and a weak dependence on the epicentral distance. This points to the presence of anisotropy and lateral heterogeneities in the vicinity of the stations.

In case of azimuthal anisotropy, it is expected that the azimuthal anomalies show a dependence on the backazimuth described by a sine function with 180° period. The phase of the sine function is determined by the fast direction of anisotropy. In case of dipping symmetry axis of anisotropy, the 180° periodicity is not broken and a 360° term becomes more visible in data. A 360° periodicity in the azimuthal deviations as function of backazimuth may also be explained in terms of velocity gradient in the receivers area. In order to extract the information about anisotropy from the data, a harmonic analysis is applied to the measurements of azimuthal deviations as function of anisotropy. In this study 10 harmonic components with periodicities going from 36° to 360° are considered.

Here we present the preliminary results on a subset of the database, consisting of 600 teleseismic events that occurred in the time range 2008-2015.

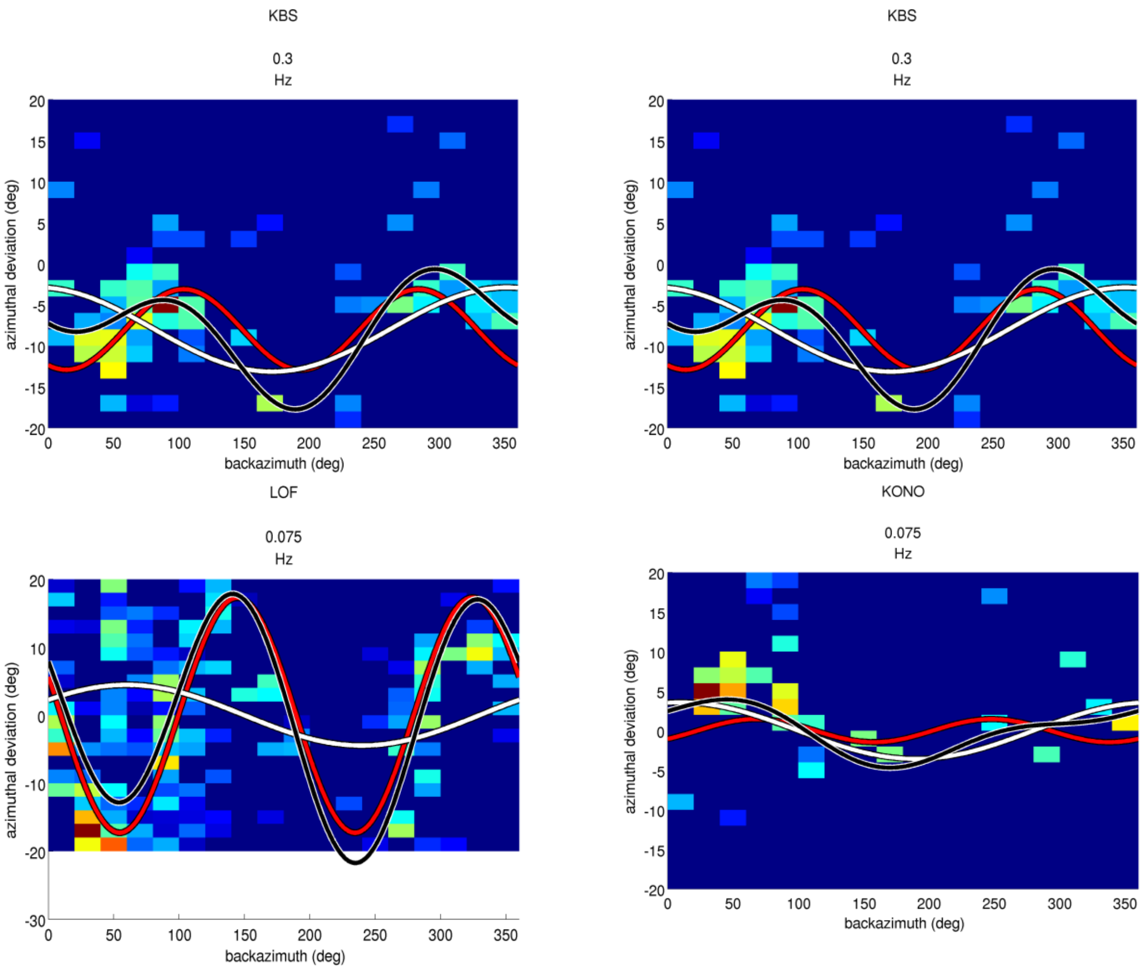

Figure 6. 2D-Histograms for measurements of azimuthal deviation for station KBS (top) in the frequency ranges 0.05-0.1 Hz and 0.1-0.5Hz, for station LOF and station KONO (down) in the frequency range 0.05-0.1Hz. The number of measurements and their quality are defining the colorscale. Red colors indicate high quality measurements for each range of backazimuth and azimuthal deviations. On the top of the deviations are shown the 360° (white) , the 180° (red) and the sum of the two terms (black).

The observed patterns of azimuthal anisotropy are overall clear, the observations can be well represented by a sum of 180° and 360° harmonic components as estimated by the harmonic analysis of the data. The phase and relative ratio of the two components observed at each station of the Norwegian National Seismic Network is strongly varying. No strong dependence on the frequencies is visible in the 2D histograms. The high quality of the measurements allows for a consistent variance reduction in the measurements of azimuthal anisotropy by using the harmonic components with periodicities 180° and 360° (Figure 6). From the phase of the 180° term is possible to determine the fast direction of azimuthal anisotropy at each station of the Norwegian National Seismic (NNSN) (Figure 7).
The amplitude of the 180° term is strongly varying along the network. In particular stations LOF and STEI show a prominent 180° term. This points to the presence of strong anisotropy felt by the P-wave polarization parameters. The fast direction of anisotropy in not changing wih frequency. Measurements at the other stations of the NNSN point to the presence of weak azimuthal anisotropy in the crust and uppermost mantle (Figure 7).

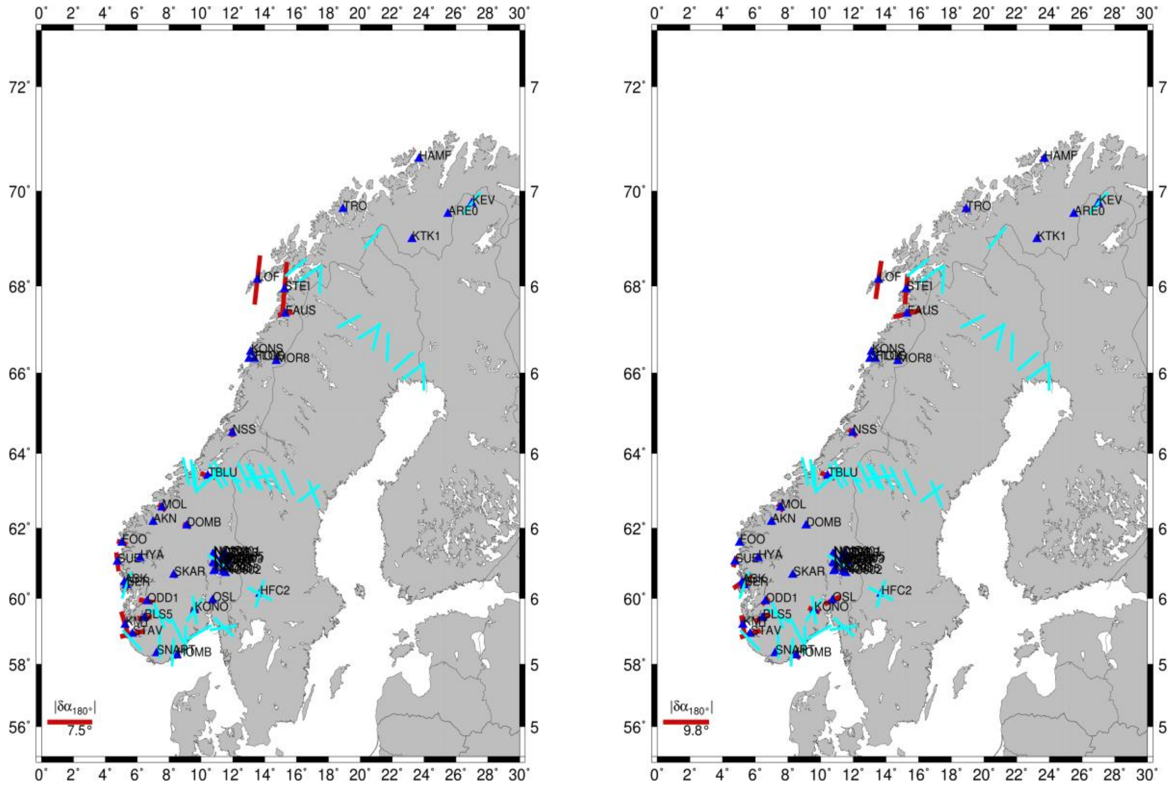

Figure 7. Plot of the fast direction of anisotropy at the stations of the NNSN at low (left) and high (right) frequencies, retrieved by teleseismic P-wave polarization analysis. The red bars are indicating the direction of fast direction and their length is scaled by the amplitude of the 180° term.

The fast directions in the different frequency bands are consistent, this points to the absence of a layered azimuthal anisotropic structure at the resolved depths (crust and uppermost mantle). Stations LOF and STEI are characterized by similar fast directions both associated to high amplitude of the 180° term. In the map are reported the fast direction estimated by previous studies in the region by SKS splitting analysis (light blue bars). The SKS splitting measurements are available also for short time deployment. The data from those stations have not been used in this study.

The fast direction of anisotropy retrieved at the NNSN by P-wave polarization analysis in the frequency ranges 0.05-0.1Hz and 0.1-0.5Hz are strongly varying along the network but they do not show strong frequency dependence. This would be related to a consistent fast direction at the various depth resolved by the considered wavelenghts (crust and uppermost mantle). The fast directions are strongly changing between stations maybe due to lateral changes in the anistropic characteristics of the region. The 180° is rather low at most of the stations, this is an indication of weak azimuthal anisotropy. In case of dipping axis of anisotropy, the fast directions of anisotropy can still be determined by the phase of the 180° term. The fast directions retrieved by P-wave polarization analysis are compared in Figure 7 to the fast directions retrieved by SKS splitting (compilation by T. Becker at University of California, Roy and Ritter, 2013). Measurements of SKS splitting and P- wave polarization parameters are characterized by different resolution in depth, with SKS splitting measurements characterized by a cumulative effect.

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4.3 NORSAR: 3-D velocity model for Southern Norway by Ilma Janutyte

The aim of this study is to develop a 3-D crustal model for the territory of Norway both on-shore and off-shore. Until now we developed the 3-D velocity model for the southern part of Norway. The workflow was divided into two steps: 1) development of an optimal 1-D velocity model, and 2) development of the 3-D velocity model.

The optimal 1-D velocity model for southern Norway was obtained using the VELEST program, which is implemented into the SEISAN program package, and the dataset of 175 local seismic events recorded at 105 stations within the study area of 58-65 N and 4-14 E. The obtained optimal 1-D velocity model with 10 layers of different seismic velocities extends from the surface down to 80 km deep. Before implementing the model into the FMTOMO program, which was used for the 3-D inversion, the 1-D velocity model was transformed into a two layer model with gradient increase in velocities with depth (Figure 8).

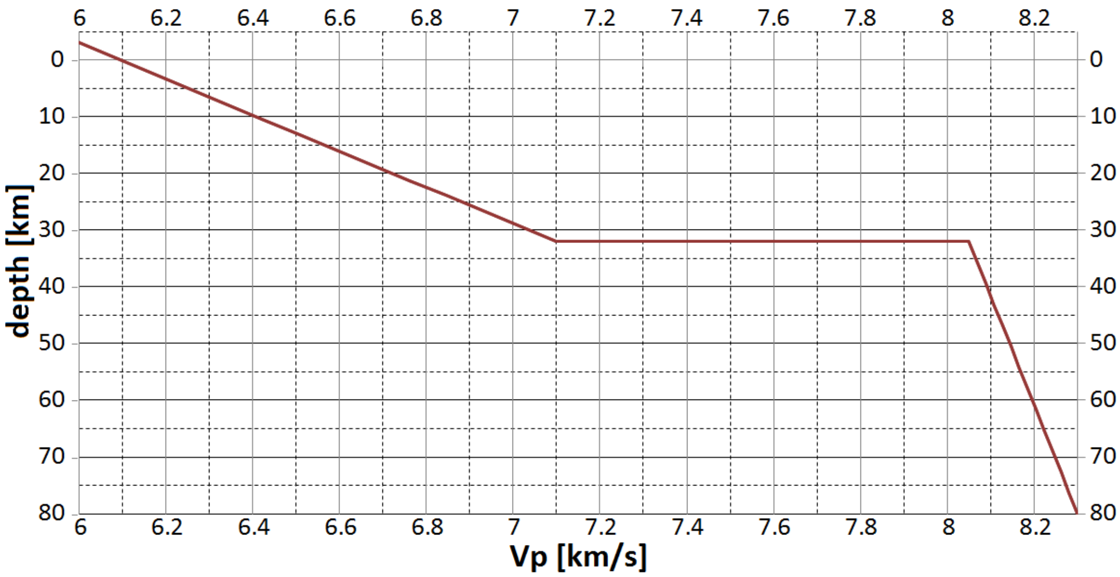

Figure 8. Reference 1-D velocity model for southern Norway used to perform inversions with the FMTOMO program.

The synthetic checkerboard tests with the current configuration of sources and receivers show good resolution in the study area just beneath the seismic network down to about 35-40 km deep. In the study area the 3-D inversion results (Figure 9) show the velocity perturbations up to ±0.4 km/s compared to the reference velocity model. The results indicate that the Moho boundary ranges from 31 km beneath Oslo Graben and SW coast to about 35 km beneath the mountain plateau. The higher seismic velocities compared to the reference velocity model dominates under the mountain plateau.

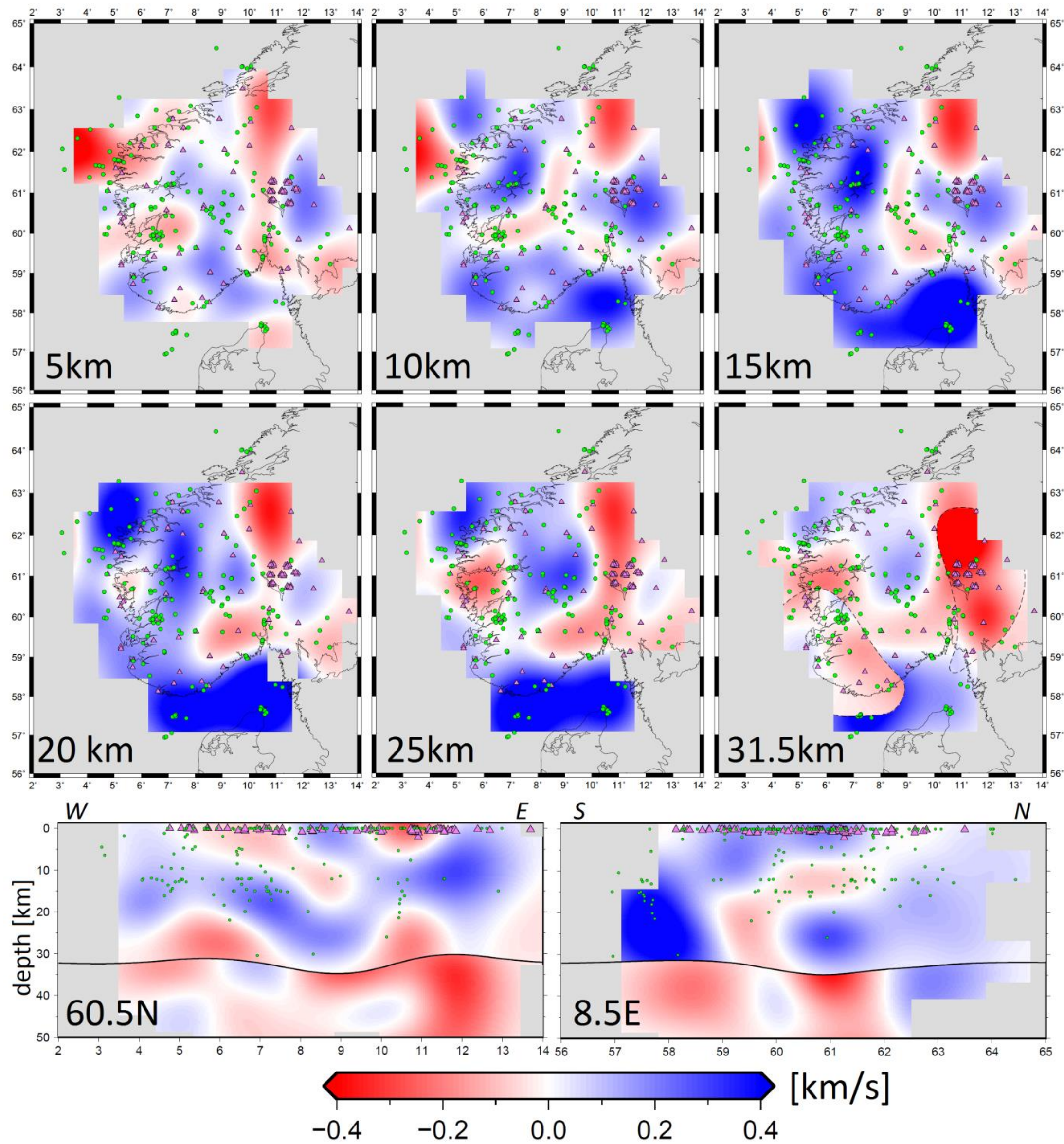

Figure 9. Inversion results with the real dataset. Horizontal and vertical slices of the target volume are shown. Blue and red colors indicate velocity perturbations which are, respectively, higher and lower compared to the reference velocity model (Figure 8). Grey color indicates areas of poor ray coverage (less than 7.5 % of total ray hits). Dashed contours on the horizontal slice at 31.5 km depth and solid lines on vertical profiles mark the Moho intersection.

5 NNSN 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. However, in areas where additional stations are deployed for local monitoring, short-period seismometers are sufficient. The number of broadband seismometers in the network will be increased to replace existing short period instruments. A general goal for the future development has to be to achieve better standardization in particular with the seismometers and digitizers. The total number of stations will remain mostly stable for now, but it is important to improve the overall network performance.

5.1 Achievements in 2015

- Two EPOS proposals have been approved, the first (EPOS-IP) will allow UiB to lead IT developments on data and service integration at the European scale; the second (EPOS-N) is funded by the Norwegian Research Council to install new monitoring stations in Northern Norway and the Arctic as well as develop tools for processing and visualization, and provide the different geo-scientific data through a web-portal.
- The seismic station on Hopen was re-built with a new vault and equipment. The digitizer is now placed at the vault.
- Bjørnøya (BJO) was improved by moving digitizer to the sensor vault.
- New cabling to connect the Nanometrics sensor to Guralp digitizer without junction boxes has been implemented at a number of sites (OSL, BJO, HOPEN, SKAR)
- The new station near Vadsø (VADS) on the Varanger peninsula is under construction. The vault is constructed and the equipment installation will be carried out in November 2015. The location of the station is shown on Figure 10.
- The KTK station has been temporarily upgraded with a broadband seismometer on loan from the Norwegian broadband pool.
- The manuscript on the seismic noise analysis and interpretation has been submitted to Journal of Seismology.
- The research work by NORSAR on travel time inversion is giving first results.
- The research work at UiB this year is carried out by two guest researchers during the fall, where the focus is on polarization analysis and development of magnitude scales in particular to address the complicated travel paths in the North Atlantic not accounted for in the current magnitude scale.
- At the Nordic Seismology Seminar progress was made to get uniform event-identification in Scandinavia. This work will shortly be finalized.
- Spectrogram displays have been implemented to discriminate between explosion and earthquake.
- A tool (PQLX) to effectively monitor station noise has been implemented and is used routinely.
- The station coordinates have been checked and corrected by comparison to online mapping services. The effect of the correction on earthquake location has been systematically investigated.

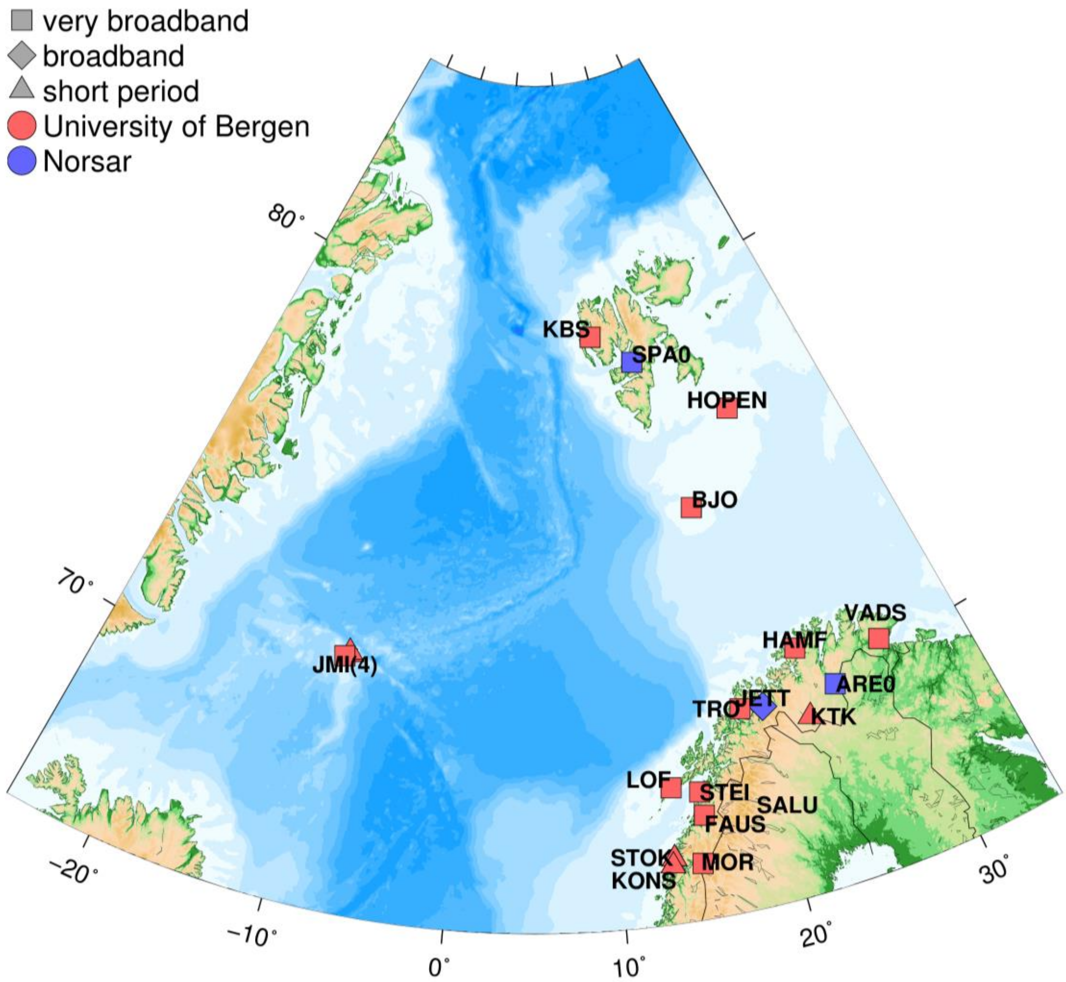

Figure 10. The location of the station VADS shown together with the existing NNSN and NORSAR stations.

5.2 Plans for 2015/2016

- Complete the installation of the new station (VADS).
- Upgrade of two short period stations in south-western Norway with a broadband sensor already purchased in 2015.
- Implement the new magnitude scales into the processing routines.
- Integrate Statoil data into the real-time processing.
- Carry out the research work on attenuation tomography.
- The research and development activity will continue in close collaboration between UiB and NORSAR.
- Strengthen the collaboration with NORSAR and the other Nordic countries on data processing through technical visits.