Operational Procedures of Agencies Contributing to the ISC

Seismic Monitoring and Data Processing at the Norwegian National Seismic Network

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Operational Procedures of Contributing Agencies

5.1 Seismic Monitoring and Data Processing at the Norwegian National Seismic Network

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5.1.1 Introduction

The Norwegian National Seismic Network (NNSN) is operated by the University of Bergen (UiB) to monitor the area covering mainland Norway, the North Sea, Norwegian Sea, Barents Sea and the arctic archipelago of Svalbard. Today, the network consists of 34 seismic stations distributed over the Norwegian mainland and the arctic islands Jan Mayen, Bjørnøya, Hopen and Spitsbergen. The main purpose of the network is to monitor the local and regional seismic activity. The Norwegian mainland and coastal areas are only moderately active, and the largest regional earthquakes occur along the Mid-Atlantic ridge. North of Iceland, Jan Mayen is an active volcanic island with most recent eruptions in 1970 and 1985 that is monitored by UiB. With its distribution and high station quality the network also provides data to various scientific studies. The network data are openly available and phase data are submitted to the ISC (agency code BER). This report gives an overview of the network history and current status, the data processing systems and the seismicity that is recorded.

5.1.2 Seismic Network

History

Instrumental seismology in Norway started with the installation of a seismograph at the Bergen Museum in 1905. This became possible due to the Oslo earthquake of 1904 and was in time to record the San Francisco earthquake of 1906. The first seismograph was a Bosch-Omori sensor that remained in

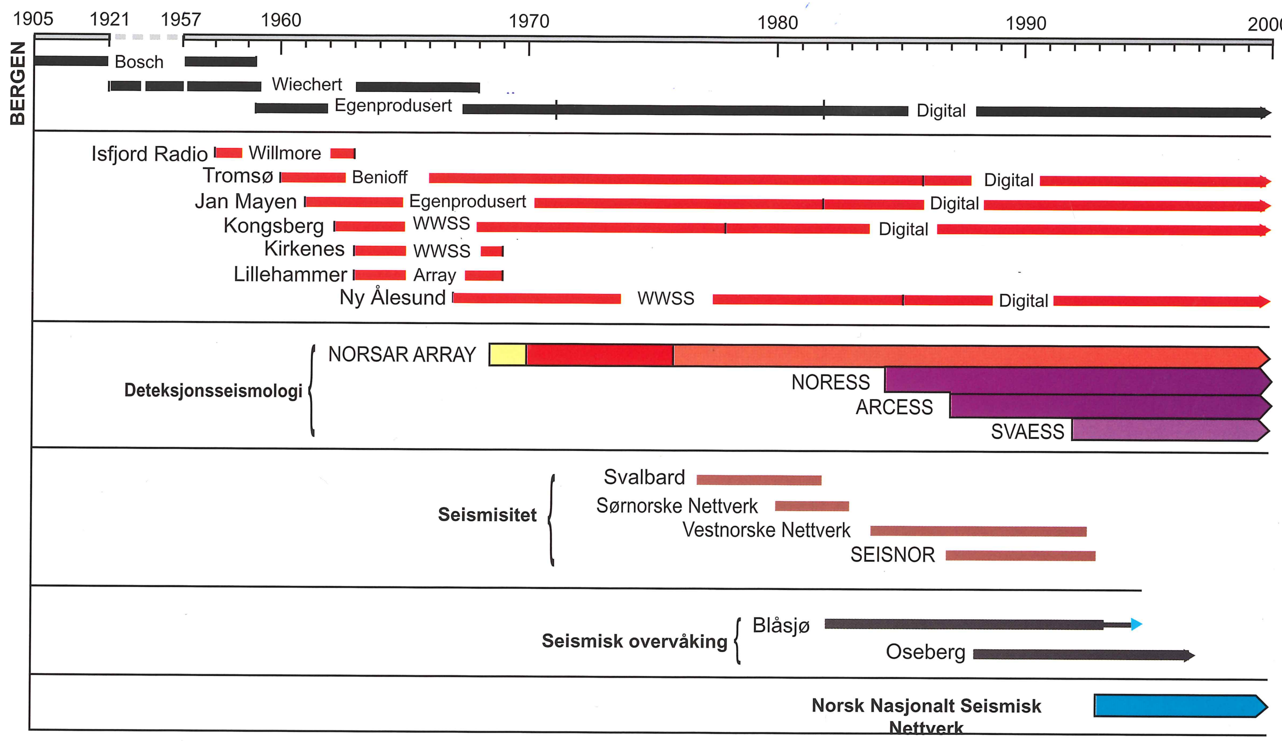

Figure 5.1: *Operation of seismic stations in Noway over time: From the top: black lines indicate stations in Bergen, thin red lines are other UiB stations, thick red lines are NORSAR arrays and thin brown and black lines are time limited local networks operated by both UiB and NORSAR. Abbreviations: WWSSN: World Wide Standard Seismic Network. NORESS, ARCESS and SVAESS are NORSAR operated arrays.*

operation until 1959. In parallel, Wiechert seismometers were operated from 1921. Additional seismic stations were built between 1958 and 1961 on Svalbard, in Tromsø and on Jan Mayen. The complete history of network development is given in *Sellevoll and Sundvor* (2001). Also, a self-built seismometer was in operation in Bergen from 1959. The University of Bergen (UiB) network expanded in the 1980s mostly with the installation of short period seismometers across Norway. Two Global Seismograph Network stations are in operation in Norway, Kongsberg (KONO) is operated by IRIS/USGS/UiB since 1978 and Kings Bay (KBS) by IRIS/USGS/GEOFON/AWI/UIB since 1994. From 1992, the UiB stations were merged into the Norwegian National Seismic Network (NNSN). An overview of the historic development is given in Figure 5.1.

Current Status

The NNSN consists of 34 seismic stations that are distributed over mainland Norway and the Norwegian Arctic regions (Figure 5.2). The majority of stations (28) are equipped with broadband sensors and high quality 24-bit digitizers, while the remaining (6) have short period sensors. Data from all stations are received in near real-time in Bergen through different modes of communication including public Internet, ADSL, GSM and satellite. In addition to the UiB stations, the NNSN receives data from NORSAR stations in Norway, but also from neighbouring networks in the UK, Denmark, Finland, Sweden, Iceland and Poland.

The NNSN instrument vaults were constructed differently over time. Some of the earlier stations have

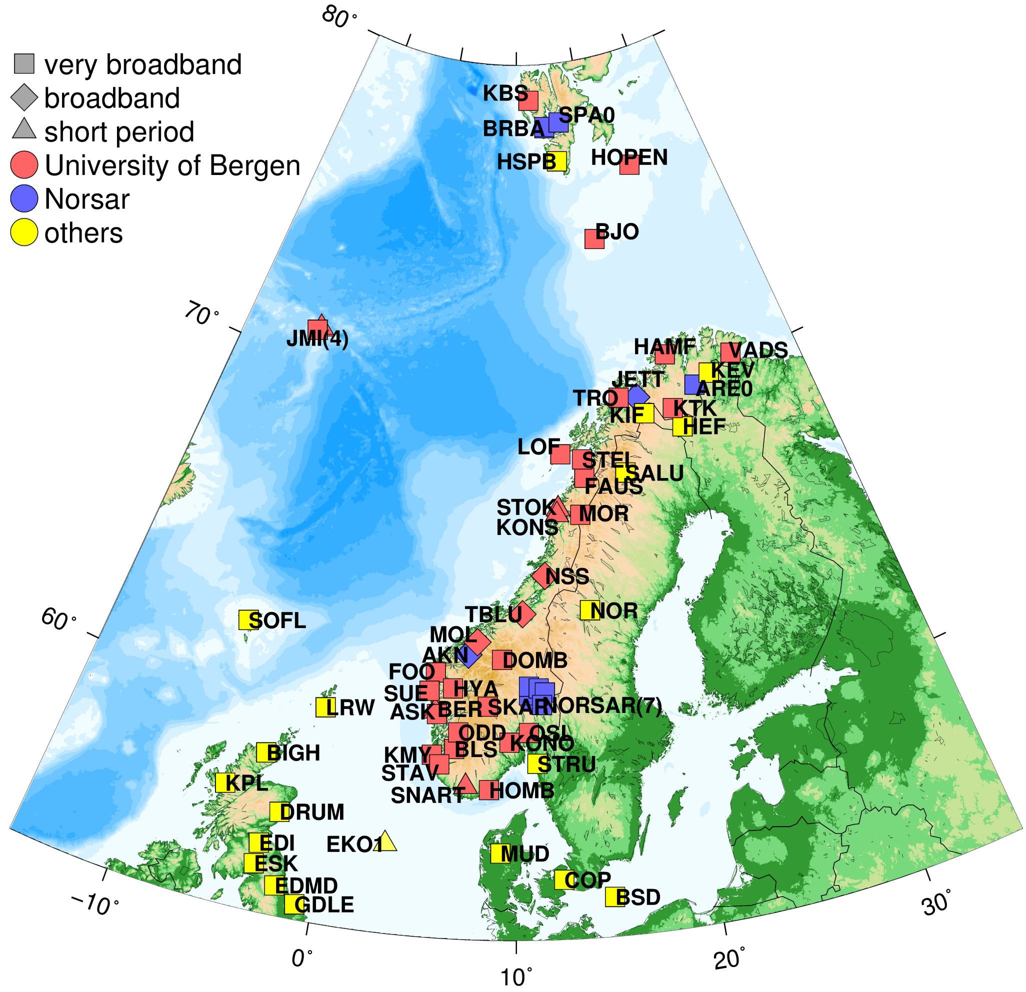

Figure 5.2: *Stations contributing to the NNSN data processing. UiB operates the 34 NNSN stations (red). The remaining stations are operated by NORSAR (blue), and selected stations by the UK, Denmark, Finland, Sweden, Iceland and Poland (yellow).*

high-quality purpose built vaults (e.g., KONO, KBS, TRO, BER). Many of the stations constructed since the 1980s were short period and have simple shallow vaults. Recent new vaults are constructed more specifically to obtain high quality broadband recordings (Figure 5.3). The final data quality results from the combination of instrumentation, vault and the noise conditions. A detailed study by *Demuth et al.* (2016) describes the noise conditions on the NNSN stations and estimates the effect of noise on the detection levels (Figure 5.4). The microseismic peaks in Norway originate from the North Atlantic and a clear correlation of weather conditions and seismic noise can be observed. An example of noise levels for station LOF (Lofoten islands in northern Norway) is given in Figure 5.5. The microseismic peaks on the NNSN stations clearly have higher amplitudes during the winter months.

The NNSN continues to develop and the remaining short period stations will be upgraded in the coming years. A recent development in Norway has been the installation of passive monitoring seafloor installations at a number of oil fields by the operating companies. Some of that data is now received in near real-time to obtain better detection and location capability especially in the offshore areas. The network will also expand in the coming years through the EPOS-Norway (`www.epos-no.org`) project that aims to install new stations in northern Norway and on Svalbard.

Figure 5.3: *Pictures from the broadband station VADS in North-eastern Norway, installed in 2016.*

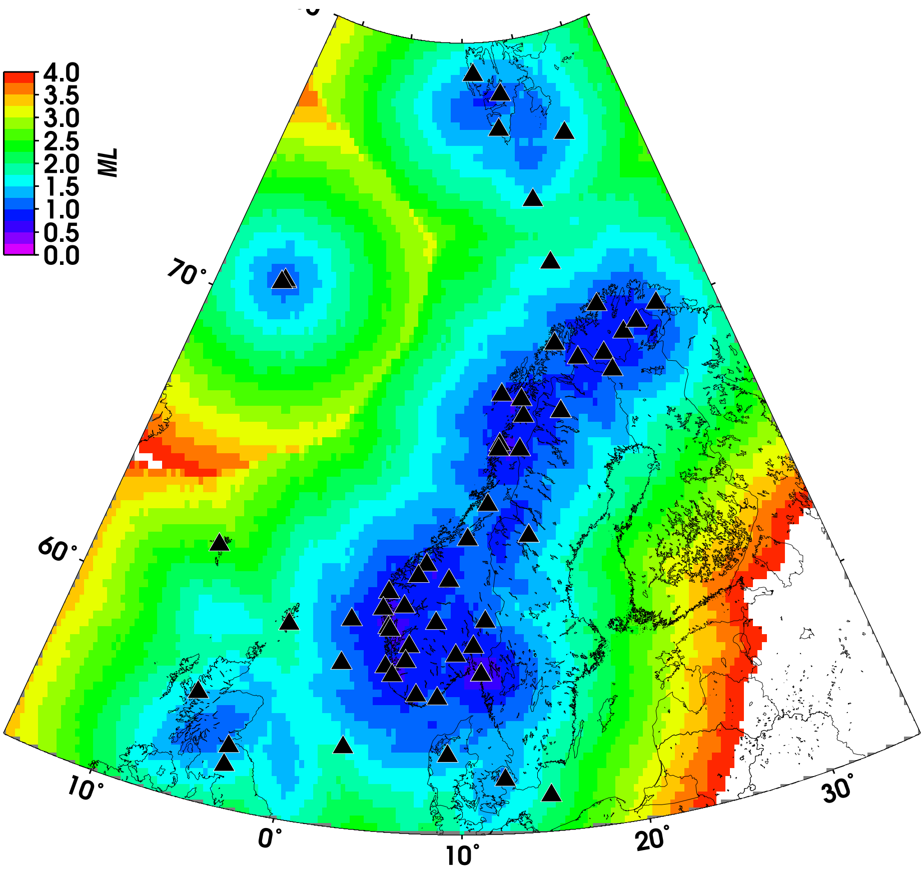

Figure 5.4: *Computed detection levels for the network of stations shown as black triangles.*

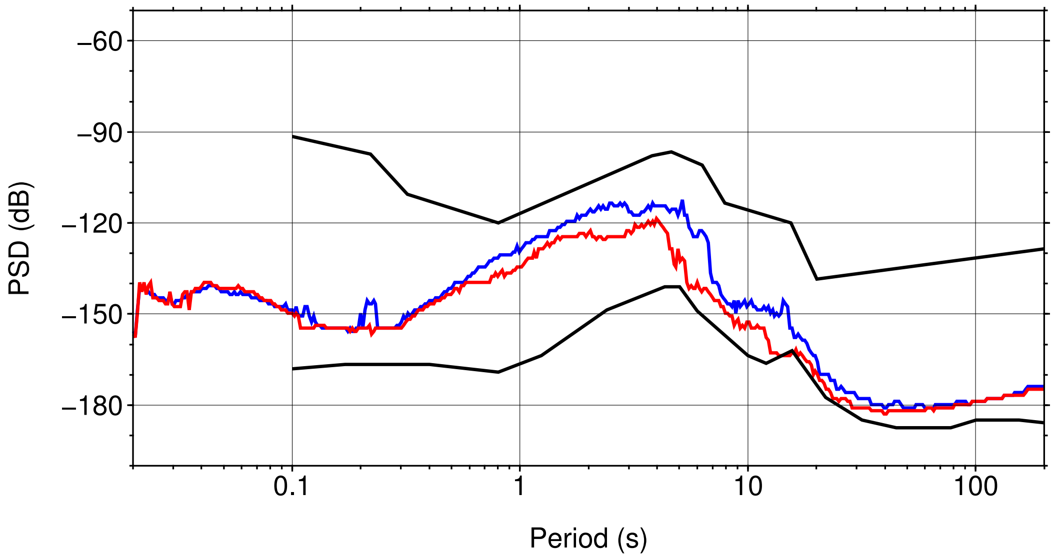

Figure 5.5: *Noise level modes for station LOF for summer (red), 1 April 2017 – 30 September 2017, and winter (blue) , 1 October 2017 – 31 March 2018.*

5.1.3 Data Processing

The real-time data arrives in Bergen and is initially processed automatically. The detected events are located manually on a daily basis, and final bulletins are produced by detailed manual interpretation of the seismograms.

Acquisition and Event Detection

Data from the NNSN and other stations are received at UiB through the seedlink protocol (`www.seiscomp3.org`). Data on the stations are provided through a seedlink server running either on the digitizer or a standard computer connected to the digitizer. Data latency is generally less than 30 seconds for the NNSN stations. All other data are received from seedlink servers running at the respective institutions. Data is archived in the standard SeisComp structure that can be accessed directly from the interactive processing software.

The automatic processing and event detection is done through Earthworm (`www.isti.com/products/earthworm`). Apart from the pre-processing, such as filtering and decimation, the main Earthworm modules used are for the creation of helicorder plots and the detection through the implementation of Carl Johnson's detection (see Earthworm documentation). The detection is configured for a number of regional sub-networks. Detection waveform files are produced, which are then injected into the processing database for further processing.

Routine Processing in SEISAN

The SEISAN software has been developed at UiB since the late 1980s (*Havskov and Ottemöller*, 1999). The development still continues and SEISAN is the main tool for the routine processing of the NNSN data. The software contains all the main tools for routine data processing and a database structure for storing the data. Recently, the SeisanExplorer has been added to provide a more user friendly, but

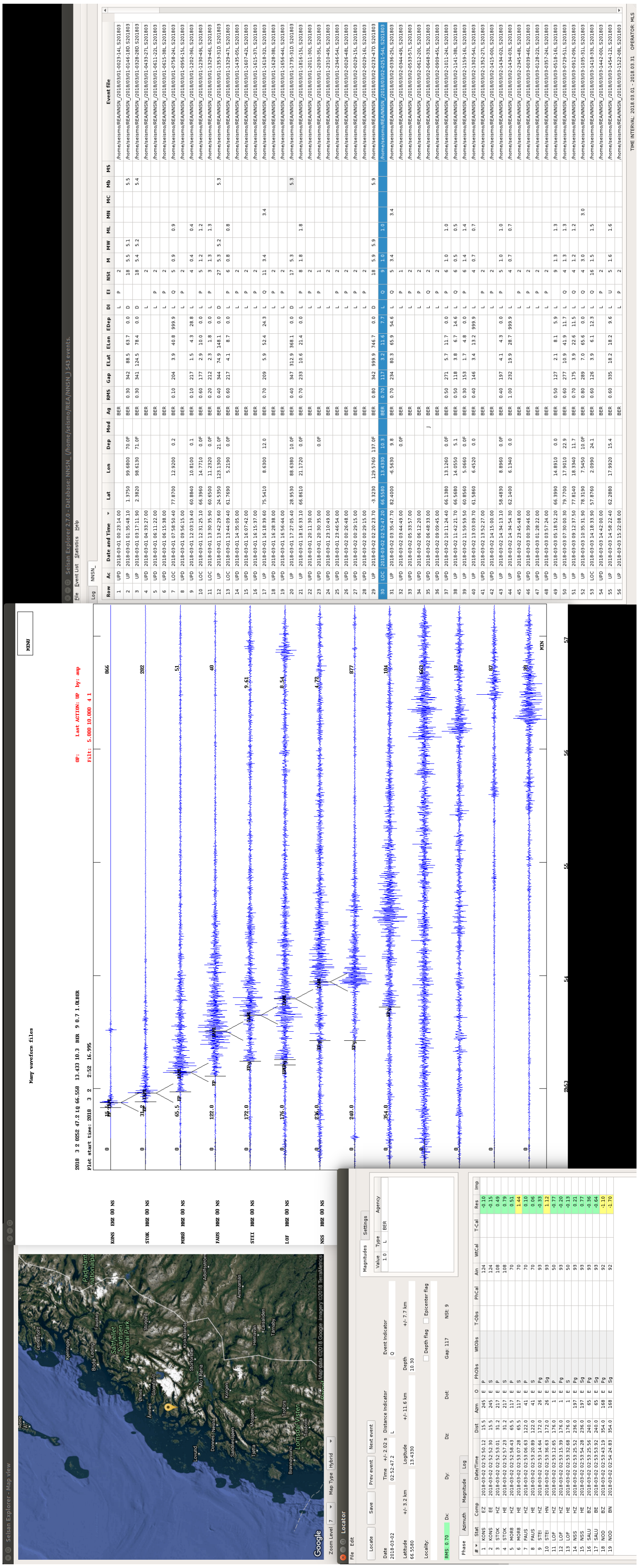

Figure 5.6: *SeisanExplorer setup. Clockwise from top: Interactive map showing location for the current solution, data trace view tool mulplt, SeisanExplorer database window, and locator window.*

still efficient, graphical user interface. With SeisanExplorer it is possible to have the main interlinked tools (database program, trace plotting, locator, mapping) available on screen to efficiently process and evaluate the results (Figure 5.6).

The interactive processing starts with the screening of detection files and dismissing false detections. While the focus of the NNSN is on regional data, teleseismic events are also processed. The routine processing includes manual phase identification and hypocentre location in an iterative manner. Event locations are performed using the HYPOCENTER program (*Lienert and Havskov*, 1995). The velocity model used for locating all local and regional events, except for earthquakes at the Jan Mayen, is given in *Havskov and Bungum* (1987). For local events, phases are picked on all possible stations. The main phases that can be identified are Pg/Pn and Sg/Sn. T-phases are also commonly observed from earthquakes on the mid-Atlantic ridge (Figure 5.7). At teleseismic distances, mostly P is picked for earthquakes below M=6.0, while additional phases are picked for larger events.

Various amplitudes are picked to calculate magnitudes using the standard IASPEI recommended scales (ML, mb, mB, Ms, MS, MW). At local and regional distances, the ML scale by *Alsaker et al.* (1991) is in use for mainland Norway. However, this does not work for the North-Atlantic as Lg does not propagate in the oceanic crust. Therefore, a new scale mb(Pn) where amplitudes are measured from the Pn wave has recently been developed (*Kim and Ottemöller*, 2017). The same method has been used to develop an mb(Sn) scale (so far unpublished), which can be used to recalculate magnitudes in the catalogue. Figure 5.8 shows that magnitudes on average were underestimated by 1.44 magnitude units.

Discrimination of Explosions

The majority of seismic events detected by the NNSN are explosions rather than earthquakes. In 2017, about 30 % of all 8685 detected local and regional events are earthquakes. Some of the mining explosions are reported to the NNSN and then marked as such in the database. While explosions can be interesting to study, they possibly contaminate the earthquake catalogue and their identification is important. Events are marked as either earthquake, probable explosion or confirmed explosion in the database. With the large proportion of explosions, quick identification is also important to minimize the processing work that is spent on them. Much research has been done on the identification of explosions (e.g. *Carr and Garbin*, 1998; *Kim et al.*, 1994; *Baumgardt and Ziegler*, 1988). However, automatic identification remains challenging, also due to the fact that there is a range of explosion source types and wave propagation differences across the area. In Finland, *Kortström et al.* (2016) have recently developed an automatic classification system based on a machine learning approach.

Applying the same algorithm as *Kortström et al.* (2016) for Norwegian data has so far only been partly successful. Instead, the focus is currently on the use of spectrogram plotting as part of the routine processing and this has been implemented into SEISAN (Figure 5.9). The single station spectrograms can be plotted after distance sorting for evaluation of the source characteristics and also to see how the spectral content changes with distance due to wave propagation, including scattering.

One difficulty is that explosions are carried out in different ways. Larger industrial explosions are often fired as sources in series with some time delay (ripple firing) to spread the energy over time to increase fracturing efficiency and reduce ground vibration. The time delay causes waves at certain frequencies

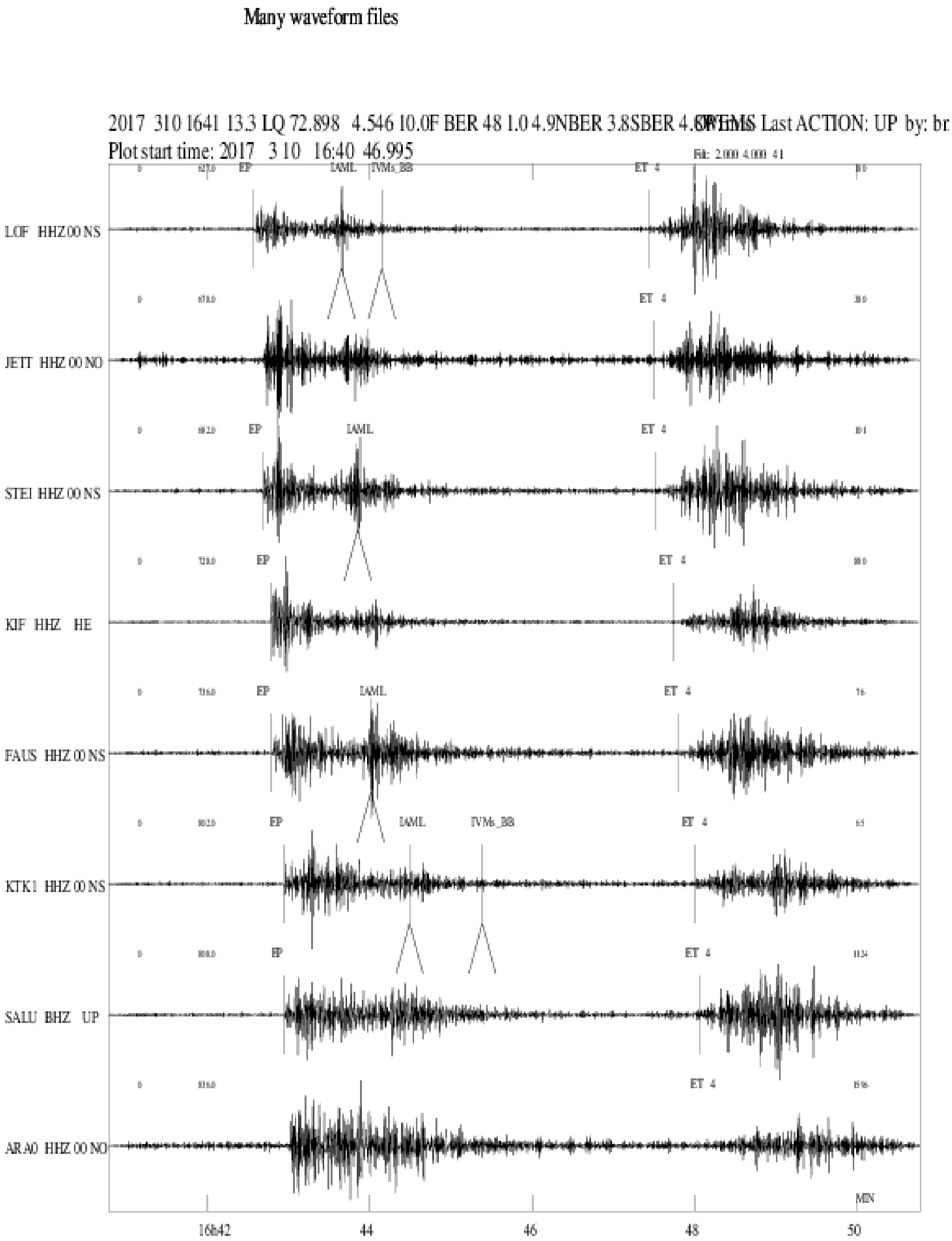

Figure 5.7: *Waveform data from event on 10 March 10 2017 at 16:41 UTC, 4.9NBER, 4.8WEMS, located at 72.898N, 4.546E, Mohns Ridge in the Norwegian Sea. The T-waves are marked with ET toward the later part of the seismograms.*

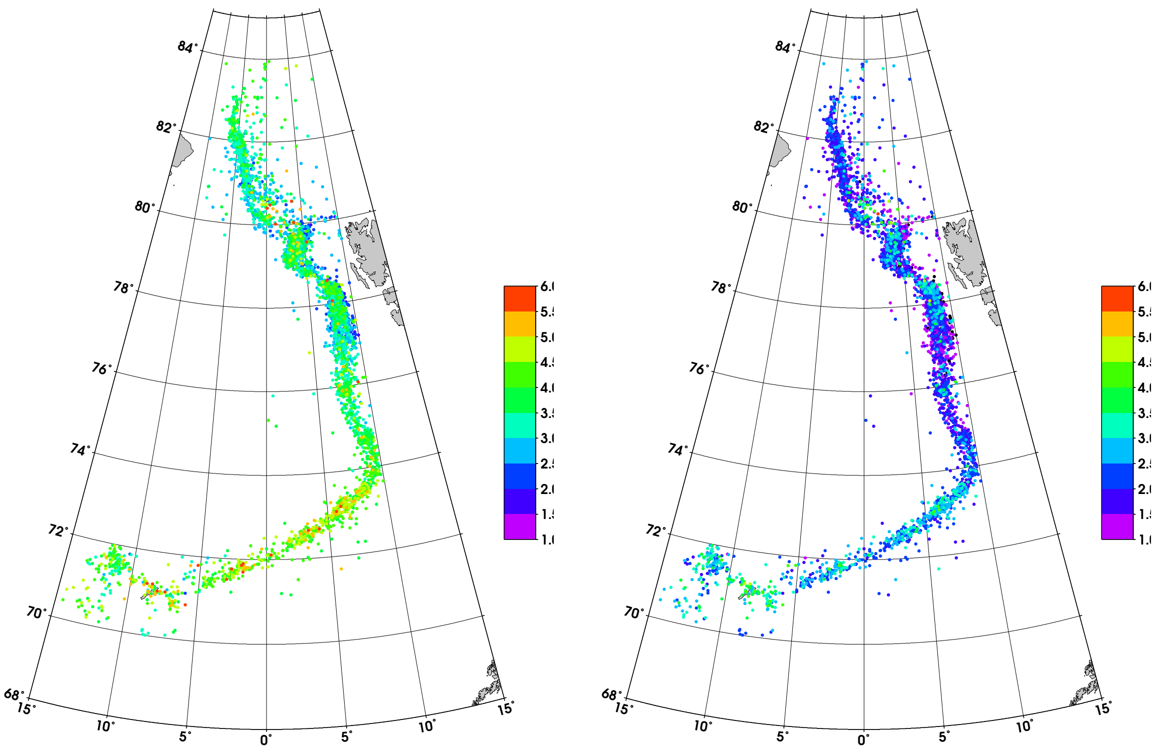

Figure 5.8: *Comparison of magnitudes for events between 1990 and 2017 in the North Atlantic. The map on the left shows the mb(sn) magnitude while the map on the right shows ML results that have been the default in the NNSN catalogue until now.*

to interfere constructively or destructively, seen as horizontal bands in the spectrograms (Figure 5.9, bottom). The ripple fired explosions are generally quite easy to identify, with some extreme cases of very clear bands.

Single charge explosions are also carried out at land or sea. For these, the energy is more evenly distributed over frequency, and they can look more like earthquakes. In some cases clear distinction from earthquakes is not possible and location (in relation to mining quarries), time of day and magnitude have to be considered in addition. However, many earthquakes are more evenly distributed over frequency and scattered S-wave energy, in particular, is seen at higher frequencies than is the case for explosions (Figure 5.9, top).

5.1.4 Seismicity Database

The NNSN maintains a database that contains local, regional and teleseismic earthquakes all in a consistent structure including historic and instrumental times. For 2017, the database contains more than 8500 local and regional earthquakes and just over 1000 teleseismic earthquakes (Figure 5.10). The yearly number of teleseismic earthquakes has been quite consistent since 2000, while local/regional event numbers have increased since 2011 (Figure 5.10). This event increase is explained by a change in the detection routine (that has resulted in a reduced detection level in the North Atlantic region), an increase in and improvement of the number of seismic stations (also in Arctic areas) and some earthquake sequences that present an actual increase in seismicity.

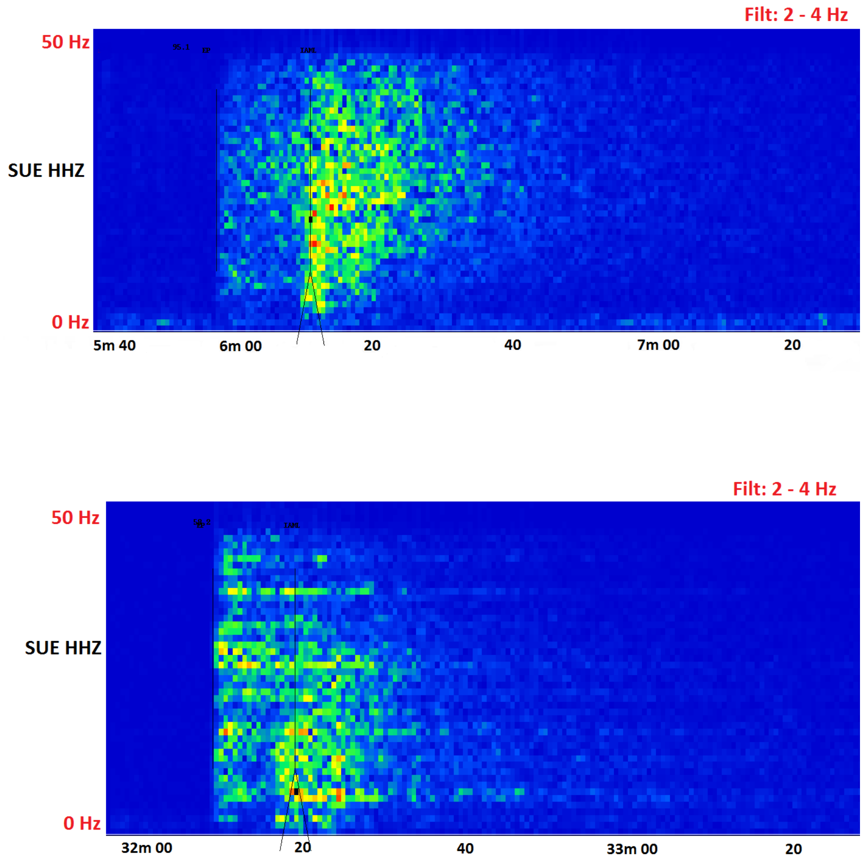

Figure 5.9: *Spectrogram comparison. Top: Probable earthquake in western Norway, station SUE Z-component, 2 min duration, ML 1.2, 95 km distance to epicentre. Bottom: Probable explosion in western Norway, station SUE Z-component, 2 minutes duration, ML 1.4, 58 km distance to epicentre.*

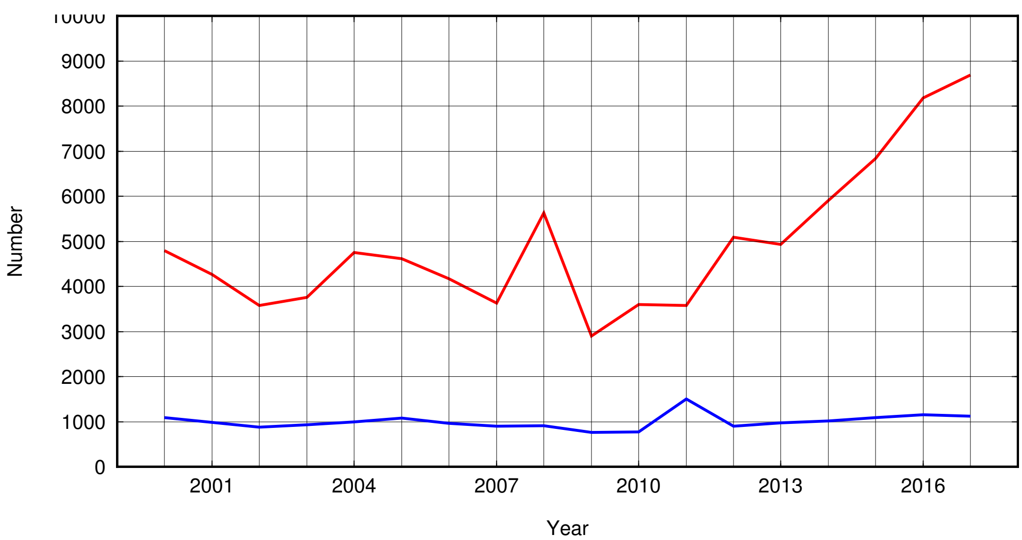

Figure 5.10: *Number of local/regional (red) and teleseismic (blue) events recorded in the NNSN database since 2000.*

Local and Regional Events

The seismicity at the regional scale is dominated by the earthquake activity along the Mid-Atlantic ridge and Jan Mayen fracture zone where earthquakes up to magnitude 7 occur (Figure 5.11). It is possible that these earthquakes are felt on Svalbard and Jan Mayen, but the risk from them is largely negligible, with the exception of Jan Mayen where minor damage has been reported in the past. The activity to the east of the ridge is of intraplate origin. Earthquakes are detected in most parts of Norway onshore. However, it is the coastal areas in northern Norway and south-western Norway that are most active (Figure 5.11). Earthquake monitoring is of particular importance for the companies extracting hydrocarbons in the North Sea, where moderate size earthquakes have occurred. The North Sea activity is considered to be mostly of tectonic origin, with the exception of an induced event in 2001 (*Ottemöller et al.*, 2005). The main characteristics of the earthquakes in Norway were presented by *Bungum et al.* (1991) and *Bungum et al.* (2010). A major earthquake sequence started in the Storfjorden area of the Svalbard archipelago in 2008 with the occurrence of a magnitude ML=6.1 earthquake (*Pirli et al.*, 2010). More than 25 moderate size earthquakes have occurred since then, and the activity still continues in 2018.

Teleseismic Events

The yearly number of teleseismic earthquakes processed by the NNSN is about 1000. Since 1990, the database contains 14,667 teleseismic earthquakes with 198,606 travel time readings that have been reported to the ISC. The distribution of shallow earthquakes and their travel times are given in Figure 5.12. This shows that direct phases (up to about 90 degrees) are recorded from regions as far as away as South America and Indonesia. Core phases are observed from the South Pacific in areas around Kermadec Islands, Fiji, Tonga etc., and in the South Atlantic (Figure 5.12).

Data Availability

Both waveform and parametric data from the NNSN are openly available. The web-portal for recent earthquake information is `http://www.skjelv.no`. Near real-time waveform data can be obtained from a seedlink server at UiB upon request. The continuous and event based waveform data are available from the following ftp server `ftp://ftp.geo.uib.no/pub/seismo/DATA`, while the macroseismic data can be looked at through the Midop interface at `http://nnsn.geo.uib.no/link_6_00b.shtml`. Data access will improve in the near future through the development of an EPOS-Norway data portal.

5.1.5 Acknowledgements

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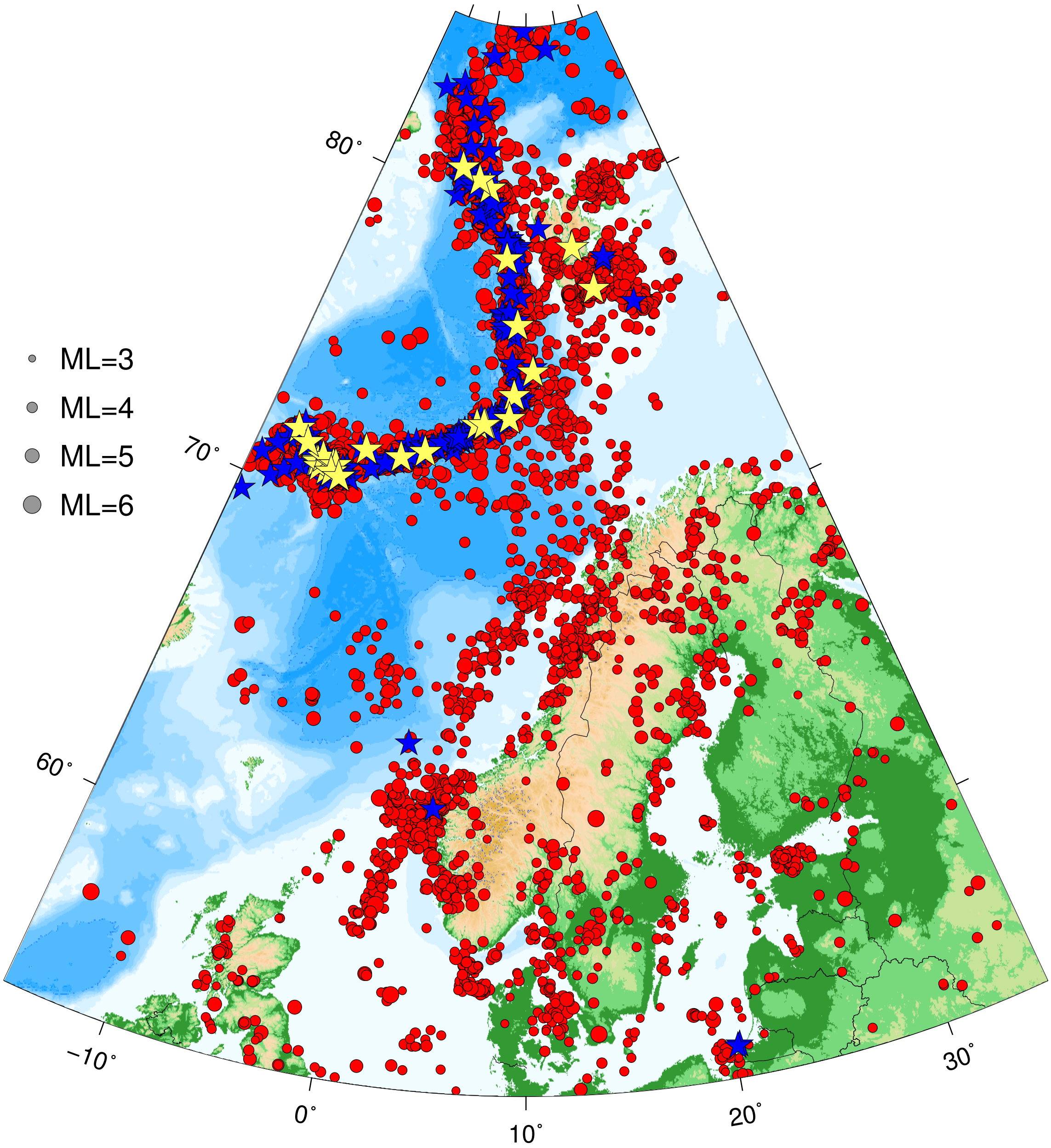

Figure 5.11: Seismicity of local events ML ≥ 2.5, located by the NNSN from January 1980 to 2017. Confirmed and probable explosions are excluded.

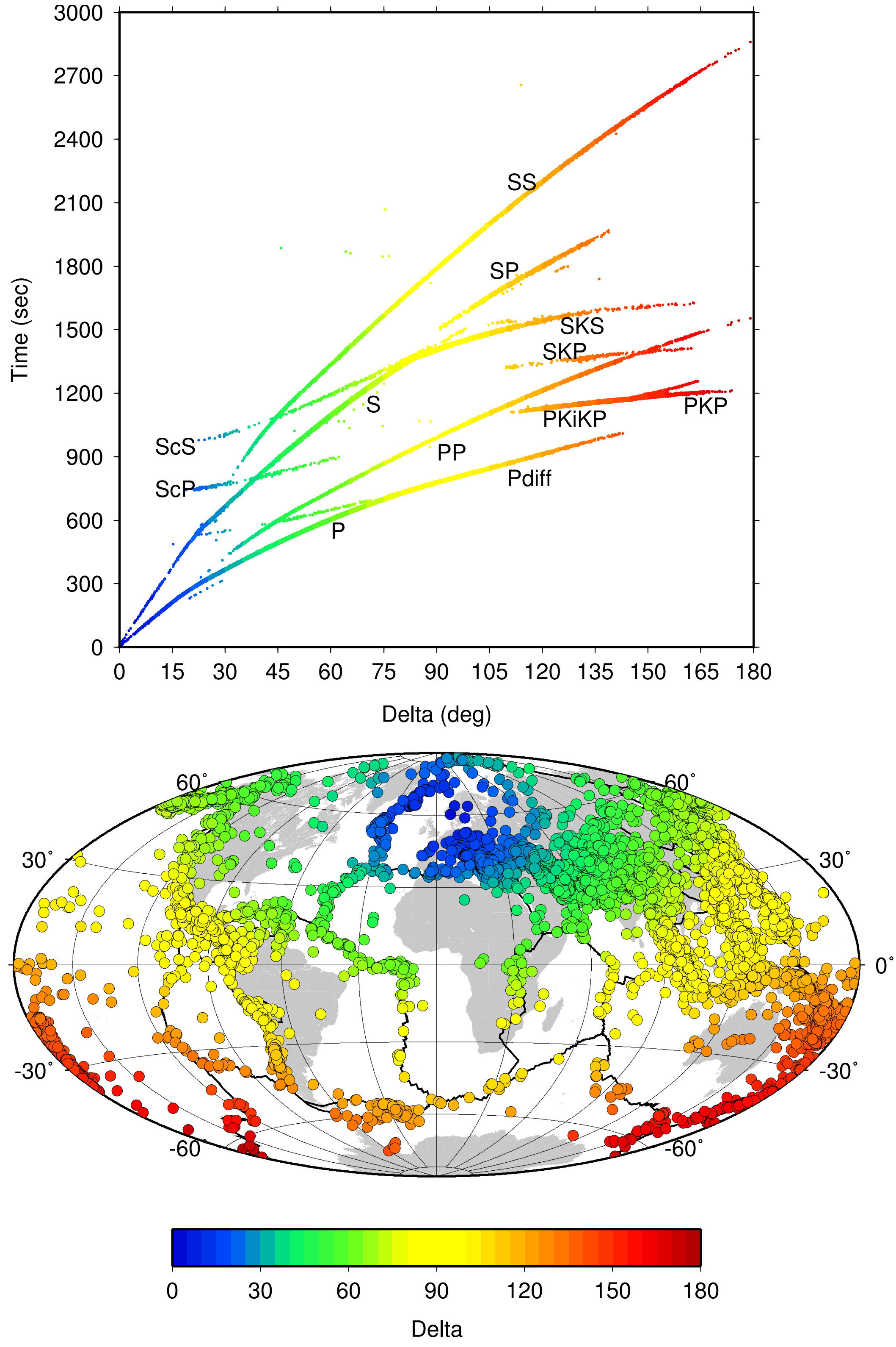

Figure 5.12: *Travel times and locations of shallow (0-60 km) teleseismic earthquakes in the NNSN database between 1990 and 2017. Top: Travel time observations, colour code gives distance from observing stations. Bottom: Location of earthquakes for which travel times are shown, distance from Bergen is colour coded.*

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