Relation between seismicity and tectonic structures offshore and onshore Nordland, northern Norway

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A temporary network of 27 seismic stations was deployed from August 2013 to May 2016 along the coast of Nordland, northern Norway, where northwestern Europe's largest earthquake of magnitude 5.8 over the last two centuries has occurred. The NEONOR2 project aimed to improve our understanding of neotectonic movements, stress regime and the overall seismicity pattern in Nordland and the adjacent offshore areas. From the data retrieved from the temporary NEONOR2 deployment and the permanent stations of the Norwegian National Seismic Network, nearly 1250 earthquakes were located in the study area. During the monitoring period, the seismic activity in Nordland was mostly sporadic, but in some areas it was clearly episodic, especially to the west of the Svartisen glacier where an earthquake swarm with several hundred small seismic events was recorded from April 2015 until March 2016. The shallow swarm activity could possibly be partly related to the changes in the glacier mass and groundwater conditions. During the monitoring period, no earthquakes were recorded along the prominent Bivrost transfer zone, on the Trøndelag Platform and in the larger Vestfjorden Basin area, and it could therefore be concluded that these areas are aseismic; however, only three years of monitoring in such areas of low deformation rates is not enough to make strict conclusions. The observed lack of seismicity in the area generally confirmed earlier observations, though in this case with much more improved new data. The observations onshore provided clear indications of seismic activity along several previously unknown structures and well-defined lineaments trending NE–SW and NNW–SSE to the southwest of Svartisen, while a migration of the seismicity on some of these features was also recorded.

Keywords: seismicity in Nordland; earthquake swarm; magnitude of completeness; Bivrost transfer zone; offshore structures

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Introduction

The territory of Nordland with adjacent offshore regions is one of the seismically most active areas in Norway. Although the majority of the earthquakes are never felt, the Nordland region is capable of releasing larger earthquakes; and the largest known historical earthquake during the last two centuries in northwestern Europe with a magnitude of about M 5.8 occurred in 1819 in the Rana area (Muir-Wood, 1989; Bungum & Olesen, 2005). Another important feature of the seismicity in Nordland is that of earthquake swarms which generally

occur along the coast (e.g., Atakan et al., 1994; Hicks et al., 2000a; Bungum et al., 2010). Moreover, it was reported that the territory of Nordland exhibits features of neotectonic movements (Dehls & Olesen, 2000), which together with the seismicity have been related to stress generation from the ridge push of the Atlantic Ocean, the post-glacial rebound, and the sediment redistribution and topography (e.g., Olesen et al., 2013a). In addition, the geological settings in Nordland are very complex: the Caledonian nappes are folded down to 5 km deep (Midtun, 1988; Olesen et al., 2002), intrusive igneous bodies, such as the Transscandinavian Igneous Belt (e.g., Gaal & Gorbatshev, 1987; Henkel & Eriksson,

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1987; Larson & Berglund, 1992; Hogdahl et al., 2004), are located onshore, while the Moho depth varies from less than 20 km offshore to the west to more than 45 km onshore to the east with a convex Moho bulge under the Lofoten–Vesterålen region (Olesen et al., 2002; Maystrenko et al., 2017). As earthquakes generally occur along pre-existing zones of weakness and result from a buildup of stress and/or reduced effective shear strength along favourably oriented faults (e.g., Davis & Reynolds, 1996), all the factors mentioned above could influence the stress field and may have an effect on the tectonic structures, which are abundant in the Nordland area. In spite of many efforts (e.g., Muir-Wood, 2000; Fejerskov & Lindholm, 2000; Redfield & Osmundsen, 2015; Fjeldskaar et al., 2000), the relative contribution of the different stress components to the overall stress field in the area is not yet fully resolved. The NEONOR2 project (Neotectonics in Nordland - Implications for petroleum exploration; <https://www.ngu.no/en/neonor2>) in 2013–2017 aimed to improve the understanding of regional-scale stress and strain dynamics in the Nordland area through a detailed monitoring of seismicity, geodetic movements and the state of in situ stress. The first step in solving the fundamental questions is through understanding the overall distribution of seismicity in the region and its possible association with the main geological and tectonic features. This paper aims to investigate the relation between earthquakes and tectonic structures in the Nordland area, both onshore and offshore, based on the up-to-date seismological data obtained during the NEONOR2 project from August 2013 to May 2016. The results will subsequently be used in the 3-D numerical modelling to correlate these observations with the denudation and depositional history in order to estimate the Pleistocene palaeo-stresses and thermal fields in 3-D.

Tectonic structures

The bedrock geology of mainland Nordland is dominated by rocks of the Caledonian Upper and Uppermost Allochthons that were thrust onto lower nappe complexes and the subjacent Precambrian basement during the Scandian continent-continent collision in Silurian and Devonian time (Roberts & Gee, 1985). In the Devonian, the nappes were dismembered by a late gravity collapse phase of the Scandian orogeny (Rykkelid & Andresen, 1994; Braathen et al., 2002; Eide et al., 2002).

The offshore area of Nordland (Fig. 1) consists of the northern Trøndelag Platform, the Træna, Vestfjorden, Ribban and Røst basins, and the Nordland, Lofoten and Utrøst ridges (Blystad et al., 1995). A major tectonic structure/zone in the area is the Bivrost Lineament (Blystad et al., 1995) that was interpreted to represent a late-Caledonian detachment reactivated as a transfer zone (i.e., the Bivrost transfer zone, BTZ) during the

subsequent rifting events (Olesen et al., 2002). The BTZ seems to divide the Precambrian rocks to the northeast from the Caledonian fold belt to the southwest. The Nesna Shear Zone (NSZ) on the mainland is the major extensional detachment that disrupted the Caledonian nappes (Braathen et al., 2002; Eide et al., 2002), while offshore to the west of Træna island, the NSZ sharply changes direction from N–S to E–W. The BTZ has most likely reactivated the NSZ or an échelon detachment parallel to the NSZ (Olesen et al., 2002). Slightly to the south of Svartisen, Gabrielsen et al. (2002) indicated two major fault trends: one group aligned NE–SW direction and the other group trending NW–SE. The NW–SE trend coincides well with the seismological observations by Hicks et al. (2000a), while Midtun (1988) reported minor offsets along the NE–SW-trending fracture zones.

Close to the Steigen area lies the Sagfjord Shear Zone (SSZ) that also formed during the gravity collapse of the Caledonide Orogen (Braathen et al., 2002). In the Lofoten and Vestfjorden areas there are two sets of lineaments trending ENE–WSW and NE–SW (Gabrielsen et al., 2002), while the Vestfjorden Basin (Blystad et al., 1995) is expressed as two half-grabens with opposing fault throw, i.e., polarity (Olesen et al., 2002). The southwestern half-graben is about 8 km deep and limited by the East Lofoten Border Fault to the northwest (Bergh et al., 2007), while the easternmost subbasin is 2–3 km deep and bordered by the Hamarøya fault to the southeast (Olesen et al., 2002). Along the Grønna fault, to the west of Bodø, there is a small, 1–2 km deep basin (Brekke et al., 1992; Olesen et al., 2002).

Offshore, the most important bathymetric features are the continental shelf edge and the Vestfjorden–Trænadjupeŧ trough. The shelf edge is characterised by sharp changes in crustal structure and depth. For instance, the boundary between the Utrøst Ridge and the Røst Basin exposes significant changes in crustal thickness and is marked by south-to-westerly dipping faults (Mjelde et al., 1992).

Closer to the shelf edge, the Nordland Ridge represents a Mesozoic flexural structure dipping northwestward underneath the Træna Basin with few basement faults. Around the Træna Basin, the sedimentary Naust–Kai formation, which occurs in the southwestern area of offshore Nordland, reaches its maximum thickness of 1.5 km (Dowdeswell et al., 2010). The Træna island, which is closer to the coast, lies just on the assumed junction of the NSZ and the BTZ. To the south of Trænadjupeŧ lies the Trænabanken; a shallow plateau of Quaternary age. Trænadjupeŧ marks the offshore southwestern limit of the erosion path of the paleo-ice stream drainage during the last glaciation when the glacial deposits had been transported from the coastal and mainland areas towards the shelf edge (Ottesen et al., 2005).

Figure 1. Map of the study area of Nordland: temporary (black triangles) and permanent (red triangles) seismic stations and earthquakes (yellow disks) recorded during the NEONOR2 project from August 2013 to May 2016. Tectonic structures and sites: COB – Continent-Ocean Boundary; BTZ – Bivrost transfer zone, which is a broad transition zone rather than a particular structure (darker blue area); ELBF – East Lofoten Border Fault; GF – Grønna fault; HB – Helgeland Basin; HF – Hamarøya Fault; HG – Hel Graben; M – Meløy; MR – Mo i Rana; NR – Nordland Ridge; UH – Utgard High; NSZ – Nesna Shear Zone; RB – Røst Basin; RIB – Ribban Basin; SSZ – Sagfjord Shear Zone; ST – Steigen; SV – Svartisen; TB – Træna Basin; TI – Træna Island; TD – Trænadjupe; UR – Utrøst Ridge; VB – Vestfjorden Basin (Blystad et al., 1995; Olesen et al., 2002). Small purple dots show historical seismicity from the FENCAT catalogue which is primarily based on the NNSN and NORSAR locations.

Historical seismicity of Nordland: single earthquakes and earthquake swarms

Before 2013, the earthquake monitoring had revealed that seismic activity in Nordland is persistent with many of the earthquakes reaching up to magnitude M 3.0, while the seismicity pattern is significantly uneven in both space and time (e.g., Bungum & Husebye, 1979; Hicks et al., 2000a). The observations also indicated that the seismicity offshore and onshore is different in character (Bungum et al., 1991; Hicks et al., 2000b). The first active attempt to study the seismicity in Nordland was carried out during the NEONOR1 project (Dehls & Olesen, 1998) in 1997–2000, and was focused mainly on the Mo i Rana region. From the collected data, Hicks et al. (2000a) concluded that the majority of earthquakes occurred along the coast between 66° and 68°N, and were generally shallow (2 to 12 km deep), i.e., within

the upper crystalline crust (Bungum et al., 1991). Hicks et al. (2000a) also showed that the onshore earthquakes around Mo i Rana occurred along well-defined lineaments with a tendency to migrate with time.

Byrkjeland et al. (2000) concluded that the oceanic crust is mostly aseismic apart from areas that have experienced a rapid glacial loading (e.g., east of the Lofoten basin), while offshore the most pronounced seismically active feature is the passive continental margin (Hicks et al., 2000a) with relatively deep earthquakes, 15 km and deeper (Hicks et al., 2000b). Flexure due to erosion and unloading may also be an important factor on the Nordland shelf (Olesen et al., 2013a). Olesen et al. (2013b) stated that flexural loading of the offshore basins due to high sedimentation rates during the Pleistocene, represents a stress source that can explain a part of the offshore seismicity (e.g., in the outer part of the Mid-Norwegian shelf and the central axis of the North Sea).

They also concluded that substantial sediment erosion must have led to a significant onshore exhumation and isostatic rebound, thus triggering the earthquakes along the coast.

An important feature of Nordland is that of earthquake swarms that occurred in Meløy in 1978–1979 (Bungum & Husebye, 1979; Bungum et al., 1979, 1982) and Steigen in 1992 (Atakan et al., 1994). The swarms, isolated in both time and space, were thoroughly studied (e.g., Bungum et al., 2010). The Meløy earthquake sequence revealed shallow (3 to 9 km deep), mostly normal-faulting earthquakes which migrated along a N–S trend (Bungum & Husebye, 1979), while Gabrielsen & Ramberg (1979) concluded that the swarm occurred along the NNE–SSW-striking oblique-slip fault or fault zone with a dominant dip-slip motion presumably combined with a right-lateral slip offset. The Steigen earthquake swarm was also found to be shallow (Atakan et al., 1994). The relatively shallow earthquake foci that were observed in both earthquake swarms seem to prevail as a common feature of the coastal onshore seismicity in Nordland.

The seismic network and data analysis

In order to monitor the seismic activity in Nordland, a temporary network of 27 broad-band seismic sensors was deployed from August 2013 to May 2016 (Fig. 1). The seismic events were located using data from both the temporary NEONOR2 deployment and the permanent stations of the Norwegian National Seismological Network (NNSN, Fig. 1), as well as other relevant stations from the neighbouring seismological networks.

The primary event analysis was conducted at the University of Bergen (UiB) as a part of their daily data processing using the SEISAN software package (Ottemoller et al., 2016) and using the STA/LTA detection method that requires at least three stations to locate the event. The automatically obtained phase picks and event locations were reviewed by analysts. The final event locations were obtained at NORSAR using the HYPOCENTER program (Lienert & Havskov, 1995) under the SEISAN program package.

In the event location a velocity model is playing an essential role. Due to the complex geology in Nordland, finding an appropriate velocity model is very challenging. We attempted to establish a 3-D velocity model, but it turned out to be too complicated and also not convincing in terms of reliable results. Thus, to locate the earthquakes we used a 1-D velocity model with 6 layers of constant velocities and the Moho depth at 31 km (Table 1), as its robustness has been demonstrated over a long period of time at the UiB. Knowing that offshore farther to the west the Moho depth is less than 20 km and onshore to the east it is more than 40 km deep, the

used 1-D model with the Moho depth at 31 km is thus approximately an average for the study area.

We also attempted to improve the locations using different 1-D velocity models for the onshore and offshore areas. For the selected onshore and offshore events we applied the 1-D velocity models with the Moho depth set to 25 km for the offshore areas and to 35 km for the onshore areas, while other model parameters were kept as shown in Table 1. The results showed that in many cases the location uncertainties have been slightly reduced; however, there were also cases where the uncertainties were slightly increased. In order to avoid complications in the uncertainties (as different models introduce different errors) we decided to present the results obtained with a single velocity model (Table 1).

In the final event location there is always an element of uncertainty due to the robustness of the 1-D velocity models, phase picking errors, and etc., that cannot be eliminated. The higher location uncertainty is usually associated with the larger seismic gap, and this was also the case in our study. An average seismic gap for the onshore earthquakes was about 140 degrees whereas for the offshore earthquakes it was about 270 degrees (as the seismic stations are located onshore, Fig. 1). Consequently, the location and depth uncertainties are generally also higher for the offshore events. Onshore, the average location uncertainty in the horizontal direction was about 7.5 km and with 6.5 km uncertainty in depth, and offshore the uncertainties were about 30 km and 15 km, respectively.

The local magnitudes, M_L , were computed based on instrument-corrected ground amplitudes and by applying the M_L scale of Alsaker et al. (1991):

$$M_L = \log(A) + 0.91 * \log(D) + 0.00087 * D - 1.67, \quad (1)$$

where A is the instrument-corrected ground amplitude in nm, and D is the hypocentre distance in km.

The origin of the seismic events was determined by analysts at the UiB using the waveforms, spectrograms

Table 1. The 1-D velocity model used at the UiB to locate the local seismic events in the Nordland area.

No.	Depth [km]	Velocity [km/s]
1	<12	6.2
2	12–23	6.6
3	23–31	7.1
4	31–50	8.05
5	50–80	8.25
6	>80	8.5

and first-motion polarities, and location information, as well as reports provided by witnesses in the cases of felt earthquakes, and quarries in the cases of quarry blasting. The detected unwanted man-made seismic events were removed from the final earthquake catalogue. Regardless of the analysts' efforts, the time-of-the-day distribution of origin times of the seismic events showed that the catalogue could still possibly contain some man-made events (up to 4% of the total dataset), which is very unfortunate. As the aim of this study was to define all possible sources of natural seismicity, this possible catalogue 'contamination' was accepted since stricter explosion filtering criteria would have certainly removed some of the real earthquakes. Therefore, the earthquake catalogue was considered to be appropriate for further analysis.

Results

During the NEONOR2 monitoring period, from August 2013 to May 2016, the local seismic network recorded 1242 seismic events which were recognised as earthquakes, including an earthquake swarm which occurred to the west of the Svartisen glacier (Fig. 1). The new data are significantly better spatially resolved compared to earlier data. However, an inherent location uncertainty, which is higher offshore and lower onshore, prevented a precise association of the earthquakes with specific faults. Nevertheless, the new dataset emphasised and revealed some new seismicity features around the region.

Figure 2. Time-normalised Gutenberg-Richter relations for the NNSN seismic catalogues obtained for year 2000–2013 (full circles) and during the NEONOR2 project (empty circles), while the bold and thin lines show approximate linear trends for the two catalogues (where the catalogues are considered complete), respectively. The catalogue obtained during the NEONOR2 project is complete for the events with magnitudes $M \geq 1.0$, compared to the $M 1.8$ before the project.

Improved detectability and completeness of the seismic catalogue

Deployment of 27 temporary NEONOR2 seismic sensors in Nordland significantly improved station coverage in the area (Fig. 1) and lowered the magnitude detection thresholds. The comparison between data recorded before and during the NEONOR2 project revealed that the overall magnitude of completeness was lowered from about $M 1.8$ to 1.0 (Fig. 2). Earthquakes of low magnitudes ($M \leq 1.0$), which form the major part of the dataset, were generally recorded by most of the stations of the local network, while many onshore events of $M > 1.0$ were detected by the entire network, and the stronger earthquakes ($M > 1.5$) were recorded also by the stations outside the study area (Fig. 3).

The earthquake detectability was improved in both the onshore and the offshore areas, especially in the close vicinity of the stations. Onshore, the weakest detected earthquakes were of $M -0.4$, while offshore the weakest detected earthquakes were of $M 1.2$ in the northern part of the continental shelf (north of Trænadjupet) and $M 1.5$ in the southern part of the shelf (south of Trænadjupet) (Fig. 4).

Earthquake distribution

The new seismicity map confirmed the previously observed uneven distribution of seismicity in Nordland and the adjacent offshore areas (Fig. 1), but in more detail. Regionally, it was puzzling to observe the quantitative difference in the number of earthquakes for the areas north and south of the BTZ: higher activity on the northern side compared to the south, while farther to the north of Lofoten the seismic activity seemed to decline again.

During the monitoring period, the most seismically active area in Nordland was to the west of the Svartisen glacier (Fig. 1). Another seismically active area was around Steigen. In contrast, no earthquakes were located in the Vestfjorden area, along the BTZ and in the large Helgeland Basin area, and just a few earthquakes occurred to the south of Mo i Rana. An absence of seismic activity in the Vestfjorden zone was also reported during earlier monitoring; however, it was previously assumed that the earthquakes (if they occur here) are too weak to be detected by the sparse permanent seismic network. The NEONOR2 data implied that the Vestfjorden area might be practically aseismic compared with its surroundings, but the monitoring period of only nearly 3 years is too short to make reliable conclusions in the areas with slow deformation rates.

In contrast to the silent Vestfjorden Basin, the seismicity was pronounced along the coastline from Trærna in the south to Steigen in the north. It is remarkable that the

Figure 3. Magnitude of events in relation to the number of stations used in the location of each event. There were around 30 stations in operation in the study area during the NEONOR2 project. The majority of the dataset consists of weak (up to M 1.0) earthquakes, which were recorded by the closest seismic stations, while the stronger earthquakes were recorded also outside the local network.

Figure 4. Spatial distribution of earthquake magnitudes. The earthquakes with $M > 2.0$ were plotted on top. Onshore, the smallest recorded earthquakes were of magnitude M -0.4, while offshore the smallest earthquakes were of M 1.2 to the north of Trænadjupet and M 1.5 to the south of Trænadjupet due to a greater distance from the seismic network deployed on land. Inset: Distribution of magnitudes compared to the total number of earthquakes.

Figure 5. Depth distribution of earthquakes in Nordland and along indicated profiles: S0–S1 across the shelf edge, Trænadjupet and the area to the south of Svartisen; M0–M1 across the shelf edge, the Vestfjorden zone and the area to the north of Svartisen; and N0–N1 across the shelf edge, Lofoten and the Steigen area. The study revealed a general tendency for mainly deeper earthquakes (about 20 km deep) to occur offshore, whereas both shallow and deeper earthquakes are located along the coastline, e.g., 0–3 km deep around the Træna Island and 12–20 km deep along the northeastern part of the Grønna fault. Onshore, the depth of the earthquakes varies; around Svartisen and Steigen the earthquakes are mostly shallow (3–8 km deep) and under the Lofotens somewhat deeper (down to 15 km).

seismicity followed the coastline without penetrating farther into the onshore or offshore regions, with an exception just to the southwest of Svartisen. Also, some earthquakes followed the Lofoten archipelago, which is also an area where man-made explosions (mostly due to road construction) might have perturbed the dataset, so full credibility to this observation cannot be given. Farther offshore along the continental shelf some stronger earthquakes up to M 3.0 were detected, confirming earlier observations.

In Nordland, several areas of earthquake clustering have been distinguished (Figs. 1 & 4). At the northern end of the Nordland Ridge, an earthquake cluster with relatively high magnitude seemed to form an E–W-elongated distribution (however, this elongation might be a product of the location errors as the seismic network lies to the east and northeast) in an area dominated by structures trending NNE–SSW (Fig. 1). Another small and shallow cluster (Fig. 5) was observed around the Træna island closer to the shore. Whereas the Ribban and Røst basins appeared to have very low seismicity, the Utrøst Ridge, which lies in between the two basins, exhibited a quite pronounced earthquake activity.

The onshore area around Svartisen exhibited the highest concentration of microseismicity that showed clustering in time (i.e., swarm activity, Fig. 6) and in some cases the microseismicity possibly migrated along structures that have not been mapped as active faults earlier (Fig. 7B, C). The observed swarm activity showed similar features

to the earlier known earthquake swarms in Meløy and Steigen.

An interesting observation in the new data was that there were somewhat larger earthquakes recorded following the Grønna fault, about 30 km northwest of Meløy (Fig. 1). To the north, the Grønna fault passes into the boundary between the coastal mountains and the Vestfjorden sedimentary basin, and the new data showed that the seismicity followed this structure.

Magnitude distribution

The local magnitude range of the recorded 1242 earthquakes was from M -0.4 to 3.2 with the majority of the dataset, i.e., 72%, up to M 1.0, 20% of the dataset between M 1.0 and 1.5, and nine earthquakes with M > 2.5 (Fig. 4). The strongest earthquake of M 3.2 recorded during the monitoring period occurred at the beginning of the swarm activity (end of April 2015) to the west of Svartisen, together with several M > 2.7 events close by. Due to the lower detection threshold, even very small earthquakes (down to M -0.4) were recorded onshore, while only stronger (M ≥ 1.2) earthquakes were recorded in the offshore areas (Fig. 4). The detection threshold magnitude for the offshore earthquakes to the north of Trænadjupet was M 1.2, while to the south of Trænadjupet the threshold was M 1.5. Along the continental shelf several earthquakes were recorded with magnitudes M ≥ 2.5.

Figure 6. (A) Number of earthquakes recorded per month by the local seismic network. (B) Magnitude vs. time distribution of the earthquakes. A significant increase in a number of recorded earthquakes in April 2015 was related to the earthquake swarm activity which occurred to the west of Svartisen. The earthquake swarm lasted almost a year with a diminishing intensity and mostly weak seismic events (up to $M 1.0$).

Depth distribution

An estimation of hypocentre depth is one of the most crucial tasks. However, this is quite challenging, especially for the offshore earthquakes which occur farther away from the monitoring network. The depth uncertainties are, therefore, higher for the offshore events compared to the onshore events, i.e., 15 km and 6.5 km, respectively. The analysis of distribution of the hypocentre depth (Fig. 5) revealed a general tendency for shallower seismic events onshore and deeper offshore Nordland. The profile crossing the Trnadjupet bathymetric depression and area to the south of Svartisen (S0–S1 in Fig. 5) indicated that the majority of earthquakes onshore, including Trna island, occurred in the uppermost 8 km of the Earth's crust, whereas offshore closer to the shelf edge earthquakes occurred in the lower crust at about 25 km depth. The profiles farther to the north (M0–M1 and N0–N1 in Fig.

5) did not reveal such an obvious difference between the hypocentre depths onshore and offshore, however, it was noticed that the majority of offshore earthquakes mostly occurred deeper than 15 km. Within this depth range there were also observed earthquakes around the Grnna fault, while in the adjacent onshore area the earthquakes occurred in the uppermost 10 km of the crust. Farther inland, both shallow and deeper earthquakes were recorded. Earlier monitoring data indicated that around the Lofotens the earthquakes tended to be deeper (mostly more than 10 km), a feature which was also confirmed in our study (N0–N1 in Fig. 5).

Time distribution of the seismicity

We distinguished three periods of increased seismic activity in Nordland: from August 2013 to May 2014,

Figure 7. The spatio-temporal distribution of earthquakes including swarm activity in specified areas of Nordland: (A) in the entire area of Nordland; (B) to the west and south of the Svartisen glacier; (C) the earthquake swarm area to the west of Svartisen. The black frames show enlargements in the indicated areas. The black lines indicate clear lineaments recognised in the seismicity distribution. The two lineaments in (C) occurred during short time periods and provided data showing that seismicity migrated from northwest to southeast.

from June 2014 to March 2015, and from April 2015 to May 2016 (Figs. 6 & 7). The seismic activity was persistent and significant during the entire NEONOR2 project period around Svartisen and along the continental shelf; however, along the shelf fewer earthquakes were recorded compared to the onshore areas. It is important to note that in some parts of Nordland the earthquake

occurrence was clearly episodic, and we therefore distinguished several groups/clusters that were active over short time periods. In late 2013–early 2014 for about three months there was a burst of activity around the Træna island (Fig. 7A), while slightly later, in mid-2014, an enhanced activity was recorded for a couple of months around the Nordland Ridge, south of the Trænadjupet,

and in late-2015 there was a burst of seismicity around Steigen following a period of silence. However, the most significant activity was the earthquake swarm at the western foot of Svartisen with several hundreds of earthquakes that continued from April 2015 to around March 2016 (Fig. 7B, C).

Discussion

An overriding feature observed in the well-mapped offshore regions (e.g., Blystad et al., 1995) of Nordland was that the earthquakes were consistently located in the upper and lower crust close to the mapped faults or fault systems, while in the onshore coastal regions, where the crust is also strongly deformed, the earthquakes mostly followed the old structures.

Lineaments southwest of Svartisen

The seismicity to the southwest of Svartisen was not only persistent during the entire monitoring period, but also the earthquakes were clustering or migrating along linear trends, which may be interpreted as active tectonic lineaments or faults (Fig. 7B). In particular, two significant NW–SE-trending lines of earthquakes (Fig. 7C) were active only during short time periods, and there was also a tendency for the activity to migrate laterally along the lines from northwest to southeast. Farther to the south, there were indications of several potential lineaments trending mostly NW–SE (Fig. 7B), which is consistent with some of the fault trends recognised by Gabrielsen et al. (2002). This area was earlier studied by Hicks et al. (2000a) who also reported on the microseismicity following lines of mostly NW–SE trend and migrating with time. Thus, the observed seismicity has confirmed the migration and lineation trends that were first recognised by Hicks et al. (2000a). However, some lineaments were active during the entire monitoring period (Fig. 7B).

The Lurøy area, adjacent to Ranafjorden, where the most intense shaking from the historical earthquake of M 5.8 in 1819 was reported (Muir-Wood, 1989; Bungum & Olesen, 2005), still exhibits high levels of seismic activity (Figs. 7A & 8). Since the temporary NEONOR2 network was located north of Mo i Rana, the detection threshold was higher farther to the south; however, the network was capable of detecting the earthquakes in those areas. The fact that only a handful of earthquakes were recorded to the south of Mo i Rana is indicative that seismic activity to the south is indeed much lower than to the north of Ranafjorden.

West of Svartisen

The area just at the western foot of the Svartisen glacier exhibited a persistent and time-varying seismic activity (Figs. 7B, C & 8). One of the most interesting features in the new data was an observed earthquake swarm which occurred in this area from April 2015 to about March 2016. In the first half of the NEONOR2 project (i.e., before the swarm), only the northern part of the area was seismically active, but activity expanded farther to the south with the onset of the swarm activity (Fig. 7A). The earthquake swarm started in April 2015 with several stronger $M > 2$ events, while the strongest earthquake of M 3.2 occurred at the end of April (Fig. 6). During the peak activity, April to August 2015, there were recorded on average 80 earthquakes per month. Since then the swarm activity has continued and gradually decreased until the spring of 2016 with the earthquake epicentres scattered all over the area, but mostly in the southern part. The swarm events were generally weak, mostly up to M 1.0 (Fig. 6B) and shallow, 3 to 8 km deep (Fig. 5), which is very similar to the earlier observations of earthquake swarms in Nordland, close to Meløy (e.g., Bungum & Husebye, 1979) and Steigen (Atakan et al., 1994). Although some faint trends in the seismicity could be observed, from the earthquake distribution alone it was not possible to associate the earthquakes with the specific tectonic faults and lineaments mapped by Gabrielsen et al. (2002).

The earthquake swarm area is located to the west of the c. 1000 m high mountain plateau hosting the Svartisen glacier. Pascal & Cloetingh (2009) showed that the topography of southern Norway is to some degree controlling the orientation of in situ rock stress, which may also be the case for the Nordland region, although the altitude of the mountains is lower compared to southern Norway. On the other hand, the mountains in Nordland are situated close to the coast, thus the increased rock stress from the coastal topography may be sufficient to trigger/influence earthquakes along the zones of weakness. We also want to emphasise that the swarm area is located north of where the NSZ possibly changes its direction and merges offshore with the BTZ; thus, the area could host a complex network of faults.

The earthquakes recorded to the west of Svartisen are mostly shallow, and the cause of the earthquake occurrence in this area is not well understood. However, there is a hypothesis that the increased activity around the Svartisen glacier could be related to the glacier itself (i.e., yearly variations of ice growth or melting). Studies of the Svartisen glacier (Nesje & Dahl, 2000) showed several kilometres of glacier advancement of its western margin during the Little Ice Age in the 18th and 19th centuries, whereas the major retreats of its western border have been reported during the 20th century (Paul & Andreassen, 2009; Haug et al., 2009). The fact that the earthquake swarm started in April and peaked in early

summer could be related to changes in the groundwater from snowmelt, which is common at that time of the year. Local observations from drilling (Kurt Brandtzæg Jensen, pers. comm.) showed that the rock quality in large parts of the Svartisen massif is extremely poor with creeks penetrating the rock interior through large open cracks and fissures that would allow the meltwater to rapidly flow to the periphery of the Svartisen massif. The poor rock quality could be most likely related to fracturing, karstification and weathering (Olesen et al., 2013b). Therefore, we concluded that water penetration into the existing faults and yearly variations in the glacier mass might have influenced the earthquake activity in this area. In contrast to its periphery, no earthquakes were recorded under the Svartisen ice sheet itself. This phenomenon is still not well understood, even though similar situations have been observed in the vicinity of other ice sheets and glaciers (e.g., in Greenland, Voss et al., 2007).

Southeast of Svartisen

A scattered cluster of seismic events was recorded to the southeast of Svartisen. The area is populated with quarries and earthquakes occur here too; thus, it might be difficult to distinguish earthquakes from the man-made explosions, especially if no quarry reports are available. Reports from the Rana iron ore mine in Storforshei to the east of Svartisen show high horizontal stresses (Myrvang, 1993), and the rock quality is similarly poor as in the area to the west of Svartisen, a feature which may here also promote shallow earthquake activity related to meltwater flow. In addition, the seismic activity coincides with rapid changes in the depth to the Precambrian basement along the NSZ (Fig. 8).

Steigen area

The level of seismicity around Steigen, which hosted an earthquake swarm in 1992 (Atakan et al., 1994), was not particularly high during the NEONOR2 monitoring period, except for a small group of earthquakes in mid-2015 (Fig. 7A). The earthquake activity occurred inside the spoon-shaped Sagfjord Shear Zone (SSZ), and it might also have occurred close to this structure farther to the southeast (Fig. 1).

Lofoten

Deep structures, even below the Moho boundary, might influence the seismicity in the crust. As Maystrenko et al. (2017) noted, there are two low-velocity zones in Norway: one under the Lofotens and another beneath SW Norway (e.g., Kolstrup et al., 2015), and these zones coincide spatially with the areas of increased seismicity. Therefore, these authors suggested that the velocity

anomalies could be one of the reasons for uplift, and could be partly associated with the earthquake activity in both areas. During the NEONOR2 project in the Lofoten area, mostly scattered and deeper (>15 km) earthquakes were recorded.

Coastline

In the coastal offshore areas the seismicity was higher on the eastern flank of the Vestfjorden Basin, i.e., to the west of Meløy, around the Grønna fault and its southern extension (Fig. 8), whereas the coastal regions south of the mouth of Rana fjord generally showed lower earthquake activity. During the NEONOR2 monitoring period, two earthquakes of M 2.5 and one earthquake of M 3.0 (Fig. 7A) were recorded to the west of Meløy, and as late as December 2016 also an earthquake of M 3.7. The strongest recorded earthquakes in this area of M $\geq$ 3.0 were mostly shallow (3–5 km deep), while a group of relatively deep earthquakes (15–20 km deep) was recorded underneath the shallow (1–2 km deep) half-graben which to the southeast is bordered by the Grønna fault. The wide range of earthquake hypocentres implies that there might be both deep and shallow seismically active tectonic structures in the vicinity of the Grønna fault.

The Vestfjorden Basin

The Vestfjorden area contains Mesozoic basement faults. Although the historical earthquake catalogues reported on a few earthquakes in the area, it cannot be ruled out that these earthquakes could have been mislocated due to the sparse permanent station network. Since there were no events recorded with the dense, temporary, NEONOR2 network, it could therefore be concluded that the Vestfjorden Basin is practically aseismic. However, the three-year monitoring period is too short to make definitive statements. On the other hand, it is very likely that the level of seismicity in the Vestfjorden area is much lower compared with the surroundings.

The Bivrost transfer zone

The offshore extension of the NSZ, which was possibly reactivated as a transfer zone (i.e., the BTZ) between the rifted segments in the Lofoten area to the northeast and the Helgeland and Træna basins to the southwest, was seismically quiet during the NEONOR2 project. Although the BTZ is a geological transition zone, as shown by Maystrenko et al. (2017), it did not appear to be an active earthquake source zone.

Figure 8. Seismicity in the northern Helgeland area. Data sources: Mesozoic sedimentary rocks – IKU (1995), Bugge et al. (2002), and Bøe et al. (2008); Precambrian granitoids – Gustavson & Gjelle (1991), and Gustavson & Blystad (1995); Detachments mainland – Eide et al. (2002); Detachments offshore – Olesen et al. (2002); Faults – IKU (1995), Bugge et al. (2002), Olesen et al. (2002), and Bøe et al. (2008); Basement depth – Olesen et al. (2002). The yellow star depicts the approximate location of the M 5.8 earthquake in 1819. Correlations between seismicity and tectonic-geological boundaries are observed along the Grønna Fault, the eastern flank of the Helgeland Basin and onshore to the north of the Nesna Shear Zone (NSZ). To the west of Svartisen, the earthquake swarm occurred from April 2015 to around March 2016 with several hundreds of weak and shallow seismic events. To the southwest of the earthquake swarm there could be distinguished a NW–SE-trending lineament that changes its orientation to NNW–SSE farther to the south.

Continental shelf edge

On the continental shelf edge, earthquakes occurred sporadically during the entire project period (Fig. 7A). The earthquake distribution was consistent with the earlier observed pattern: relatively deep hypocentres (mostly in the lower crust), and the earthquakes followed the shelf edge with somewhat enhanced activity west of the Røst Basin and with clearly reduced activity south of the BTZ. The Ribban and Røst basins showed relatively sparse seismicity, and the large Trøndelag Platform and the Helgeland Basin also appeared to be practically aseismic (Fig. 1).

At the shelf edge the rapid changes in both the Moho depth and the density of the rocks have earlier been associated with earthquake occurrence (Fejerskov & Lindholm, 2000), while the deeper structures, mapped by Maystrenko et al. (2017), coincide quite well with the earthquake distribution observed at the northern end of the Nordland Ridge/Utrøst High (Fig. 1). This observation confirmed that the earthquake occurrence might be following the old zones of deformation and geological contacts.

Nordland Ridge and Træna island

The new data have confirmed the earlier observed seismicity pattern around the Nordland Ridge. In addition, an earthquake clustering was detected at the northern termination/bending of the Nordland Ridge, east of the Utgard High. This group of earthquakes occurred during a short period in the summer 2014 around the Nordland Ridge with deep hypocentres (about 20 km deep). Another time-space clustering of the earthquakes was observed closer to the coast, around Træna island, where the seismicity peaked in early 2014 but with only shallow hypocentres. These earthquakes coincide well with the mapped faults (IKU, 1995) along the eastern border of the deep Helgeland Basin and the offshore extension of the NSZ (Fig. 8).

Olesen et al. (2013a, b) pointed out that the seismicity in the Træna Basin could be influenced by the thickest unit of the Naust formation and related the earthquakes to loading of the crust, thus following the interpretation of Byrkjeland et al. (2000) for the eastern Lofoten Basin. A small cluster of earthquakes was located c. 30 km to the east of the maximum thickness of the Naust–Kai formation. Taking into account the focal depths, these earthquakes occurred deeper than in the area of the Naust formations.

Conclusions

The enhanced earthquake monitoring in Nordland during the NEONOR2 project improved our knowledge of the seismic conditions in the region. As a result, we obtained a more detailed seismicity map and interpreted the possible relationship between the earthquakes and the tectonic structures in the Nordland area. Our conclusions are the following:

1. During the NEONOR2 project, the magnitude of completeness in the Nordland area was lowered from magnitude M 1.8 to 1.0 onshore. Onshore, the smallest recorded earthquakes were of M -0.4, while offshore the detection threshold was M 1.2 to the north of Trænadjupet and M 1.5 to the south of Trænadjupet.
2. Seismic activity in Nordland was mostly persistent and sporadic (e.g., along the continental shelf edge and around Svartisen), but in some places it was episodic (e.g., around Steigen, the Nordland Ridge and west of Svartisen).
3. The most seismically active area in Nordland during the NEONOR2 project was to the west of Svartisen, where an earthquake swarm was recorded. The shallow swarm activity in this area could be partly associated with changes in the glacier mass and groundwater conditions.
4. During the monitoring period the offshore basins appeared practically aseismic or showed very little seismic activity. No earthquakes were recorded along the Bivrost transfer zone and in the Helgeland and Vestfjorden basins. Consequently, it could be concluded that the Bivrost transfer zone is tectonically quiet, and that the large offshore regions of the Trænabanken and Vestfjorden are very stable, which largely confirm earlier assumptions though with better data compared with the earlier observations. However, the three-year period of enhanced monitoring is too short a time to confirm a complete absence of seismicity in the offshore basins that are characterised by slow deformation rates. Relatively few earthquakes were recorded also north of the Røst Basin, along the continental shelf (west of Vesterålen).
5. The Naust–Kai depocentre could be associated with an area of increased seismic activity. However, the seismicity is possibly controlled by deep crustal inhomogeneities.
6. Seismicity along the coast was clearly less pronounced to the south of Mo i Rana compared to the coastline farther to the north.

7. There was a tendency for generally shallow (3 to 10 km deep) earthquakes to occur onshore and for deeper (15 to 25 km depth) earthquakes to be located offshore.
8. The seismicity was generally observed in the areas with faulted upper and/or lower crust. Offshore, the seismicity mostly appears to be following sharp changes in crustal depth, such as along the continental shelf edge and along the coastline.
9. To the south of Svartisen, the seismicity followed well-defined lineaments trending mostly NE–SW and NNW–SSE. Some of the lineaments were active only for a certain period of time, and there was also a lateral migration of seismicity along them (from northwest to southeast). However, other lineaments and structures remained active during the entire observation period.
10. Except for the Grønna fault and the eastern margin of the Helgeland Basin, it was not possible to associate the offshore earthquakes with specific faults. The pattern of the onshore earthquakes showed a good correlation with the structural trends mapped by Gabrielsen et al. (2002).

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