The Finnish National Seismic Network: Toward Fully Automated Analysis of Low-Magnitude Seismic Events

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Abstract

We present an overview of the seismic networks, products, and services in Finland, northern Europe, and the challenges and opportunities associated with the unique combination of prevailing crystalline bedrock, low natural intraplate seismic background activity, and a high level of anthropogenic seismicity. We introduce national and local seismic networks, explain the databases, analysis tools, and data management concepts, outline the Finnish macroseismic service, and showcase data from the 2017 M 3.3 Liminka earthquake in Ostrobothnia, Finland.

Cite this article as Veikkolainen, T., J. Kortström, T. Vuorinen, I. Salmenperä, T. Luhta, P. Mäntyniemi, G. Hillers, and T. Tiira (2021). The Finnish National Seismic Network: Toward Fully Automated Analysis of Low-Magnitude Seismic Events, *Seismol. Res. Lett.* **XX**, 1–11, doi: 10.1785/0220200352.

Supplemental Material

Introduction

The first serious intent to join the international activities of the new discipline of seismology was proposed at the meeting of the Geographical Society of Finland on 24 May 1902 (Simojoki, 1978). It was only after Finland gained its independence in 1917, however, that these plans were successfully implemented. A seismic station equipped with Mainka seismographs was in operation in the Finnish capital Helsinki from 1924 to the early 1960s. This became the main Finnish contribution to global seismology in the early instrumental era. The International Geophysical Year of 1957–1958 gave an incentive to the deployment of various geophysical instruments in the country, including seismographs (Pirhonen, 1996), which facilitated short-period seismology and the monitoring of local seismic events. The Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) was a major reason behind the establishment of the Institute of Seismology, University of Helsinki (ISUH) in 1961 (Luosto and Hyvönen, 2001). The Finnish seismic array FINES in Sysmä, Central Finland, serves today as one of the 50 global primary monitoring stations of the CTBTO (Coyne *et al.*, 2012). The modern network has improved seismic event detection capabilities on the Finnish territory and adjacent areas, and frequent local network densifications continue to challenge the associated data processing and management facilities.

Current Seismic Networks in Finland

In 2020, the Finnish National Seismic Network (FNSN; network code HE) (Institute of Seismology, University of Helsinki, 1980) consists of 31 permanent seismic stations, including the FINES array. Nine stations are part of the Northern Finland Seismic Network (FN) maintained by the Sodankylä Geophysical Observatory, University of Oulu (Kozlovskaya *et al.*, 2016). Data from these stations are integrated in the daily seismic analysis and research at the National Seismological Data Center at ISUH. One station in the Åland archipelago in southwestern Finland is operated by the Swedish National Seismic Network. Figure 1 shows these stations on a map with earthquakes in Finland and adjacent areas.

Bilateral agreements allow for data exchange from stations close to the Finnish border collected by seismological agencies in the neighboring countries Sweden, Norway, Estonia, and Russia. These data reduce the azimuthal gaps and thus improve the detection and location of the seismic events that occur in Finland. In southern Finland, data from the Estonian network (EE) and in northern Finland data from the Norwegian (NS and NO) (University of Bergen, 1982) and Swedish (UP) (University of Uppsala, 1904) networks are frequently used. EE is operated by the Tallinn University of Technology, NS by the University of Bergen, NO by Norwegian Seismic Array, and UP by Uppsala University. To the east of Finland, data from GEOFON Seismic network (GE) (GEOFON Data Centre, 1993) station PUL and IRIS (IDA) (Scripps Institution of Oceanography, 1986) Network (II) station LVZ are used. Figure 2a shows the azimuthal gap over the region when only the permanent Finnish stations are taken into account. Figure 2b shows the azimuthal gap for the improved situation in which all permanent stations with constant data exchange are considered. Part of data are routinely transferred to the GEOFON waveform archive hosted by GFZ German Research Centre for Geosciences and Observatories and Research Facilities for

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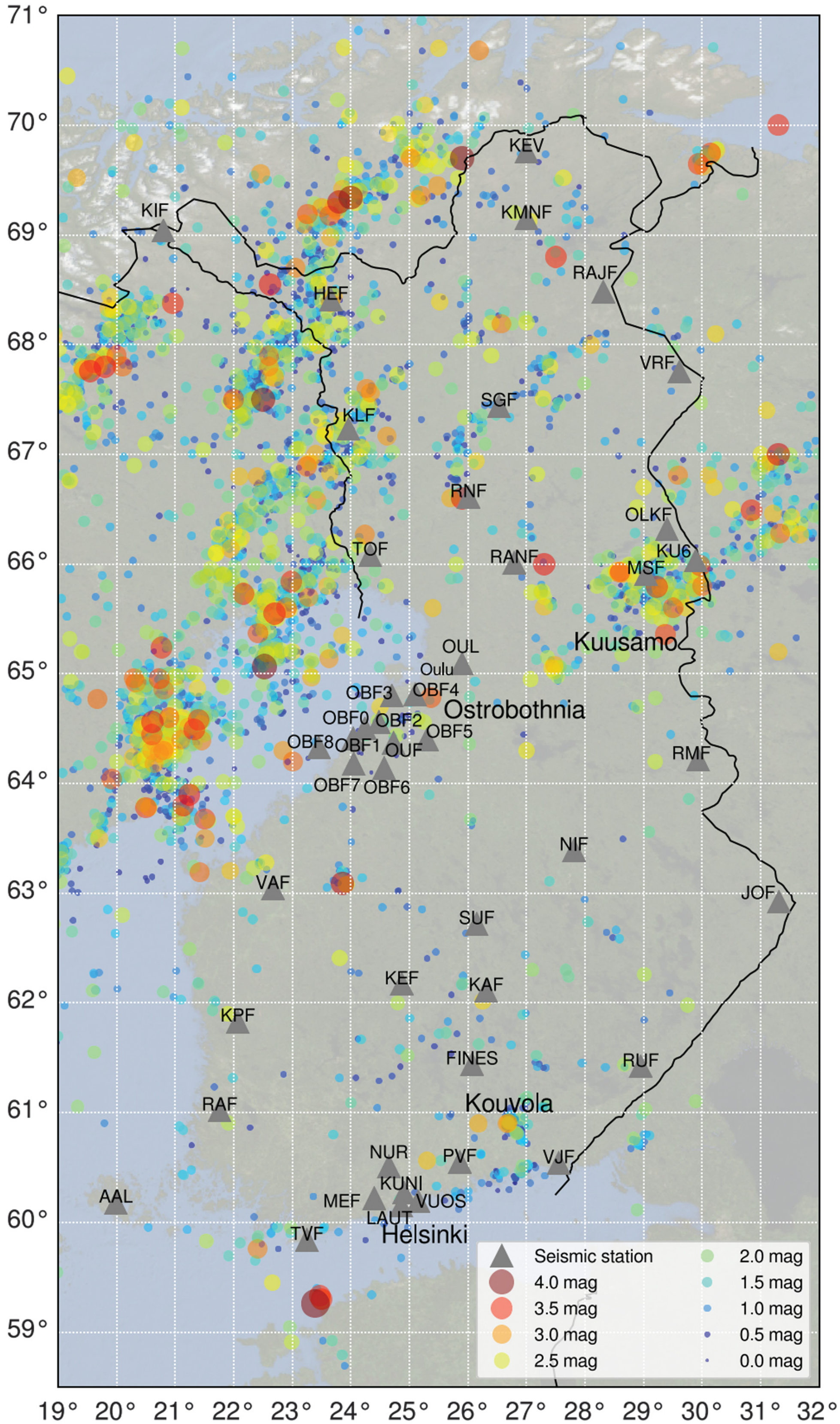


Figure 1. Earthquakes (circle symbols, $M_L \geq 0$) in Finland and adjacent areas on a map with Finnish seismic stations. Color and circle size scale with the magnitude of the event. Symbols are slightly transparent, and for clarity, greater events are plotted with larger symbols. Areas of notable seismic activity (Kouvola and Kuusamo) and those with network densifications (Helsinki and Ostrobothnia) are labeled. Earthquake data derive from the Fennoscandian Earthquake Catalog (FENCAT), covering years 1375–2014, and ISUH seismic bulletins, covering years 2015–2020.

European Seismology. All seismic stations in the HE network are equipped with broadband seismometers. The sensor instrumentation comes from manufacturers Geotech, Güralp, Nanometrics, and Streckeisen, whereas the accompanying digitizers are from Earthdata and Nanometrics.

Finland is situated on the Fennoscandian Shield, where the surface area covers some of the most ancient crust of Earth from Precambrian time (Lehtinen *et al.*, 2005). Most seismic stations have been deployed on bedrock outcrops, and some FN stations such as OLKF (66.321° N, 29.400° E; see Fig. 1) have been installed in boreholes drilled into the bedrock. The seismic waveform data are of high quality, not only because of state-of-the-art instrumentation but also because of the crystalline bedrock and only thin sedimentary layer where it exists (Nironen, 2017; Tiira *et al.*, 2020). In contrast, the geology of Estonia, our southern neighbor, is characterized by a sedimentary layer hundreds of meters thick that increases toward the south (Raukas and Teedumäe, 1997).

Data from all seismic stations fuel research activities, including investigations of postglacial faults, shallow swarm-type seismicity, and properties of induced seismicity. Temporary local seismic networks have been installed for research purposes in the Kuusamo and Kouvola regions, which exhibit a higher level of natural seismicity compared with other parts of the country (Veikkolainen *et al.*, 2017). In addition, a local network of eight stations has been installed to monitor the site of a possible future nuclear power plant in Ostrobothnia, according to regulations of the International Atomic Energy Agency (Vuorinen *et al.*, 2019). Data from the Ostrobothnian deployment have been important for developing a ground-motion prediction equation for Fennoscandia (Fülöp *et al.*, 2020). The areas of notable seismic interest as well as earthquakes of M_L 0.0 and greater are plotted in Figure 1, along with permanent seismic stations in Finland. Probability density functions of power spectral density (McNamara and Buland, 2004) for selected stations show low ambient noise. They are available in Figures S1–S4, available in the supplemental material to this article.

The use of carbon-neutral sources of energy is on the increase in Finland, and geothermal energy is considered to have a lot of potential. A consequence is a new focus on urban areas, which were previously disregarded in seismic monitoring. A semipermanent network of five seismic instruments was deployed around the site of a geothermal heating facility in Espoo in the Helsinki capital region to monitor induced earthquakes and to regulate operation during the stimulations in 2018 and 2020 (Ader *et al.*, 2020). The network was complemented by the temporary deployment of dozens of short-period sensors arranged in different array configurations (Hillers *et al.*, 2020). Data from the temporary networks used in such projects may have restricted data access (Hillers *et al.*, 2019).

Another network consisting of three stations with the same instrumentation as the national network has been established in Helsinki following the initiative of the city of Helsinki. Data from the Helsinki network follow the same standards as the national network. The Helsinki network allows for monitoring seismicity in the Helsinki region with lower detection threshold and better location accuracy than before and is expected to facilitate research on natural and induced seismicity as well as on the numerous explosions associated with infrastructure development in urban areas.

Automatic Seismic Data Classification and Magnitude Determination

In a seismically quiet intraplate region, most seismic events are explosions. Since May 2010, only local events have been processed in the daily analysis of the FNSN, except for events from known nuclear test sites. Events at a distance >1000 km from Oulu, Finland (65.017° N, 25.467° E; see Fig. 1) are regarded as teleseismic events that are not processed in the daily analysis. Oulu has been selected as the reference location because it is located very close to the geographic center of the analysis area.

Until May 2010, teleseismic events were routinely reviewed. As real-time data access and seismic data analyses methods have developed, handpicking data in national data centers was no longer needed for global seismic research. The shift of focus of analyses to local seismology had become possible as the instruments got better and station network denser, providing data on higher frequencies and sufficient network coverage to detect and analyze typically small local events. Detection of large global earthquakes is still implemented in the national natural disaster warning system Luonnononnettomuuksien varoitusjärjestelmä (LUOVA) maintained by ISUH in cooperation with the Finnish Meteorological Institute and the Finnish Environment Institute (Säntti and Kortström, 2010) under the control of the Finnish Ministry of Transport and Communications. No routine analysis of waveform data is carried out in the on-duty LUOVA service except for nuclear tests for which data from the FINES array are used. Waveform data from the FINES array are continuously transferred to the headquarters of the CTBTO using a secured satellite network.

The automatic seismic event classification tool Automaija (Kortström *et al.*, 2016) uses the signal energy distribution of the incoming waveform data to detect seismic events and to distinguish between natural and anthropogenic events. It calculates a preliminary origin time, location, and magnitude for each event. It also analyzes the probability for each event to be an earthquake or explosion and provides timing for identifiable seismic phases. Automaija classifies seismic data into seven different groups:

1. Probable earthquakes
2. Uncertain classification
3. No recognizable station (this previously included events only observed by FINES; this is a legacy category to be removed in future)
4. No classification, small or only observed by FINES

5. Probable explosion
6. Possible explosion at a mining site
7. Probable explosion located at a mining site

For groups 6 and 7, the system relies on an internal database of mining sites in the analysis region. A separate flag is given for events for which the closest operating seismic station is any of the Ostrobothnia network stations. The success rate of Automaija classifications is 94%–97% for all data, as determined subsequently by comparing reviewed daily analysis results with automatic determinations. The rate is slightly better for events with higher magnitudes and larger depths. The daily and weekly distribution of events is utilized to resolve a blasting time window for each mine, and signals not associated with natural earthquakes within this time–space window are interpreted as recurring blasts. Successive explosions with a very small time interval so that signals overlap may be sometimes mistaken for earthquakes in the fully automatic classification process because of misidentification of phases after the first *P*- and *S*-wave picks. For shallow events with assigned fixed depths, more accurate location and depth estimates may be obtained by studying the maximum amplitude ratio of Rayleigh wave *Rg* to *Sg* as done, for example, for swarm-type seismicity in the relatively homogeneous Vyborg rapakivi granite batholith (Uski *et al.*, 2006) in the southeast of Finland.

Calculation of distance and back azimuth to the epicenter is based on travel-time differences of seismic phases and on the ISUH crustal model. For Finnish earthquakes, the automatic procedure usually estimates location, time, and magnitude from waveform data better than depth; therefore in automatic processing, the depth is always fixed to zero. In manual analyses, the depth is fixed if the standard deviation of depth determinations of permanent stations is $>30\%$ of the estimated depth value, if the distance to the closest station is >100 km, or the azimuthal gap is $>180°$. The typically used values for fixed depths are 1, 2, 5, 10, and 15 km. In particular, shallow events with clearly discernible surface waves often fall into this category. Although the FNSN is a relatively sparse network, the locations of its stations have been optimized to keep the azimuthal gap below 90° over most of the territory. The situation is the poorest in eastern Finland (Fig. 2), and data from seismic stations in northwestern Russia do not improve the situation significantly. Although the number of seismic stations in this region is reasonable (Morozov *et al.*, 2019), only the PUL and LVZ stations occasionally provide waveform data for our analysis.

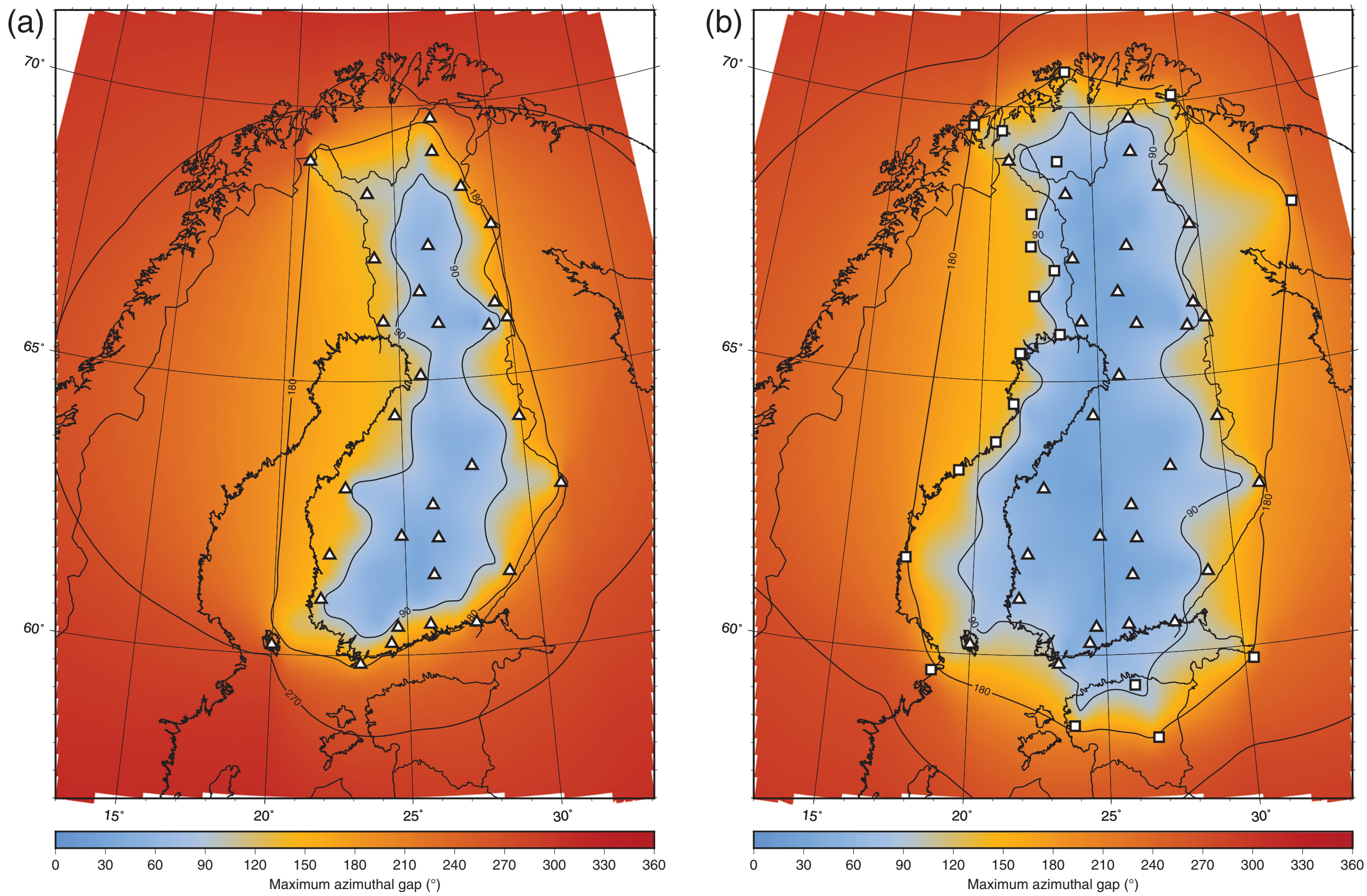
All FNSN seismic stations deliver waveform data in vertical, east-west and north-south components. The magnitude used is the local Helsinki magnitude M_L(HEL) (Uski and Tuppurainen, 1996), which is always calculated from the vertical component. The magnitude was originally estimated using the period and arrival time of *Sg* phases recorded at stations with distances >150 km from the epicenter, but the method has been further developed so that it is valid also for shorter distances.

When M_L(HEL) was introduced in the late 1990s, instruments were mainly short period, operating with a comparatively low sampling rate of 20 Hz. Very sparse near-source data are available from this time. Modern broadband seismometers with a sampling rate of 40–500 Hz have been deployed since then, and the station density of the network increased in tandem, leading to more accurate magnitude estimates.

All individual FNSN stations transmit continuous waveform data to the ISUH servers at a sampling frequency of 100–250 Hz, and all FINES array substations at a frequency of 40 Hz. Data are stored in miniSEED archive format, with event files stored separately in CSS 3.0 format (Anderson *et al.*, 1990). These are further processed using the Geotool software (Henson and Coyne, 1993) in the daily analysis. Seismogram data are produced for visual inspection in three time intervals: 0–8, 8–16, and 16–24 UTC (local time is in the East European Standard Time Zone, UTC+2). These data are updated hourly. The amplitude of the ambient noise in the data typically varies with the atmospheric and weather conditions. Most permanent stations are situated in wind-shielded cabins outside major population centers and away from large water bodies. However, an adequate network geometry means that certain stations are inevitably located close to the Baltic Sea. The detection threshold of the network is M_L 0.9 for the Finnish territory as determined with seismic network simulations using magnitude and maximum detection distance (Tiira *et al.*, 2016). The threshold is significantly lower in areas with network densifications.

In the current ISUH crustal velocity model, the topmost granitic layer spans from surface to 15 km depth and the basaltic layer from 15 to 40 km, which is the Moho depth. *P* and *S* waves refracted from the granitic layer are indicated with *g* (*Pg*, *Sg*), waves refracted from basaltic layer with *b* (*Pb*, *Sb*), and waves refracted from the Moho with *n* (*Pn*, *Sn*). A 3D crustal velocity model is being developed at ISUH and will be implemented in the daily workflow of event determination. The model utilizes results of numerous Finnish structural seismology experiments and tomographic studies (e.g., Kukkonen and Lahtinen, 2006; Hyvönen *et al.*, 2007; Tiira *et al.*, 2020). It is expected to be a significant improvement over the current layer-cake model for providing more accurate location estimates.

In 2018 (2019), the FNSN stations detected 19,431 (20,286) seismic events, of which 421 (371) or 2% (2%), were interpreted as earthquakes. The overwhelming number of seismic events not classified as earthquakes are explosions, mining-induced events, or unidentified events in the classification scheme used by the institute. The increase of detected events from 2018 to 2019 is most likely a result of an improved network that can more easily detect anthropogenic seismic sources, especially in the Finnish capital region. The decrease of the seismic background noise during the societal restrictions of the COVID-19 pandemic was also visible in Helsinki and its vicinity, in line with global trends (Lecocq *et al.*, 2020), albeit in a higher frequency band.



NorDB Database and NorLyst Analysis Tool

Since 2017, the NorDB database has been developed at ISUH to store Nordic format seismic data in a secure and coherent manner. The database runs on PostgreSQL and Python 3 in Unix-based operating systems. It is currently only used internally at ISUH, although it can handle all Nordic format data from other countries as well. NorDB is accessible via command line tool, through which most basic functions are available. The Nordic event table is the most important item in the database, linking one seismological event to all relevant metadata. The Nordic event table also links to a Nordic event root table, which links to all different analyses of the same event. These analyses can include the automatic solution and various analyst-reviewed solutions. This technique ensures that there is no need to delete old records of the event when a new analysis is completed. In addition, all analyses can adhere to a strict hierarchy by comparing their event type.

In the NorDB structure, each seismic event is read from a file contained in a Nordic filename table. New events from the network are automatically fed to the database using a shell script that generates a date and timestamp to a creation information table. Because the script is usually run periodically, creation information may be the same for various events with different origin times. Instrumental data related to each event include information about the number of observing stations,

Figure 2. (a) Map of permanent seismic stations in Finland. Stations of network densifications in Ostrobothnia and Helsinki are excluded. Color scale shows the maximum azimuthal gap of a seismic event recorded by these stations. Because data are transmitted to Finland from nearest stations in neighboring countries as well, the true azimuthal gap in Finnish border regions is smaller than that visible in the map. See (b) for a map with Finnish stations and other stations delivering data to the Institute of Seismology, University of Helsinki (ISUH). (b) Map of permanent seismic stations in Finland (triangles) and adjacent areas (squares) delivering data to ISUH. Stations of network densifications in Ostrobothnia and Helsinki are not shown. Color scale shows the maximum azimuthal gap of a seismic event recorded by these stations. See (a) for a map with Finnish stations only.

azimuthal gap, and minimum distance to a station for all data from the year 2000 and earlier.

Each solution of a seismic event in NorDB is associated with a permanent unique identifier. The same event may have two or more solutions in the database with different solution types. The currently used values of solution type are:

- F (final),
- A (automatic),
- O (other),
- REV (reviewed event), and
- TRASH (duplicates as well as noise and incorrect data).

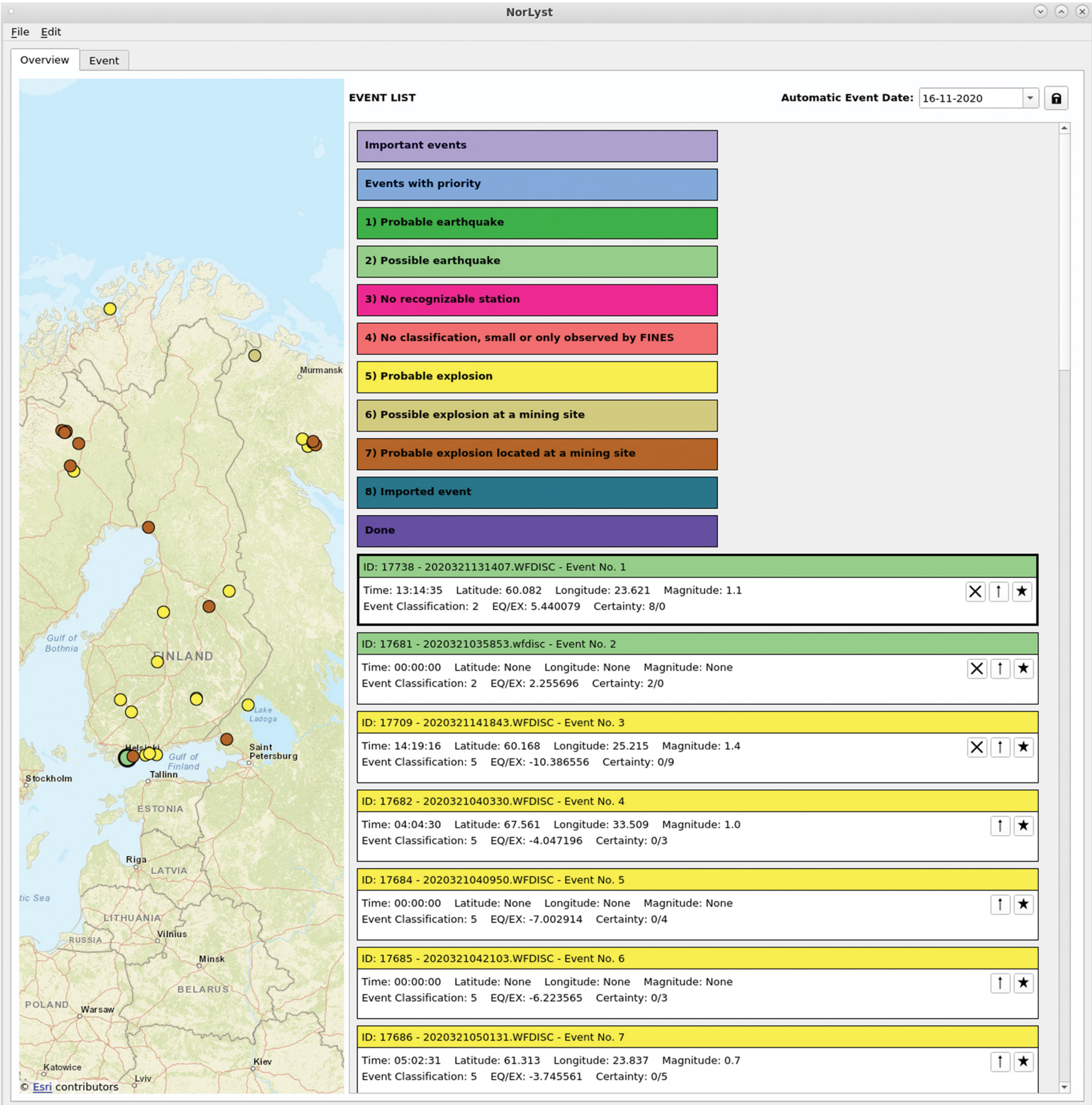
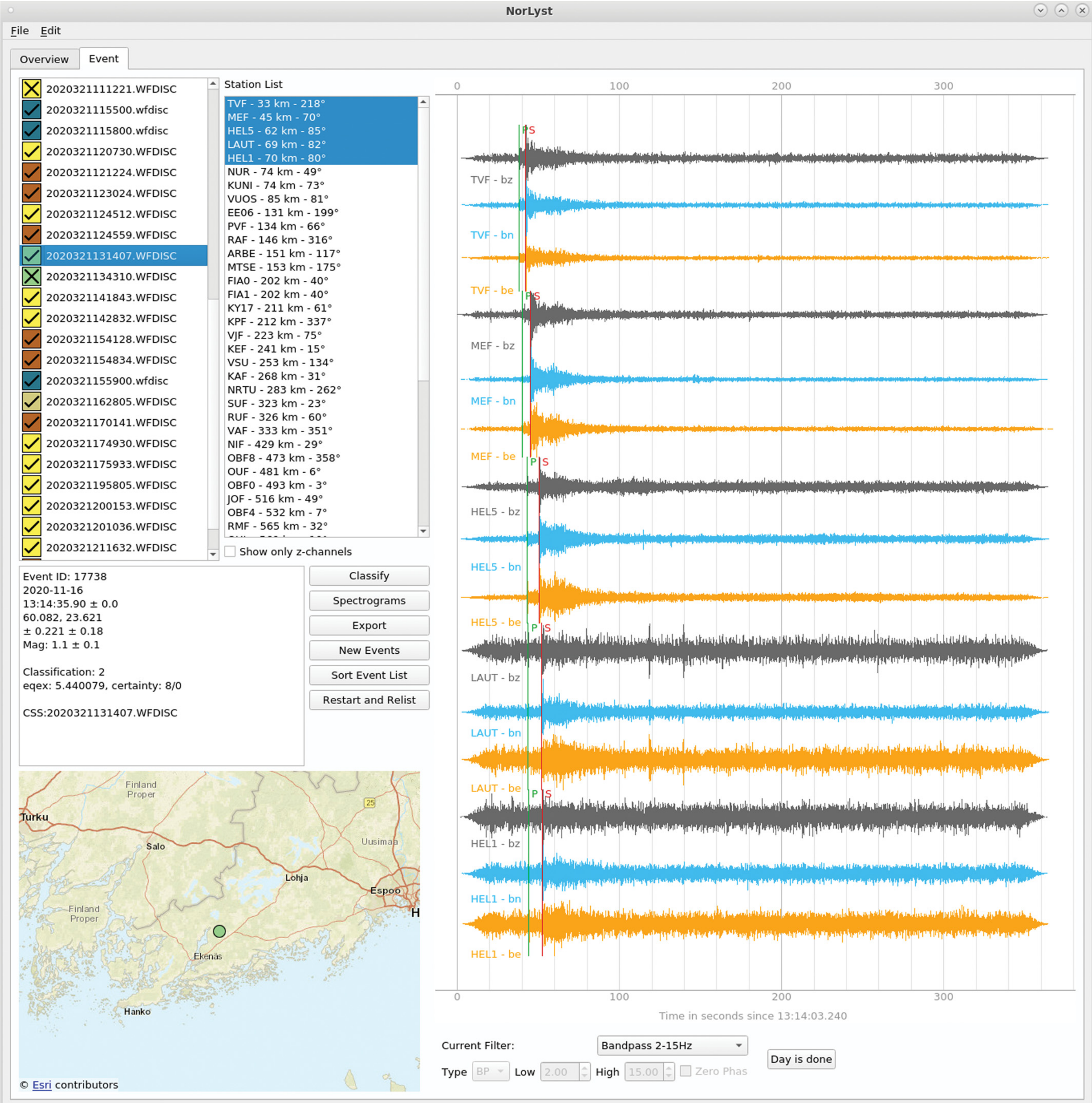


Figure 3. Illustration of a daily event list in the user interface of NorLyst software. Events from Monday, 16 November 2020 are shown here according to the classification scheme. Each event class is associated with a specific color in the list and in the map.

Automatic events (A) are pushed to the database each night and reviewed in the daily analysis. After the analysis of an event, a reviewed solution (REV) is generated, but the automatic solution for the same event is still retained in the database. Final event solutions (F) are generated when seismic bulletins are constructed, but the two other solutions (A) and (REV) are also retained in this situation. The user may also add new solution types to the database. In addition to solution types, solution tags may be added to the database in the future. Tags are intended for distinguishing project data from other data.

The seismic analysis tool NorLyst fetches data from NorDB. It features a graphical user interface based on PyQt5 (Figs. 3 and 4), allowing the user to filter seismograms, view spectra, and carry out other core analysis tasks.

The focus of analysis is nowadays on the verification of automatically detected events rather than picking events manually.



Fully manual analysis is conducted for earthquakes and exceptionally large or otherwise interesting societally relevant seismic events, such as mine collapses or events that could be induced by other engineering activity. In June 2020, the analysts of the institute began using NorLyst for reviewing events that do not require manual picking of seismic phases. Most of these are explosions from mines in Finland and adjacent areas. Geotool is still used for manual picking of seismic phases, and manually analyzed Nordic files are typically imported to NorLyst before the completion of the daily analysis in NorLyst.

The stable version of NorDB runs on a database server at ISUH and automatic backups are generated to a server in a

Figure 4. Illustration of a confirmed earthquake from Raasepori, southern Finland, on 16 November 2020 in the user interface of the NorLyst software. Waveform data and automatic phase picks for stations that have registered the event are available by selecting events in the list. Phase picks are denoted by green and red colors. In the event list, colors are the same as in Figure 3. HEL1 and HEL5 are temporary stations in the Finnish capital region.

remote location once a day. Development of the database continues, and the data structure, which now closely follows the Nordic format, may be updated in the future. For example, the need for calculating more than three magnitudes for a certain event will be considered. Other development targets include the removal of the need for reconfiguring NorDB for a certain user after installing a version update and the direct transfer of macroseismic data to the database.

Macroseismic Observatory Practice in Finland

Macroseismology is an important interface between the seismological community and the general public. The crystalline bedrock and low attenuation of seismic waves make it possible for the local population to observe and experience even low-magnitude seismic events. Since the turn of the 2000s, an online macroseismic questionnaire is maintained on the ISUH website, available in Finnish, Swedish, and English. Submission of an observation automatically transfers it to a spreadsheet file at the server. Seismologists and seismic analysts handle the data according to the General Data Protection Regulation of the European Union. All personal information is removed 30 days after the submission. Prior to this, the observer is contacted upon request. Macroseismic intensity is not assigned to locations routinely because of the low magnitudes, but the observations are classified into categories of "not felt" and "felt" and/or "heard." Larger-magnitude earthquakes can be subjected to specific macroseismic investigations. In the ISUH seismic bulletins, the code "FELT" is used for events observed by citizens.

The online macroseismic data are strongly biased toward positive responses, but they are obtained without any survey launched by seismologists. Combined with the denser networks available today, this means that macroseismic observations can be associated with very small events, far below M_L 1, if they are shallow, and close to population centers. Seismic events observed noninstrumentally in the 2000s include local, regional, and global earthquakes; induced earthquakes; explosions; cryoseisms; and supersonic booms. Providing an accurate reason for the observation has value in situations of sudden confusion and concern by citizens.

In 2019, ISUH received 496 macroseismic observations, 98 of which could be associated with a known earthquake. Other sources were supersonic booms (19 observations), a sewage plant construction site (30), and quarry explosions (75). For 251 observations, no specific source could be identified.

The second important reason behind continued macroseismic activities is comparison with preinstrumental earthquakes. The seismicity record can be extended back in time about three centuries with the help of preinstrumental data (Mäntyniemi, 2017a,b). The time span is sufficient to demonstrate that earthquakes with larger areas of perceptibility have occurred in the past, although they have not occurred during the instrumental era. The Lurøy, Norway, earthquake of 31 August 1819 is an illustrative example (Mäntyniemi *et al.*, 2020).

The 2017 M 3.3 Liminka Earthquake: An Example of Collecting Waveform and Macroseismic Data

Waveform data from all permanent seismic stations in Finland can be conveniently processed using ObsPy modules of the Python language (Krischer *et al.*, 2015). Here, we present an example of handling waveform data from one of the deepest earthquakes in Finland. It occurred in Liminka, northern Ostrobothnia, on 7 December 2017 at 22:32:16.6 UTC (8 December at 00:32:16.6 local time) and was assigned a local magnitude of 3.3. It was the strongest earthquake in Finland since the M_L 3.5 Kuusamo event of 15 September 2000. The Liminka event was located at 64.785° N, 25.370° E, at the boundary of mudstone-dominated lithology in the north and granitoid-dominated lithology in the south. This is 25 km south-southwest of downtown Oulu and 10 km north-northeast of the nearest known surface fault, yet the true distance to this fault may differ because the event was as deep as 32 km as estimated from data of OBF0–OBF8 stations (Vuorinen *et al.*, 2018). See Figures 5 and 6 for details.

As part of the annual reporting of operation and seismic activity in the area monitored by OBF0–OBF8 stations, a fault-plane solution is available for the earthquake. The solution shows a mainly horizontal dislocation along the strike of the fault. The fault plane is nearly vertical and in north-northwest–south-southeast direction (strike 333°, dip 87°, rake −20°). The auxiliary plane (strike 65°, dip 70°, rake 176°) is an unlikely solution considering the local geology. Some uncertainty in the solution is evident because the event was located outside the local network, yet the solution is very similar to solutions for other smaller earthquakes in the same region and is therefore assumed to reflect the general trend of tectonic structures in the area. The similarity to the fault plane of the M_L 1.3 earthquake in Lumijoki on 8 October 2018 is particularly important because the epicentral distance between these two events is only 14 km (Vuorinen *et al.*, 2018). It is possible that the events occurred on the same fault, particularly because the Lumijoki event also was deep, with a focal depth of 28 km. The azimuth, as seen from the Liminka event, also follows the trend of faults in the area. The fault plane of the Lumijoki earthquake strongly resembles that of Liminka event (strike 329°, dip 78°, rake −9°) and of the auxiliary plane (strike 61°, dip 81°, rake −168°).

ISUH received >500 citizen observations of the Liminka earthquake. These are illustrated in Figure 5. The farthest observations were over 240 km from the epicenter. In the vicinity, ground shaking was widely felt (intensities IV, IV–V, and V European Macroseismic Scale-98), but no damage to property was reported. Instrumental data were available from stations at much longer distances. Figure 6 shows waveform data of the Liminka earthquake recorded by the Oulainen (OUF) and

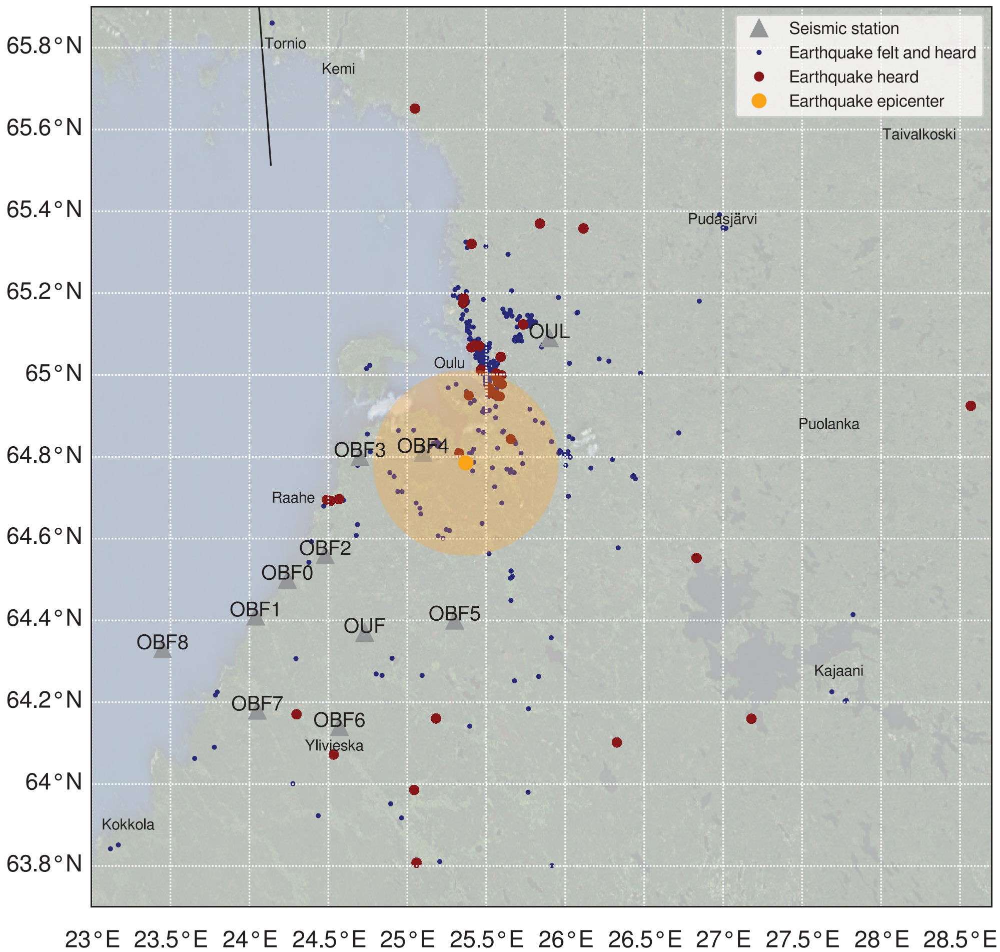


Figure 5. Macroseismic map of the M_L 3.3 Liminka earthquake of 7 December 2017. Small blue dots denote felt observations, and red dots audible ones. The shaded orange circular area has a radius of 25 km around the epicenter, which is marked with a solid orange dot. Seismic stations are denoted by triangle symbols. Locations of the city of Oulu and other remarkable towns are also shown.

Kuusamo (Riekki) (KU6) stations located 56 km and 251 km from the epicenter, respectively. The event was also observed by all OBF stations (Valtonen *et al.*, 2013) that were all located <100 km away from the epicenter with an azimuth range of 187°–284° (south to west-northwest). The azimuthal gap of the event was only 49°, and reliable observations were available from as many as 42 stations, the farthest ones being in Åland (AAL) and Kevo (KEV), at 584 and 560 km distance. This is an exceptionally large number of stations that contributed to the observation of an earthquake in Finland.

Finnish Waveform Data and Online Services in EPOS

Integration of ISUH services to European Plate Observing System (EPOS) is in progress in the framework of the FIN-EPOS (The Finnish Initiative for EPOS) consortium (Korja and Vuorinen, 2016). FIN-EPOS is a consortium of Finnish universities (University of Helsinki, University of Oulu, and Aalto University) and research institutions (Geological Survey of Finland, National Land Survey, Finnish Meteorological Institute, VTT Technical Research Centre of Finland, and CSC - IT Centre for Science) with the core task of maintaining geophysical observatories and laboratories in Finland. In addition to the University of Helsinki, the Sodankylä Geophysical Observatory at the University of Oulu produces and delivers seismic data and services in the FIN-EPOS framework.

EPOS is the pan-European research infrastructure for data in Solid Earth Geophysics, aiming to support a safe and sustainable society. In the Nordic countries, its implementation in the form of Nordic EPOS has been initiated recently, but the history of Nordic co-operation in seismology dates further back. The Nordic Seminars in Seismology have been organized since 1969 in Finland, Sweden, Norway, Denmark, and Iceland to provide an annual forum for interaction and exchange, and Nordic format has been applied for seismic bulletin data since 1985 to allow convenient data transfer. However, QuakeML is the standard seismological data format within EPOS. Tools for data conversion between Nordic and QuakeML formats have been developed at the University of Bergen, Norway (Rønnevik *et al.*, 2019). Using NorDB, the conversion between Nordic files and QuakeML is also possible.

ISUH offers an online map search tool to locate earthquakes from the North European Seismic catalog (Fennoscandian Earthquake Catalog; Ahjos and Uski, 1991). The catalog includes natural seismic events only and therefore excludes induced earthquakes. In the map and search results, all reviewed data from ISUH seismic bulletins are included. Bulletin data marked "preliminary" at the website have undergone the daily analysis workflow and can be used in research but are potentially subject to small updates related to magnitude homogenization and addition of data from partner institutions. No waveform data are provided via this service, but future plans include a browser-based interface of NorLyst for review of seismic event locations without

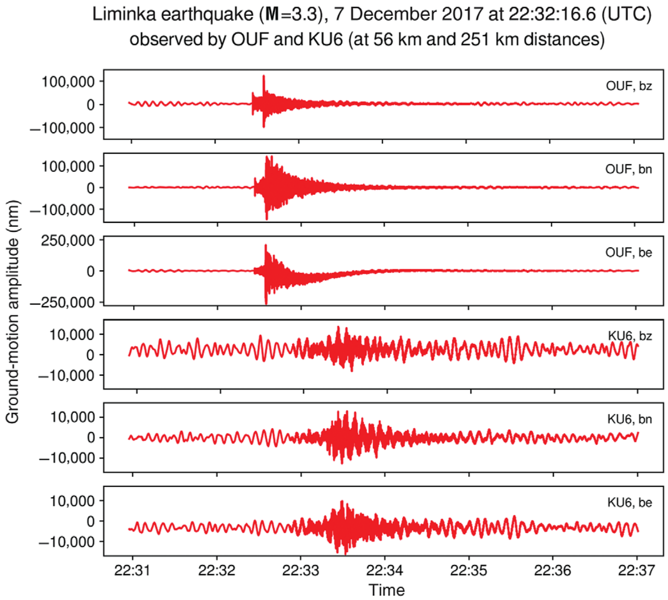


Figure 6. Plotted waveform data of Liminka earthquake as observed by stations in Oulainen (OUF) and Kuusamo (Riekki) (KU6). Vertical axis shows the ground motion amplitude in nanometers and horizontal axis the time in UTC.

the need to install software locally. We also aim at the integration of the online earthquake map to NorDB.

Data and Resources

The Finnish National Seismic Network (HE) is available at doi: 10.14470/UR044600, the University of Bergen Seismic Network (NS) is available at doi: 10.7914/SN/NS, the Swedish National Seismic Network (UP) is available at doi: 10.18159/SNSN, the GEOFON (GFZ) German Research Centre for Geosciences Network (GE) is available at doi: 10.14470/TR560404, and the IRIS (IDA) Seismic Network (II) is available at doi: 10.7914/SN/II. Access https://www.orfeus-eu.org for Observatories and Research Facilities for European Seismology (ORFEUS). Reviewed FNSN seismic bulletin data obtained from the daily analysis are accessible at https://www.seismo.helsinki.fi/bulletin/list/norBull.html. Final bulletins after magnitude homogenization and addition of data from partner institutes are available from 1991 to June 2018 and preliminary bulletins from July 2018 to recent days. Some figures in this article were generated using Generic Mapping Tools (Wessel *et al.*, 2013) and ObsPy (Krischer *et al.*, 2015). The documentation of NorDB is available at https://nordb.readthedocs.io and is subject to changes during the development of the software. Noise levels of seismic stations RMF, PVF, SUF, and VRF were investigated using PQLX software (https://ds.iris.edu/ds/nodes/dmc/software/downloads/pqlx), and resulting power spectral density probability density functions for the period of 1 January to 1 December 2020 are provided in the form of supplemental material (Figs. S1–S4). All websites were last accessed in December 2020.

Declaration of Competing Interests

The authors acknowledge there are no conflicts of interest recorded.

Acknowledgments

The authors thank all contributing to the operation, maintenance, and expansion of seismic networks in Finland and the Academy of Finland (the Finnish initiative for the European Plate Observing System [FIN-EPOS]), Finnish Ministry for Foreign Affairs, the City of Helsinki, and Fennovoima Inc. for funding. The helpful comments and suggestions by Editor-in-Chief Allison Bent, Reviewer Emily Wolin, and an anonymous reviewer were of great value.

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Manuscript received 1 October 2020
Published online 24 February 2021