Geosci. Instrum. Method. Data Syst. Discuss., doi:10.5194/gi-2015-36, 2016
Manuscript under review for journal Geosci. Instrum. Method. Data Syst.
Published: 19 January 2016

Geoscientific Instrumentation Methods and Data Systems
Discussions
Open Access

Seismic observations at the Sodankylä Geophysical Observatory: history, present and the futureitle of the manuscript

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Abstract. Instrumental seismic observations in northern Finland started in 1950's. They were originally initiated by the Institute of Seismology of the University of Helsinki (ISUH), but the staff of the Sodankylä Geophysical Observatory (SGO) and later, geophysicists of the University of Oulu (OU) were involved in development of seismological observations and research in northern Finland from the very beginning. This close cooperation between seismologists and technical staff of ISUH, OU and SGO continued later in a number of significant international projects and enabled a high level of seismological research in Finland. In our paper we present history and present state of seismic observations and seismological research in northern Finland at the OU and the SGO. This includes both seismic observations at permanent seismic stations and temporary seismic experiments by portable seismic equipment. We describe the present seismic instrumentation and major research topics of seismic group at the SGO and discuss the plans for future development of permanent seismological observations and portable seismic instrumentation at the SGO as a part of the EPOS-European Plate Observing System research infrastructure. We also present the research topics of recently organised Laboratory of Applied Seismology of the SGO, show examples of seismic observations performed by new seismic equipment of the Laboratory and selected results of time-lapse seismic body wave travel time tomography using the data of microseismic monitoring in the Pyhäsalmi Mine (northern Finland).

1 Introduction

As described in Luosto (2001), development of seismology in Finland in 20th century comprises several distinct periods. The initial non-instrumental period began already in 19th century, when systematic collecting of data about local seismic events in Finland started at the University of Helsinki. The second period started in 1921 when the first privately financed seismograph station in Helsinki was put in operation. This event marks also beginning of the era of instrumental seismology in Finland.

The next period in development of Finnish seismology started at the end of 1950s and it was motivated by development in seismic instrumentation worldwide. During this period several short period analogue seismograph stations with photo paper registration were founded in Finland, although the instrumentation had not been standardized yet and home-made seismic sensors were used (see Luosto, 2001, for details). These seismographs were capable to record both minor local and teleseismic earthquakes, however.

The forth development period started when World Wide Standard Seismograph Network (WWSSN) was founded and funded by the United States of America at the beginning of the 1960's. Then several Finnish seismic stations were equipped by standard WWSSN short period Benioff and long period Press-Ewing seismometers, network of seismic stations was enhanced and the first efforts were made to transmit analogue signals from remote stations via telephone cables. The Institute of Seismology of the University of Helsinki (ISUH) was established as an independent unit in the 1961. The developments of seismology in Finland at that time was strongly influenced by the huge nuclear explosion tests in Novaya Zemlya (Russia), by the increased activities in geophysical observations in connection with the International Geophysical Year 1957–58 and with the XII General Assembly of International Union of Geodesy and Geophysics held in Helsinki in 1960.

The period of digital seismology and broadband seismometry in Finland started in 1970's-1980's. In 1981 the analogue instrumentation at WWSSN stations in Finland was upgraded to digital data acquisition systems. In the 1970's, engineer Seppo Nurminen started to design digital recorders and transmission systems at the ISUH (Nurminen, 1974, 1976). The same technique was applied in 1980's when constructing three- or five-channel PCM-1218-80 recorders (Nurminen and Hannula, 1981), which were first digital portable field recorders in Europe. Just at the end of the 20th century Nurminen designed a completely new digital seismic recorder, model DAS-98, which runs under the Linux operating system. These recorders were used both in the permanent stations and in temporary field experiments. Until the end of the century almost the entire seismic network in Finland was operating using digital telemetric or dial-up method.

Progress in portable digital recording systems gave a start to controlled source wide-angle reflection and refraction studies in Finland in 1970th-1990th and a large-scale marine deep seismic reflection experiment BABEL in 1989 (Luosto, 1987, 2001, Table 1 and Figure 1). The advanced portable instrumentation provided an opportunity to Finnish geophysicists to participate in a number of international controlled-source seismic experiments (Table 2).

Since 1950's the scientific and technical staff of the SGO and of the geophysical group of the OU was actively involved in the above mentioned observatory activities and seismic projects initiated by the ISUH. As the SGO was founded much earlier than the OU (1914 and 1958, respectively) and was originally operated as an independent research institution, the seismological observations and research at these two organisations were originally developing in parallel, until the SGO became an independent department of the OU in 1997. Nowadays the research based on seismological observations is performed by seismic group located in Oulu (Oulu Unit of SGO) and comprises a significant part of the total scientific output of the SGO.

The main target of our paper is to document the history of seismic observations and research in northern Finland, both at the UO and at the SGO. In the paper we do not repeat the scientific results of seismological studies published elsewhere, but mainly concentrate on such practical things as description of instrumentation, tracing of instruments movement to alternative sites, data formats and data availability, and staff in charge. We also discuss the future of the seismology at the SGO in 21th century that is connected with the newly established Laboratory of Applied Seismology (SEISLAB) and with participation of the seismic group of the SGO in EPOS: European Plate Observing System pan-European research infrastructure for solid Earth geosciences.

2 History of seismic observations in Northern Finland

In 1954, Dr. Eijo Vesanen, who then was a head of the ISUH, proposed to install a seismic station at the SGO. The idea received support from the observatory administration, and the first seismic test measurements at the SGO started on 11.6.1954. The instrument was a copy of the vertical component Sprengnether seismometer made at the Department of Physics of the University of Helsinki (Kataja, 2008). The measurements by the short-period vertical component Benioff seismometer at the SGO site in Tähtelä (station code SOD) started on 28.06.1956. The results showed, however, that the site was not suitable for observatory seismic measurements, because of thick (about 50 m) sand layer. The measurements at Tähtelä site continued using different type of analogue equipment (Table 3) until a new site (station code SDF) was found in Pittittövaara hill near Sodankylä. The seismic sensors were moved to the new site, while connection and communication between sensors and recording system was established using radiolink (Kataja, unpublished memoirs). In 2001 a digital seimic station with new equipment was established at the new site in underground tunnel (station code SGF) (Table 3). The station recorded three-component seismic data with sampling rate of 50 sps in CSS data format (Anderson et al., 1990).

During the 1950's the seismographs at SGO were under the maintenance of the observatory staff. In 1959, the Finnish Academy of Sciences and Letters founded a position of seismologist at the observatory. The position was held by Airi Kataja till 1991. The seismologist was responsible for the maintenance of the seismographs and also for investigations of the seismicity in northern Finland. In 1991 this position was cancelled.

The first seismic measurements in Oulu were initiated by the University of Helsinki and the registration at the Oulu station started on 17.12.1959, soon after the University and its Department of Physics were founded in 1958 and 1959, respectively. Originally, the seismic equipment was installed at the Myllytulli hydroelectric power plant, not far from the centre of Oulu. That temporary station was equipped with Nurmia seismograph made at the University of Helsinki and it was operated by the staff of the Department of Physics of the University of Oulu till autumn, 1960.

In 1963 the Department of Physics founded a new seismic station in quiet site of Aarne Karjalainen Observatory in Huttukylä (about 18 km from Oulu). The land and observatory buildings were donated to the University of Oulu by Mr. Aarne Karjalainen. The new station was equipped with the Benioff seismometer and Geotech Co. helicorder and later, by the short-period vertical Willmore seismometer and long-period vertical Sprengnether seismometer (Table 3). Since 1980 the station was operated at the Ervasti site nearby (the station code was not changed) until the equipment of the station was destroyed by thunderstorm in summer, 1996.

In 1970 the OU founded a new seismic station in Maaselkä site (station code MSF), about 10 km from Kuusamo town in northeastern Finland (Table 3). Digital registration using new type of seismic equipment started at Oulu station (Huttukylä site) in 1999 and in MSF station in 2000 (Table 3) in CSS data format (Anderson et al., 1990) with sampling rate of 50 sps.

The data acquisition system was the same as the system installed in other Finnish permanent stations operated by the ISUH (Luosto, 2001). Continuous data was recorded to the hard disk drive of the station Linux computer and transmitted to the data server located at the OU via telephone lines.

In 1968, the position of seismologist was founded at the OU together with the foundation of the Department of Geophysics. Heikki Korhonen was appointed to the first seismologist at Oulu in 1968 and Jukka Yliniemi followed him in 1977. The position was transferred to the Geophysical Observatory founded in 1985 at the OU. The Sodankylä Geophysical Observatory was united to the University of Oulu in 1997 and the Geophysical Observatory was merged with it in the following year. The position of seismologists was simultaneously moved to the SGO, and Jukka Yliniemi was responsible for seismic measurements at the SGO until 2004, followed by Elena Kozlovskaya.

At first, studies of microseismic ambient noise and local seismicity were the main research branches of seismology in the Oulu University (Korhonen et al., 1980). Since 1980's the geophysicists of the University have participated actively in deep seismic wide-angle reflection and refraction surveys in Finland and abroad (Luosto, 2001, Table 1 and Table 2). As a result, the research direction was changed towards interpretation of controlled source seismic experiment data and lithosphere studies (Yliniemi, 1991, 1992).

3 Northern Finland Seismological Network: seismology in the 21st century

In 2004 it became clear that existing permanent seismic stations of the SGO did not satisfy the requirements of the 21st century seismology. Firstly, they were equipped by the short-period Geotech S-13 seismic sensors, while the majority of seismic network operators in Europe had already changed the equipment to broadband force-balanced seismic sensors. Another problem was that the data of the SGO stations were not open and had been used by the ISUH solely for location of local seismic events. The continuous seismic data was not archived in any international data centre and recordings of teleseismic events were not used in seismological research.

During 2005-2007 the Oulu Unit of the SGO started to modernise its own permanent seismic stations. During this modernisation the short-period seismic instruments were replaced by Streckeisen STS-2 broadband seismometers and existing data acquisition system was replaced by the Earth Data PR6-24 24-bit digitisers and Linux computers with SeisComP seismic data acquisition software (SeisComP Manual, 2006). The agreement was reached with the GeoForschungsZentrum (GFZ) Postdam about archiving and distribution of the seismic data via GFZ Data Archive. A new seismic broadband station in Rovaniemi (station code RNF) with the same type of equipment was established in 2008.

At the moment SGO operates the Northern Finland Seismological Network (network code FN). It is a permanent real-time broadband seismic network consisting of four real-time stations (OUL, MSF, SGF, RNF). The information about stations of the FN network is given in Table 4 and Fig. 2 shows the noise level at these stations in 2014. Two new stations (Oulanka (OLKF) and Kolari (KLF)) were installed during 2014. They are working now in test regime and will be connected to the network after testing. The network is a part of GEOFON Extended Virtual Network - GEVN, of the Virtual European Broadband Seismograph Network (VEBSN) operated by ORFEUS (Observatories and Research Facilities for European

Seismology) and of the global International Federation of Digital Seismograph Network (FDSN). The Oulu Unit of the SGO represents the University of Oulu in the IRIS- Incorporated Research Institutions for Seismology (as a Foreign Affiliate).
The continuous seismic data of the Northern Finland Seismological Network in MiniSeed format (SEED Manual, 2002) is archived in the GFZ Seismological Data Archive of the GeoForschungsZentrum Potsdam (Germany) and at the own archive of the Oulu Unit. Since 2011 the data is archived also in the European ORFEUS Data Centre (www.orfeus-eu.org). The data are used for monitoring of seismic activity in Northern Europe and world-wide and for detection of local and teleseismic events. Information about seismic events is published in several on-line bulletins, including bulletin of seismic events in Fennoscandia by ISUH (http://www.helsinki.fi/geo/seismo/english/bulletins/).

4 Temporary seismic experiments at the SGO

4.1 Seismic wide-angle reflection and refraction experiments

Seismic group of the Sodankylä Geophysical Observatory of the University of Oulu has participated with own resources and equipment in many seismic controlled-source experiments in Finland and abroad (Figure 1, Table 1 and Table 2). The scientific results of these experiments have been published in numerous papers summarized by Luosto (2001) and Grad et al. (2006). During 2001-2005 the seismic group of the SGO participated in the FIRE-Finnish Reflection Experiment carried out by the consortium consisting of the Geological Survey of Finland, the ISUH, Department of Geosciences of the University of Oulu and the SGO. Deep seismic reflection soundings were made along four main transects with a total length of 2104 km in the central and northern parts of the Fennoscandian Shield (Kukkonen and Lahtinen, 2006). The main contractor of the project was Spetsgeofizika S.E. (Russia). The Oulu seismic group and ISUH organised also wide-angle reflection and refraction measurements along FIRE lines using own equipment (Silvennoinen et al., 2010).
The Oulu University is responsible for storing the data of several controlled-sources seismic experiments. In Finland, the ISUH and the Geological Survey of Finland (GSF) are also archiving the data of a number of such experiments.
Originally, the equipment of the seismic group for controlled-source seismic experiments included Willmore vertical seismometers and PCM-1218-80 recorders developed by the ISUH. Since 1996 the equipment consisted of 8 Reftek 72 data loggers (used in cooperation with the Department of Geophysics of OU) and 8 three-component Mark Products L4C seismometers with natural frequency of 2 Hz.

4.2 SVEKALAPKO passive seismic array research

In 1997-1999 the seismic group of the SGO, together with the Department of Geophysics of Oulu University and ISUH, participated in the SVEKALAPKO Deep Seismic Tomography project (Hjelt and Daily, 1996, Bock et al., 2001, Hjelt et al., 2006). The project was a passive seismic array research in southern and central Finland aiming at studying the lithosphere-asthenosphere transition in the suture zone of Proterozoic Svecofennian and Archaean Karelian domains of the Fennoscandian Schield (Fig. 1). The detailed description of experiment, including sites and equipment description is given in Sandoval (2002). The results of the SVEKALAPKO array research changed dramatically the point of view on the strucrure of the mantle lithosphere beneath Finland. Prior to the experiment it was expected that the lithosphere there is thick and the structure of the mantle lithosphere is relatively simple. This opinion was based on world-wide studies of upper mantle xenoliths from Archaean and Proterozoic areas that demonstrated certain correlation between composition of the subcontinental lithospheric mantle (SCLM) and crustal tectonothermal age (see, for example, Griffin et al., 2003). Thus prior to the SVEKALAPKO experiment, higher velocities and lower densities in Archaean domain and lower velocities and higher densities in Proterozoic domain were expected. Instead, inhomogeneous and anisotropic upper mantle beneath the Proterozoic-Archean suture zone has been revealed (Sandoval, 2002, Sandoval et al., 2003, 2004, Bruneton et al., 2002, 2004, Funke and Friedrich, 2003, Yliniemi et al., 2004, Plomerová et al., 2006, Vescey et al., 2007, Kozlovskaya et al., 2008, Pedersen et al., 2006).

4.3 ALPASS: (Alpine Lithosphere and Upper Mantle PASsive Seismic Monitoring) experiment

Leading organisation of the ALPASS project was Institute of Geodesy and Geophysics, Vienna University of Technology, principal investigator Prof. E. Brückl.

ALPASS was a passive seismic monitoring project aiming to reveal lower lithosphere and upper mantle beneath the wider Eastern Alpine region, and to contribute to a better understanding of the geodynamic processes at work. Participating countries were Austria, Croatia, Finland, Hungary, Poland, USA. The seismic group of the SGO participated in the passive seismic experiment in 2005-2006 with own field instruments. In 2009 it participated in data processing and teleseismic tomography studies (Mittelbauer et al., 2011).

4.4 PASSEQ 2006-2007: Passive seismic experiment in Trans European Suture Zone (TESZ)

The main aim of the PASSEQ 2006-2007 passive seismic array experiment was an investigation of the seismic structure of the mantle and lithosphere-asthenosphere boundary in the Trans-European Suture Zone (TESZ) in Central Europe, between young Palaeozoic platform of the Western Europe and Precambrian East European platform (Wilde-Piortko et al., 2007).

The SGO participated in the passive measurements in the territory of Lithuania in 2006-2007 with its own equipment. In 2009 PASSEQ research continued within the project “Investigation of local seismicity in Lithuania using the data of Passive Seismic Experiment PASSEQ 2006-2008” that was carried out by the seismic group of the SGO in collaboration with the University of Vilnius and Geological Survey of Lithuania (Janutyte, 2012). In addition, the seismic group of the SGO provided training in seismology for one PhD student and for one MSc student from the University of Vilnius in the framework of ERASMUS and CIMO programs. The teleseismic P-wave tomography using the PASSEQ 2006-2007 data (Janutyte et al., 2015) showed significant differences in seismic velocity structure beneath the TESZ, young Palaeozoic Western Europe and East European platform.

4.5 POLENET/LAPNET seismic array experiment during the International Polar Year 2007-2009

POLENET/LAPNET (Fig. 1) was a sub-project of the IPY 2007-2009 POLENET consortium related to seismic studies in the Arctic (http://ipydis.org). The main target of the project was to carry out an ambitious temporary broadband seismic array research in northern Fennoscandia (northern parts of Finland, Sweden, Norway and Russian Karelia). The POLENET/LAPNET array, with the average spacing between stations of 70 km, was designed to solve specific tasks of polar seismology. The collected POLENET/LAPNET dataset includes high-frequency continuous data (sampling rate from 50 to 100 sps) of 37 temporary stations, which were in operation during the time frame from 01.05.2008 to 31.09.2009, and of 21 stations of selected permanent networks in Fennoscandia. Most of the stations of the array were equipped with broadband sensors. The data of broadband stations, pre-processed into the standard seismological miniSeed format, are now deposited to the database of FOSFORE Data Centre at the University of Grenoble (France) (RESIF, 2007). The metadata about POLENET/LAPNET stations, their coordinates and instrumentation is also deposited to the database. The backup copy of all continuous data is stored at the SGO. In addition, the data of several short period stations is archived at the SGO and at the Geophysical Centre RAS, Institute of Physics of the Earth RAS, Russia.

The data of the POLENET/LAPNET array have been interpreted by different research groups at the participating institutions, using different techniques. The main results of the POLENET/LAPNET project were published in a number of papers. Plomerová et al. (2011) and Vinnik et al. (2014) estimated seismic anisotropy in the upper mantle beneath the LAPNET study area. Vinnik et al. (in print) estimated variations of S- and P-wave velocities, Vp/Vs ratio and major boundaries in the upper mantle beneath the POLENET/LAPNET array using joint inversion of P- and S- receiver functions. Pedersen et al. (2013) presented results of surface wave studies. Silvennoinen et al. (2014) presented a new map of the Moho boundary for the northern part of Fennoscandia and an upper mantle P-wave velocity model estimated by teleseismic tomography (Silvennoinen et al., 2015). Krasnoshchekov et al. (in print) used the data of the array for studying of the Earth's inner core. For the first time Poli et al. (2012, 2013) used ambient seismic noise recorded in Finland in order to estimate inner structure of the Earth's crust and upper mantle. Usoltseva et al. (2015) presented results of local events studies and Gibbons et al. (2015) used the POLENET/LAPNET array data to investigate propagation of infrasound signals.

4.6 DAFNE- seismic monitoring of postglacial faults and the ICDP drilling project

The Drilling Active Faults in Northern Europe (DAFNE) project (Kukkonen et al., 2010) aims to investigate, via scientific drilling, the tectonic and structural characteristics of postglacial (PG) faults in northern Fennoscandia. During the last stages of the Weichselian glaciation (ca. 9,000 - 15,000 years B.P.), reduced ice load and relaxation of accumulated tectonic stress resulted in rapid uplift in Fennoscandia. Active faulting occurred with fault scarps up to 150 km long and up to 30 m high. Some of these faults show week seismicity even presently. That is why studying of PGFs would create information relevant for proper seismic hazard evaluation and for planning and exploitation of such critical facilities as nuclear waste disposal and underground mines. The main purpose of the DAFNE/FINLAND passive seismic array experiment was to characterize the present-day seismicity of the Suasselkä post-glacial fault (SPGF) that was proposed as one potential target for the DAFNE project. As the fault is located at large distances from permanent stations of regional seismic networks in Fennoscandia, no natural seismicity from the fault was reported previously. In order to check whether the fault is still active, 8 short- period and 4 broad-band 3-component seismic stations were installed in the close vicinity of the fault area in September 2011. During September, 2011-May, 2012 we have collected the data of more than 70000 seismic events (teleseismic, regional and local ones). Recordings of the array have being analyzed manually and automatically, in order to find natural earthquakes from the fault area. The detected events were relocated and spectral characteristics of signals were analyzed, in order to discriminate natural events originating from the fault from both production blasts and mining induced events originating from the Kittilä Gold Mine. As a result, we found several dozens of events originating from the fault area that could be of natural origin. We also found and analysed a number of events originating from the Kittilä Gold Mine that could correspond to rock falls in the areas of production and mine development (Kozlovskaya et al., 2013).

5 Laboratory of Applied Seismology (SEISLAB)

5.1 General target of the Laboratory of Applied Seismology of the SGO

Nowadays it is recognised that the Fennoscandian Shield with resources and proven potential is the most prospective ground in Europe. However there are under-explored geological formations for a number of commodities such as base metals, gold, platinum group metals, iron ore, and diamonds. This requires development of new geophysical methods for investigation of sub-surface structures, in particular, methods capable of mapping 3-D geological structures: metallic and non-metallic ore bodies, faults, fractured zones, overburden, intrusions, fault zones etc. at a depth of several kilometres. In order answer to these new challenges, the seismic group of the SGO decided to upgrade its own portable seismic instrumentation and organise the Laboratory of Applied Seismology (SEISLAB). In addition to the traditional tasks of applied and engineering seismology, the target of the new laboratory is to develop monitoring techniques for mining-induced seismicity and passive seismic interferometry methods for mapping of 3-D geological targets (e.g. fault zones, intrusions, ore bodies). The project was funded by the European Regional Development Fund (ERDF), Council of Oulu region and Pyhäsalmi Mine Oy in April, 2012-January, 2014.

5.2 SEISLAB instrumentation

5.2.1 Portable broadband seismic instruments

The portable broadband equipment consists of 11 Trillium Compact 120 broadband 3-axial seismic sensors (cut-off period of 120 s) manufactured by Nanometrix Ltd. (www.nanometrics.com), 4 Reftek130 24-bit 3-channel portable data loggers (www.trimble.com), 3 Earh Data PR6-24 24-bit 3-channel portable data loggers and 4 ED210 24-bit portable data loggers. Power supply for autonomous operation is provided using Li batteries. The detailed description of each instrument and their technical characteristics are available at the web-pages of correspondent manufacturers.

The portable equipment is used in passive seismic experiments, both in Finland and in Europe (c.f. ALPASS, PASSEQ, POLENET/LAPNET, DAFNE, SEISLAB) for monitoring local earthquakes and mining-induced seismic events and for crustal and lithosphere studies using seismic tomography, receiver functions and ambient noise methods. The equipment can be also used in active source applied geophysics experiments (depth to several km).

5.2.1 Sercel Unite multichannel system

Seismic instrumentation of the laboratory includes also the Sercel Unite multichannel seismic equipment manufactured by Sercel Ltd. (www.sercel.org). The equipment has 40 3-component DSU-SA MEMS sensors and 40 RAUD –eX data acquisition units with internal batteries, totally 120 channels. The field equipment also includes:

1) Wireless data harvester (Tablet PC) with cables for data harvesting and quality control
2) PFT-Portable field terminal for uploading serial numbers of RAU and initiating experiment
3) Portable version of Unite LITE acquisition system with software license for max 150 channels.
4) Special battery charger for 20 RAUD units.

Sercel UNITE system is an autonomous recording system composed of Remote Acquisition Units (RAUex-D) and MEMS based accelerometers within a Digital Sensor Unit (DSU3SA) [SERCEL]. Previously UNITE system has been used in reflection and refraction surveys with active energy sources (Lansley 2008, McWhorter 2012).

RAUex-D houses an internal Li-Ion battery, a non-volatile memory (32 GB), integrated GPS and WiFi in a compact IP68 rated case weighting less than 2 kg. A radio identification (RFID) is also included to case enabling a fast identification of recording unit. Internal battery enables 130 hours autonomous operation, which can be further extended with usage of external battery. Memory autonomy with 500 Hz sampling rate is more than 300 hours. Acquisition parameters can be set and data retrieved trough Ethernet port or wirelessly via WiFi transmission. Additionally, the licence free wireless communication enables real time Quality control (QC) of the system (Sercel Ltd.).

The DSU3SA is a 3-component (3C) accelerometer that is powered by remote autonomous unit (RAUex-D). The sensor is based on MEMS (Micro-machined Electro-Mechanical Sensor) technology. These digital accelerometers provide a broadband linear response (DC to 800 Hz) (www.sercel.com). DSU3SA is a digital sensor unit in a sense that 24-bit ADC is interconnected to the MEMS and thus, output of the sensor unit is digital. Digital data transmission to RAUDex-D avoids pick-up noise and cross-talk related to conventional analogue transmission between sensor and digitizer (Mougenot 2004). DSU3SA has a full scale of 5 m/s2, dynamic range of 120 dB @ 250 Hz sampling rate and self-noise on 400nm /s2/√Hz (10-200Hz)(www.sercel.com).

Typical MEMS accelerometer is a small silicon chip, with size of 1 cm2, weight < 2 g and proof mass in microgram scale. From the application point of view the main advantage of MEMS accelerometers over traditional electromagnetic coil based sensors is their broadband linear phase and amplitude response that may extend from 0 (DC) to 800 Hz within 1 dB.

Additionally, MEMS resonant frequency is far above the seismic band pass (1 kHz). This makes it possible to record frequencies below 10 Hz without attenuation, including the direct current (DC) related to the gravity acceleration (Laine, 2014).

The main challenges related to MEMS technology are related to the sensitivity and self-noise affecting signal-to-noise ratio, especially in low frequencies.

The DSU3SA has self-noise of 400nm /s2/√Hz (between 10-100Hz). However, self-noise increases toward low frequencies; below 55 Hz, it becomes higher than that of geophone-digitizer system and below 5 Hz, it can exceed ambient noise (Laine 2014), making ambient noise recording in this frequency domain impossible. As a reference, according to New-Low-Noise-Model (NLNM) the minimum terrestrial noise to be reached is 40 nm/√Hz (1-100 Hz) (Peterson, 1993). At high frequencies (>50 Hz) the floor/electric noise of the MEMS is lower than that of the equivalent geophone/station electronics (Mougenot 2004).

5.3 Examples of measurements and research made during the SEISLAB project

5.3.1 Passive measurements using MEMS based sensors

Recording of ambient seismic noise (vibration of the Earth due to natural or industrial sources) is nowadays used in many passive seismic methods. Ambient noise measurements can be used to extract information on geological structures or locate underground oil or gas reservoirs, or other resources. Passive seismic methods are becoming more and more important since new passive seismic methods are developed due to scientific, economic and ecological reasons.

Suitability of new type of seismic equipment, based on MEMS technology, to record ambient seismic was tested during the experiment in Haukipudas area near Oulu in 2013 (Fig. 1) where the MEMS seismic sensors were installed along a small-scale profile cutting known sedimentary formation. The aim was to extract information on the subsurface structure using H/V (horizontal-to-vertical) spectral ratio of ambient seismic noise. The technique originally proposed by Nogoshi and Igarashi (1971), and wide-spread by Nakamura (1989), consists in estimating the ratio between the Fourier amplitude spectra of the horizontal (H) to vertical (V) components of the ambient noise vibrations recorded at one single station. The computation of the H/V ratio follows several steps and includes a) recording a 3-component ambient noise signal; b) selection of the most stationary time windows (e.g., using an anti-triggering algorithm) in order to avoid transient noise; c) computation and smoothing of the Fourier amplitude spectra for each time windows; d) averaging the two horizontal component (using a quadractic mean); e) computation of the H/V ratio for each window; f) computation of the average H/V ratio (SESAME, 2005).

In our study we used the Geopsy software (http://www.geopsy.org) in order to perform the H/V analysis of the ambient noise data recorded by the Sercel multichannel seismic equipment. Figure 3 demonstrates a typical example of the H/V data analysis and interpretation. Results of the measurements along the Haukipudas porfile were compared with those extracted with conventional coil based broadband seismometers (Nanometrics Trillium Compact) and were also compared with results from other methods such as ground penetration radar (Fig. 4). The comparison showed that the new equipment of the SEISLAB can be used in passive seismic methods based on ambient noise analysis and in a number of other applied seismology tasks as well.

5.3.2 Seismic travel-time tomography in Pyhäsalmi mine

During the SEISLAB project we started to investigate whether or not passive microseismic monitoring data from Pyhäsalmi mine, Finland, (Fig. 5) can be used in order to model seismic velocity structure within the mine. The seismicity in the Pyhäsalmi mine is driven by the changes in rock mechanic state due the ongoing mining operation, thus it is a mine-induced seismicity. The mine-induced seismic event data in Pyhäsalmi mine has been recorded since 2002 when the passive microseismic monitoring network designed by the Institute of Mine Seismology (http://www.imseismology.org) was installed in the mine (Fig. 6). Since that over 120000 microseismic size events have been observed (First Quatum minerals Ltd., 2015). An example of seismogram of microseismic event is shown in Fig. 7.

The purpose of our study was to test how the travel-time seismic tomography performs with the passive microseismic monitoring data where the source-receiver geometry is based on non-even distribution of mine-induced events in the mine and hence, is a non-ideal one for the travel-time tomography. The tomographic inversion procedure was tested with the synthetic data and real source-receiver geometry and with the real travel-time data of the first arrivals of P-waves from the microseismic events. The synthetic modelling gave positive results as known synthetic model was retrieved by used SIRT-method (Lo & Inderwiesen, 1994). The results showed that the travel time tomography is capable to reveal differences in seismic velocities in the mine area corresponding to different rock types (for example, the velocity contrast between the ore body and surrounding rock can be easily distinguished). The velocity model recovered corresponds well to the known geological structures in the mine area (Fig. 8).

The second target was to apply the travel-time tomography to microseismic monitoring data recorded during different time periods in order to track temporal changes in seismic velocities within the mining area as the excavation proceeds. The result shows that such a time-lapse travel-time tomography can recover such changes (Fig. 8). In order to obtain good ray coverage and good resolution, the time interval for a single tomography iteration need to be selected taking into account the number of events and their spatial distribution.

From our results it can be concluded that seismic tomography is applicable on Pyhäsalmi mine passive seismic monitoring data and the dense ore body can be detected by seismic tomography. There is also a variability between results obtained using different weekly data sets, as the number of microseismic events and correspondent ray coverage depends on ore production and changes from week to week. From the results it can be seen, however, that there are periods of time that the distribution has been favourable for tomography even for as short time period as one week.

An example of microseismic monitoring data from the Pyhäsalmi mine will be included into a database of induced seismicity episodes of the European Plate Observation System (EPOS) Anthropogenic hazard (AH) node. At Pyhäsalmi episode the effect of underground mining operation to the induced seismicity in the mine will be considered. (EPOS, 2015).

6 EPOS-European Plate Observing System at the University of Oulu

The European Plate Observing System (EPOS) is the integrated open access solid Earth Sciences research infrastructure approved by the European Strategy Forum on Research Infrastructures (ESFRI) and included in the ESFRI Roadmap in December 2008 (European Commission, 2011). EPOS is a long-term integration plan of national existing Research Iinfrastructures (RI). The implementation phase of EPOS will be during 2015-2018. The result will be a single sustainable, permanent geophysical observational infrastructure, integrating existing monitoring networks (e.g. seismic and geodetic networks), local observatories (e.g. volcano observatories) and experimental laboratories (e.g., experimental and analytic laboratories for rock physics and tectonic analogue modelling) in Europe and adjacent regions (EPOS, 2015). Partners of the FIN-EPOS national Finnish EPOS consortium are Universities of Helsinki and Oulu, National Land Survey, Finnish Meteorological Institute, Geological Survey of Finland, CSC – IT Center for Science and VTT Technical Research Centre of Finland Ltd. The consortium is hosted by the Institute of Seismology, University of Helsinki (ISUH). The national co-ordination office will be placed at ISUH. The consortium leader/chair and PI is Annakaisa Korja, Director of ISUH and the consortium's vice-chair and co-PI is prof. Markku Poutanen from the National Land Survey.

The EPOS will a) build up excellent science opportunities in Earth sciences, b) strengthen capacity building for new generations, c) contribute to the natural hazard mitigation, d) provide easily accessible geoscientific real-time data and data products, e) maintaining reference frameworks for society and industry, f) foster IT innovations related to analysis and management of large distributed data sets.

At the OU, two Departments contributing to the FIN-EPOS infrastructure are the SGO and Oulu Mining School (OMS) (Fig. 9).

The Finnish National Seismic Network (FNSN) comprises national Helsinki University Seismological network (HE) and the Northern Finland Seismological Network (FN) hosted by the SGO. As a part of EPOS activities, both organisations started to upgrade their own networks in 2015. ISUH focuses on increasing the nation-wide permanent station coverage by 4 stations, while the SGO focuses on increasing the permanent station coverage in the Polar region (4 stations, Fig. 10). As the networks are overlapping and complementary, additions in one network are also beneficial to the other one. The consortium project is funded by the Academy of Finland in 2015-2017. In addition, the SGO will establish a new national central hub for induced seismicity data. Initiation of the national induced seismicity database will contribute significantly to one of the focus research areas of the OU: The Environment, Natural resources and Materials as well as to the Mining and Mineral field OU development area that has recently resulted in the establishment of a new mining faculty (Oulu Mining School).

The new permanent stations of the SGO will be installed in boreholes and equipped with the Trillium Posthole 120PH seismometers. This type of instrument is under testing at the OLKF station in Oulanka since 2014, where the staff of SGO is testing various materials and technical solutions for installation of equipment, insulation of sensor, power supply and data transmission. Figure 11 shows the process of installation of the posthole seismometer at the Oulanka site. Figures 12 and 13 demonstrate comparison of recordings of existing permanent stations of FN equipped with the STS-2 seismometer with the recordings of stations working in a test regime and equipped with Trillium Posthole 120PH seismometer (OLKF station) and Trillium 120PA broadband sensor (KLF station).

In summary, the seismic group of the SGO has gained a long experience in carrying out seismological studies in polar region of northern Fennoscandia. This experience and new seismic instrumentation of the Northern Finland Seismological Network and Laboratory of Applied Seismology can be used to initiate new projects and continue a high level seismological research at the SGO.

7 Acknowledgements

POLENET/LAPNET Working Group: Elena Kozlovskaya (1), Helle Pedersen (3), Jaroslava Plomerova (6), Ulrich Achauer (4), Eduard Kissling (7), Irina Sanina (8), Teppo Jämsen (1), Hanna Silvennoinen (1), Catherine Pequegnat (3), Riitta Hurskainen (1), Robert Guiguet (3), Helmut Hausmann (5), Petr Jedlicka (6), Igor Aleshin (10), Ekaterina Bourova (3), Reynir Bodvarsson (11), Evald Brückl (5), Tuna Eken (6), Pekka Heikkinen (2) Gregory Houseman (14), Helge Johnsen (12), Elena Kremenetskaya (9), Kari Komminaho (2), Helena Munzarova (6) Roland Roberts (11), Bohuslav Ruzek (6), Hossein Shomali (11), Johannes Schweitzer (13), Artem Shaumyan (8), Ludek Vecsey (6), Sergei Volosov (8)

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Equipment for the temporary deployment was provided by RESIF – SISMOB, FOSFORE, EOST-IPG Strasbourg Equipe sismologie (France), seismic pool (MOBNET) of the Geophysical Institute of the Czech Academy of Sciences (Czech republic), instrument pool of Sodankylä Geophysical Observatory (Finland), Institute of Geosphere Dynamics of RAS (Russia), Institute of Geophysics ETH Zürich (Switzerland), Institute of Geodesy and Geophysics, Vienna University of Technology (Austria), University of Leeds (UK).

Funding agencies provided support for organisation of the experiment are:

Finland : The Academy of Finland (grant No. 122762) and University of Oulu

France: BEGDY program of the Agence Nationale de la Recherche, Institut Paul Emil Victor and ILP (International Lithosphere Program). task force VIII.

Czech Republic: grant No. IAA300120709 of the Grant Agency of the Czech Academy of Sciences

Russian Federation : Russian Academy of Sciences (programs No 5 and No 9).

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The SEISLAB project was funded by the European Regional Development Fund (ERDF), Council of Oulu region and Pyhäsalmi Mine Oy. Geopsy free software (www. Geopsy.org) was used for the data analysis of SEISLAB project.

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Table 1. Controlled source seismic experiments in Finland, in which seismic group of the University of Oulu participated with OU equipment

Experiment abbreviation	Year of data acquisition
FINNLAP	1979
SVEKA'81	1981
BALTIC	1982
POLAR	1985
BABEL	1989
SVEKA'91	1991
FENNIA	1994
FIRE	2001-2003

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Table 2. International controlled-source seismic experiments, in which seismic group of the University of Oulu participated

Experiment name	Region	Year of data acquisition
EGT (European Geotraverce)	Italy, Germany	1986
LT-7	Poland	1987
TTZ	Poland	1993
EUROBRIDGE'94	Lithuania	1994
EUROBRIDGE'95	Lithuania	1995
EUROBRIDGE'96	Belarus	1996
POLONAISE	Poland, Lithuania	1997
EUROBRIDGE'97	Belarus, Ukraine	1997
CELEBRATION 2000	Austria, Germany, Poland, Hungary, Slovakia, Czech Republic, Russia, Belarus,	2000
ALP2002	Austria	2002
SUDETES	Poland	2003
DANUBE	Hungary	2004

Table 3. The instrumentation of the seismic stations in northern Finland prior to 2005

Station	Component	Type of instrument	Period T^{0}sec	Magnification at T^{0}sec	Damping Ratio	Recording Type	Drum speed mm/min	Geographical Coordinates	Type of Amplifier	Operation period
SOD Tähtelä	Z	Benioff	1.	34000	15:1	Ph. Paper	60	67^{0}22'16.2''N 26^{0}37'44.7''E h=181 m	Galv.	Nurmia: 28.6.1956-1966 Benioff till 14.6.1992
	N	Nurmia	0.5	35000	3:1	Ph. Paper	30		Galv.	
	E	Nurmia	0.5	35000	3:1	Ph.Paper	30		Galv.	
	Z	Nurmia	0.5	1000000	2:1	Smoked p.	60		Electr	
	Microbar.	-	-	-	-	Smoked p.	5		Mech.	
	Z	Willmore				Heat paper				1966-1973
	Z	Kirnos				Ph.paper	60		Galv.	1968-1973
	N					Ph.paper	30		Galv.	
	E					Ph.paper	30		Galv.	
OUL Huttukylä	Z	Press-Eving	30	1500	Inf	Ph. Paper	30	65^{0}05'07''N 25^{0}53'47''E h=60 m	Galv.	9.10.1963-1987
	Z	Willmore	0.65	80000	4:1	Heat paper	30		Photo-tube	
				T/dB		Recorder				
SDF Pittiövaara	Z	Kirnos			-	Ph.paper	60	67.420 N 26.394 E h=276.5 m	Galv.	Spring, 1973
	N					Ph.paper	30		Galv.	
	E					Ph.paper	30		Galv.	
	Z N E	S-13	0.8	282k/.32		Lennarz ink paper recorder				1983-17.05.2000
SGF Sodankylä	Z N E	S-13	0.8	282k/.32	-	DAS-98	-	67.442 N 26.526 E h=180 m	-	18.05.2001-04.01.2006
OUL Ervasti	Z	S-13	1.0	450k/.2	-		-	65.085 N 25.842 E h=72 m		Dec. 1980-July 1996
OUL Huttukylä	Z N E	S-13	1.0	450k/.2	-	DAS-98	-	65.0528 N 25.8964 E h=60 m	-	26.10.1999-31.12.2005
MA Maaselkä	Z							65.9113 N 29.0402 E h=365 m		Jan, 1970-Jun, 1998

MSF Maa-selkä	Z N E	S-13	1.0	-		DAS-98	-			17.05.2000-01.05.2005

Table 4. Northern Finland Seismological Network (network code FN). Station information.

Station name	Code	Lat. N (deg)	Long.E (deg)	Elev. (m)	Sensor	Data aquisition	Digitiser sensitivity (microvolt/ count)	Data transfer	Data format	Start of operation
Oulu, Huttukylä	OUL	65.085	25.896	60	Streckeisen STS-2, 2nd generation	EarthData PS6-24+Linux SeisComP	2.5	Internet ADSL	mSEED	10.08.2005
Kuusamo, Maaselkä	MSF	65.911	29.040	365	Streckeisen STS-2, 2nd generation	EarthData PS6-24+Linux SeisComP	2.5	Internet WLAN	mSEED	17.10.2005
Sodankylä	SGF	67.442	26.526	180	Streckeisen STS-2, 2nd generation	EarthData PS6-24+Linux SeisComP	1.	Internet WLAN	mSEED	04.01.2006
Rovaniemi	RNF	66.612	26.010	198.1	Streckeisen STS-2, 2nd generation	EarthData PS6-24+Linux SeisComP	1.	Internet WLAN	mSEED	06.11.2007

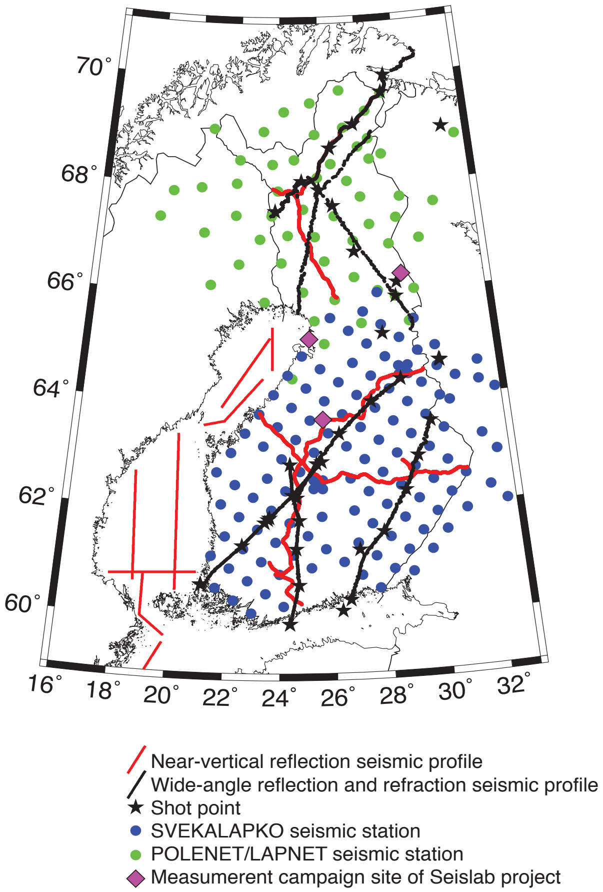

Figure 1. Map showing position of seismic controlled-source and passive seismic experiments in Finland, in which seismic group of the OU and SGO has participated since 1980th (see also Table 1 and description o experiments in the text).

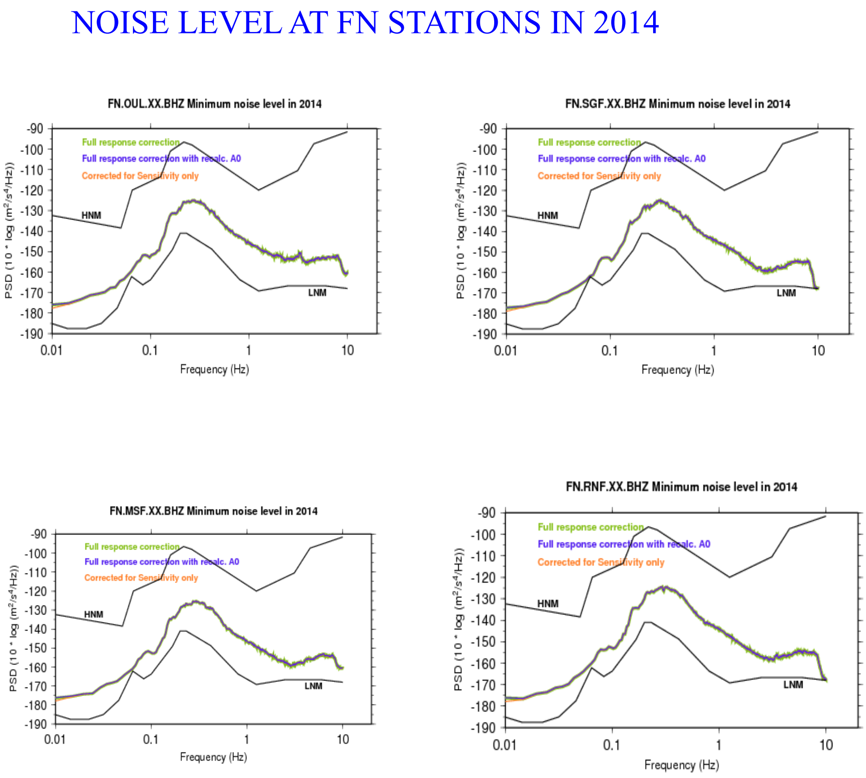

Figure 2. Noise level at the permanent stations of the Northern Finland Seismological Network in 2014. HNM and LNM show high noise model and low noise models, respectively (Peterson, 1993).

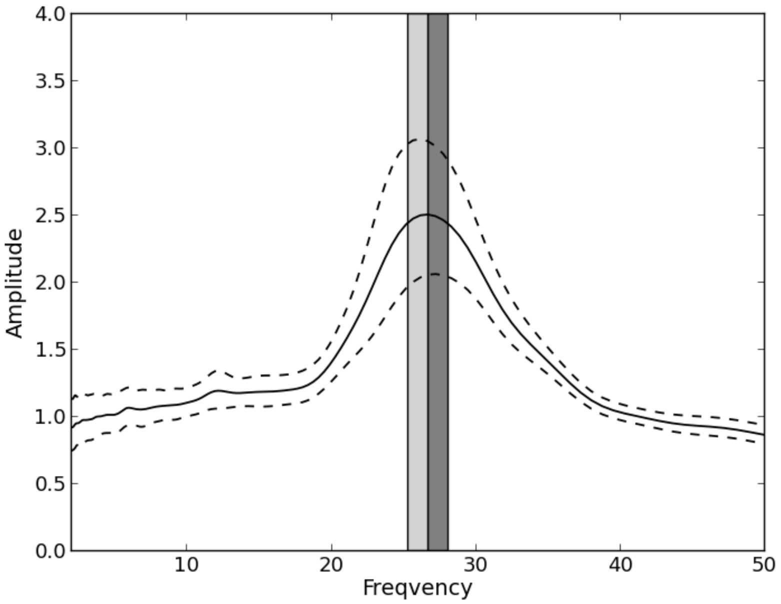

Figure 3. A typical H/V- curve measured with MEMS based 3-component accelerometer. The peak frequency corresponds to ~1 m sediment thickness.

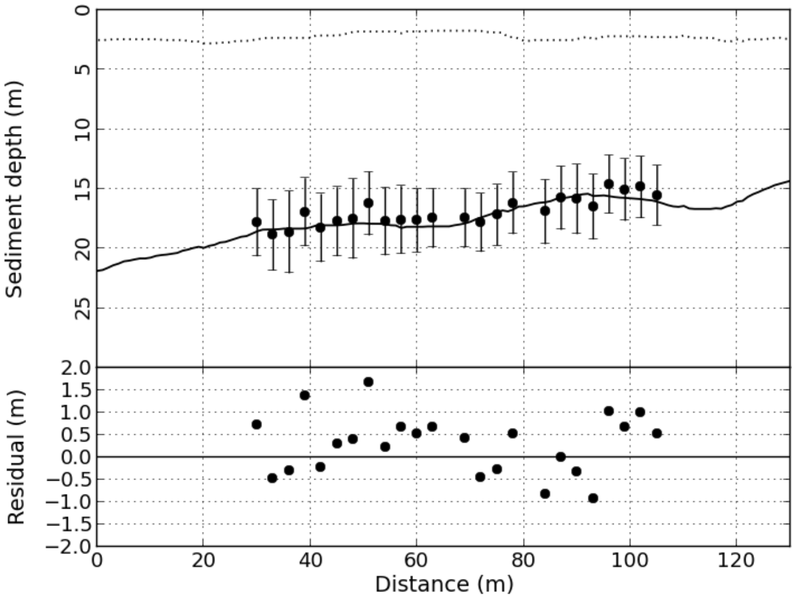

Figure 4. Sediment thickness extracted by the H/V method (black dots) and compared with results from ground penetrating radar (black line). The error bars correspond to the width of the H/V curve. The dotted line corresponds to water level depths.

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Manuscript under review for journal Geosci. Instrum. Method. Data Syst.
Published: 19 January 2016

Figure 5. Overview of the Pyhäsalmi mine, Finland, Photo was kindly provided by Timo Mäki, First Quantum Minerals Ltd.

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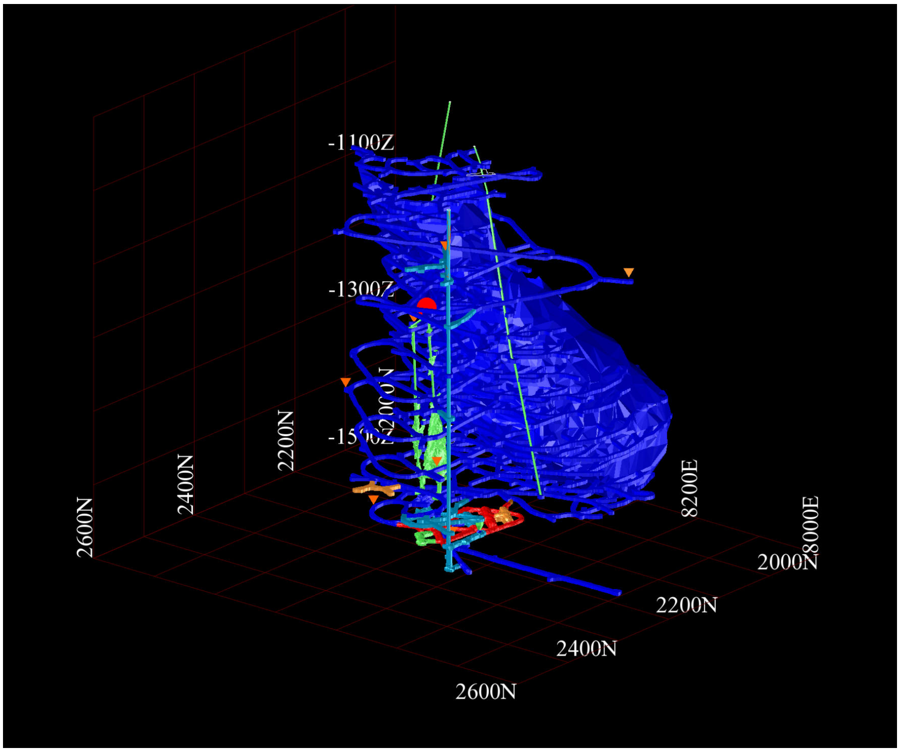

Figure 6. Pyhäsalmi mine deep ore body and work routes. The red ball represents seismic event and orange triangles geophones that detected it.

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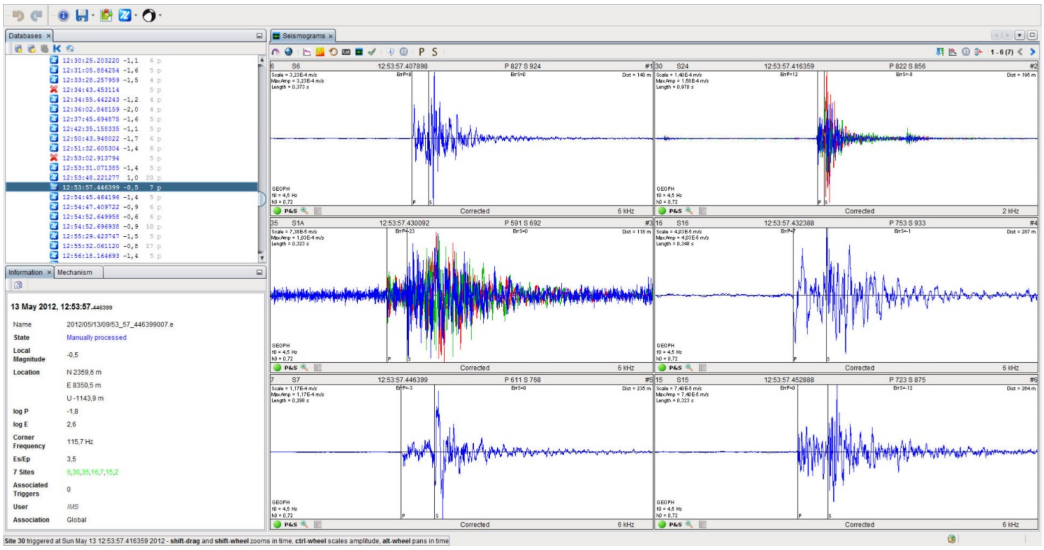

```
12:30:25.203220 -1,1   6 p
12:31:05.884254 -1,6   5 p
12:33:28.257959 -1,5   4 p
12:34:43.453114        5 p
12:34:55.442243 -1,2   4 p
12:36:02.848159 -2,0   4 p
12:37:45.694875 -1,6   5 p
12:42:35.158335 -1,1   5 p
12:50:43.948022 -1,7   6 p
12:51:32.605304 -1,4   8 p
12:53:02.913794        5 p
12:53:31.071385 -1,4   5 p
12:53:48.221277  1,0  20 p
12:53:57.446399 -0,5   7 p
12:54:45.464196 -1,4   5 p
12:54:47.409722 -0,9   6 p
12:54:52.649958 -0,6   6 p
12:54:52.696938 -0,9  10 p
12:55:29.423747 -1,5   5 p
12:55:32.061120 -0,8  17 p
12:56:18.164693 -1,4   5 p
```

13 May 2012, 12:53:57.446399

Name	2012/05/13/09/53_57_446399007.e
State	Manually processed
Local Magnitude	-0,5
Location	N 2359,6 m E 8350,5 m U -1143,9 m
log P	-1,8
log E	2,6
Corner Frequency	115,7 Hz
Es/Ep	3,5
7 Sites	6,30,35,16,7,15,2
Associated Triggers	0
User	*IMS*
Association	Global

Site 30 triggered at Sun May 13 12:53:57.416359 2012 - **shift-drag** and **shift-wheel** zooms in time, **ctrl-wheel** scales amplitude, **alt-wheel** pans in time

Figure 7. Example of seismograms of microseismic event recorded by mycroseismic monitoring network in Pyhäsalmi mine (by permission of First Quantum minerals Ltd.)

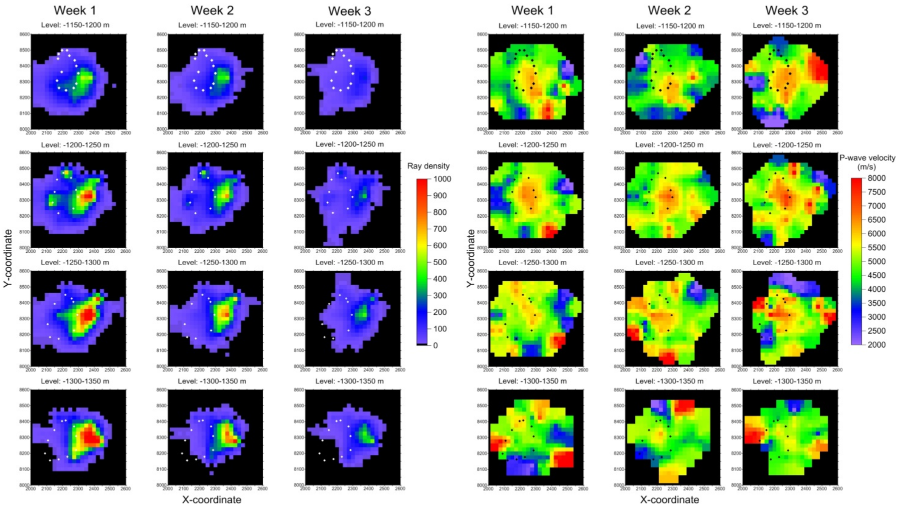

Figure 8. An example of results of travel time tomography using the data of microseismic monitoring network in Pyhäsalmi Mine. The left panel: ray density images for three first weeks of May, 2012. The right panel: the results of seismic travel time tomography for same time period. White and black dots show the average boundary of Pyhäsalmi deep ore body for the corresponding depths levels.

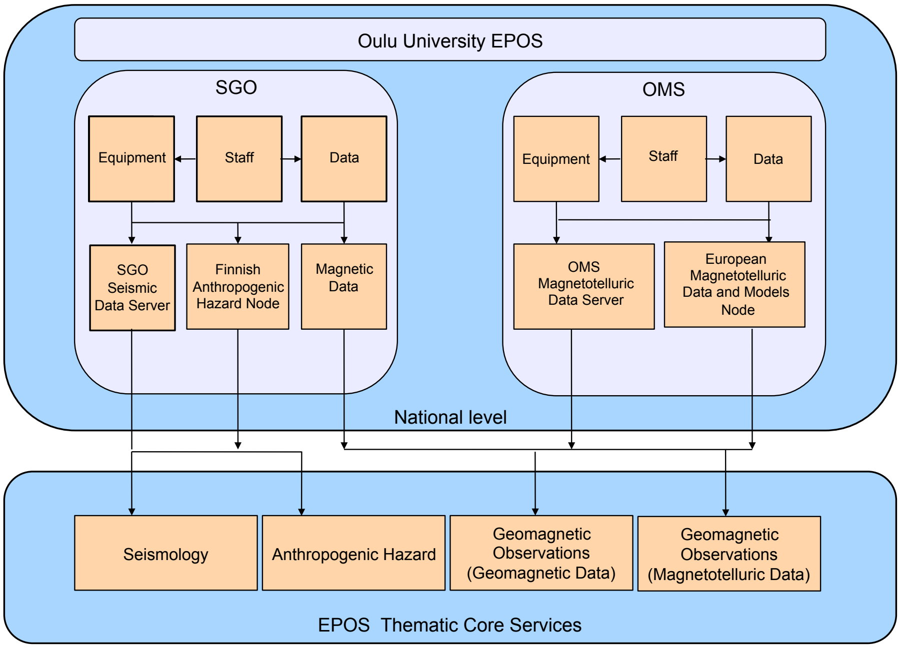

Figure 9. EPOS infrastructure at the University of Oulu.

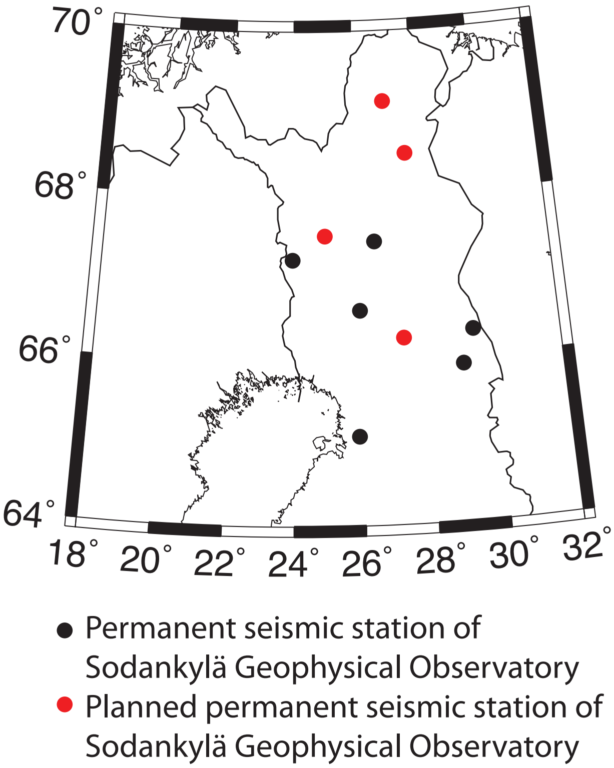

Figure 10. Location of seismic stations of the FN network. Black dots indicate position of stations that are in operation in 2015, including OLKF and KLF station operating in test regime. Red dots indicate position of stations that will be installed in 2016-2017.

Figure 11. Installation of the Trillium Posthole 120PH seismometer in a drillcore of depth of 5.5 m at the Oulanka site (station code OLKF). Photo by Hanna Silvennoinen.

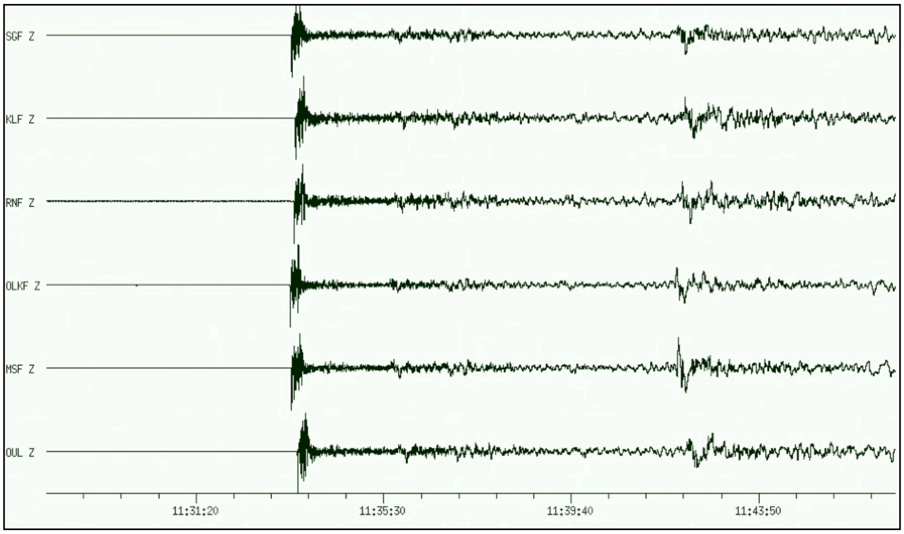

Figure 12. An example of unfiltered seismogram of teleseismic event on 29.05.2015 at 11:23:02 from Bonin Island with Mw=7.8 recorded by the upgraded FN array in 2015. Stations OLKF and KLF are included.

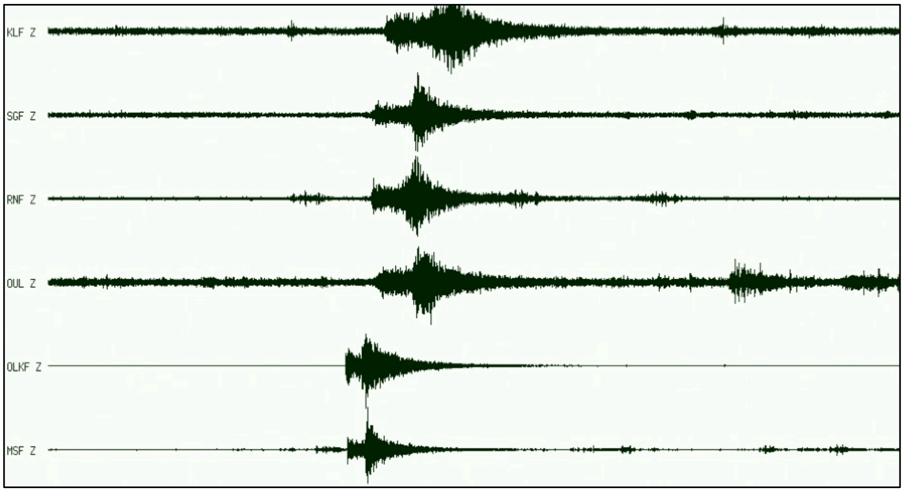

Figure 13. An example of seismograms of local event from northern Russia on 29.06.2015 at 13:05:08 with M=1.9 recorded by the upgraded FN array. Recordings are filtered by the 2-22 Hz bandpass filter. Stations OLKF and KLF are included