Geosci. Instrum. Method. Data Syst., 5, 365–382, 2016
www.geosci-instrum-method-data-syst.net/5/365/2016/
doi:10.5194/gi-5-365-2016

Geoscientific Instrumentation Methods and Data Systems
Open Access

Seismic observations at the Sodankylä Geophysical Observatory: history, present, and the future

Elena Kozlovskaya[1,2], Janne Narkilahti[1], Jouni Nevalainen[1,2], Riitta Hurskainen[1], and Hanna Silvennoinen[1]

[1]Sodankylä Geophysical Observatory, University of Oulu, POB 3000, Oulu, 90014, Finland
[2]Oulu Mining School, University of Oulu, POB 3000, Oulu, 90014, Finland

Correspondence to: Elena Kozlovskaya (elena.kozlovskaya@oulu.fi)

Received: 29 December 2015 – Published in Geosci. Instrum. Method. Data Syst. Discuss.: 19 January 2016
Revised: 13 April 2016 – Accepted: 31 May 2016 – Published: 10 August 2016

Abstract. Instrumental seismic observations in northern Finland started in the 1950s. They were originally initiated by the Institute of Seismology of the University of Helsinki (ISUH), but the staff of Sodankylä Geophysical Observatory (SGO) and later geophysicists of the University of Oulu (UO) were involved in the development of seismological observations and research in northern Finland from the very beginning. This close cooperation between seismologists and the technical staff of ISUH, UO, and SGO continued in many significant international projects and enabled a high level of seismological research in Finland. In our paper, we present history and current status of seismic observations and seismological research in northern Finland at the UO and SGO. These include both seismic observations at permanent seismic stations and temporary seismic experiments with portable seismic equipment. We describe the present seismic instrumentation and major research topics of the seismic group at SGO and discuss plans for future development of permanent seismological observations and portable seismic instrumentation at SGO as part of the European Plate Observing System (EPOS) research infrastructure. We also present the research topics of the recently organized Laboratory of Applied Seismology, and show examples of seismic observations performed by new seismic equipment located at this 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

Sodankylä Geophysical Observatory (SGO) was established in 1913 by the Finnish Academy of Science and Letters to perform geophysical measurements and research based on the observation results. Measurements of the Earth's magnetic field began on 1 January 1914. On 1 August 1997, the observatory became an independent research department of the University of Oulu (UO). Currently, the Sodankylä Geophysical Observatory performs continuous measurements of the Earth's magnetic field, cosmic radio noise, seismic activities, and cosmic rays. The observatory is located in central Finnish Lapland in the municipality of Sodankylä (see Fig. 1).

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

The next period in the development of Finnish seismology started at the end of the 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 yet been standardized and home-made seismic sensors were used (see Luosto (2001) for details). However, these seismographs were capable of recording both minor local and teleseismic earthquakes.

Published by Copernicus Publications on behalf of the European Geosciences Union.

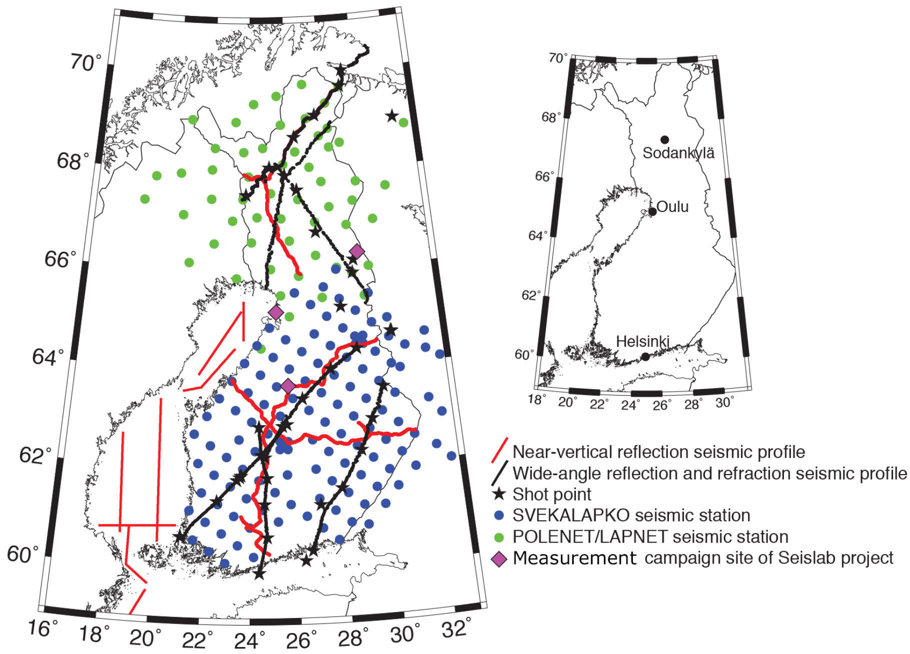

Figure 1. Map showing position of seismic controlled-source and passive seismic experiments in Finland, in which the seismic group of the UO and SGO has participated since the 1980s (see also Table 1 and the description of the experiments in the text). The smaller map on the right shows the locations of towns and municipalities mentioned in the text.

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

Experiment abbreviation	Year of data acquisition	References
FINNLAP	1979	Luosto et al. (1983)
SVEKA'81	1981	Luosto et al. (1984)
BALTIC	1982	Luosto (2001)
POLAR	1985	Luosto et al. (1989)
BABEL	1989	BABEL Working Group (1993)
SVEKA'91	1991	Luosto (2001)
FENNIA	1994	Luosto (2001)
FIRE	2001–2003	Kukkonen and Lahtinen (2006)

The fourth development period started when the World Wide Standard Seismograph Network (WWSSN) was founded and funded by the United States of America at the beginning of the 1960s. Then several Finnish seismic stations were equipped with standard WWSSN short-period Benioff and long-period Press–Ewing seismometers, a 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 1961. In this era, the development of seismology in Finland was strongly influenced by the massive nuclear explosion tests in Novaya Zemlya (Russia), by the International Geophysical Year 1957–58, and by the Seventh 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 the 1970s–1980s. In 1981, the analogue instrumentation at WWSSN stations in Finland was upgraded to digital data acquisition systems. In the 1970s, engineer Seppo Nurminen started to design digital recorders and transmission systems at the ISUH (Nurminen, 1974, 1976). The same technique was applied in the 1980s when constructing three- or five-channel PCM-1218-80 recorders (Nurminen and Hannula, 1981), which were the first digital portable field recorders in Europe. Just at the end of the 20th century, Nurminen designed an entirely 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 the 1970s–1990s and the large-scale marine deep seismic reflection experiment BABEL in 1989 (Luosto, 1987, 2001; Table 1 and Fig. 1). The advanced portable instrumentation provided an opportunity for Finnish geophysicists to participate in many international controlled-source seismic experiments (Table 2).

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

Experiment name	Region	Year of data acquisition	Reference
EGT (European Geotraverce)	Italy, Germany	1986	Blundell et al. (1992)
LT-7	Poland	1987	Guterch et al. (1994)
TTZ	Poland	1993	Grad et al. (1999)
EUROBRIDGE'94	Lithuania	1994	Grad et al. (2006)
EUROBRIDGE'95	Lithuania	1995	Grad et al. (2006)
EUROBRIDGE'96	Belarus	1996	Grad et al. (2006)
POLONAISE	Poland, Lithuania	1997	Grad et al. (2006)
EUROBRIDGE'97	Belarus, Ukraine	1997	Grad et al. (2006)
CELEBRATION 2000	Austria, Germany, Poland, Hungary, Slovakia, Czech Republic, Russia, Belarus	2000	Grad et al. (2006)
ALP2002	Austria	2002	Bleibinhaus et al. (2006)
SUDETES	Poland	2003	Majdanski et al. (2006)
DANUBE	Hungary	2004	Hegedus et al. (2005)

Since the 1950s, the scientific and technical staff of SGO and the geophysical group of the UO was actively involved in the above-mentioned observatory activities and seismic projects initiated by the ISUH. Since SGO was founded much earlier than the UO (1914 and 1958, respectively) and was initially operated as an independent research institution, the seismological observations and research at these two organizations were originally developing in parallel. Presently, the research based on seismological observations is performed by the seismic group located in Oulu (Oulu unit of SGO) and comprises a significant part of the total scientific output of SGO.

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

2 History of seismic observations in northern Finland

In 1954, Eijo Vesanen, who was the head of the ISUH at the time, proposed to install a seismic station at SGO. The idea received support from the observatory administration, and the first seismic test measurements at SGO started on 11 June 1954. The instrument was a copy of the vertical component Sprengnether seismometer made at the Department of Physics at 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; Fig. 2) started on 28 June 1956. The results showed, however, that the site was not suitable for observatory level seismic measurements because of a thick (about 50 m) sand layer. The measurements at the Tähtelä site continued using a different type of analogue equipment (Table 3) until a new site (station code SDF) was found in Pittiövaara hill near Sodankylä. The seismic sensors were moved to the new site while connection and communication between sensors and recording system were established using radio link (Kataja, unpublished memoirs). In 2001, a digital seismic station with new equipment was established at the new site in an underground tunnel (station code SGF; Fig. 2, Table 3). The station recorded 3-component (3C) seismic data with a sampling rate of 50 sps in CSS data format (Anderson et al., 1990).

During the 1950s the seismographs at SGO were under the maintenance of the observatory staff. In 1959, the Finnish Academy of Sciences and Letters founded the 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 Dec 1959, soon after the university and its Department of Physics were founded in 1958 and 1959, respectively. Initially, the seismic equipment was installed at the Myllytulli hydroelectric power plant, not far from the centre of Oulu. That temporary station was equipped with the 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.

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

Station	Component	Type of instrument	Period T°s	Magnification at T°s	Damping ratio	Recording type	Drum speed mm min^{-1}	Geographical coordinates	Type of amplifier	Operation period
SOD	Z	Benioff	1.0	34 000	15 : 1	Ph. Paper	60	67°22′16.2″ N	Galv.	Nurmia:
Tähtelä	N	Nurmia	0.5	35 000	3 : 1	Ph. Paper	30	26°37′44.7″ E	Galv.	28 Jun 1956–1966
	E	Nurmia	0.5	35 000	3 : 1	Ph.Paper	30	$h = 181$ m	Galv.	Benioff till 14 Jun 1992
	Z	Nurmia	0.5	1 000 000	2 : 1	Smoked p.	60		ElectrMech.	1966–1973
	Microbar.	Willmore	–	–	–	Smoked p.	5		Galv.	1968–1973
	Z	Kirnos				Heat paper	60		Galv.	
	Z					Ph. paper	30		Galv.	
	N					Ph. paper	30			
	E					Ph. paper				
OUL	Z	Press–Eving	30	1500	Inf	Ph. paper	30	65°05′07″ N	Galv.	9 Oct 1963–1987
Huttukylä	Z	Willmore	0.65	80 000	4 : 1	Heat paper	30	25°53′47″ E	Phototube	
								$h = 60$ m		
				T / dB		Recorder				
SDF	Z	Kirnos	0.8	282k/.32	–	Ph.paper	60	67.420° N	Galv.	Spring 1973
Pittiövaara	N	S-13				Ph.paper	30	26.394° E	Galv.	1983–17 Jun 2000
	E					Ph.paper	30	$h = 276.5$ m	Galv.	
	Z					Lennarz ink paper recorder				
	N									
	E									
SGF	Z	S-13	0.8	282k/.32	–	DAS-98	–	67.442° N	–	18 May 2001–4 Jan 2006
Sodankylä	N							26.526° E		
	E							h|,= 180 m		
OUL	Z	S-13	1.0	450k/.2	–		–	65.085° N		Dec 1980–Jul 1996
Ervasti								25.842° E		
								$h = 72$ m		
OUL	Z	S-13	1.0	450k/.2	–	DAS-98	–	65.0528° N	–	26 Oct 1999–31 Dec 2005
Huttukylä	N							25.8964° E		
	E							$h = 60$ m		
MA	Z	S-13	1.0	–		DAS-98	–	65.9113° N		Jan 1970–Jun 1998
Maaselkä	Z							29.0402° E		17 May 2000–1 May 2005
MSF	N							$h = 365$ m		
Maaselkä	E									

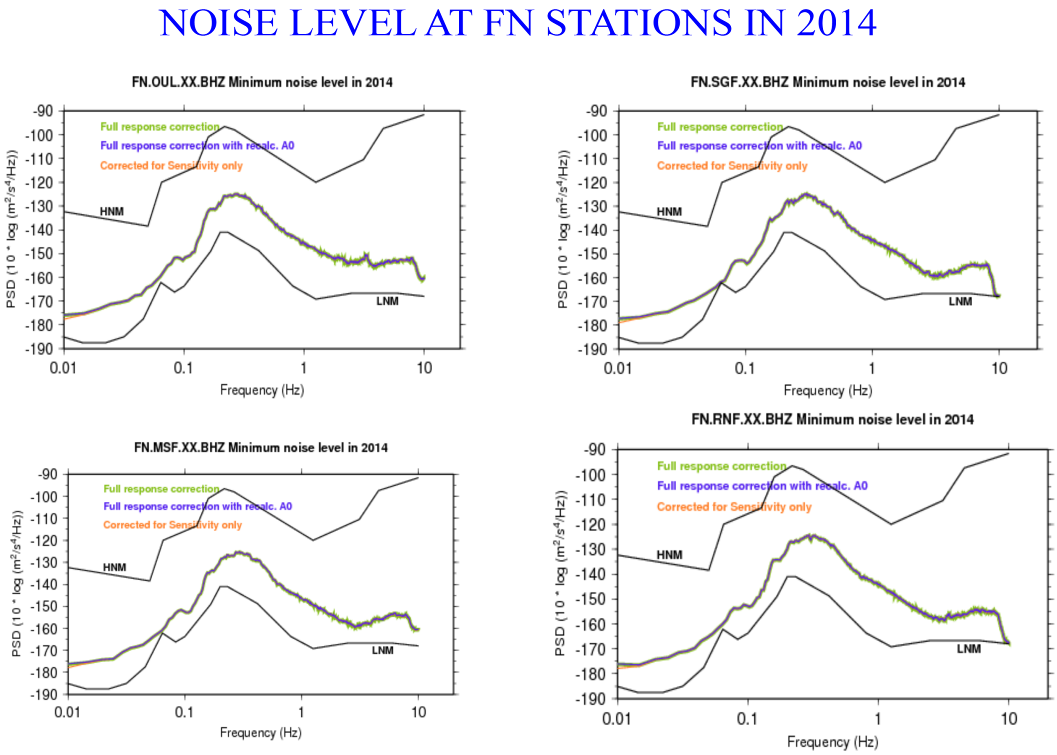

Figure 2. Noise level at the permanent stations of the Northern Finland Seismological Network in 2014. HNM and LNM show high noise model and low noise models, respectively (Peterson, 1993).

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

Station name	Code	Lat. N (deg)	Long. E (deg)	Elev. (m)	Sensor	Data acquisition	Digitizer 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 Aug 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 Oct 2005
Sodankylä	SGF	67.442	26.526	180	Streckeisen STS-2, 2nd generation	EarthData PS6-24+Linux SeisComP	1.0	Internet WLAN	mSEED	4 Jan 2006
Rovaniemi	RNF	66.612	26.010	198.1	Streckeisen STS-2, 2nd generation	EarthData PS6-24+Linux SeisComP	1.0	Internet WLAN	mSEED	6 Nov 2007

In 1963, the Department of Physics founded a new seismic station on the quiet site of Aarne Karjalainen Observatory in Huttukylä (about 18 km from Oulu; station code OUL; Fig. 2). The property and observatory buildings were donated to the University of Oulu by 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 had operated at the Ervasti site nearby (the station code was not changed) until the equipment of the station was destroyed by a thunderstorm in summer 1996.

In 1970, the UO founded a new seismic station at the Maaselkä site (station code MSF; Fig. 2), about 10 km from town of Kuusamo in north-eastern Finland (Table 3). Digital registration using a 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 a 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 were recorded to the hard disk drive of the station's Linux computer and transmitted to the data server located at the UO via telephone lines.

In 1968, the position of seismologist was founded at the UO together with the foundation of the Department of Geophysics. Heikki Korhonen was appointed as the first seismologist at Oulu in 1968 and Jukka Yliniemi became his successor in 1977. The position was later transferred to the Geophysical Observatory founded in 1985 at the UO. The Sodankyla Geophysical Observatory was united with the University of Oulu in 1997, and the Geophysical Observatory was merged into it in the following year. The position of seismologists was simultaneously moved to SGO, and Jukka Yliniemi was responsible for seismic measurements at SGO until 2004; Elena Kozlovskaya was his successor.

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

3 Recent seismic observations at SGO

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

In 2004, it became apparent that existing permanent seismic stations of SGO did not satisfy the requirements of the 21st century seismology. First, they were equipped with the short-period Geotech S-13 seismic sensors, while the majority of seismic network operators in Europe had already changed their 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 locating local seismic events. The continuous seismic data were 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 SGO started to modernize its permanent seismic stations. During this modernization, the short-period seismic instruments were replaced by Streckeisen STS-2 broadband seismometers and the existing data acquisition system was replaced by the Earth Data PR6-24 24-bit digitizers and Linux computers with SeisComP seismic data acquisition software (SeisComP Manual, 2006). The agreement was reached with the GeoForschungsZentrum (GFZ) Potsdam on archiving and distribution of the seismic data via the 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 Federation of Digital Seismograph Networks (FDSN 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 the vertical component of these stations in 2014. Two new stations (Oulanka – OLKF and Kolari – KLF) were installed in 2014. They are now working in test regime and will be connected to the network after testing. The network is a part of GEOFON (GEOFOrschungsNets: http://www.geofon.gfz-potsdam.de/wave) 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 SGO represents the University of Oulu in the Incorporated Research Institutions for Seismology (IRIS; 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 GFZ Potsdam (Germany) and at their own archive of the Oulu unit. Since 2011, the data are also archived in the European ORFEUS Data Centre (www.orfeus-eu.org) that now holds the European Integrated Data Archive (EIDA) of seismological data. The data are used for monitoring of seismic activity in northern Europe and worldwide as well as for detection of local and teleseismic events. Information about seismic events is published in several online bulletins, including the bulletin of seismic events in Fennoscandia by ISUH (http://www.helsinki.fi/geo/seismo/english/bulletins/). The data are, via the GFZ, distributed through the ORFEUS (EIDA) data distribution system.

3.2 Temporary seismic experiments at SGO

The seismic group of the Sodankylä Geophysical Observatory of the University of Oulu has participated with its own resources and equipment in many seismic projects in Finland (see Fig. 1) and abroad. The controlled-source seismic projects are listed in Tables 1 and 2 with references to publications introducing the projects and collaborations. See Sect. 3.2.1 for more details. In addition, SGO has participated in several passive seismic experiments that are shortly introduced in Sect. 3.2.2–3.2.4 and 3.2.6 and coordinated a passive seismic POLENET/LAPNET experiment (Sect. 3.2.5) during International Polar Year (IPY) 2007–2009.

3.2.1 Seismic wide-angle reflection and refraction experiments

The Seismic group of the Sodankylä Geophysical Observatory of the University of Oulu has participated with its own resources and equipment in many seismic controlled-source experiments in Finland and abroad (Fig. 1, Tables 1 and 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 SGO participated in the Finnish Reflection Experiment (FIRE) carried out by a consortium consisting of the Geological Survey of Finland, the ISUH, Department of Geosciences of the University of Oulu, and 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 also organized wide-angle reflection and refraction measurements along FIRE lines using its own equipment (Silvennoinen et al., 2010).

Oulu University is responsible for storing the data of several controlled-source seismic experiments. In Finland, the ISUH and the Geological Survey of Finland (GSF) are also archiving the data of a number of such experiments.

Initially, 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 has consisted of 8 Reftek 72 data loggers (used in cooperation with the Department of Geophysics of UO) and eight 3C Mark Products L4C seismometers with a natural frequency of 2 Hz.

3.2.2 SVEKALAPKO passive seismic array research

In 1997–1999, the seismic group of SGO, together with the Department of Geophysics of Oulu University and ISUH, participated in the EUROPROBE/SVEKALAPKO Deep Seismic Tomography project (Hjelt and Daily, 1996, 2006; Bock et al., 2001). These papers also provide the information about which individual researchers and research organizations participated in the project. The project was a passive seismic array research in southern and central Finland aimed 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 the experiment, including sites and equipment information, is given in Sandoval (2002). The results of the SVEKALAPKO array research dramatically changed the point of view of the structure of the mantle lithosphere beneath Finland. Prior to the experiment, it was assumed that the lithosphere there is thick, and the structure of the mantle lithosphere is relatively simple. This opinion was based on worldwide studies of upper mantle xenoliths from Archaean and Proterozoic areas that demonstrated a certain correlation between the 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 the Proterozoic domain were expected. Instead, inhomogeneous and anisotropic upper mantle beneath the Proterozoic–Archean suture zone has been revealed (Alinaghi et al., 2003; Kozlovskaya et al., 2004; Kozlovskaya et al., 2007; Sandoval, 2002; Sandoval et al., 2003, 2004; Bruneton et al., 2002, 2004a, b; Yliniemi et al., 2004; Plomerová et al., 2006; Vescey et al., 2007; Kozlovskaya et al., 2008; Pedersen et al., 2006, 2007).

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

Leading organization of the ALPASS project was Institute of Geodesy and Geophysics, Vienna University of Technology, principal investigator E. Brückl. For more information on ALPASS, see Mittelbauer et al. (2011).

ALPASS was a passive seismic monitoring project aimed at revealing 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, and the USA. The seismic group of SGO participated in the passive seismic experiment in 2005–2006 with their own field instruments. In 2009, it participated in data processing and teleseismic tomography studies (Mittelbauer et al., 2011).

3.2.4 PASSEQ 2006–2007: passive seismic experiment in the Trans-European Suture Zone

The primary 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 the young Palaeozoic platform of the western European and Precambrian eastern European platform (Wilde-Piortko et al., 2008).

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 SGO in collaboration with the University of Vilnius and the Geological Survey of Lithuania (Janutyte, 2012). 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 eastern European platform.

3.2.5 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 experiment was initiated by the group of scientists, who participated previously in the SVEKALAPKO experiment (Helle Pedersen, Jaroslava Plomerová, Ulrich Achauer, Eduard Kissling, Irina Sanina, Elena Kozlovskaya) and its aim was to continue the SVEKALAPKO array to the north. Equipment for the temporary deployment was provided by RESIF-SISMOB, FOSFORE, EOST-IPG Strasbourg Equipe seismologie (France), Seismic pool (MOBNET) of the Geophysical Institute of the Czech Academy of Sciences (Czech Republic), the Sodankylä Geophysical Observatory (Finland), the Institute of Geosphere Dynamics of the Russian Academy of Sciences (RAS) (Russia), the Institute of Geophysics ETH Zürich (Switzerland), the Institute of Geodesy and Geophysics, the Vienna University of Technology (Austria), and the University of Leeds (UK). For a full list of the working group see, for example, Plomerová et al. (2011) and Pedersen et al. (2013). The project was coordinated by SGO with Elena Kozlovskaya as the principal investigator. SGO also carried the responsibility of serving the stations during the data acquisition period.

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 data set (Kozlovskaya et al., 2007) includes continuous high-frequency data (sampling rate from 50 to 100 sps) of 37 temporary stations, which were in operation during the period from 1 May 2008 to 31 September 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 into the database of RESIF Data Centre at the University of Grenoble (France) (http://seismology.resif.fr). The metadata about POLENET/LAPNET stations, their coordinates, and instrumentation are also deposited into the database. The backup copy of all continuous data is stored at SGO. In addition, the data of several short-period stations are archived at SGO and Geophysical Centre RAS, Schmidt 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. (2016) estimated variations of S- and P-wave velocities, the 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., 2016). Krasnoshchekov et al. (2016) used the data from 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 to estimate the inner structure of the Earth's crust and upper mantle. Usoltseva and Kozlovskaya (2016) presented results of local event studies, and Gibbons et al. (2015) used the POLENET/LAPNET array data to investigate the propagation of infrasound signals.

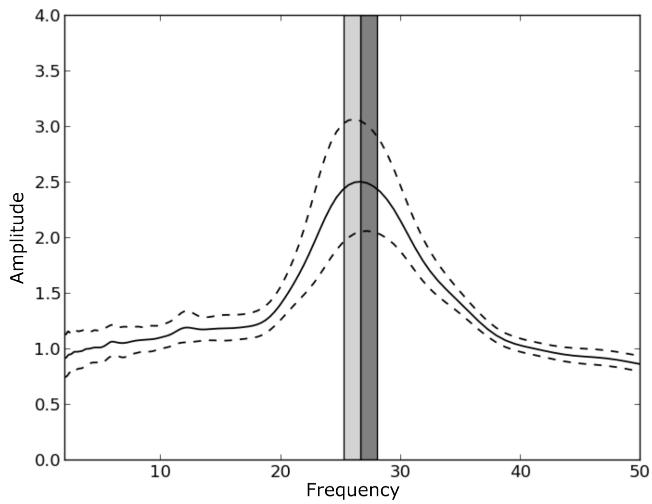

Figure 3. A typical H / V curve measured with MEMS-based 3-component accelerometer. The peak frequency corresponds to ∼ 1 m sediment thickness.

3.2.6 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 faults (PGFs) in northern Fennoscandia. During the last stages of the Weichselian glaciation (ca. 9000–15 000 years B.P.), reduced ice load and relaxation of accumulated tectonic stress resulted in a 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 planning and exploitation of such critical facilities as nuclear waste disposal and underground

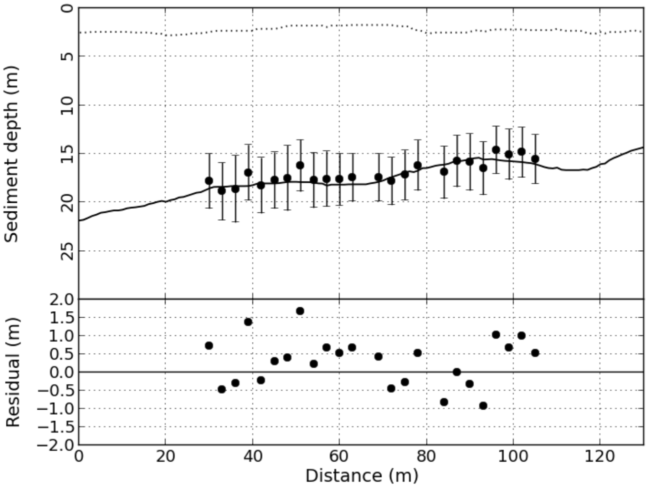

Figure 4. Sediment thickness extracted by the H / V method (black dots) and compared with results from ground penetrating radar (black line). The error bars correspond to the width of the H / V curve. The dotted line corresponds to water level depths.

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

mines. The main purpose of the DAFNE/FINLAND passive seismic array experiment was to characterize the present-day seismicity of the Suasselkä postglacial fault (SPGF) that was proposed as one potential target for the DAFNE project. As the fault is located far 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, eight short-period and four broadband 3C seismic stations were installed in the close vicinity of the fault area in September 2011. During September 2011–May 2012, we collected the data of more than 70 000 seismic events (teleseismic, regional and local ones). Recordings of the array have been analysed manually and automatically, in order to find natural earthquakes from the fault area. The detected events were located and spectral charac-

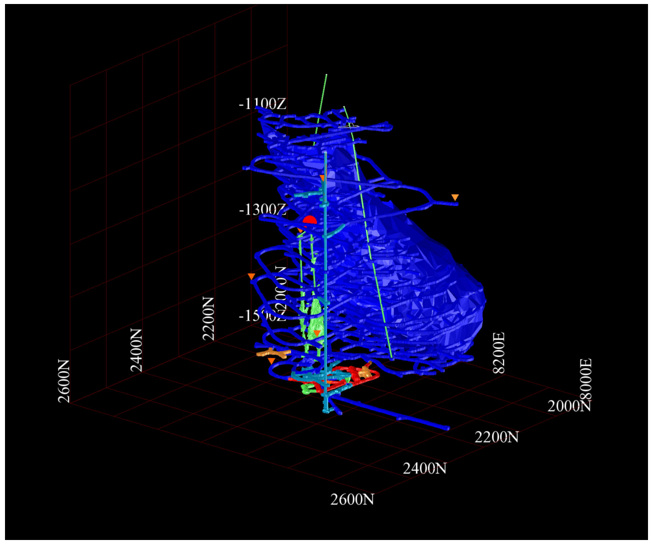

Figure 6. Pyhäsalmi mine deep ore body and work routes. The red ball represents seismic event and orange triangles geophones that detected it. Published with permission of First Quantum Minerals Ltd.

teristics of signals were analysed, 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 fall in the areas of production and mine development (Kozlovskaya et al., 2013).

4 Future of seismic observations at SGO

4.1 European Plate Observing System at the University of Oulu

The 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 road map in December 2008 (European Commission, 2011). EPOS is a long-term integration plan of national existing research infrastructures (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, 2016). Partners of the FIN-EPOS national Finnish EPOS consortium are THE Universities of Helsinki and Oulu, National Land Survey, Finnish Meteo-

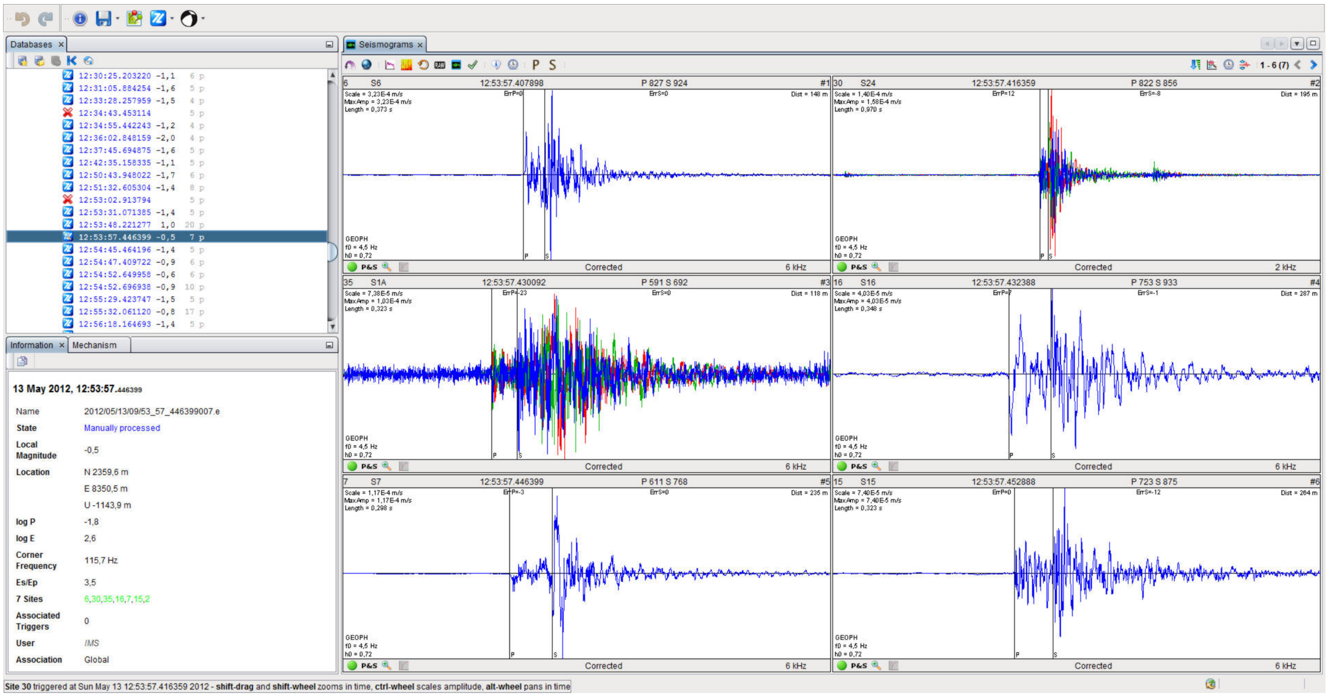

Figure 7. Example of seismograms of microseismic event recorded by mycroseismic monitoring network in Pyhäsalmi mine (with permission of First Quantum minerals Ltd.).

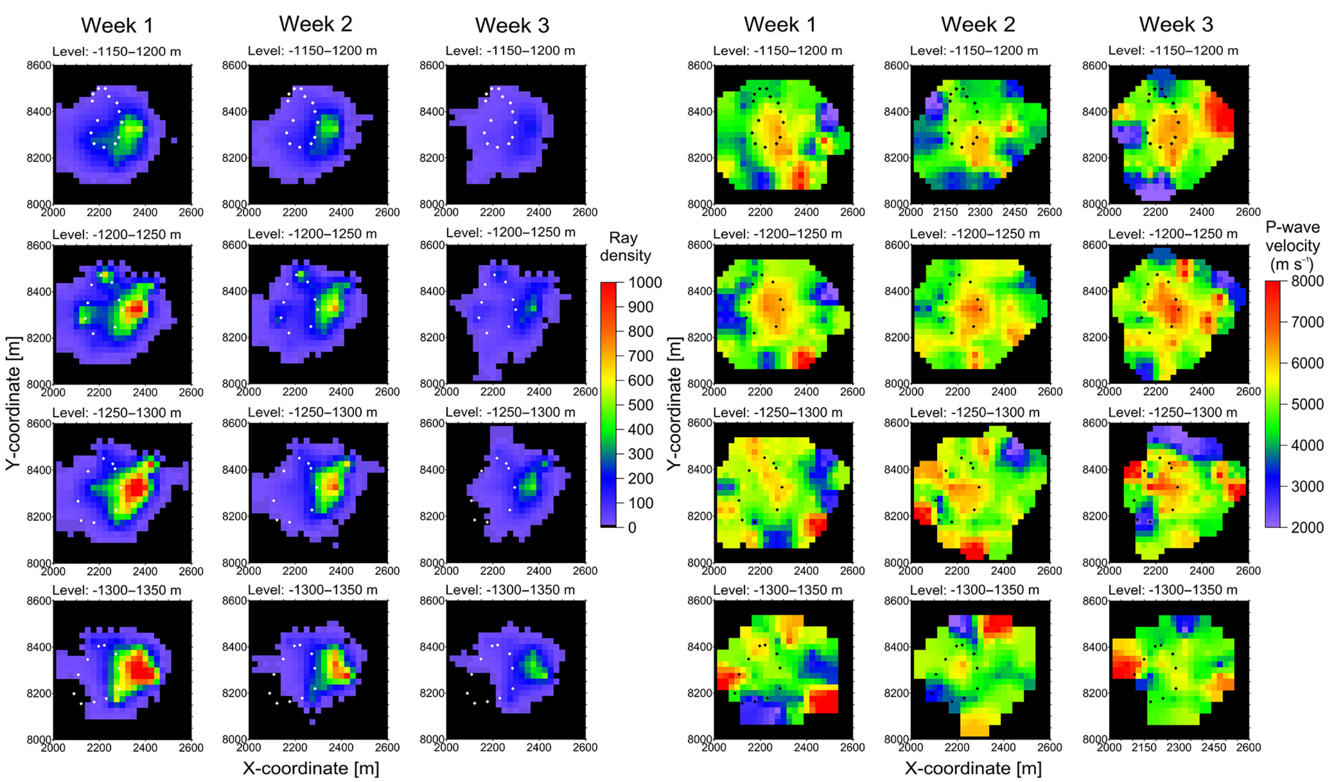

Figure 8. An example of results of travel-time tomography using the data of microseismic monitoring network in Pyhäsalmi Mine. Left panel: ray density images for the first 3 weeks of May 2012. Right panel: the results of seismic travel-time tomography for same time period. White and black dots show the average boundary of Pyhäsalmi deep ore body for the corresponding depths levels.

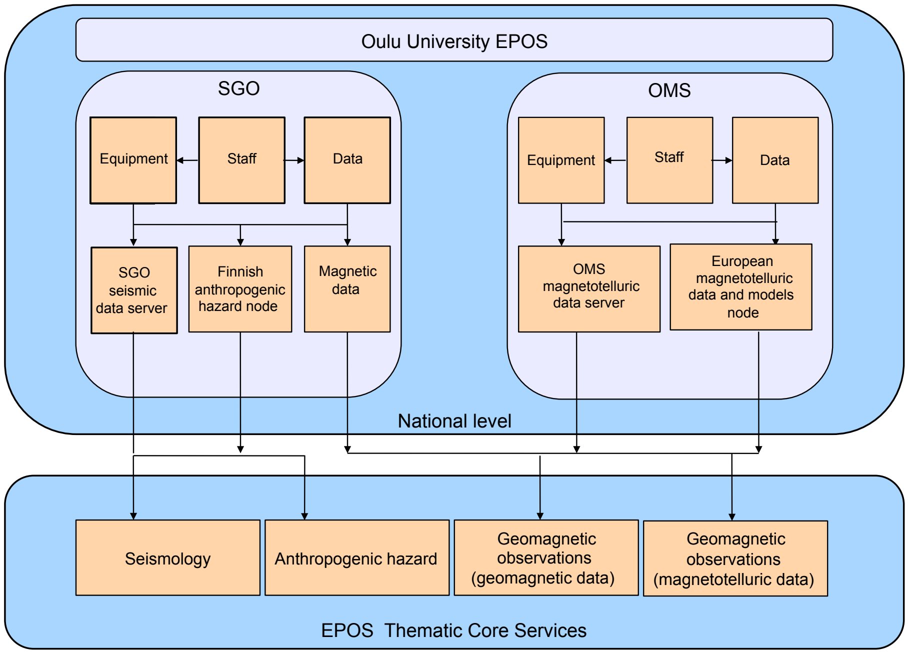

Figure 9. EPOS infrastructure at the University of Oulu in 2015.

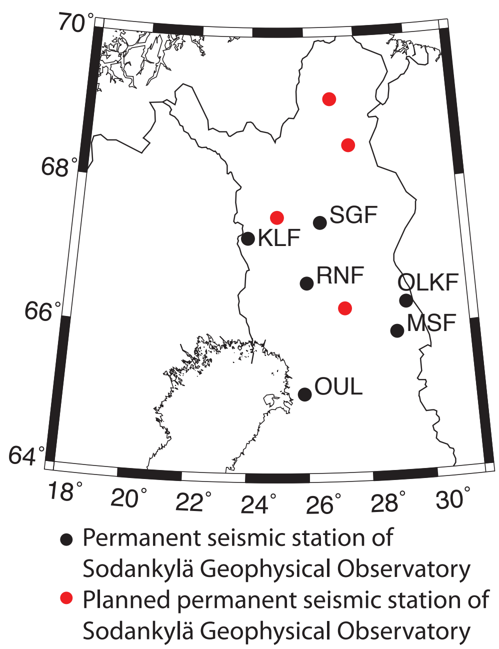

Figure 10. Location of seismic stations of the FN network. Black dots indicate position of stations that are in operation in 2015, including OLKF and KLF stations operating in the test regime. Red dots indicate position of stations that will be installed in 2016–2017.

rological Institute, Geological Survey of Finland, CSC – IT Center for Science, and VTT Technical Research Centre of Finland Ltd. The consortium is hosted by the ISUH. The national coordination office will be placed at ISUH. The consortium leader/chair and principal investigator (PI) is Annakaisa Korja, Director of ISUH, and the consortium's vice-chair and co-PI is 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 UO, two Departments contributing to the FIN-EPOS infrastructure are SGO and Oulu Mining School (OMS) (Fig. 9).

4.2 Upgrading the Northern Finland Seismological Network (FN)

The Finnish National Seismic Network (FNSN) comprises the national Helsinki University Seismological Network (HE) and the Northern Finland Seismological Network (FN) hosted by SGO. As a part of EPOS activities at the national level, both organizations started to upgrade their networks in 2015. ISUH focuses on increasing the nation-wide permanent station coverage by four stations while SGO focuses on increasing the permanent station coverage in the polar region (four 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. Also, SGO will establish a new national central hub for induced seismicity data. Ini-

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

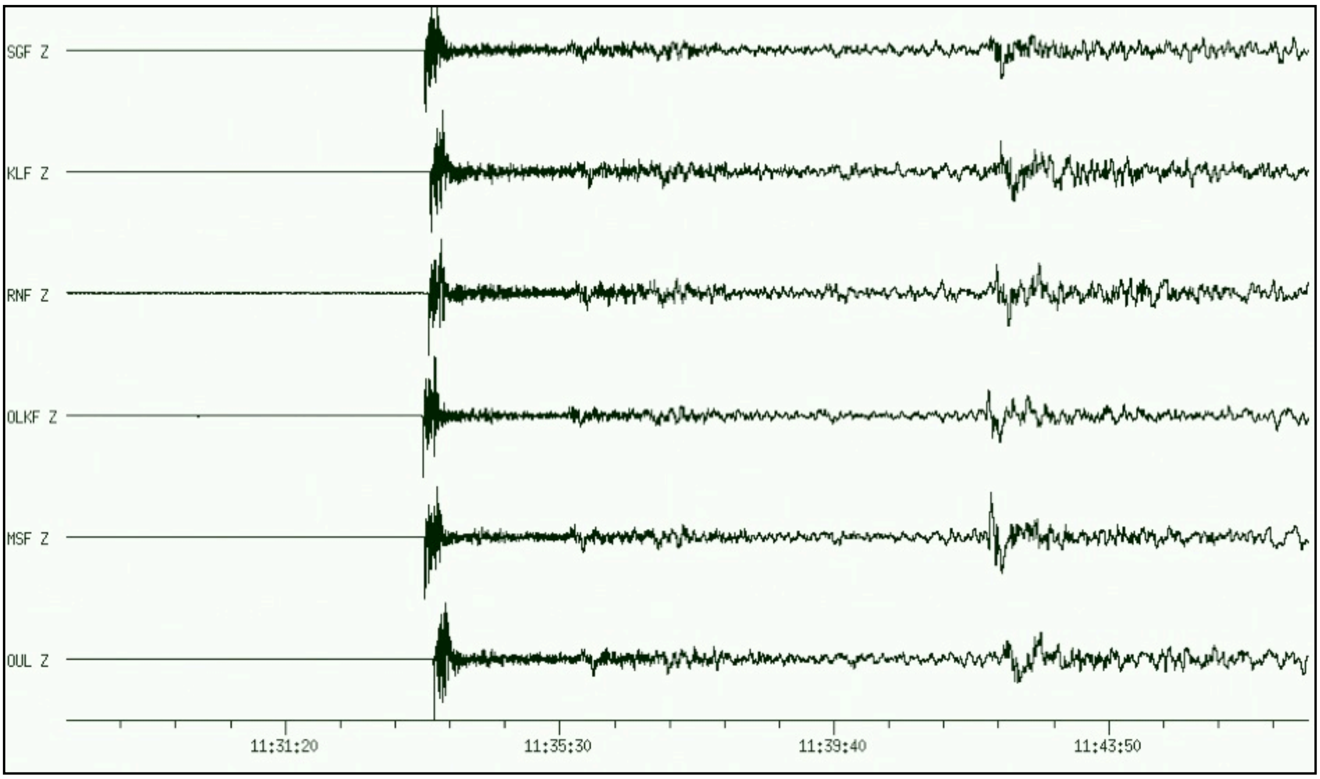

Figure 12. An example of unfiltered seismogram of teleseismic event on 29 May 2015 at 11:23:02 UTC from Bonin Island with $M_{\mathrm{w}} = 7.8$ recorded by the upgraded FN array in 2015. New stations OLKF and KLF are included.

tiation of the national induced seismicity database will contribute significantly to one of the research focus areas of the UO: the environment, natural resources and materials as well as to the mining and mineral field development area that has recently resulted in the establishment of a new mining faculty (Oulu Mining School).

The new permanent stations of SGO will be installed in boreholes and equipped with the Trillium Posthole 120PH seismometers. This type of instrument has been 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,

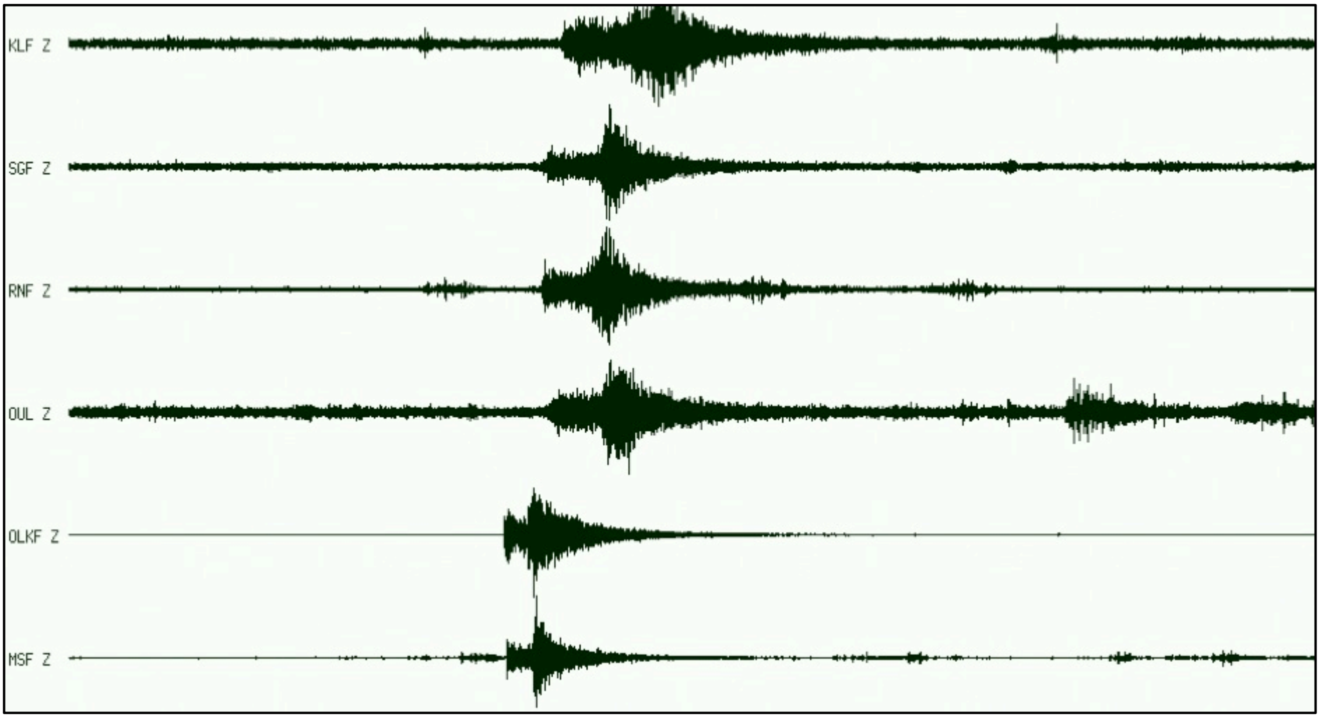

Figure 13. An example of seismograms of local event from northern Russia on 29 June 2015 at 13:05:08 UTC with $M = 1.9$ recorded by the upgraded FN array. Recordings are filtered by the 2–22 Hz bandpass filter. Stations OLKF and KLF are included.

power supply, and data transmission. Figure 11 shows the process of installation of the posthole seismometer at the Oulanka site. The station network of SGO is located north of 65° N, which causes some particular challenges related to the limited infrastructure and the subarctic climate of the area. For most of northern Finland, the population density is less than 1 person km^{-2} (Population Register Centre of Finland), which limits the availability of necessary infrastructures such as electricity and even roads. The subarctic climate (extreme cold temperature and snow coverage) and polar night limit working during winter months. The installation of the seismometer into a borehole offers stable registration temperature throughout the year but above-ground registration electronics still require insulation and a heating system to keep operational.

Figures 12 and 13 demonstrate a 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).

4.3 Laboratory of Applied Seismology

4.3.1 General target of the Laboratory of Applied Seismology of SGO

Currently it is recognized 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 a 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, fracture zones, overburden, intrusions, fault zones, etc., at a depth of several kilometres. In order answer to these new challenges, the seismic group of SGO decided to upgrade its portable seismic instrumentation and organize the SEISLAB. The laboratory aims to ascertain the availability of equipment and personnel to participate in both SGO's own and collaborative short-term projects. Also, 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, orebodies). The project was funded by the European Regional Development Fund (ERDF), Council of Oulu region and Pyhäsalmi Mine Oy in April 2012–January 2014.

4.3.2 SEISLAB instrumentation

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 Nanometrics Ltd. (www.nanometrics.com), four Reftek130 24-bit 3-channel portable data loggers (www.trimble.com), three Earth Data PR6-24 24-bit 3-channel portable data loggers, and four EDR-210 24-bit portable data loggers. Power supply for autonomous operation is provided by lead acid 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 also be used in active source applied geophysics experiments (depth to several km).

Sercel Unite multichannel system

Seismic instrumentation of the laboratory also includes the Sercel UNITE multichannel seismic equipment manufactured by Sercel Ltd. (www.sercel.com). The equipment has 40 3C DSU-SA Micro-machined Electro-Mechanical Sensor (MEMS) sensors and 40 RAU ex-D 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. a portable version of Unite LITE acquisition system with a software license for max 150 channels
4. special battery charger for 20 RAU ex-D units.

Sercel UNITE system is an autonomous recording system composed of remote acquisition units (RAU ex-D) and MEMS-based accelerometers within a digital sensor unit (DSU3SA). Previously UNITE system has been used in reflection and refraction surveys with active energy sources (Lansley et al., 2008; McWhorter et al., 2012).

RAU ex-D houses an internal Li-ion battery, a non-volatile memory (32 GB), integrated GPS and Wi-Fi in a compact IP68 rated case with weight less than 2 kg. A radio identification (RFID) enables a fast identification of recording unit. Internal battery enables 130 h autonomous operation, which can be further extended by using an external battery. Memory autonomy with 500 Hz sampling rate is more than 300 h. Acquisition parameters can be set, and data retrieved trough Ethernet port or wireless via Wi-Fi transmission. Additionally, the licence free wireless communication enables real-time quality control (QC) of the system (Sercel Ltd.).

The DSU3SA is a 3C accelerometer that is powered by remote autonomous unit (RAU ex-D). The sensor is based on MEMS technology. These digital accelerometers provide a broadband linear response (DC to 800 Hz) (www.sercel.com). DSU3SA is a digital sensor unit in the same way that a 24-bit analogue-to-digital converter (ADC) is interconnected to the MEMS, and thus the output of the sensor unit is digital. Digital data transmission to RAUDex-D avoids pick-up noise and crosstalk related to conventional analogue transmission between sensor and digitizer (Mougenot and Thorburn, 2004). DSU3SA has a full scale of $5\,\mathrm{m\,s^{-2}}$, dynamic range of 120 dB @ 250 Hz sampling rate and self-noise on 400 nm /s2/$\sqrt{}$Hz (10–200 Hz) (www.sercel.com).

A typical MEMS accelerometer is a small silicon chip, with a size of $1\,\mathrm{cm^{-2}}$, 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 at low frequencies.

The DSU3SA has self-noise of $400\,\mathrm{nm\,s^{-2}}\,\sqrt{\mathrm{Hz}}^{-1}$ (between 10 and 100 Hz). However, self-noise increases toward low frequencies; below 55 Hz it becomes higher than that of a 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 $40\,\mathrm{nm}\,\sqrt{\mathrm{Hz}}^{-1}$ (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 and Thorburn, 2004).

4.3.3 Examples of measurements and research made during the SEISLAB project

Passive measurements using MEMS-based sensors

Recording of ambient seismic noise (vibration of the Earth due to natural or industrial sources) is presently 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.

The suitability of a 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 promulgated by Nakamura (1989), consists of estimating the ratio between the Fourier amplitude spectra of the horizontal to vertical 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 3C ambient noise signal, (b) selection of the most suitable time windows (e.g. using an anti-triggering algorithm), (c) computation and smoothing of the Fourier amplitude spectra for each time window, (d) averaging the two horizontal components (using a quadratic mean), (e) computation of the H / V ratio for each window, and (f) computation of the average H / V ratio (SESAME, 2005).

In our study, we used the Geopsy software (http://www.geopsy.org) 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 profile 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.

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 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, and thus it is a mine-induced seismicity. The mine-induced seismic event data in Pyhäsalmi mine have 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 then over 120 000 microseismic size events have been observed (Pekka Bergström, personal communication, 2015). An example of seismogram of a 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 a 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 the SIRT (simultaneous iterative reconstruction technique) method (Lo and Inderwiesen, 1994). The results showed that the travel-time tomography is capable of revealing differences in seismic velocities in the mine area corresponding to different rock types (for example, the velocity contrast between the orebody 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 needs 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 to 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 a time period as 1 week.

An example of microseismic monitoring data from the Pyhäsalmi mine will be included in a database of induced seismicity episodes of the EPOS anthropogenic hazard node. At the Pyhäsalmi episode, the effect of the underground mining operation to the induced seismicity in the mine will be considered (EPOS, 2016).

5 Conclusions

In this paper, we have reviewed the history of seismic observation at the Sodankylä Geophysical Observatory. Also, we presented most recent and significant seismic experiments that the seismic group of the observatory has participated.

Over the years, the seismic group of SGO has gained long experience in carrying out seismological studies in the 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 SGO.

The Supplement related to this article is available online at doi:10.5194/gi-5-365-2016-supplement.

Acknowledgements. The staff of the seismic group of SGO acknowledges very much kind cooperation with the scientific and technical staff of the Institute of Seismology of the University of Helsinki during numerous common research projects and operating of permanent seismic stations. We appreciate scientific cooperation with many research organizations in Europe during temporary seismic experiments, in which the seismic group of the UO has participated. We are grateful to the technical staff of SGO, who helped a lot in installation and operation of permanent seismic stations.

The POLENET/LAPNET project is a part of the International Polar Year 2007–2009 and a part of the POLENET consortium. The study was financed by the Academy of Finland (grant no. 122762) and the University of Oulu (Finland), FBEGDY programme of the Agence Nationale de la Recherche, Institut Paul Emil Victor (France) and ILP (International Lithosphere Program) task force VIII, grant no. IAA300120709 of the Grant Agency of the Czech Academy of Sciences, and by Russian Academy of Sciences (programmes nos. 5 and 9). 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.

DAFNE/FINLAND Working Group:

Ilmo Kukkonen, Principal Investigator (University of Helsinki, Department of Physics), Pekka Heikkinen (University of Helsinki, Institute of Seismology), Kari Komminaho (University of Helsinki, Institute of Seismology), Elena Kozlovskaya (Sodankylä Geophysical Observatory and Oulu Mining School, University of Oulu), Riitta Hurskainen, Tero Raita, Hanna Silvennoinen (all from the Sodankylä Geophysical Observatory, University of Oulu).

Edited by: J. Pulliainen
Reviewed by: H. Pedersen and P. Voss

References

Alinaghi, A., Bock, G., Kind, R., Hanka, W., Wylegalla, K., and TOR and SVEKALAPKO Working Group: Receiver function analysis of the crust and upper mantle from the North German Basin to the Archaean Baltic Shield, Geophys. J. Int., 155, 641–652, 2003.

Anderson, J., Farrell, W., Garcia, K., Given, J., and Swanger, H.: Center for Seismic Studies Version 3 Database: Schema Reference Manual, SAIC Technical Report C90-01, 1990.

BABEL Working Group: Integrated seismic studies of the Baltic shield using data in the Gulf of Bothnia region, Geophys. J. Int., 112, 305–324, 1993.

Bleibinhaus, F., Brueckl, E., and ALP 2002 Working Group: Wide-angle observations of ALP 2002 shots on the TRANSALP profile: Linking the two DSS projects, Tectonophysics, 414, 71–78, 2006.

Bock, G. and SVEKALAPKO Seismic Tomography Working Group: Seismic probing of Fennoscandian lithosphere. EOS, Trans. AGU, 82, 628–629, 2001.

Blundell, D. J., Freeman, R., and Mueller, S. (Eds.): A Continent revealed. The European Geotraverse, Structure and dynamic evolution, Cambridge University Press, 288 pp., 1992.

Bruneton, M., Farra, V., Pedersen, H. A., and the SVEKALAPKO Seismic Tomography Working Group: Non-linear surface wave phase velocity inversion based on ray theory, Geophys. J. Int., 151, 583–596, 2002.

Bruneton, M., Pedersen, H. A., Vacher, P., Kukkonen, I. T., Arndt, N. T., Funke, S., Friederich, W., Farra, V., and SVEKALAPKO STWG: Layered lithospheric mantle in the central Baltic Shield from surface waves and xenolith analysis, Earth Planet. Sci. Lett., 226, 41–52, 2004a.

Bruneton, M., Pedersen, H. A., Farra, R., Arndt, N. T., Vacher, P., Achauer, U., Alinaghi, A., Ansorge, J., Bock, G., Friederich, W., Grad, M., Guterch, A., Heikkinen, P., Hjelt, S. E., Hyvonen, T. L., Ikonen, J. P., Kissling, E., Komminaho, K., Korja, A., Kozlovskaya, E., Nevsky, M. V., Paulssen, H., Pavlenkova, N. I., Plomerova, J., Raita, T., Riznichenko, O. Y., Roberts, R. G., Sandoval, S., Sanina, I. A., Sharov, N. V., Shomali, Z. H., Tiikainen, J., Wieland, E., Wylegalla, K., Yliniemi, J., and Yurov, Y. G.: Complex lithospheric structure under the central Baltic Shield from surface wave tomography, J. Geophys. Res.-Solid Earth, 109, B10303, doi:10.1029/2003JB002947, 2004b.

European Commission: Building a pan-European Observation System for Geosciences. EU Support for research infrastructures in environmental sciences, A working document, 32 pp., http://ec.europa.eu/research/infrastructures/pdf/ last access: 2011.

EPOS: European Plate Observing System webpages, www.epos-eu.org, last access: 2016.

First Quantum Minerals: Information of Pyhäsalmi mine, Fisrt Quantum minerals Ltd., www.firstquantum.com last access: 2016.

Gibbons, S. J., V. Asming, L. Eliasson, A. Fedorov, J. Fyen, J. Kero, E. Kozlovskaya, T. Kværna, L. Liszka, S. Peter Näsholm, Tero Raita, Michael Roth, Timo Tiira, and Yuri Vinogradov: The European Arctic: A Laboratory for Seismoacoustic Studies, Seismol. Res. Lett., 86, 917–940, doi:10.1785/0220140230, 2015.

Grad, M., Janik, T., Yliniemi, J., Guterch, A., Luosto, U., Tiira, T., Komminaho, K., Środa, P., Höing, K., Makris, J., and Lund, C.-E.: Crustal structure of the Mid-Polish Trough beneath the Teisseyre–Tornquist Zone seismic profile, Tectonophysics, 314, 145–160, 1999.

Grad, M., Janik, T., Guterch, A., Sroda, P., and Czuba, W.: EUROBRIDGE '94–97, POLONAISE'97 and CELEBRATION 2000 Seismic Working Groups: Lithospheric structure of the western part of the East European Craton investigated by deep seismic profiles, Geol. Quart., 50, 9–22, 2006.

Griffin, W. L., O'Reilly, S. Y., Abe, N., Aulbach, S., Davies, R. M., Pearson, N. J., Doyle, B. J., and Kivi, K.: The origin and evolution of Archaean lithospheric mantle, Precambrian Res., 127, 19–41, 2003.

Guterch, A., Grad, M., Janik, T., Materzok, R., Luosto, U., Yliemiemi, J., Lück, E., Schulze, A. & FÖrste, K.: Crustal structure of the transition zone between Precambrian and Variscan Europe from new seismic data along LT-7 profile (NW Poland and eastern Germany), C. R. Acad. Sci. Paris, 319, 1489–1496, 1994.

Hegedus, E., Brueckl, E., Csabafi, R., Fancsik, T., Grad, M., Guterch, A., Hajnal, Z., Keller, R., Kovacs, A. C., Komminaho, K., Kozlovskaya, E., Tiira, T., Torok, I., and Yliniemi, J.: DANUBE 2004 Lithosphere Research Program, in: Eos, 86, B254 pp., 2005.

Hjelt, S.-E., Daly, S., and SVEKALAPKO colleagues: SVEKALAPKO, in: Evolution of Palaeoproterozoic and Archaean Lithosphere, 56–67, edited by: Gee, D. and Zeyen, H., EUROPROBE 1996 – Lithosphere Dynamics: Origin and Evolution of Continents, EUROPROBE Secretariate, Uppsala University, p. 138, 1996.

Hjelt, S.-E., Korja, T., Kozlovskaya, E., Yliniemi, J., Lahti, I., BEAR and SVEKALAPKO Working Groups: Electrical conductivity and seismic velocity structures of the lithosphere beneath the Fennoscandian Shield, edited by: Gee, D. and Stephenson, R., Europ. Lithos. Dynam., 541–559, 2006.

Janutyte, I., Kozlovskaya, E., Motuza, G., and PASSEQ Working Group: Study of Local Seismic Events in Lithuania and Adjacent Areas Using the Data of PASSEQ Experiment, PAGEOPH, Online First, doi:10.1007/s00024-012-0458-8, 2012.

Janutyte, I., Majdanski, M., Voss, P. H., Kozlovskaya, E., and PASSEQ Working Group: Upper mantle structure around the Trans-European Suture Zone obtained by teleseismic tomography, Solid Earth, 6, 73–91, doi:10.5194/se-6-73-2015, 2015.

Kataja, E.: Seismic station at the SGO, unpublished memoirs and presentation at the meeting of Finnish Geophysical Society, 18 March 2008, 2008.

Korhonen, H., Luosto, U., and Yliniemi, J.: Microseismic storms in December 1975 at the Finnish seismograph stations, Publ. Inst. Geophys. Pol. Acad. Sc., A-9, 183–189, 1980.

Kozlovskaya, E. and Kozlovsky, A.: Influence of high-latitude geomagnetic pulsations on recordings of broad-band force-balanced seismic sensors, Geosci. Instrum. Method. Data Syst., 1, 85–101, doi:10.5194/gid-2-107-2012, 2012.

Kozlovskaya and POLENET/LAPNET Working Group, POLENET/LAPNET, RESIF – Réseau Sismologique et géodésique Français, Seismic Network, doi:10.15778/RESIF.YV2011, http://data.datacite.org/10.15778/RECIF.XK2007, 2007.

Kozlovskaya, E., Elo, S., Hjelt, S.-E., Yliniemi, J., Pirttijärvi, M., and SVEKALAPKO Seismic Tomography Working Group: 3D density model of the crust of southern and central Finland obtained from joint interpretation of SVEKALAPKO crustal P-wave velocity model and gravity data, Geophys. J. Int., 158, 827–848, 2004.

Kozlovskaya, E., Vecsey, L., Plomerová, J., and Raita, T.: Joint inversion of multiple data types with the use of multiobjective optimization: problem formulation and application to the seismic anisotropy investigations, Geoph. J. Int., 171, 761–779, 2007.

Kozlovskaya, E., Kosarev, G., Aleshin, I., Riznichenko, O., and Sanina, I.: Structure and composition of the crust and upper mantle of the Archean-Proterozoic boundary in the Fennoscandian Shield obtained by joint inversion of receiver function and surface wave phase velocity of recording of the SVEKALAPKO array, Geoph. J. Int., 175, 135–152, 2008.

Kozlovskaya, E., Usoskina, I., and Silvennoinen, H.: Study of local seismicity in the area of Suasselkä postglacial fault (DAFNE/FINLAND project), Preliminary Technical Report, doi:10.13140/RG.2.1.4990.9600, 2013.

Krasnoshchekov, P. Kaazik, V. Ovtchinnikov, E. Kozlovskaya. Seismic structures in the Earth's inner core below Southeastern Asia, Pure Appl. Geophys., doi:10.1007/s00024-015-1207-6, 2016.

Kukkonen, I. and Lahtinen, R. (Eds.): Finnish Reflection Experiment FIRE 2001–2005, Geological Survey of Finland Special Paper 43, 2006.

Laine, J. and Mougenot, D.: A high-sensitivity MEMS-based accelerometer, The Leading Edge, 33, 1234–1242, doi:10.1190/tle33111234.1, 2014.

Lansley, M., Laurin, M., and Ronen, S.: Modern land recording systems: How do they weigh up?, The Leading Edge, 27, 888–894, doi:10.1190/1.2954029, 2008.

Lo, T. and Inderwiesen, P.: Fundamentals of Seismic Tomography, Geophysical Monograph Series, Soc. Explor. Geophys., No. 6, 1994.

Luosto, U.: Deep seismic sounding studies in Finland 1979–86, Inst. Seismology, Univ. Helsinki, Report S-15, 21 pp., doctoral dissertation, 1987.

Luosto, U.: Seismology in Finland in the Twentieth Century, Geophysica, 37, 147–185, 2001.

Luosto, U., Zverev, S. M., Kosminskaya, I., and Korhonen, H.: Observations of FENNOLORA shots on additional lines in Finnish Lapland, edited by: Biszttricsany, E. and Szeidovitz, G., Proc. 17th Assembly of the EGS Budapest, 24–29 August 1980, Elsevier, Amsterdam, 517–521, 1983.

Luosto, U., Lanne, E., Korhonen, H., Guterch, A., Grad, M., Materzok, R., and Perchuc, E.: Deep structure of the earth's crust on the SVEKA profile in central Finland, Ann. Geophys., 2, 559–570, doi:10.5194/angeo-2-559-1984, 1984.

Luosto, U., Flueh, E. R., and Lund C.-E.: Working group: The crustal structure along the POLAR Profile from seismic refraction investigation, Tectonophysics, 162, 51–85, doi:10.1016/0040-1951(89)90356-9, 1989.

McWhorter, R., Schultz, G., Clark, A., Branch, T., and Lansley, M.: 3D seismic operational optimization in the lusitanian basin, portugal. First Break, Special Topic: Land Seismic, 30, 103–108, 2012.

Majdanski, M., M. Grad, A. Guterch ja SUDETES 2003 Working Group: 2-D seismic tomographic and ray tracing modelling of the crustal structure across the Sudetes Mountains basing on SUDETES 2003 experiment data, Tectonophysics, 413, 249–269, 2006.

Mittelbauer, U., Behm, M., Brückl, E., Lippitsch, R., Guterch, A., Keller, R., Kozlovskaya E., Rumpfhuber, E.-M., and Šumanovac, F.: Shape and origin of the East-Alpine slab constrained by the ALPASS teleseismic model, Tectonophysics, 510, 195–206, 2011.

Mougenot, D. and Thorburn, N.: MEMS-based 3D accelerometers for land seismic acquisition: Is it time?, The Leading Edge, 23, 246–250, doi:10.1190/1.1690897, 2004.

Nakamura, Y.: A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, Quaterly Report of the Railway Technical Research Institue, 30, 25–30, 1989.

Nogoshi M. and Igarashi T.: On the amplitude characteristics of microtremor (part 2) (in Japanese with english abstract), J. Seismol. Soc. Jpn., 24, 26–40, 1971.

Nurminen, S.: Digital 12-bit C-MOS telemetric system for seismological use, Geophysica, 13, 89–94, 1974.

Nurminen, S.: PCM tape-recording system for seismological use, constructed of C-MOS integrated circuits. Geophysica 14, 1, 141–146, 1976.

Nurminen, S. and Hannula, A.: Deep seismic sounding equipment model PCM 1218–80, service manual, Inst. Seismology, Univ. Helsinki, Report T-7, 33 pp., 1981.

Plomerova, J., Babuska, V., Vecsey, L., Kozlovskaya, E., Raita, T., and SVEKALAPKO STWG: Proterozoic-Archean boundary in the upper mantle of eastern Fennoscandia as seen by seismic anisotropy, J. Geodynam., 41, 369–450, 2006.

Plomerová, J., Vecsey, L., Babuška, V., and LAPNET Working Group: Domains of Archean mantle lithosphere deciphered by seismic anisotropy – inferences from the LAPNET array in northern Fennoscandia, Solid Earth, 2, 303–313, doi:10.5194/se-2-303-2011, 2011.

Pedersen, H. A., Bruneton, M., and Maupin, V.: Lithospheric and sublithospheric anisotropy beneath the Baltic shield from surface-wave analysis, Earth Planet. Sci. Lett., 244, 590–605, 2006.

Pedersen, H. A., Krüger, F., and the SVEKALAPKO Seismic Tomography Working Group: Influence of the seismic noise characteristics on noise correlations in the Baltic Shield, Geophys. J. Int., 168, 197–210, 2007.

Pedersen, H. A., Debayle, E., Maupin, V., and the POLENET/LAPNET Working Group: Strong lateral variations of lithospheric mantle beneath cratons – Example from the Baltic Shield, Earth Planet. Sci. Lett., 383, 164–172, 2013.

Peterson, J.: Observations and modeling of seismic background noise, U.S. Geol. Survey Open – File Report, 93-322, 1–95, 1993.

Poli, P., Pedersen, H., Campillo, M., and LAPNET Working Group: Body-wave imaging of Earth's mantle discontinuities from ambient seismic noise, Science, 338, 1063–1065, doi:10.1126/science.1228194, 2012.

Poli, P., Campillo, M., Pedersen, H., and the POLENET/LAPNET Working Group: Noise directivity and group velocity tomography in a region with small velocity contrasts: the northern Baltic shield application to the northern Baltic Shield, Geoph. J. Int., 192, 413–424, doi:10.1093/gji/ggs034, 2013.

Sandoval, S.: The lithosphere-asthenosphere system beneath Fennoscandia (Baltic Shield) by body-wave tomography, PhD thesis, ETH, Zürich, 2002.

Sandoval, S., Kissling, E., Ansorge, J., and the SSTWGL High-resolution body wave tomo-graphy beneath the SVEKALAPKO array. I. A priori 3D crustal model and associated travel time effcets on teleseismic wave fronts, Geophys. J. Int., 153, 75–87, 2003.

Sandoval, S., Kissling, E., Ansorge, J., and SVEKALAPKO STWG: High-resolution body wave tomography beneath the SVEKALAPKO array: II. Anomalous upper mantle structure beneath the central Baltic Shield, Geophys. J. Int., 157, 200–214, 2004.

SeisComP 2.5 Configuration Manual: GeoForschungsZentrum Potsdam, 30 pp., 2006.

SESAME: Guidelines for the implementation of the H / V spectral ratio technique on ambient vibrations – measurements, processing and interpretations, SESAME European research project, deliverable D23.12, 2005.

Silvennoinen, H., Kozlovskaya, E., Yliniemi, J., and Tiira, T.: Wide angle reflection and refraction seismic and gravimetric model of the upper crust in FIRE4 profile area, northern Finland, Geophysica, 46, 21–46, 2010.

Silvennoinen, H., Kozlovskaya, E., Kissling, E., Kosarev, G., and POLENET/LAPNET working group: A new Moho boundary map for northern Fennoscandian shield based on combined controlled-source seismic and receiver function data, Geo. Res. J., 1–2, 19–32, 2014.

Silvennoinen, H., Kozlovskaya, and Kissling, E.: POLENET/LAPNET teleseismic P-wave traveltime tomography model of the upper mantle beneath northern Fennoscandia, Solid Earth, 7, 425–439, doi:10.5194/se-7-425-2016, 2016.

Standard for the Exchange of Earthquake Data: Reference Manual, SEEDFormat v2.3, FDSN, IRIS, USGS, 1992.

Usoltseva, O. A. and Kozlovskaya, E. G: Studying local earthquakes in the area Baltic-Bothnia Megashear using the data of the POLENET/LAPNET temporary array, Solid Earth, 7, 1095–1108, doi:10.5194/se-7-1095-2016, 2016.

Vecsey, L., Plomerova, J., Kozlovskaya, E., and Babuska, V.: Shear-wave splitting as a diagnostic of varying upper mantle structure beneath eastern Fennoscandia, Tectonophysics, 438, 57–77, 2007.

Vinnik, L., Oreshin S., Makeyeva, L., Peregoudov, D., Kozlovskaya, E., and POLENET/LAPNET Working Group: Anisotropic lithosphere under the Fennoscandian shield from P receiver functions and SKS waveforms of the POLENET/LAPNET array, Tectonophysics, 628, 45–54, doi:10.1016/j.tecto.2014.04.024, 2014.

Vinnik, L, Oreshin, S., Kozlovskaya, E., Kosarev, G., Piiponen, K., and Silvennoinen, H.: The lithosphere, LAB, LVZ and Lehmann discontinuity under central Fennoscandia from receiver functions, Tectonophysics, 667, 189–198, doi:10.1016/j.tecto.2015.11.024, 2016.

Wilde-Piórko, M., Geissler, W. H., Plomerová, J., Grad, M., Babuška, V., Brückl, E. Čyžienė, J., Czuba, W., Eengland, R., Gaczyński, E., Gazdova, R., Gregersen, S., Guterch, A., Hanka, W., Hegedüs, E., Heuer, B., Jedlička, P., Lazauskienė, J., Randy Keller, G., Kind, R., Klinge, K., Kolinsky, P., Komminaho, K., Kozlovskaya, E., Krüger, F., Larsen, T., Majdański, M., Málek, J., Motuza, G., Novotný, O., Pietrasiak, R., Plenefish, Th., Ržek, B., Šliaupa, S., Środa, P., Świeczak, M., Tiira, T., Voss, P., and Wiejacz, P.: PASSEQ 2006–2008: PASsive Seismic Experiment in Trans-European Suture Zone, Stud. Geophys. Geod., 52, 439–448, 2008.

Yliniemi, J.: Deep seismic sounding in the University of Oulu. Inst. Seismol., Univ. Helsinki, Report S-25, 1-6, 1991.

Yliniemi, J.: Oulun yliopisto Geofysiikan Observatorio: Seismografiasemat, in: BABEL, WABEL, SVEKA ja EUROPROBE, edited by: Manninen, J., XXVI Geofysiikan Observatoriopäivät Sodankylässä 8–10 January 1992, 79–86, 1992.

Yliniemi, J., Kozlovskaya, E., Hjelt, S.-E., Komminaho, K., Ushakov, A., and SVEKALAPKO Seismic Tomography Working Group: Structure of the crust and uppermost mantle beneath southern Finland revealed by analysis of local events registered by the SVEKALAPKO seismic array, Tectonophysics, 394, 41–67, 2004.