Working Report 2012-29

Local Seismic Network at the Olkiluoto Site

Annual Report for 2011

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June 2012

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Working Reports contain information on work in progress or pending completion.

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ABSTRACT

This report gives the results of microseismic monitoring during 2011. Excavation of the underground characterisation facility called ONKALO started in 2004. Before that, in February 2002, Posiva Oy established a local seismic network of six stations on the island of Olkiluoto. After that the number of seismic stations has increased gradually. In 2011 Posiva's permanent seismic network consists of 15 seismic stations and 20 triaxial sensors.

The purpose of the microearthquake measurements at Olkiluoto is to improve understanding of the structure, behaviour and long term stability of the bedrock. The investigation area includes two target areas. The larger target area, called *seismic semi-regional area*, covers the Olkiluoto Island and its surroundings. The purpose is to monitor explosions and tectonic earthquakes in regional scale inside that area. The smaller target area is called the *seismic ONKALO block*, which is a 2 km *2 km *2 km cube surrounding ONKALO. It is assumed that all the expected excavation induced events occur within this volume. At the moment the seismic ONKALO block includes ten seismic stations. An additional task of monitoring is related to safeguarding of the construction of ONKALO.

The configuration of the seismic network as well as the software packages applied in data processing and analyses have remained during the previous year. The design model of ONKALO and the brittle fault zone model of the Olkiluoto of the seismic visualization package Jdi were upgraded in 2011.

The network has operated nearly continuously. There was a 14 minutes and 30 second long operation failure in December 2011. That was the first network operation failure in five years.

Altogether 1223 events have been located in the Olkiluoto area, in the reported time period. Most of them (1098) are explosions that occurred inside the seismic semi-regional area and especially inside the seismic ONKALO block (1064 events). The magnitudes of the observed explosions inside the semi-regional area range from M_L = -2.2 to M_L = 1.5 (M_L = magnitude in local Richter's scale). Most of them are explosions. Three of the events are classified as induced microearthquakes.

Three excavation induced earthquakes were observed in 2011. The magnitude of the first event (9 February 2011) was significantly larger (M_L = -0.5) than the magnitudes of the two events (M_L = -2.0 and -1.9) that occurred on 14 May 2011. Estimated peak slip values of the earthquakes are 1 - 20 μm and the source radiuses about 10 meters.

Any known geologic structure could not be associated with the location of the first induced microearthquake, but it is possible to see an interconnection between the location of the events in May 2011 and the pervasive foliation of the bedrock surrounding the ONKALO.

According to the seismic monitoring the rock mass surrounding ONKALO has been stable in 2011. Indications of undeclared or inappropriate works, which would have influence on the safety of ONKALO, have not been found.

Keywords: Seismic network, microearthquake, monitoring, interpretation, safety, safeguards, stress field, fault plane.

Olkiluodon seisminen asemaverkko
Vuosiraportti 2011

TIIVISTELMÄ

Tässä raportissa esitetään seismisen monitoroinnin tulokset vuodelta 2011. Maanalaisen tutkimustilan (ONKALO) rakennustyöt alkoivat vuonna 2004. Tätä ennen, vuoden 2002 helmikuussa, Posiva Oy perusti Olkiluotoon kuuden seismisen aseman paikallisen asemaverkon. Sen jälkeen asemien määrä on kasvanut vähitellen. Vuonna 2011 Posivan kiinteä asemaverkko koostui 15 seismisestä asemasta ja 20 kolmikomponenttisesta anturista.

Mikromaanjäristysmittausten avulla pyritään lisäämään tietoa Olkiluodon kallioperän rakenteesta, liikkeistä ja vakaudesta. Tutkimuksen kohteena ovat tektoniset ja louhinnan indusoimat maanjäristykset. Seismisellä monitoroinnilla on kaksi kohdealuetta. Laajempi kohdealue, *seisminen lähialue*, sisältää Olkiluodon saaren lähiympäristöineen. Alueelta havainnoidaan räjäytyksiä ja tektonisia maanjäristyksiä. Pienempi kohdealue on sivuiltaan kaksikilometrinen kuutio (2 km *2 km *2 km) ONKALO-alue, joka ympäröi maanalaista tilaa. Tällä alueella tapahtuvat kaikki louhinnan indusoimat tapaukset. Alueen ulkopuolelle jääviä järistyksiä voidaan varmuudella pitää tektonisina. Seisminen seuranta on myös osa ONKALOn ydinsulkuvalvontaa.

Asemaverkon rakenne sekä datan prosessoinnissa ja analysoinnissa käytetyt ohjelmistot olivat samat kuin edellisenä vuonna. Tutkimusten visualisoinnissa käytettävä ONKALOn ja sitä ympäröivän kallion rakennemalli päivitettiin vuoden 2011 aikana.

Asemaverkko monitoroi lähes ilman toimintakatkoksia vuonna 2011. Joulukuussa oli 14 minuuttia ja 30 sekuntia kestänyt katkos. Se oli ensimmäinen asemaverkon toimintakatkos viiteen vuoteen.

Olkiluodon alueelle paikallistettiin raportoidulla ajalla yhteensä 1223 tapausta. Suurin osa näistä (1098) sijaitsi seismisellä lähi alueella ja erityisesti ONKALOn (1064 tapausta) alueella. Havaittujen räjäytysten magnitudit paikallisella Richterin asteikolla (M_L) olivat välillä -2.2 - 1.5. Lähes kaikki havainnot olivat räjäytyksiä. Kolme tapausta voitiin luokitella rakennustöiden indusoimiksi mikromaanjäristyksiksi..

Vuonna 2011 havaittiin kolme louhinnan indusoimaa mikromaanjäristystä. Ensimmäisen mikromaanjäristyksen (9.2.2011) magnitudi (M_L = -0.5) oli selvästi suurempi kuin 14.5.2011 tapahtuneilla järistyksillä (M_L = -2.0 ja M_L= -1.9). Kalliossa tapahtuneelle siirtymälle lasketut arvot olivat 1 -20 μm ja laskettujen siirrostasojen säteet olivat noin 10 metriä.

Ensimmäistä helmikuussa tapahtunutta maanjäristystä ei voida yhdistää mihinkään tunnettuun kallion rakenteeseen, mutta toukokuussa tapahtuneilla järistyksillä voidaan nähdä yhteys ONKALOa ympäröivän kallion rakenteelliseen suuntautuneisuuden kanssa.

Seismiset mittaukset osoittavat, että ONKALOa ympäröivä kalliomassa on pysynyt stabiilina vuonna 2011. Alueella ei ole havaittu ydinsulkuvalvonnan kannalta turvallisuuteen vaikuttavaa toimintaa.

Avainsanat: Seisminen asemaverkko, mikromaanjäristys, monitorointi, tulkinta, turvallisuus, ydinsulkuvalvonta, jännityskenttä, siirrostaso.

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1 INTRODUCTION

According to the Nuclear Energy Act, all nuclear waste generated in Finland must be handled, stored and permanently disposed in Finland. The two nuclear power companies, Teollisuuden Voima Oy (TVO) and Fortum Power and Heat Oy, are responsible for the safe management of the waste and for all associated expenses. These companies have established a joint company, Posiva Oy, to implement the disposal programme for spent fuel. Seismic monitoring is a part of this programme (Miller et al. 2002; Posiva 2003 and 2006). Possible applications of microearthquake monitoring at the repository are introduced in the Posiva's working report (Saari 1999).

In February 2002, Posiva Oy established a local seismic network of six stations on the island of Olkiluoto. The system is manufactured and installed by IMS (Institute of Mine Seismology). This network was designed for monitoring the rock volume surrounding the preliminary location of the underground characterisation facility called ONKALO. Later, in June 2004, the seismic network was expanded with two new seismic stations (OL-OS7 and OL-OS8). These stations made the network geometry more suitable for monitoring the final location of the ONKALO. The technical features of the microearthquake monitoring system are described in details in the Posiva's working reports (Saari 2003 and 2005).

In the beginning of 2006, the target area of the seismic monitoring expanded to regional scale. The four new seismic stations (OL-OS9…OL-OS12) were in operation in February 2006. The stations are equipped with three component 1 Hz geophones, which are suitable for investigations of regional tectonic seismicity. The new seismic stations locate from 3 to 7 km from the ONKALO.

At the end of 2006, two new triaxial geophones (OL-OS13 and OL-OS14) were installed into a borehole inside the ONKALO spiral. The new geophones aimed to improve the sensitivity and the depth resolution of the measurements inside the ONKALO block. They were fully integrated to the Posiva's network in 2007. Cable isolation of OL-OS14 was damaged during the installation and later in 2007 the electric wires were corrupted. The sensor was permanently disconnected from the network in October 2007.

In November 2008, the seismic network was upgraded by a new triaxial borehole seismometer in order to improve the sensitivity and the depth resolution inside the ONKALO block. The sensor (ONK-OS1) was the first one inside ONKALO. The next seismic station (ONK-OS2) inside ONKALO was integrated to Posiva's seismic network in Olkiluoto in March 2010.

In May 2010 one new triaxial and three new uniaxial sensors were integrated to Posiva's network. Those four sensors form a small scale subnetwork, which relates to the heating experiment in the ONK-TKU-3620 niche. After the experiment (18 August 2011), these sensors were utilized in a new temporary task. The settings of these sensors were changed to support the general measurements of the ONKALO block.

In the beginning, the network monitored tectonic earthquakes in order to characterise the undisturbed baseline of seismicity of the Olkiluoto bedrock. When the excavation of

ONKALO started, in August 2004, the network monitors also explosions and excavation induced seismicity. Since February 2006 explosions and tectonic earthquakes are monitored in regional scale. In 2008 started a new practice to report also other seismic observations that are located in the ONKALO region. Those events, which are not explosions or earthquakes, are mainly rock falls.

The purpose of the microearthquake measurements at Olkiluoto is to improve understanding of the structure, behaviour and long term stability of the bedrock. The observations give an opportunity to approximate in what extent and where the bedrock is disturbed, the stability of the rock facility and the adjustment processes occurring in the surrounding rock mass. A further task is mapping of the disturbed weakness zones in the rock mass surrounding the excavated construction.

The main target volume of the seismic monitoring is the underground rock characterisation facility and the rock mass surrounding it. According to the simulation done by IMS, the expected sensitivity is of the order M_L = -2.5 in the ONKALO area. The regional sensitivity of the Olkiluoto area is approximately of the order of M_L = -1.0 inside the Posiva’s regional network.

Identification of active fracture zones is an essential element in a comprehensive study of potential hazards related to the final disposal of spent nuclear fuel. The weakness zones adjust releasing stresses and strains of the rock mass as well as they are the main paths of hydraulic flow in the bedrock. The movements occurring on these zones accumulate during the lifespan of the repository and possibly can cause changes in the stability, stress field and groundwater conditions of the rock mass. When the fracture zone model is presented together with the observed seismic events, active or unstable zones can be identified. The interpretation can bring out changes in the rock mass that, for example, may result to re-evaluation of certain water conducting zone and even further cause changes to final disposal facility layout.

The main purpose of annual reports is to support modelling of the rock mass surrounding ONKALO. If possible, interpretation of the observed seismicity related to certain areas or weakness zones of the rock mass is presented. The annual reports also include descriptions of technical events, like changes in the configuration of the seismic network, technical failures occurred, etc. The reports can be utilized as a source material in further seismic, geophysical and/or rock mechanical interpretations.

Monitoring of regional tectonic seismicity aims at better understanding of ongoing seismotectonic processes in the Olkiluoto area. Although the focus of regional seismic monitoring is limited inside and close to the seismic network other regional earthquakes are also recorded and stored in the Posiva’s data archive. These recordings from the Olkiluoto site are valuable in seismic hazard studies, for example when attenuation of seismic signal is evaluated.

The seismic monitoring is also a part of Posiva's safeguards programme. Therefore all the observed clustering of explosions of the area are analyzed and reported in the monthly reports, which are archived in the Posiva’s electronic document management system (Kronodoc). The monthly reports are compiled into four month period interim reports and delivered to the Radiation and Nuclear Safety Authority of Finland (STUK).

The seismic events are also examined in longer time spans. If a slowly developing clustering of explosions is recognized, the origin of the clustering is explained as well. The results of the monthly reports are edited to annual safeguard report and to annual report of rock mechanical monitoring by Posiva (e.g. Lahti et al. 2009).

2 OPERATION OF THE SEISMIC NETWORK

2.1 Upgrades of Instrumentation

During 2011, the configuration of the seismic network has remained mainly the same as in 2010 (Saari & Malm 2011).

In May 2010 one triaxial and three uniaxial accelerometers were integrated to Posiva's network. Those four sensors formed a small scale subnetwork, which relates to the thermal spalling experiment inside the ONK-TKU-3620 niche also known as the POSE niche (Posiva Olkiluoto Spalling Experiment). This subnetwork was capable to locate events of magnitude ML > -5 inside its area. The events occurred inside the ONK-TKU-3620 niche are analyzed and reported separately as a part of the thermal spalling experiment.

First two phases of the POSE heating experiment in the ONK-TKU-3620 niche were finished in the beginning of June 2011 and the local microseismic measurements were stopped in August 2011. The setting of the sensors in the niche were changed on 18 August 2011 so that they correspond the settings of other seismic stations inside the ONKALO (P-wave velocity α = 5800 m/s, S-wave velocity β = 3450 m/s, Sampling rate = 6000 Hz, etc.). The new temporary settings support the general measurements of the ONKALO block. The geophones aim to improve the sensitivity and the depth resolution of the measurements inside the ONKALO block.

2.2 Upgrades of data processing and interpretation

The new brittle fault zone model of the Olkiluoto area was integrated in the seismic visualization package Jdi in February 2011 (Aaltonen et al. 2010).

The applied design model of the ONKALO in Jdi was dated on 11 May 2010. In 2011 the upgrade of the model included the lowermost part of the ONKALO. The new TU5 model (dated 29 March 2011) was updated to Jdi in April 2011.

2.3 Interpretation practice

The interpretation of seismic data is performed within the frameworks of the lineament interpretation of the Olkiluoto area (Korhonen et. al 2005) and the geological model of the Olkiluoto site (Paulamäki et al. 2006). Those models applied in the visualisation and in the interpretation of the seismicity are the same as in 2006 and they are included in the visualisation software Jdi. The models are described in the previous annual report (Saari & Lakio 2007).

Inside the Olkiluoto site there will be several different study areas and models produced which will not necessary cover the same volume of rock (Posiva 2005). The selected volume of the rock depends on its application. However, for reasons of clarity, a standardized nomenclature is adopted. Altogether seven expressions are presented (Posiva 2005), and the following two of them are applied in seismological interpretation. According to that nomenclature: 1) Site area includes the well investigated area covered by deep drillholes and the associated shallow monitoring holes. 2) Any particular area larger than the Olkiluoto site is called semi-regional.

In 2005 the seismic network consisted of eight stations close to the ONKALO. The monitoring and interpretation was focused on volume called the ***seismic ONKALO block.*** The seismic ONKALO block is a 2 km *2 km *2 km cube surrounding the ONKALO (See Chapter 4.2). It is assumed that all the expected excavation induced events occur within this volume (site area). At the moment the seismic ONKALO block includes eleven seismic stations. Two of them are equipped with triaxial drillhole seismometers.

Outside the ONKALO block the location accuracy is not as good as inside or close to it. In 2006, four new 1 Hz seismometers were installed and the focus of interpretation was expanded to semi-regional scale. Inside this area, called the ***seismic semi-regional area*** the sensitivity and location accuracy of the seismic network is good or sufficient. It also covers the semi-regional area of the lineament interpretation of the Olkiluoto area (Korhonen et al. 2005). The Posiva’s 1 Hz seismic stations improve the understanding of the general seismotectonic behaviour of the Olkiluoto region.

It is likely that potential tectonic earthquakes occur in existing weakness zones of the bedrock. Lineaments coincide often with those zones. One of the main purposes of the semi-regional monitoring is to identify and characterize seismically active fracture zones. Activity somewhere in a fracture zone indicates potential activity also elsewhere in that structure. The ONKALO site is 6-8 km from the sides of the seismic semi-regional area, close to the middle of the area. The main orientation of the lineaments is NW-SE. In that orientation, the seismic semi-regional area is 17-20 km long, close to the ONKALO (Saari & Lakio 2007).

The lineament interpretation of the Olkiluoto area comprised geophysical and topographic data (Korhonen et al. 2005). The geophysical data included magnetic, electromagnetic, seismic and acoustic data from aerogeophysical, ground and marine surveys. In the final integrated interpretation the lineaments are classified by their uncertainties into three groups: low, medium and high uncertainty. The lineament interpretation of the Olkiluoto area is integrated in the seismic visualisation program Jdi applied in the seismic interpretation.

The geological model of the Olkiluoto site consists of four submodels: the lithological model, the ductile deformation model, the brittle deformation model and the alteration model (Paulamäki et al. 2006). The model is utilised in interpretation of seismic processes, for example, when active faults or volumes prone to seismic movements are identified and analysed. Any unit of the model can be selected for closer visual analysis. That kind of approach is used when the results of fault plane solution of microearthquakes are interpreted together with brittle deformation model (see e.g. Saari & Lakio 2007).

The observations are presented separately for the seismic semi-regional area and the seismic ONKALO block by the visualisation program Jdi. The onset times of the events are recorded in Coordinated Universal Time (UTC), which is commonly used in seismic bulletins. Compatible time systems make the comparison and integrated use of seismic data fluent. Local time in Finland is UTC + 2h during normal time and UTC + 3h during summer time (daylight saving time).

The Institute of Seismology, University of Helsinki, maintains the regional seismic station network in Finland. The nearest seismic stations are in Laitila, about 40 km and in Åland, over 100 km from Olkiluoto. Furthermore, the closest stations are in Åland over 100 km SW and about 200 km from Olkiluoto: three SE (in Metsähovi, Nurmijärvi and Pernaja), three East (in Keuruu, Sumiainen and Kangasniemi) and one North of Olkiluoto (in Ylistaro). At the same distance, are also the nearest Swedish stations, at the western coast of the Bothnian Sea. The detection threshold of the Fennoscandian seismic stations in the Olkiluoto area is of the order of M_L = 1.5 or less.

Only the events occurred within the seismic semi-regional area are included in the event tables of the monthly reports. However, when earthquakes and potential earthquakes are concerned, the investigation area is not that limited. The observations of the Posiva's network are compared with the events reported in the bulletins of the Institute of Seismology (Seismic Events in Northern Europe). If there is an earthquake within a distance of 200 km from Olkiluoto in the bulletins, it is rather likely recorded also in Olkiluoto. Those recordings are reported and stored in the Posiva's data archive. These recordings from the Olkiluoto site are valuable in seismic hazard studies, for example when attenuation of seismic signal is evaluated. Also other unusual events outside the seismic semi-regional area, such as events from the sea area, are under special attention.

Although, the geophones are capable to observe explosions and earthquakes within a much wider area, the analysis is focused on the seismic semi-regional area. It is assumed that regional events occurring outside that area are located by the Finnish and Swedish regional seismic networks. The recordings of the Posiva's stations can be utilized, if necessary, to improve the interpretation based on recordings the national seismic stations. Posiva's recordings of three Finnish earthquakes (19 March 2011, Mäntsälä M_L =2.6, 1 December 2011, Kouvola, M_L = 2.8 and 22 December 2011, Kouvola, M_L = 2.6) were archived for purposes of possible further studies.

Also teleseismic events, i.e. events occurring over 1000 km from Olkiluoto, are recorded. Those can be recognized by comparing the recordings to the bulletins of Institute of Seismology, University of Helsinki (http://www.helsinki.fi/geo/seismo/) and international data centres, such as EMSC/CSEM (http://www.emsc-csem.org/). Teleseismic events are rejected and not included in the data archive.

2.4 Data availability

There are eleven permanent seismic stations in operation for monitoring the seismic ONKALO block and five for the seismic semi-regional area. Station OL-OS8 has sensors suitable for monitoring of the ONKALO block and for the semi-regional area. In addition, the temporal network in the ONK-TKU-3620 niche gave additional support to the analysis of the ONKALO block in 2011.

Partial breaks in network operation, like failure of single station or component, are unavoidable in any continuous monitoring. However, those can lower the quality of operation, like the location accuracy of seismic events. Minimum number of stations needed for the event location is three. Temporal failure of one station has only minor influence on the reliability of the operation or on the location accuracy.

The event detector of each seismic station compares the short term average (STA) of the amplitudes to the long term average (LTA) of the amplitudes. The event detector starts recording data when the STA/LTA ratio exceeds the pre-set trigger value. The field stations monitor continuously, but only the signals that can be related to a seismic event, are sent to the central site computer. The recordings which are related to the same seismic event are associated automatically. An event is sent, when a predetermined number of seismic stations detect earth vibrations that exceed the trigger value within a certain time window. The number of sensors applied in event association was set to four, because five of the stations inside the ONKALO block (OL-OS2, OL-OS3, OL-OS4, OL-OS7 and OL-OS8) are equipped with two different types of sensors. Otherwise three sensors would be enough for event association. In addition to that, it was set another number of associations for the group of the 1 Hz seismic stations. If three of those five stations can be associated, the recordings are interpreted to be from the same source.

In Posiva’s seismic measurements, a special attention has been paid to reliable data recording and transmission. All detected events are stored in the field stations until they are safely transmitted to the site computer. The central site server in Olkiluoto associates the recordings of the same origin and emails the recorded events to the office computer in Vantaa, where the events are analysed.

Events are associated in the Olkiluoto site computer in real time. If connection to one of the stations is failed, the recording of that station is not associated. However, generally the analysis can be based on the recordings of the remaining sites. The unsent event stays several months in the hard disk drive of the data acquisition unit (SAQS or GS) and it can be downloaded to the office PC, if necessary.

The possibility of data loss due to failure of the site computer is reduced by the redundant hardware configuration. Practically, when the data has arrived to the Olkiluoto server, it cannot be lost. Between Olkiluoto and Vantaa the data management is based on internet technology. Email server keeps the seismic data until the office computer has received the data. In practice, the design of the data management guarantees that simultaneous power or communication failure in all stations or nearly all stations is needed to cause an operation break of the seismic network. Some of the breaks just postpone the data transmission from seismic stations via the Olkiluoto server to Vantaa (Table 2-1 and Figure 2-1).

The whole chain of data management is checked every morning by a test signal. The signal controls the prevailing status of the seismic sensors and the data flow from a single station to the office computer in Vantaa. If the test signal from any sensor is missing or looks unusual, the troubleshooting is started. This kind of procedure aims to keep operational breaks as short as possible.

The two way data transmission between four semi-regional seismic stations (OL-OS9…OL-OS12) and the server in Olkiluoto is done via radio links. The connection is polled every four seconds. If it appears that the connection is down, it is checked every two minutes to see if it can be re-established. The data acquisition units of the seismic stations are able to buffer the data, so no data is lost if there are short temporary interruptions (1-2 minutes) to the communication system. Data is also logged to the local disk on the SAQS as a backup, should there be a need to recover data from an important event.

Partial failures of the network, that just lower the quality of operation, are usually related to a single station. Typical duration of the break is from few hours to few days. Breaks related to rearrangement or troubleshooting of the monitoring are designed in advance to be as short as possible.

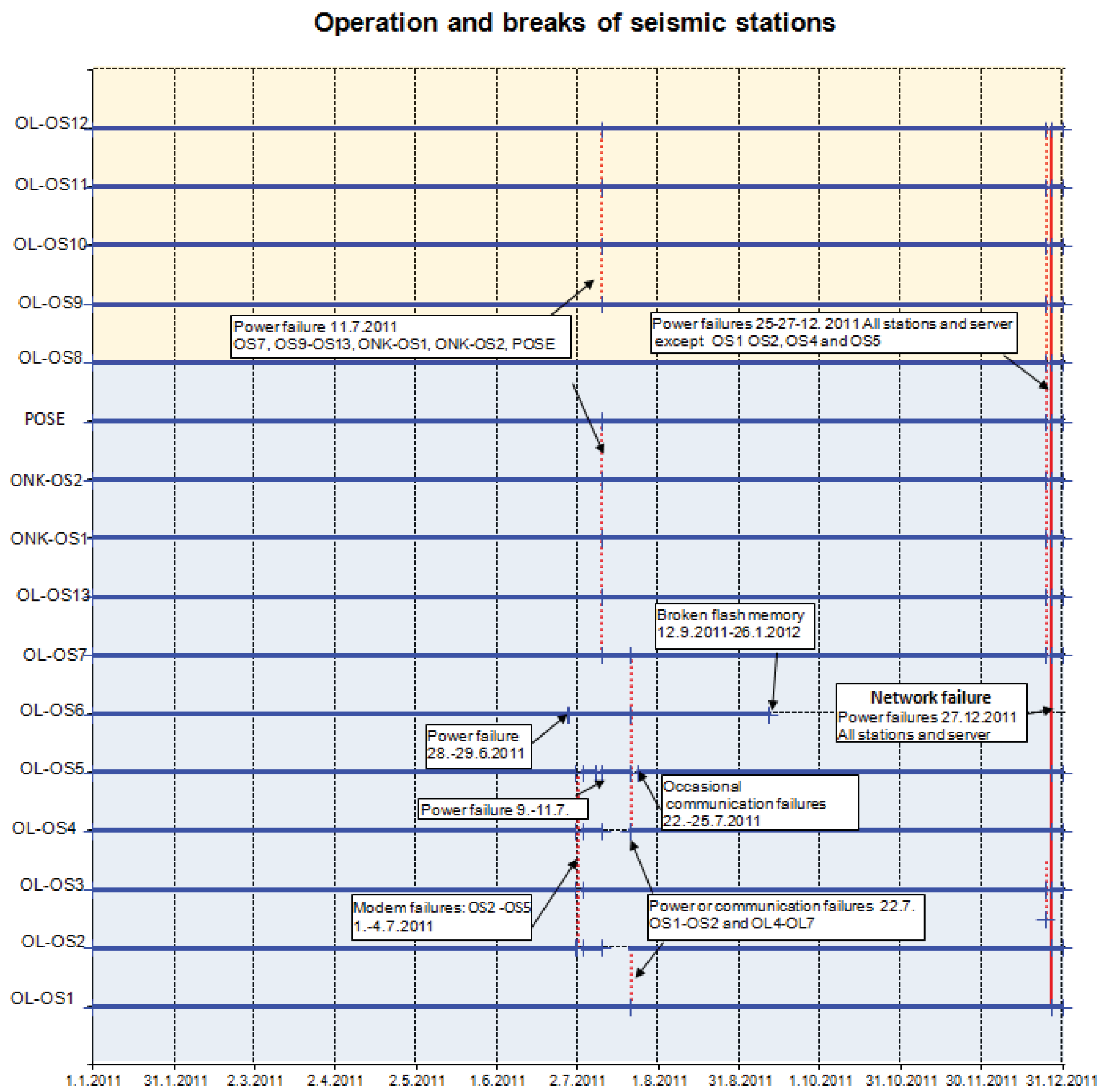


Figure 2-1. Operation times and breaks of the seismic stations monitoring mainly the ONKALO block (blue region) and the semi-regional area (light brown). Station OL-OS8 has sensors suitable for monitoring of the ONKALO block and for the semi-regional area. POSE refers to the subnetwork in the *ONK-TKU-3620 niche.*

The operation reliability of the network has been almost as good as during the previous year. In 2011 there was one 14 minutes and 30 second long network operation failure. This failure occurred on 27 December 2011. This is the only network operation failure in five years. In spite of few breaks in different parts of the system the network has operated continuously during previous years 2006 - 2010. The failures in 2011 relate mainly to strong storms in July and December 2011. These storms caused coincident failures in four to 15 stations. During the rest of the months there have been only two failures in 2011.

The first operation failure in 2011 was at the end of June. The seismic station OL-OS6 had a 14 hours and 22 minutes long operation failure, which started on 28 June at 16:14 and was over on 29 June at 06:36. There was not any noticeable reason for the failure and it was fixed by resetting the current switch of the data acquisition unit of OL-OS6.

Table 2-1. *Operation failures in monitoring.*

Date	Duration	Comments	Station
28.-29.6.2011	14 h 22 min	Power failure	OL-OS6
1.-4.7.2011	2 days	Modem failures, thunder	OL-OS2… OL-OS5
9-11.7.2011	1 h 24 min	Power failure, thunder	OL-OS5
11.7.2011	10 min	Communication failure, thunder	OL-OS7, OL-OS9 ... OL-OS13, ONK-OS1, ONK-OS2 and POSE
12.9.2011-26.1.2012	3 months 18 days in 2011	Flash memory failure	OL-OS6
25.-27.12.2011	35 hours	Power failure, storm	All stations and server except OL-OS1, OL-OS2, OL-OS4 and OL-OS5
27.12..2011	14 min 30 s	Network failure, storm	All stations and server

The island of Olkiluoto experienced exceptionally strong thunderstorms in the beginning of July (1-3 July 2011). Over 500 lightnings were recorded by the seismic network and connections to the stations OL-OS2, OL-OS3, OL-OS4 and OL-OS5 were lost. Few modems and modem cards were broken and the connections were fixed on 4th of July 2011. Station OL-OS2 was down 2 days 2 hours and 20 minutes. The failure started on 1 July 11:30 and was over on 4 July 8:50. The stations OL-OS4 and OL-OS5 went down on 1 July 11:34. The failure of OL-OS4 was fixed about 3 days later (2 days 23 hours 38 minutes) on 4 July 10:56. The failure of OL-OS5 was fixed after 2 days, 21 hours and 21 minutes on 4 July 8:11. Station OL-OS3 went down on 3 July 01:00 and it was up on 4 July 7:54 (after 1 day, 7 hours and 54 minutes).

There were also weaker thunderstorms later in July. They caused operation failures that are reported in automatic downtime reports generated by the Olkiluoto server. Station OL-OS5 went down on 9 July 2011 9:11 and was up on 11 July 8:51 (1 day 23 hours and 50 minutes later). On 11 July at about three o’clock UTC stations OL-OS7, OL-OS9, OL-OS10, OL-OS11, OL-OS12, OL-OS13, ONK-OS1 and ONK-OS2 as well as the stations of the temporary network in the ONK-TKU-3620 niche experienced about 10 minutes long communication failure.

The next failures started on 22 July 2011 20:50 at it related to six stations: OL-OS1, OL-OS2, OL-OS4, Ol-OS5, OL-OS6 and OL-OS7. The duration of the power or communication failures was about 5 minutes. After that there were occasional communication failures between OL-OS5 and the Olkiluoto server until morning of 25 July.

At the end of August 2011 the majority of the failures were fixed. Altogether 13 of the 15 permanent seismic stations were running correctly. OL-OS1 and OL-OS2 had response failure in one of the accelerometers components. Those sensors can be used in the event location, but they are not suitable for a more sophisticated analysis. However, the recordings of the triaxial geophones of OL-OS2 can be used when data from that station is utilized in calculations of source parameters and fault plane solutions. OL-OS1 has only triaxial accelerometer, but no triaxial geophone installed. It seems that the EMI filters in the CPU cards inside SAQS units related to accelerometers in OL-OS1 (E-W component) and OL-OS2 (N-S component) are broken by lightning.

An operation failure in station OL-OS6 started on 12 September 2011 at 10:00:10. Troubleshooting revealed that the flash memory of the station was broken. The flash memory takes care that the information stored in the chip is retained also during a power failure.

The vertical component of the pulse in OL-OS10 was slightly anomalous in the beginning of November 2011. The main pulse was normal but decay phase of the test pulse was slower than usual. The quality of the recordings of the stations was still fine, but the test pulse indicated need of checking and maintenance. The cable connectors were cleaned and the lightning unit was replaced with a new one on 16 November 2011. After that the test pulse has been normal.

Several stations (OL-OS3, OL-OS7, OL-OS8, OL-OS9, OL-OS10, OL-OS11, OL-OS12, OL-OS13, ONK-OS1 and ONK-OS2) and the Olkiluoto server had a 35 hours long power failure which started on 25 December at 22:30 and ended on 27 December at 09:32 (UTC). In four stations (OL-OS1, OL-OS2, OL-OS4 and OL-OS5) the failure was only 14 minutes 30 seconds long. This failure started on 27 December 16:15:34. These failures were caused by a strong storm.

All detected events are stored in the field stations until they are safely transmitted to the site computer. This means that even though the server was down four stations were still in operation. Minimum number of stations needed for the event location is three. The seismic network was out of operation for 14 minutes and 30 second on 27 December 2011.

Except the short failure on 27 December, the seismic network has operated continuously in December 2011. The 35 hours long failures during Christmas time have lowered the location accuracy of the seismic events during that interval. Since there was a break in the ONKALO excavation between 22 December 2011 and 2 January 2012 it is presumable that no excavation related events happened during this failure.

Before the failure of OL-OS6 on 16 September 2011 all permanent stations are practically in continuous operation. Altogether 14 of the total 15 permanent seismic stations are running about 3 and half months after that. However, the sensors of the heating experiment measurements in the ONK-TKU-3620 niche were changed to support the general measurements of the ONKALO block in August 2011. Those sensors compensate the lack of OL-OS6 at the end of the year 2011. OL-OS6 was back in operation on 16 January 2012, when the new CPU card was installed.

In spite of the above mentioned failures, the seismic network has operated continuously. These failures have slightly lowered the location accuracy of the seismic events during the remaining months of the year 2011. The decreased quality of recordings of the stations OL-OS1 and OL-OS2 have also a minor influence on the quality of the analysis in general. Maybe due to its location nearly above the ONKALO, the lack of station OL-OS6 seems to influence the location accuracy more than absence of a single station is expected.

3 EVENTS RECORDED BY THE SEISMIC NETWORK

3.1 Uncertainties related to measurements

Identification of an individual earthquake among the cluster of excavation blasts includes elements of uncertainty. The majority of the excavation induced seismicity (type A) tends to occur very close, in time and space, to the latest excavation blast. These events occur often in swarms and their seismic signals are not representing a typical earthquake signal. They are associated with the “fracture-dominated” rupture. Type B events are temporally and spatially distributed throughout the active excavation region. They represent “friction-dominated” slip in existing shear zone such as faults or dikes and have source properties similar to tectonic earthquakes (Richardson & Jordan, 2002). Type B events have many characteristic that make them easier to identify in comparison to type A events.

Although tectonic earthquakes are easier to identify than some of the induced earthquakes (type A), the orientation of seismic stations with respect to the hypocentre is essential. It is important to get a seismic signal from many different directions. This is important not only for location but also for a successful identification of the seismic event and for calculations of the fault plane solution. This fundamental condition is fulfilled inside the seismic semi-regional area. Outside this area the support of recordings of other seismic networks is valuable.

Accurate location of a seismic event is one of the key parameters of the seismological interpretation. If the location is incorrect, the subsequent seismological analysis is inaccurate. The velocity model (P-wave velocity, α = 5600 m/s and S-wave velocity, β = 3250 m/s) seems to give rather good results within the seismic ONKALO block, when the surface stations (OL-OS-1 ... OL-OS8) are concerned. For the underground sensors of the ONKALO block (OL-OS13, ONK-OS1 and ONK-OS2) the preset default velocities are: α = 5800 m/s and β =3350 m/s. For the stations used mainly in the studies of semi-regional seismicity (OL-OS9 … OL-OS12) the corresponding default velocities are also α = 5800 m/s and β = 3350 m/s. These velocities are used in automatic event association and location procedures. They are usually applicable also when the result of automatic location is improved manually. In that phase, the station specific velocities can be changed. That may be necessary, for instance, when a seismic signal arriving to a seismic station runs through a structure, which lowers the average seismic velocity.

The seismological data processing software (Jmts) accepts just one station specific P-wave and S-wave velocity. Simple velocity model serve automatic event location, which is necessary in mines where hundreds or thousands events occur in a day. This software limitation reduces the location accuracy of seismic events, if the velocity structure of the bedrock is complicated. However, the P- and S-onsets picked by the analyst are available. Those onset times can be used as input for a more sophisticated program for event location.

The blasting work is generally detonated in sequences. Usually, that means that the S-phases are hidden in the signals of blasts following each other and the event location is based only on P-onsets. The lack of S-onset dilutes the location accuracy. Similar problem is related to above mentioned type A events. They occur very close, in time and space, to the latest excavation blast and their mechanism is similar to explosions. S-phases are difficult to distinguish. Therefore, a special attention is paid to the latest events of the blasting sequence.

When the event is detected, it is immediately emailed to the office PC in Vantaa, where it is automatically analysed. The location and magnitude of an event is determined when the email has arrived, basically in few minutes. The result of automatic analysis is uncertain and always verified manually. The decision of the seismic source (explosion or earthquake) is done by experienced analyst.

Some of the detected events are rejected. Those recordings are caused by lightning, raise boring machine, coincidental artificial noise (electronic failure, vehicles, visitors, construction work, forest work, rock falls, etc.), natural noise (e.g. frost, wind shaking trees or strong waves hitting the shoreline) and distant teleseismic earthquakes or by a combination of those.

3.2 General statistics

Generally the number of rejected events is from few tens to a few hundred per month. Exceptionally high monthly number of rejected events is usually related to lightning, or human activity.

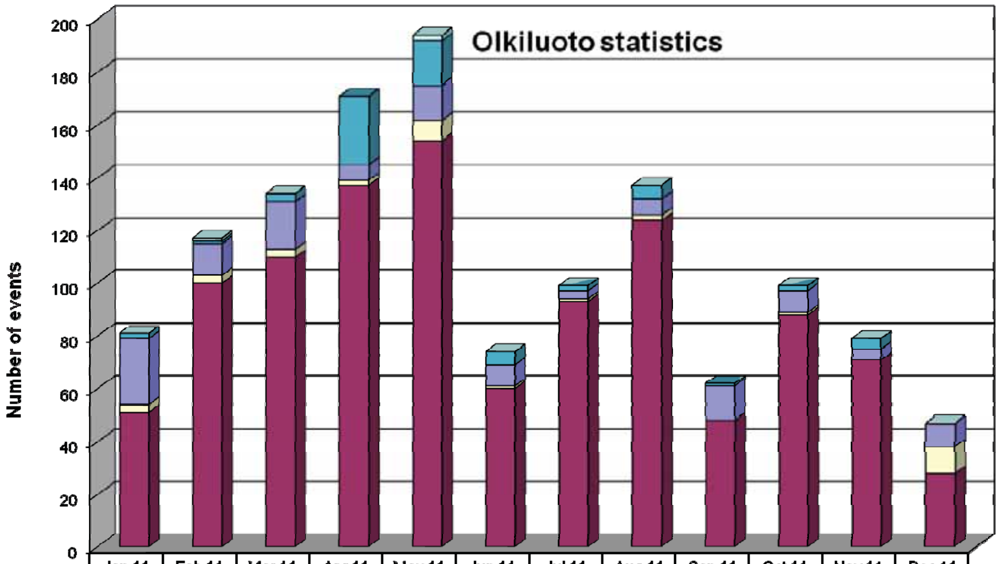
Until August 2011 a large number of rejected events relate mainly to the experiment that is conducted in the ONK-TKU-3620 niche. The numbers of rejected event were from 200 to over 2000 events per month. There were four accelerometers below the floor of the niche, which are capable to locate events of magnitude $M_L > -5$ inside the area of this temporary subnetwork. The rejected events in ONK-TKU-3620 were observed only by those four sensors. They were different kind of artificial seismic signals generated by the works done inside the niche.

July 2011 was characterized by about 2500 rejected events. Those events relate mainly to the thunderstorms but also to the experiment that is conducted in the ONK-TKU-3620 niche. August 2011 was characterized by nearly 2000 rejected events. Those events relate mainly to the experiment that is conducted in the ONK-TKU-3620 niche. Another larger group of rejected events associate with the troubleshooting of failures that occurred during the thunders in July 2011. The nearly 600 rejected events in December 2011 were mainly caused by strong storms.

In 2011 the number of accepted events is 1223 (Figure 3-1). The majority of the events (1064) are explosions inside the seismic ONKALO block (87 %). Altogether 159 of the accepted events have been located outside the seismic ONKALO block. Only 34 of them are located inside the seismic semi-regional area. Two of those are not explosions, but they relate to other kind of human activity (dredging, see Figure 3-1). Those two events are not separated in general statistics, but included in the group of explosions. The other accepted events (125) are located mainly close to the semi-regional area. Also three earthquakes occurred in southern Finland are in this group.

As in 2010 the seismic events other than explosions or earthquakes that are located in the ONKALO block are also reported. The number of those miscellaneous small seismic events (68) in 2011 is much larger than in 2010 (10). The events are mainly caused by rock falls and human activity (truck loading, scaling etc.), but also other types of events are included in that group (see Chapter 4). However, most of those miscellaneous events are so small and disturbed by noise that they cannot be located and therefore they are rejected.

The majority of the accepted events were explosions. Six of the recorded events were earthquakes. Three of them were tectonic that occurred in southern Finland and three other ones were excavation induced microearthquakes inside the ONKALO. Detailed descriptions of those earthquakes can be found later in Chapter 5 in this report.



	Jan 11	Feb 11	Mar 11	Apr 11	May 11	Jun 11	Jul 11	Aug 11	Sep 11	Oct 11	Nov 11	Dec 11
induced earthquakes	0	1	0	0	2	0	0	0	0	0	0	0
misc. small events	2	1	3	26	17	5	2	5	1	2	4	0
other accepted	25	12	18	6	13	8	3	6	13	8	4	9
semi-reg. not ONKALO	3	3	3	2	8	1	1	2	0	1	0	10
ONKALO block	51	100	110	137	154	60	93	124	48	88	71	28

Figure 3-1. *Monthly statistic of the monitoring in the Olkiluoto area in 2011.*

The overall activity inside the seismic semi-regional area has been rather constant (Figure 3-2). The annual average number of events has been of the order of 92 per month, which is about as much as in 2009 (97/month) but more than in 2010 (79/month). The activity of the seismic semi-regional area is dominated by the activity of the seismic ONKALO block.

The increase of the cumulative number of events is high until 8 June. After that the number of events is low until 5 July (Figure 3-2). That is related to period of lower excavation activity in the ONKALO. After that the number of events increase again, but not as fast as in the beginning of 2011. The highest activity rates in 2011 are of the order of 13 events per day during the period from March to May 2011. The highest activity rates in 2010 were of the order of 10 events per day.

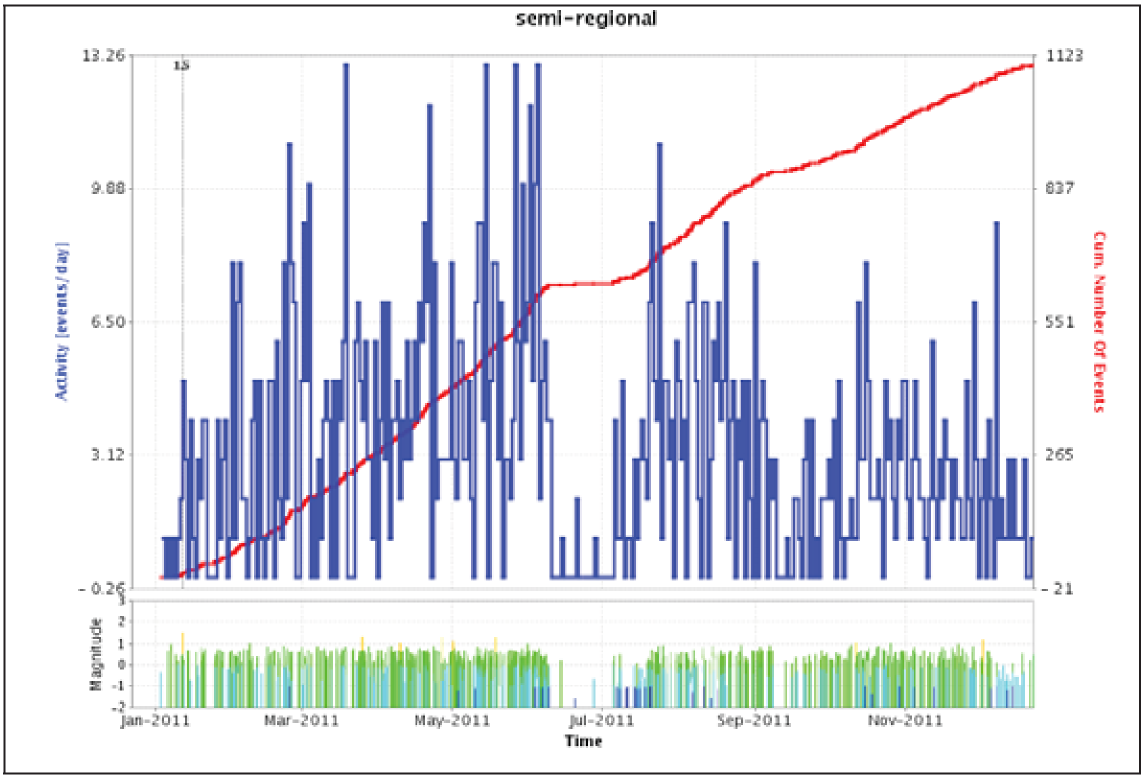


Figure 3-2. *Number of explosions per day (blue) and cumulative number of explosions (red) inside the seismic semi-regional area (altogether 1098), in 2011.*

The most active months in 2011 were February, March, April, May and August, when there were over 100 recorded events inside the semi-regional area. Figures 3-1 and 3-2 show that the number of explosions increases gradually in the beginning of 2011. The numbers of accepted events are 145 in April and 175 in May. During those months the number of explosions inside the ONKALO block is high (April 137 and May 154). Also the number of miscellaneous small events is higher than usual, which is another indication of increased excavation activity. The increased excavation activity may be one of the factors, which are associated with the microearthquakes occurred on 14 May 2011.

4 EXPLOSIONS AND MISCELLANEOUS SMALL EVENTS

4.1 Explosions in seismic semi-regional area

Because the seismic monitoring is part of Posiva's safeguards programme (Posiva 2006), the observed explosions inside the seismic semi-regional area are located. If clustering of explosions is recognised, the origin will be verified. The applied interpretation practice is presented in Chapter 2.3.

Altogether 1098 explosions located in the seismic semi-regional area in 2011 are presented in Figure 4-1. The magnitudes range from M_L = -2.2 to M_L = 1.5. The events outside the ONKALO have occurred on the ground surface. The number of those surface events (34) is smaller than in 2010 (48) and larger than in 2009 (26).

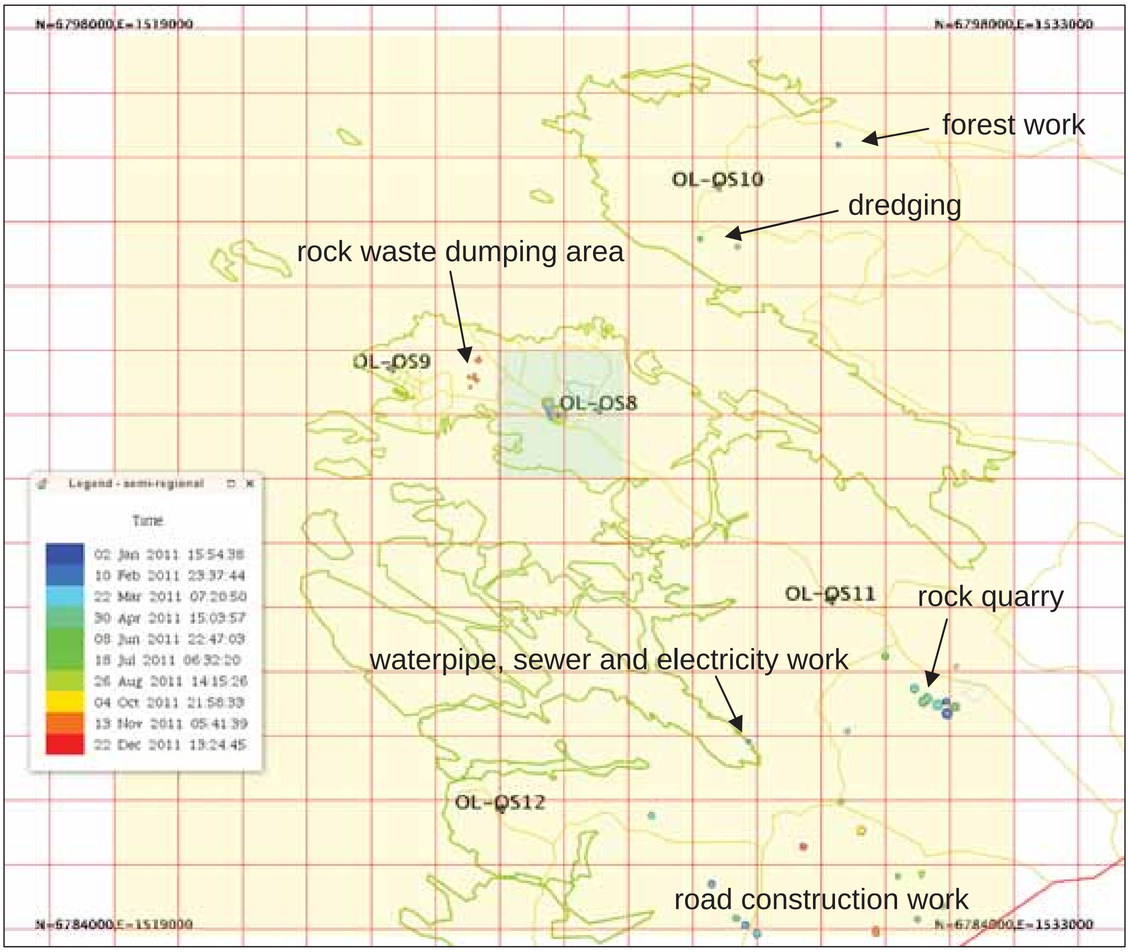


Figure 4-1. Observed 1098 explosions inside the seismic semi-regional area (light brown), in 2011. Seismic stations equipped with 1 Hz geophones are shown as blue triangles. Events are coloured by time. The size of sphere is relative to the events magnitude. Grid size is 1 km².

The main clustering of epicenters outside the Olkiluoto Island represents explosions from the rock quarry owned by Interrock Oy. The other clustering of events is in the Olkiluoto Island. Those nine explosions are related to works in the rock waste dumping area 2011. Other observations are rather occasional: Forest work in January, explosions related to water pipe, sewer and electricity construction works in February and dredging in May 2011. Because of the wave form of the seismic signal, the location of dredging is not very accurate. The true locations of those two events are at the shore line, where the dredging area was discovered. The rest of the events relate to road construction works in the south-eastern corner of the semi-regional area (Figure 4-1).

4.2 Explosions in seismic ONKALO block

The explosions (1064 events, M_L = -2.2…1.2) located inside the seismic ONKALO block are presented in Figures 4-2 and 4-3. In addition to the underground explosions in the ONKALO, there is one event located at the surface of the block (Figure 4-2). The event at surface occurred on Sunday 2 of January 2011. Although the origin of the event is not confirmed by Posiva, it is quite likely an artificial event. The recordings of the event do not look like they were generated by an earthquake. Actually the location of the event and the waveforms of the recordings are very similar to the shots related to the excavation work of the ventilation building's canal in 10 - 12 December 2010. Instead of explosions the event could be related to loading or frost at the ventilation building site. All the other explosions in the ONKALO block relate construction works at the level about -420 m and below that (Figures 4-2 and 4-4). Those blasts are mentioned in the daily reports of Destia Oy, which is responsible for the excavation of the ONKALO.

Figures 4-3 and 4-4 illustrate how the excavation has proceeded during the year 2011. In January and February 2011 the blasts in the ONKALO associate with the excavations of the main tunnel, central tunnel (PL4512) and in the demo tunnel area. In March start excavations also in some parts of access tunnel. The excavations of the main tunnel and the access tunnels continue during every month from March to December. That covers mainly the area south of parking halls 1 & 3, in Figure 4-3.

The excavations of the ONKALO are at the highest level from April to 8 June 2011 (see Figure 3-1). During that period excavations were done at the same time in the main access tunnel, demonstration area and in the technical rooms.

Excavations of the second demonstration tunnel started in July 2011 at depth of about 420 m. After that the excavations of demonstration area are done in phases (in August, October and December). Constructions of the parking hall 1 & 3 (ONK-TPH-4665-154) started in October 2011 (see Figure 4-3). During the last three months of 2011 also the deepest parts of the ONKALO at depths of about 440-455 m were excavated (Figures 4-3 and 4-4).

The rooms constructed in 2011 are at the depth of about 420 m (demonstration area and central tunnel) and depths from about 430 m to 455 m (the main access tunnel and the technical rooms).

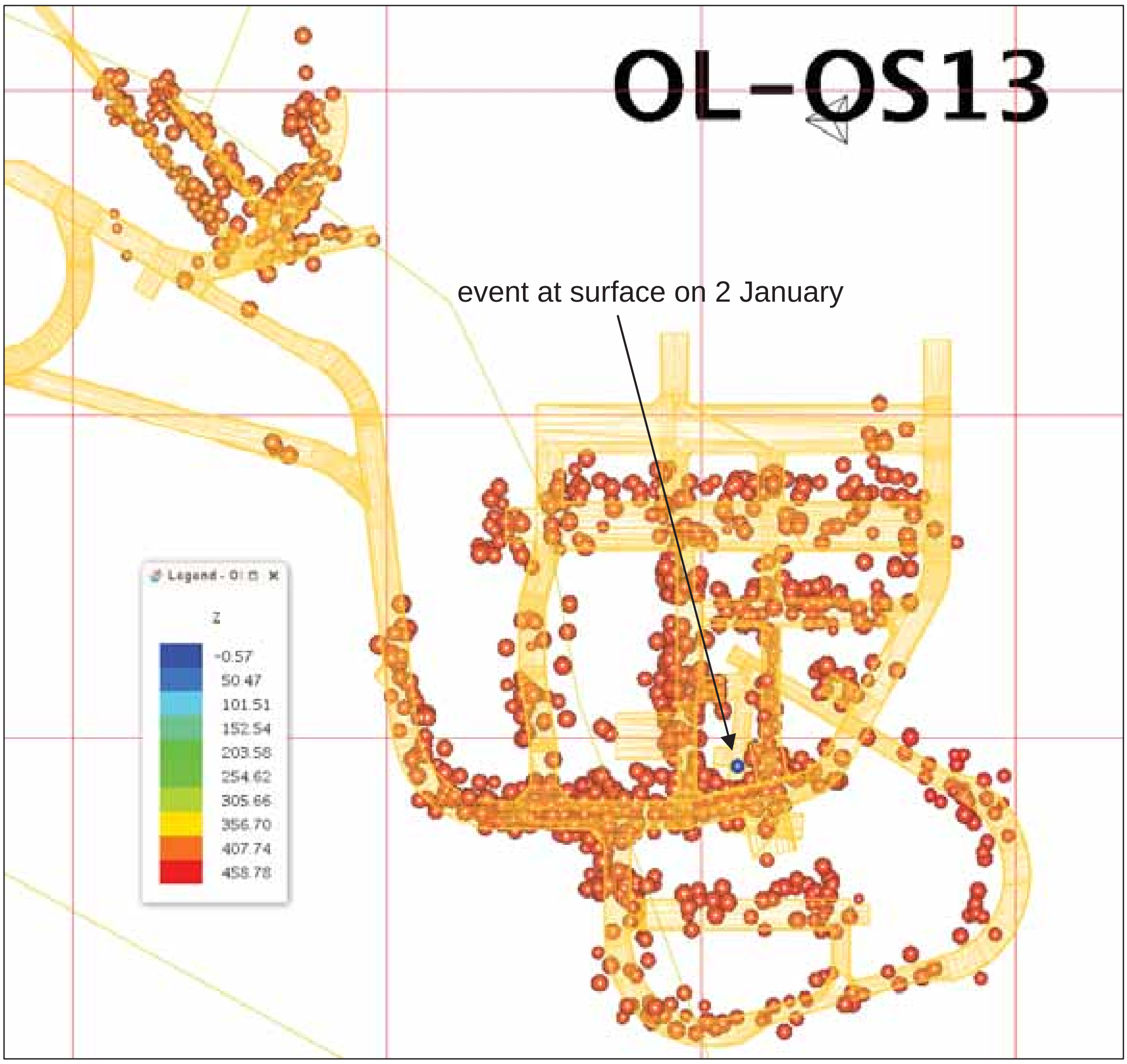


Figure 4-2. *Explosions (1064 events) inside the seismic ONKALO block, in 2011. Colour = depth (negative z above the sea level). Distance between gridlines is 100 m.*

The excavation blasts coincide nicely with the Posiva's planned layout of the ONKALO. The individual epicenters further away from the tunnel are mainly located by less than five seismic stations or the recordings of the seismic signal are contaminated by some disturbance. The locations of those events are not as accurate as in general.

The locations of the blasts are generally rather good in horizontal direction, but some events tend to be few meters below the ONKALO model (Figure 4-3 and 4-4). Also some locations suffer from inaccuracy caused by simultaneous blasts in other parts of the ONKALO.

After the experiment (18 August 2011) in the ONK-TKU-3620 niche the settings of these utilized sensors were changed temporarily to support the general measurements of the ONKALO block. The geophones improved the sensitivity and the depth resolution of the measurements inside the ONKALO block.

The events locate occasionally 5 - 10 meters below the floor of the ONKALO model (Figure 4-4). The explanation to this location anomaly relate likely to anomalous velocity due to the orientation of the pervasive foliation and anisotropy of the bedrock that dips towards SE in the ONKALO area with a medium dip of the order of 40 – 60 degrees (see e.g. Mattila et al. 2008).

The purpose of Posiva's nuclear non-proliferation control is to ensure that activities in the final disposal facility comply with all relevant laws and degrees as well as the obligations prescribed in international agreements. The aim of the nuclear material control in the disposal facility is also to ensure that the facility, especially in its underground part, has no rooms, materials or operations outside the system of nuclear material accounting and that the waste canisters remain in their declared positions during the operation and after the closure of the facility (Posiva 2006). It has been demonstrated (Saari & Lakio 2007) that microseismic monitoring is a capable tool to locate activities related to construction of any undeclared rooms.

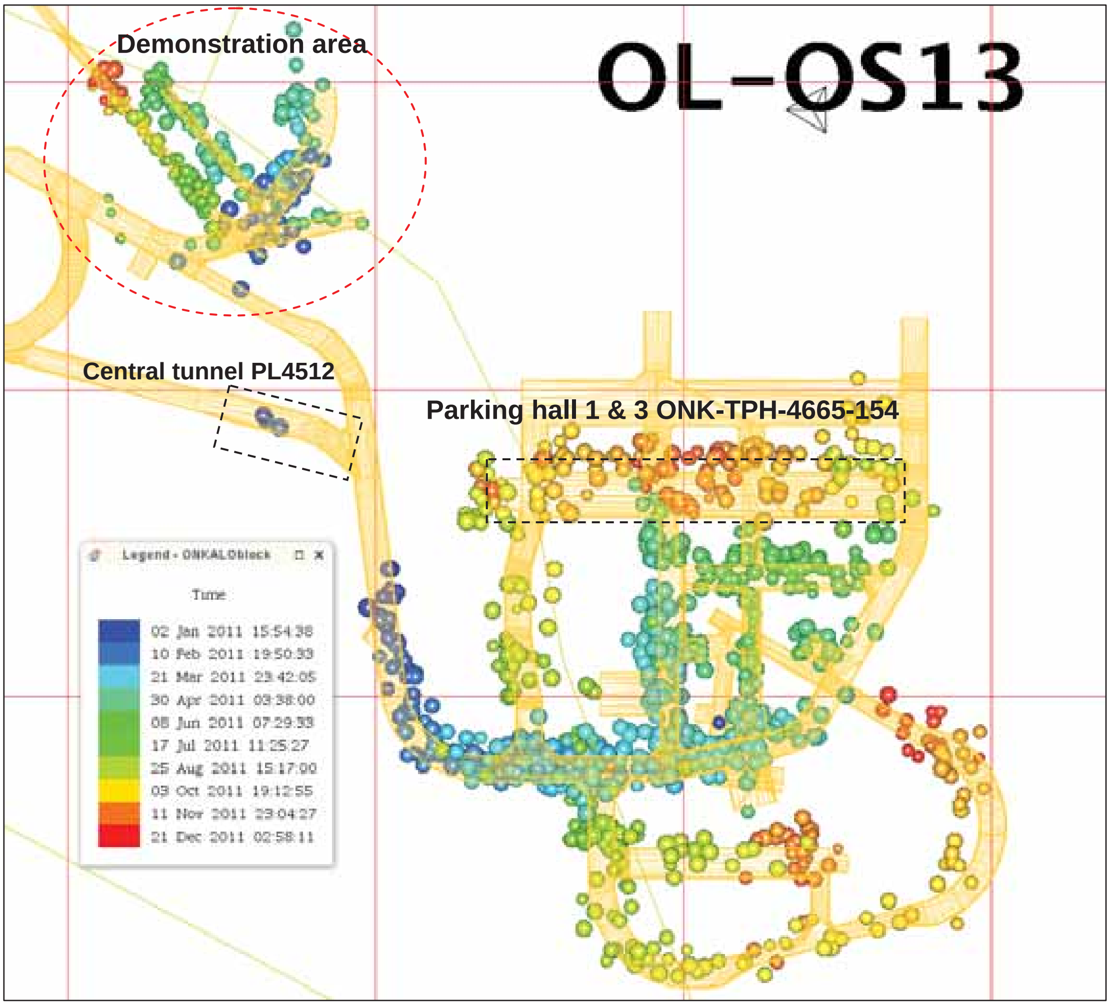


Figure 4-3. *Explosions (1064 events) inside the seismic ONKALO block, in 2011. Colour = time. Distance between gridlines is 100 m.*

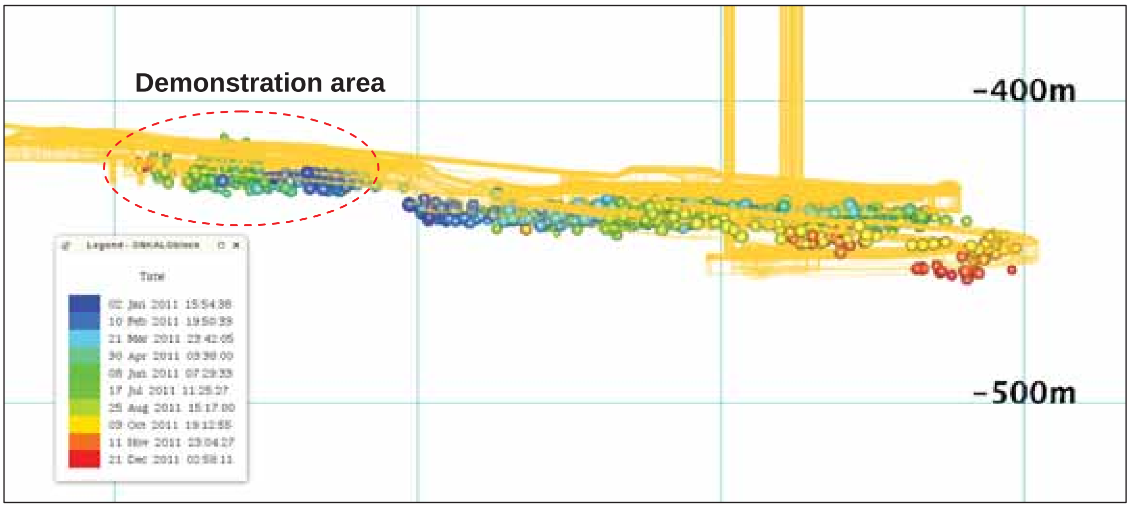


Figure 4-4. *Cross section of the explosions (1063) inside the seismic ONKALO block. View from south.*

4.3 Miscellaneous small events

Seismic network detects several seismic signals that are not generated by explosions. Some of those are strong enough to be located by the seismic network. Because the seismic monitoring is part of the safeguards project of Radiation and Nuclear Safety Authority of Finland, also origins of these events are verified. Most of them are related to manual and mechanical rock removal works. Another group of events is related to loading. Rock removal and loading are normal phases in tunnel construction, but apparently in these cases the block has been larger than usual.

The location of the miscellaneous events (Figures 4-5 and 4-6) is normally based on recordings of only three or five stations. In addition, the amplitudes of the seismic signals are small and the wave characteristics, like P-onsets, are often unclear. Therefore their location accuracy is mainly not as good as for excavation blasts or earthquakes. The located events are small in magnitude (M_L = -2.5 … -0.7) but still bigger than those that were rejected because of too weak and noisy recordings. The majority of the rock falls cannot be located. There are also rock falls that are not recorded even by the closest stations.

The observed miscellaneous small events occur usually close to area under construction. The origins of the events are mainly confirmed by Posiva or by the daily reports of Destia Oy.

The number of located miscellaneous events (68) in 2011 is much larger than in 2010 (10). Observations were throughout the year except in December. Most of the observations (63 %, 43 events) relate to scaling and truck scaling in during the active phase of excavation in April and May (see Figure 3-1).

Two miscellaneous events were detected in January. They were probably rock falls that related to construction activities in the demonstration area. The artificial events detected in February related to truck loading in the same area (Figure 4-5).

Three artificial seismic events were registered in March 2011. The first one happened in the surface and is probably related to hoist building construction work (Figure 4-5). The other events in March are likely related to truck loading or scaling.

The 56 events from April to September are all related to scaling or truck loading. In October there was one event that related to scaling, but the artificial event at the level about -295 m was related to raise boring (Figure 4-6).

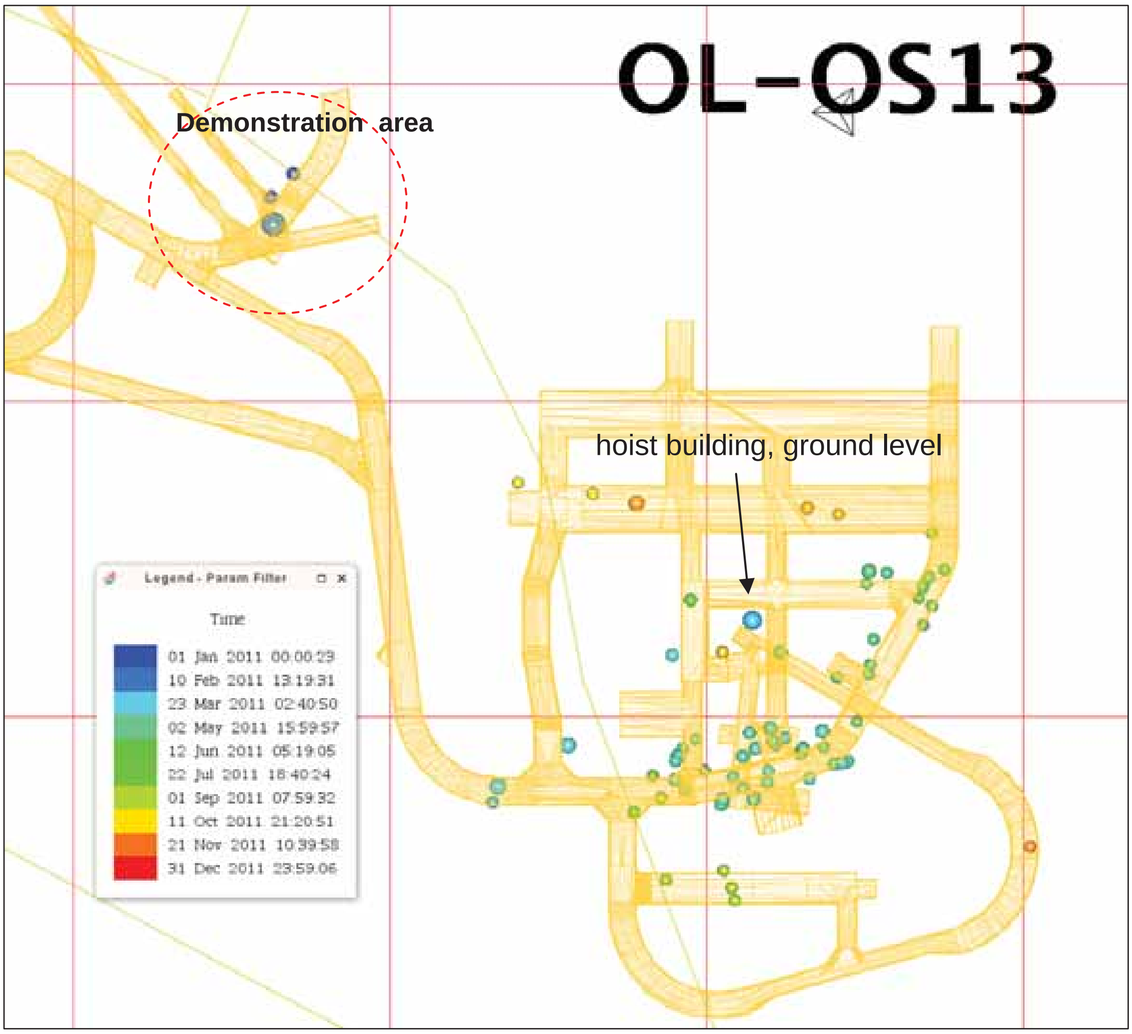


Figure 4-5. *Miscellaneous (68) small events related to the ONKALO constructions. The distance between the grid lines is 100 m. The size of the sphere is relative to the magnitude. Colour legend shows the date of the event.*

The possibility to excavate an undeclared access tunnel to ONKALO from the outside has been concerned as a potential safeguards issue. In that context, a concept of undeclared explosions, detonated at the same time as the declared excavation blasts, has been discussed. According to the experience gained at Olkiluoto, as long as the seismic network is in operation and the results are analysed by a skilled person, undeclared activities would be detected by microseismic monitoring.

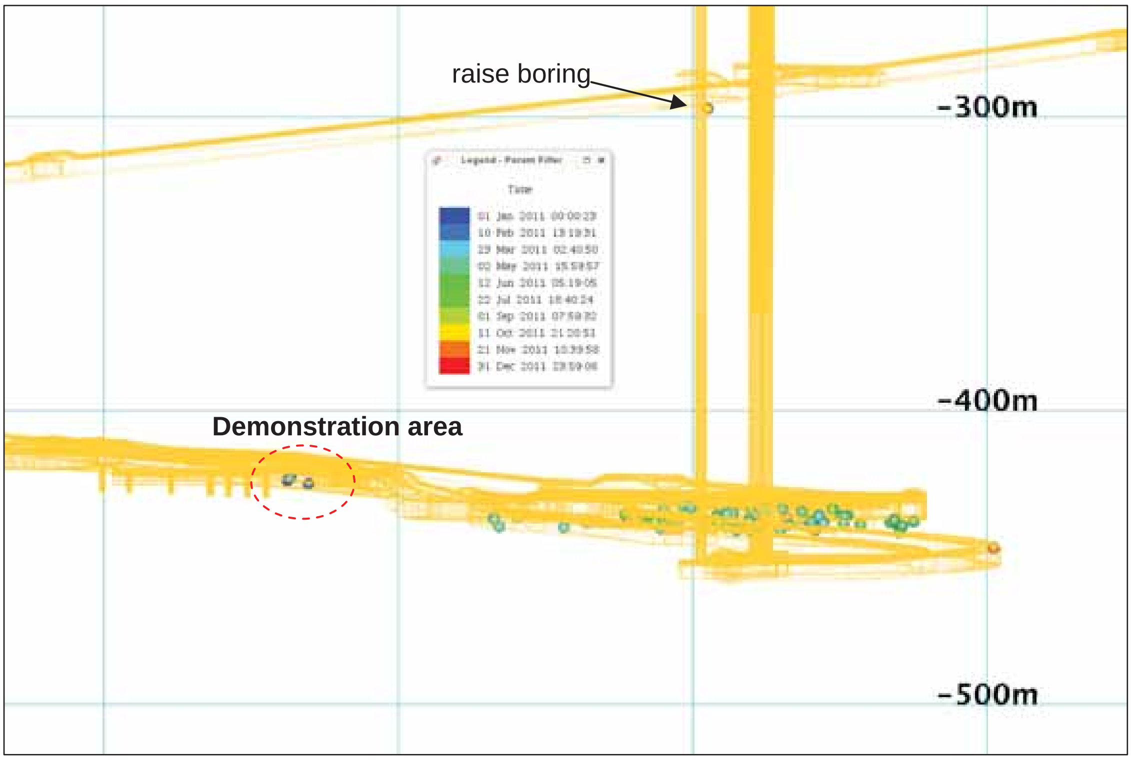


Figure 4-6. Miscellaneous small events (67) inside the ONKALO. View from the south. The distance between the grid lines is 100 m. The size of the sphere is relative to the magnitude. The colour legend shows the date of the event.

There are examples of legal explosions performed closely in time and space in the ONKALO. Explosions from these sites were clearly distinguishable. But, as reported above, the location of events might be less accurate, when explosions are performed simultaneously close to each other in more than two sites. Seismic monitoring of possible illegal and legal excavation done by a tunnel boring machine has been investigated in a separate report (Saari & Lakio 2009). The observed signals generated by dredging of the sea bottom are quite similar. Examination of miscellaneous small events serves also this task.

Regarding safeguards the conclusion of the observations inside the seismic ONKALO block and in the seismic semi-regional area are similar. Indications of undeclared or inappropriate works, which would have influence on the safety of ONKALO, cannot be found.

5 EARTHQUAKES

5.1 Recordings of Tectonic earthquakes in southern Finland

In 2011 there were three excavation induced earthquakes inside the ONKALO block (see Chapter 5.2). In addition to that there were no earthquakes inside the seismic semi-regional area in 2011. However, the seismic network at Olkiluoto recorded three tectonic earthquakes that occurred in southern Finland. The earthquake detections in the Olkiluoto network were confirmed by the Institute of Seismology, University of Helsinki.

The first recorded tectonic earthquake occurred on 19 March 2011 at 11:21 (UTC) in Mäntsälä (60.569°N, 25.296°E) about 210 km east from Olkiluoto (M_L = 2.6, FENCAT, http://www.helsinki.fi/geo/seismo/english/bulletins/index.html). The event was felt widely in southern Finland. The event was recorded by four triaxial geophones (OL-OS8, OL-OS9, OL-OS10 and OL-OS12) of the Posiva's seismic network.

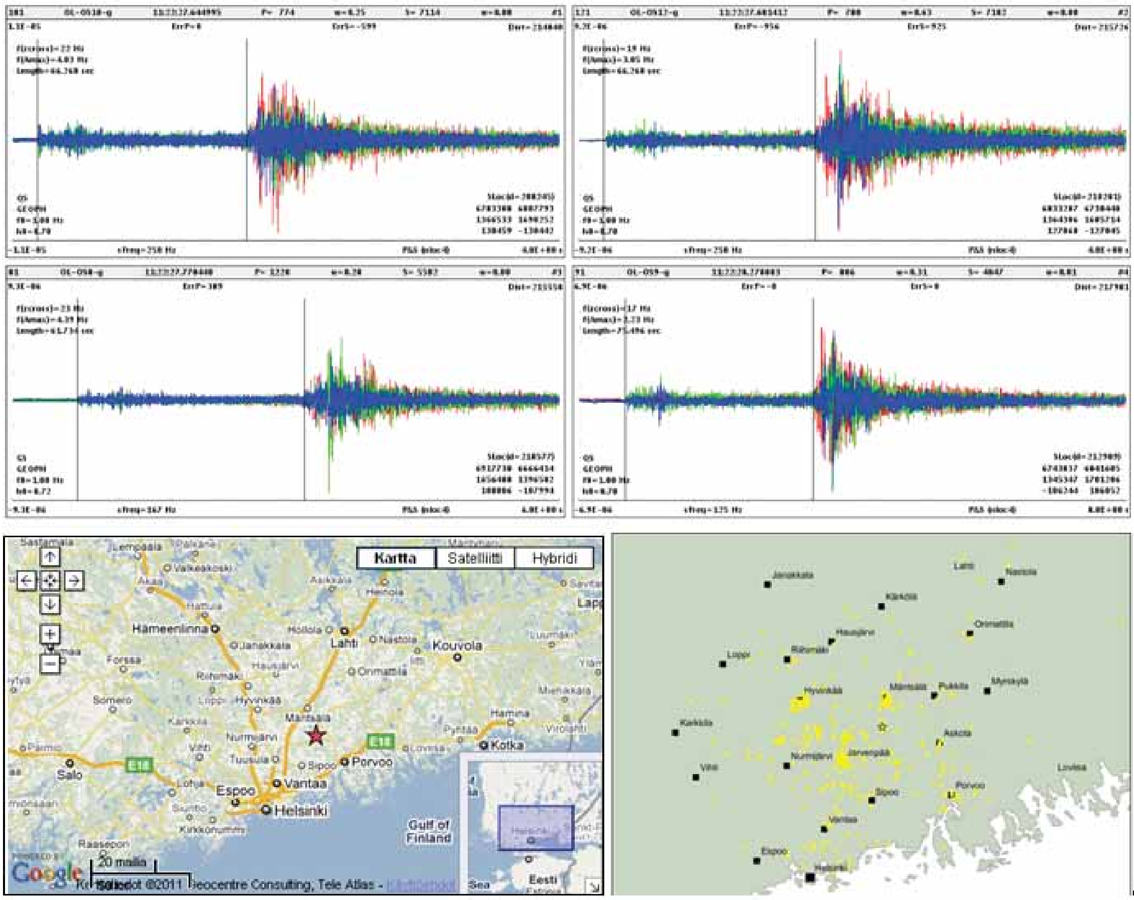


Figure 5-1. *Tectonic earthquake in Mäntsälä, Finland on 19 March 2011. Up: Registrations from Posiva's network. Bottom left: Location of the earthquake (red star, website of the Institute of Seismology, 20.4.2011). Bottom right: Locations of the first 400 felt reports and location of the earthquake (yellow star, website of the Institute of Seismology, 2.4.2012).*

A swarm of tectonic earthquakes occurred in December 2011 in Kouvola, about 280 km east from Olkiluoto. Two of these earthquakes were recorded by the Olkiluoto network on 1 December at 06:04 (UTC) (60.901°N, 26.670°E; M_L = 2.8) and 22 December at 07:21 (UTC) (60.900°N, 26.678°E; M_L = 2.6) (FENCAT). These events were recorded clearly by three triaxial geophones (OL-OS9, OL-OS10 and OL-OS12) and were felt widely in southern Finland (Figure 5-2).

Institute of Seismology installed a temporary local network of four seismic stations in the active area. Altogether 67 earthquakes (ML = 0.4 -2.8) were recorded in the area in December 2011. The swarm has continued also in the beginning of 2012. The number of earthquakes in the beginning of April is 85 (Figure 5-2).

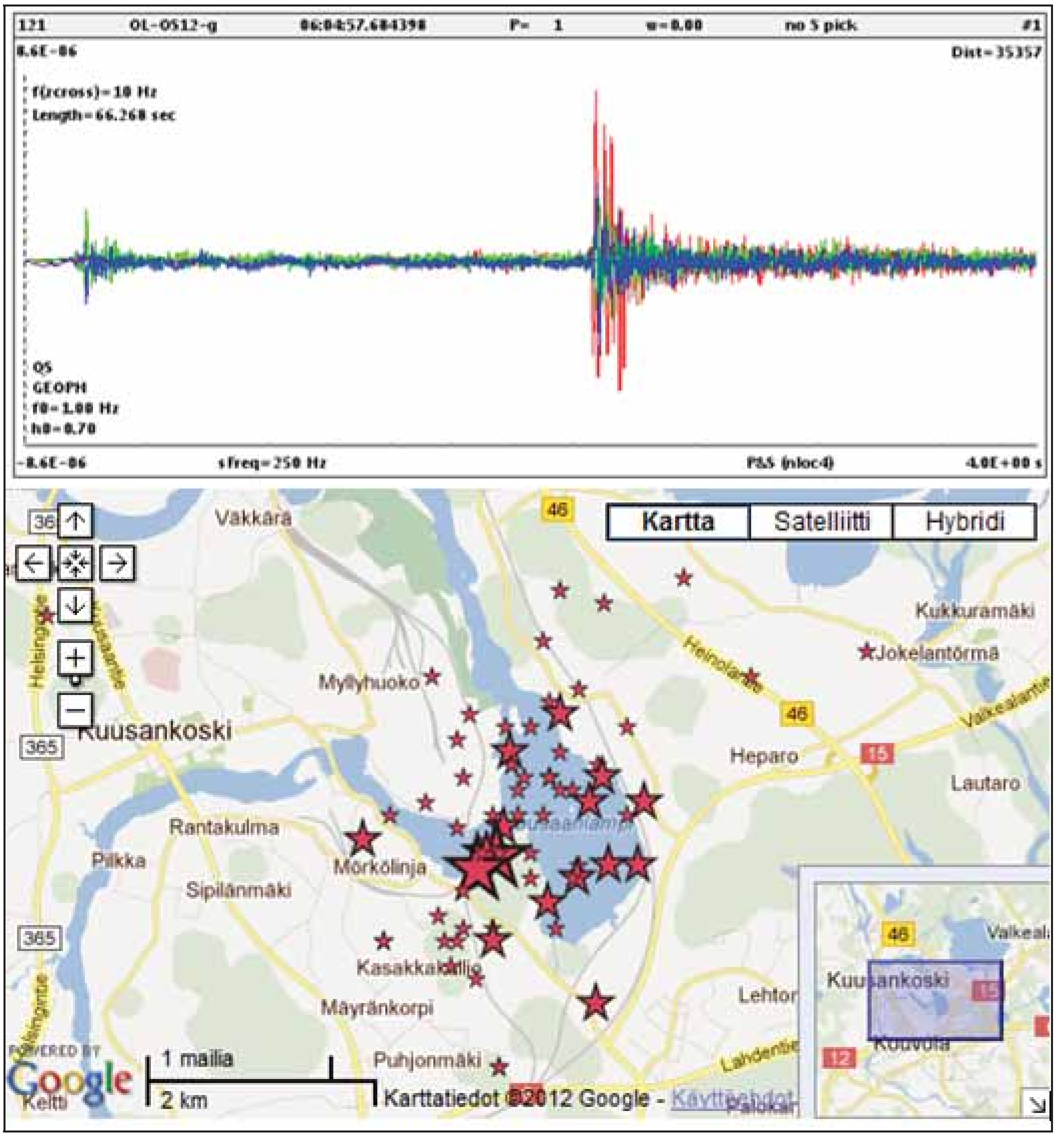


Figure 5-2. Above: Recording of the Kouvola earthquake on 1 December 2011 on station OL-OS12. Below: Locations of the Kouvola earthquake swarm. The two events with magnitudes 2.8 and 2.6 recorded also in Olkiluoto region are presented with bigger stars. Middle size star = magnitude below two and above 1. Small star = magnitude below one (website of the Institute of Seismology, 2.4.2012).

Monitoring of regional tectonic seismicity aims at better understanding of ongoing seismotectonic processes in the Olkiluoto area. Although the focus of regional seismic monitoring is limited inside and close to the seismic network other regional earthquakes are also recorded and stored in the Posiva's data archive. These recordings from the Olkiluoto site are valuable in seismic hazard studies, for example when attenuation of seismic signal is evaluated. It is assumed that regional events occurring outside that area are located by the Finnish and Swedish regional seismic networks.

5.2 Seismicity of the ONKALO block

5.2.1 Source parameters

The fault plane is represented by its strike, dip and plunge angles. Strike is the angle at which the plane cuts the horizontal measured clockwise from north [0, 360]. Dip is the vertical angle at which the foot wall of the plane cuts the horizontal and ranges from 0 (horizontal) to 90 (vertical) degrees. Plunge (i.e. rake i.e. orientation of slip vector) is the angle (measured in the plane of the fault) at which the hanging wall moves relative to the foot wall with reference to the strike direction. It ranges between -180 and +180 degrees. A plunge of +90 degrees indicates a reverse fault and a plunge of -90 degrees a normal fault.

The radiation pattern generated by an earthquake is characterised by axial symmetry. On the basis of seismic data, there always exist two mutually perpendicular fault planes, which can produce the same radiation pattern. This means that the plane geometry of the fault is not unambiguous. On the other hand, the stress field as given by the directions of the compression and tension can be determined unambiguously. The real and the auxiliary fault plane can be distinguished with the aid of additional information. For example, an interpretation can be done when the other fault plane orientation coincides with the local bedrock model or with some other explanatory factors.

The fault plane solutions can be calculated when the event is located. The data processing software (Jmts) calculates fault plane solution in two different ways. The traditional double couple solution is based on P-wave polarities. The more sophisticated solutions (full moment tensor and pure double couple) are calculated in time and in frequency domain (see e.g. Hudson et al. 1989). The polarity analysis is also included in those solutions. Generally, double couple solutions are suitable when the true mechanism includes a shear on a surface. But, if the event locates close to an opening, including possibly volume change, then the solution based on full moment tensor would be more illuminating.

The seismological data processing software (Jmts) of ISS International calculates numerous parameters characterising the seismic event. However, displacement related to an earthquake is not included in the list of output parameters. The peak slip ($\hat{U}$), or dislocation across the fault is calculated from (Eshelby 1957):

$$\hat{U} = 1.1\ \Delta\sigma r/\mu$$

The values of stress drop (Δσ) and source radius (r) are routinely calculated by Jmts. Shear modulus (μ) is a function of S-wave velocity (β = 3250 m/s) and density (ρ = 2700 kg/m^3):

$$\beta = (\mu/\rho)^{1/2}\ .$$

5.2.2 Excavation induced earthquakes in 2011

Three induced earthquakes were observed in 2011 (Table 5-1). The magnitude of the first event (9 February 2011) was significantly larger (M_L = -0.5) than the magnitudes of the two events (M_L = -2.0 and -1.9) occurred in May 2011. This difference can be seen also in the peak slip rates of the events, but the source radiuses are about the same order (7.5 - 11 m).

Table 5-1. *Excavation induced earthquakes in 2011. Loc. Err = location error, Mag Loc = local magnitude, Seismic Mom. = seismic moment, r = estimated radius of the seismic source and peak slip = dislocation across the fault.*

Date	Origin Time (UTC)	North (m)	East (m)	Depth (m)	Loc. Err. (m)	Mag Loc	Seismic Mom. (log10)	r (m)	Û (μm)
9.2.2011	03:32:05.8	6791975.1	1525827.4	-437	4	-0.5	9.1	11	18
14.5.2011	10:26:28.6	6792041.1	1525961.1	-450	5	-2.0	7.3	7.5	0.8
14.5.2011	10:26:31.3	6792029.0	1525953.7	-448	4	-1.9	7.4	8.2	1.2

On 9 February 2011 at 03:32 (UTC) an excavation induced earthquake or rockburst occurred about six hours after the last explosion of the round blasted in the ONKALO. The earthquake occurred at the same location where that round was blasted. According to Destia Oy and Posiva Oy there has not been any human activity at that time and in that location. The event was small (M_L = -0.5) and located by 9 seismic stations (OL-OS13, OL-OS1, OL-OS2, OL-OS3, OL-OS4, OL-OS5, OL-OS6, OL-OS7 and OL-OS8). The estimated peak slip value of the earthquake was 18 μm. In source calculations, the fault area is approximated by a circle. The estimated source radius was 11 m (Table 5-1, Figures 5-1 and 5-2).

Usually, in Olkiluoto and elsewhere, the majority of the excavation induced seismicity tends to occur very close, in time and space, to the latest excavation blast. Like this event, they typically occur close to the tunnel wall. It seems that the preceding blast has disturbed the excavated part of the ONKALO and the microearthquake was caused by the adjustment processes occurring in the surrounding rockmass. This time the delay after the round blast was longer than usual, but not exceptional.

The radiation pattern generated by an earthquake is characterised by axial symmetry. On the basis of seismic data, there are always two mutually perpendicular fault planes, which can produce the same radiation pattern. This means that the plane geometry of the fault is not unambiguous. On the other hand, the stress field given by the directions of the compression and tension can be determined unambiguously. The real and the auxiliary fault plane can be distinguished with the aid of additional information. For example, an interpretation can be done when the other fault plane orientation coincides with the local bedrock model or with some other explanatory factors. In this case there was not any compatible bedrock structure in the recently updated Jdi model.

The full moment tensor solution gives the two ambiguous fault planes (Table 5-2 and Figures 5-1 and 5-2). The plane is either gently (37^{o}) dipping (Fault plane 1 in Table 5-2) or vertical (Fault plane 2). The estimated angles of strike, dip and plunge in Table 5-2 do not fit any other structure in the geological model of the Olkiluoto site (Aaltonen et al. 2010). Fault plane 1 in Table 5-2 represents pure strike slip fault and Fault plane 2 reverse right-lateral oblique fault. Both of the fault planes align the geometry of the ONKALO tunnel. The event is also very close to the tunnel, which suggests that the event is not tectonic but induced by excavations. Fault plane 1 is nearly parallel to the floor and tunnel roof (Figure 5-2). The location could be on the roof, because the event locations in this area tend to be too deep. The hanging wall has moved towards SW. Fault plane 2 is vertical and fit the geometry of the tunnel curve (Figure 5-1). If this interpretation is the correct one, the eastern side of the fault has moved about 0.02 mm relative to the western side.

Table 5-2. *The ambiguous fault planes of the microearthquakes in 2011. The final choice is highlighted in yellow.*

Date	Origin time (UTC)	Fault plane 1			Fault plane 2		
		strike	dip	plunge	strike	dip	plunge
09.02.2011	03:32:05.8	237	37	2	145	89	127
14.05.2011	10:26:28.6	206	52	95	18	39	84
14.05.2011	10:26:31.3	254	80	111	8	23	26

Strike slip and reverse faults are typical in the environment characterized by crustal compression. The orientations of the compressional and tensional axes related to the microearthquake are presented in Table 5-3 and in Figures 5-1 and 5-2. The orientation of the compressional axis (205°) related to the microearthquake is nearly perpendicular to the estimated E-W oriented maximum in-situ stress field in Olkiluoto (Posiva Oy, 2009). The estimated plunge of the compressional axis is -33°, i.e. the northern end of the compressional axis is pointing towards the surface. It may indicate that the excavation of the ONKALO has local influence on the orientation of the stress field.

Table 5-3. *Orientation of compressional and tensional axes related to the microearthquake on 9 February 2011. It was not possible to calculate the stress field, based on the few recordings available of the events 15 May 2011.*

Date	Compression azimuth	Compression plunge	Tension azimuth	Tension plunge
9.2.2011	205	-33	86	-36

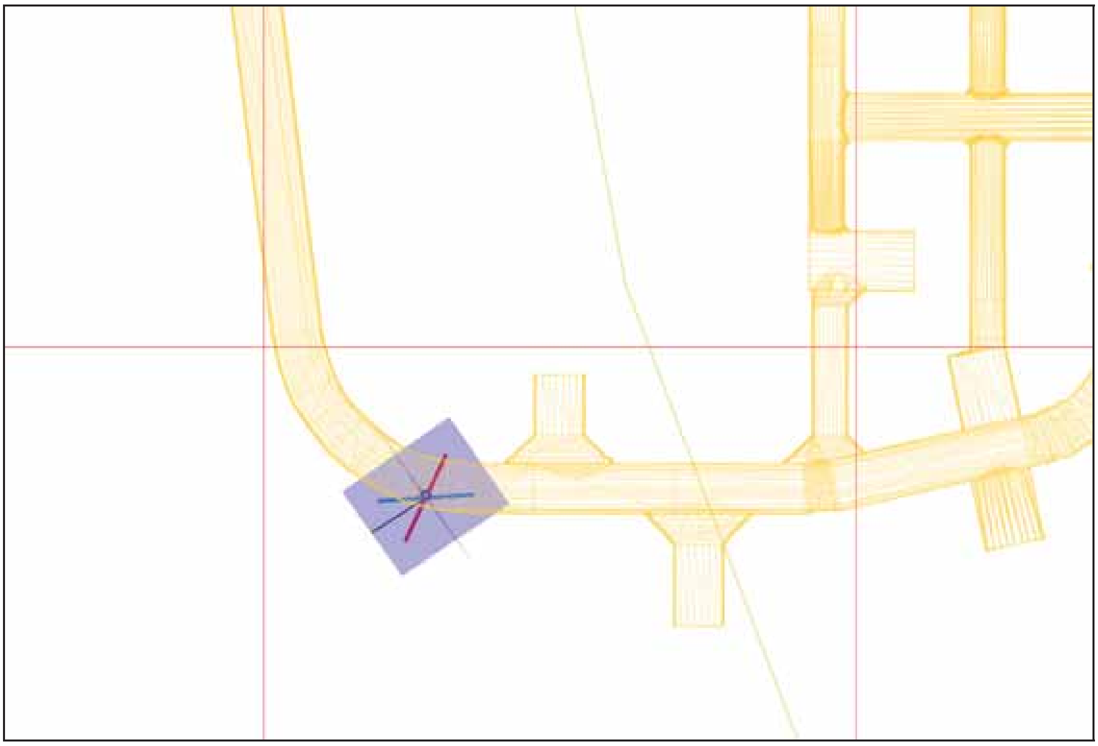


***Figure 5-1**. Fault plane of the induced earthquake occurred on 9 February 2011 (view from above). The fault plane 1 is presented by a blue square and fault plane 2 by a green square. Side length of the square (22 m) is the same as the diameter of the estimated spherical fault. Slip direction of the hanging wall is shown by black line pointing from the hypocenter to the edge of the fault. Orientations of compression (red line) and tension (blue line) are included.*

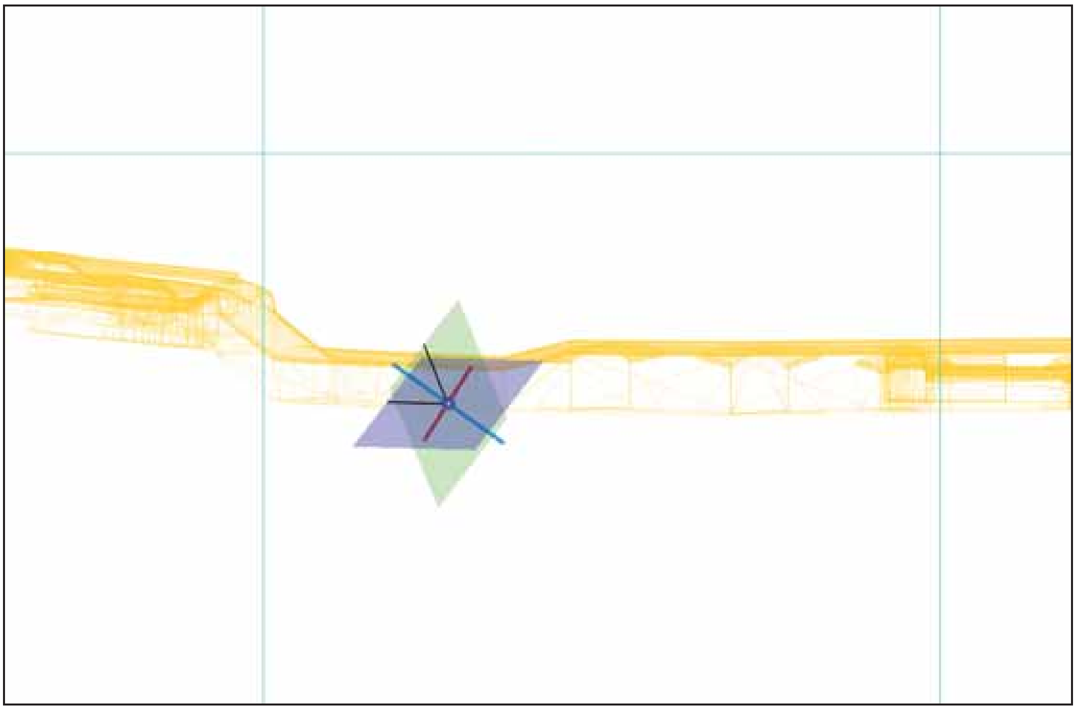


***Figure 5-2.** Induced earthquake in the ONKALO on 9 February 2011. View from the south. The distance between the grid lines is 100 m.*

The full moment tensor solution of the main shock contains 96.9 % of double couple and 3.1 % of isotropic component (Figure 2-9). The volume change related to the source has been explosion like and it seems that the fault has expanded. The estimated volume change has been between $6.7*10^{-4}$ m^3 (670 cm^3, minimum) and $1.2*10^{-3}$ m^3 (maximum). Because the event was in the immediate vicinity of the ONKALO wall, the expansion could have produced a rock burst.

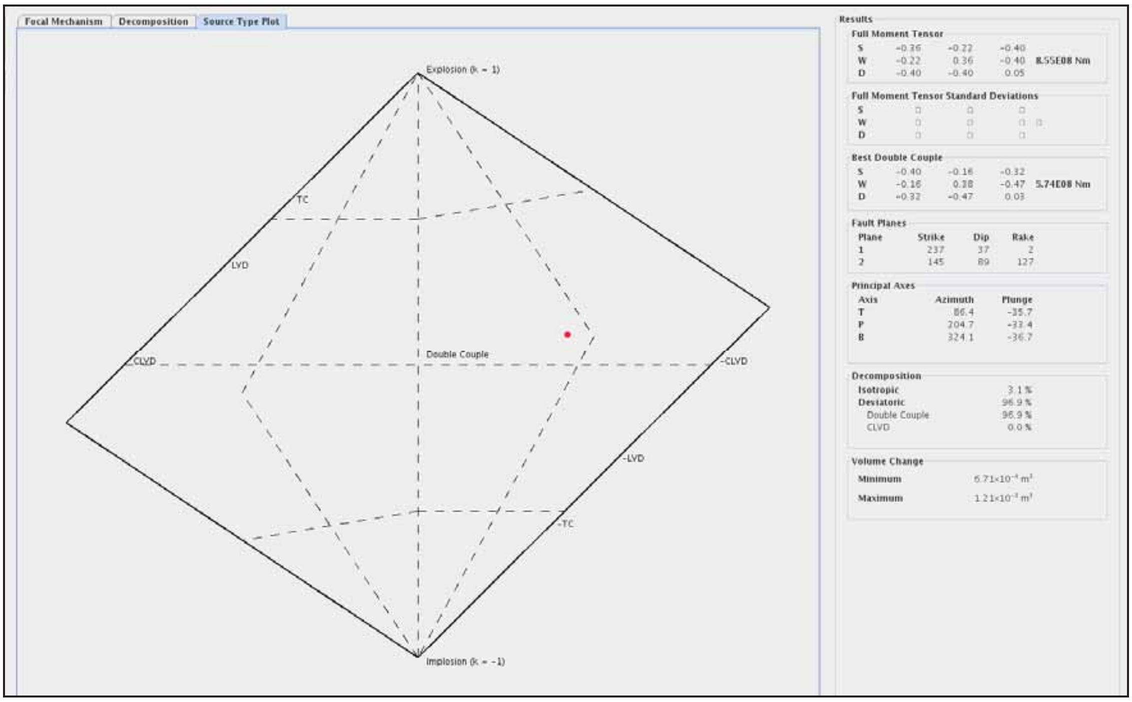


Figure 5-3. *Source type plot (Hudson et al. 1989; Hardebeck & Shearer, 2002) and focal mechanism (lower right corner) of the earthquake on 9 February 2011. The moment tensor solution indicates that the event represented mainly (96.9 %) a pure slip along a fault plane. The share of volume change (explosion) was 3.1 %.*

On 14 May 2011 two small excavation induced earthquakes (Figures 5-4, 5-5 and Table 5-1) occurred about four minutes after the last explosion of the round blasted in the ONKALO. It looks like the tremor of the round blast has triggered the microearthquakes. The earthquakes were located 20 - 25 meters in front of the round in the area that was not yet excavated. The microearthquakes were located inclined below the round blast.

The events were very small (M_L = -2.0 and -1.9) and located only by five seismic stations (ONK-OS1, ONK-OS2, OL-OS13, OL-OS6, and OL-OS7). Three of those are borehole stations. The time difference between the earthquakes was about 2.5 seconds. Estimated peak slip values of the earthquakes were about 1 μm, which is clearly less than usually estimated. In source calculations, the fault area is approximated by a circle. The radiuses of the faults are 7.5 and 8.2 meters (Table 5-1). That parameter gives an impression of the dimensions of the disturbed or moved rock mass.

If the excavation induces an earthquake further away from the excavated area (or as now four minutes after the round) there often is a clear connection between the earthquake and the excavation. This time there is not any known structure that could explain the connection between the induced earthquakes and the round blast. However, the explanation could be associated with the orientation of the pervasive foliation of the bedrock that dips towards SE in the ONKALO area with a medium dip of the order of 40 – 60 degrees (e.g. Mattila et al. 2008). That is close to the dip angle between the round blast and the microearthquakes and also fits also to the fault plane solutions (Figure 5-5).

In this case the software could not calculate the moment tensor solution. That would require more seismograms. Also the double couple solution is rather uncertain. Because the events were so small, there were only few certain P-wave polarities available. In addition, it was not possible to calculate the stress field.

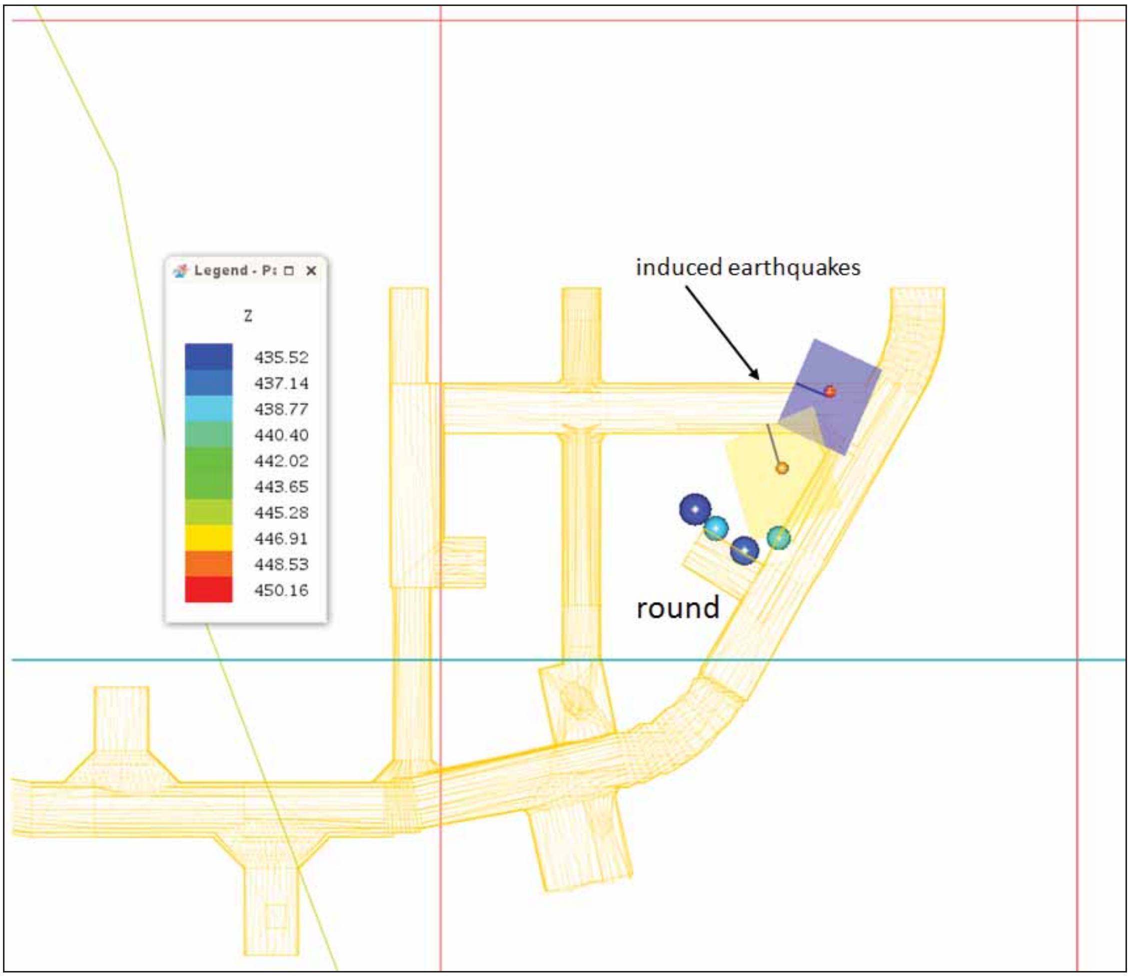


Figure 5-4. *Round blast shot at 10:22 (UTC) on 14 May 2011 and induced earthquakes. The distance between the grid lines is 100 m. The size of the sphere is relative to the magnitude. The fault planes are presented by squares. Side length of the square is the same as the diameter of the estimated spherical fault. Slip direction of the hanging wall is shown by black line pointing from the hypocenter to the edge of the fault.*

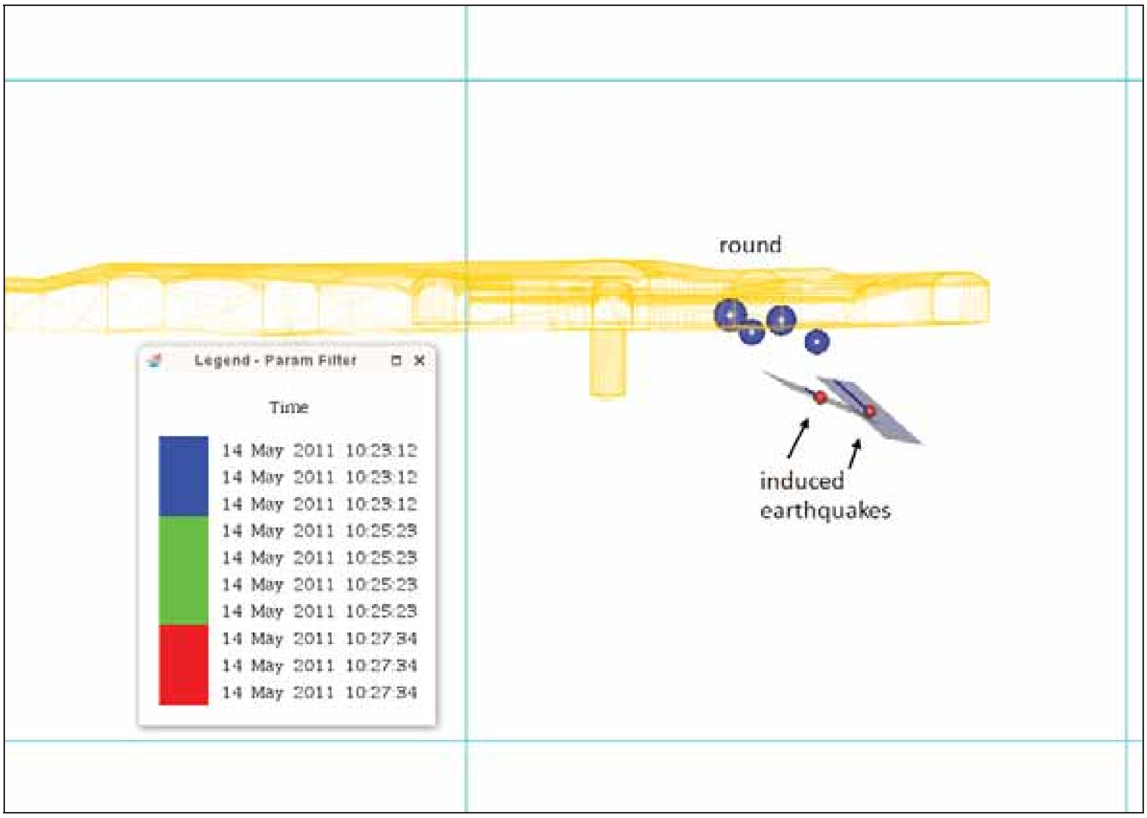


Figure 5-5. *Round blast shot at 10:22 (UTC) on 14 May 2011 and induced earthquakes. The distance between the grid lines is 100 m. The size of the sphere is relative to the magnitude.*

The solutions of the earthquakes are presented in Table 5-2 is based on double couple solution. The dip and strike of the Fault plane 2 of both earthquakes fit rather nicely the orientation of the foliation, which supports the conclusion that the preceding round blast has induced the earthquakes. The fault planes with their slip vectors are presented in Figure 5-4 and Figure 5-5. The fault planes are presented by squares, where the length of the side is the same as the diameter of the estimated spherical fault. The estimated fault types are reverse (first earthquake) and reverse left-lateral oblique (second earthquake) i.e. reverse fault with a component of left-lateral strike. The slip vectors show that the hanging wall has moved 1 μm upwards and towards NE.

6 SUMMARY

This report summarizes the status of operation and results of the local seismic network at Olkiluoto in 2011. The local seismic network established in 2002 first monitored tectonic earthquakes in order to characterise the undisturbed baseline of seismicity of the Olkiluoto bedrock. When the excavation of the ONKALO started, in August 2004, the network started also to monitor excavation induced seismicity. The number of seismic stations has increased gradually from the original network of six stations. At the end of 2011 Posiva's permanent seismic network consists of 15 seismic stations and 20 triaxial sensors.

The investigation area includes two different target areas. The larger target area, called the *seismic semi-regional area*, is monitored mainly by five 1 Hz geophones. The purpose is to monitor explosions and tectonic earthquakes in regional scale inside the area that covers the Olkiluoto Island and its surroundings. The other target area is called the *seismic ONKALO block*, which is a 2 km *2 km *2 km cube surrounding the ONKALO. It is assumed that all the expected excavation induced events occur within this volume.

During 2011, the configuration of the seismic network has remained basically the same as in 2010. The seismic ONKALO block is mainly monitored by eleven permanent stations and the semi-regional area by five stations. Station OL-OS8 has sensors suitable for monitoring both areas. In addition, the temporal network in the ONK-TKU-3620 niche gave additional support to the analysis of the ONKALO block in 2011.

One triaxial and three uniaxial accelerometers were integrated to Posiva's network in 2011. Those four sensors formed a small scale subnetwork, which related to the thermal spalling experiment inside the ONK-TKU-3620 niche. This subnetwork was capable to locate events of magnitude ML > -5 inside its area. The main purpose of the temporal subnetwork was to monitor thermal induced spalling in the test holes, but it was also utilized when events elsewhere in the ONKALO were located. The events occurred inside the ONK-TKU-3620 niche are analysed and reported separately as a part of the thermal spalling experiment. After the experiment (August 2011), the settings of these sensors were changed to support only the general measurements of the ONKALO block.

The Olkiluoto server supports the run time system (RTS) program, which continually acquires, processes, analyses and archives seismic data. In addition, RTS calculates automatic event locations. RTS was not upgraded in 2011. The latest upgrade of RTS was done in 2010.

The new brittle fault zone model of the Olkiluoto area was integrated in the seismic visualization package Jdi in February 2011. The upgrade of the applied design model of the ONKALO in Jdi was extended to the lower parts of ONKALO in April 2011.

The observations of the seismic network and the results of the analysis are reported in the monthly reports. Since August 2009 the reports are published and archived in the Posiva's electronic document management system (Kronodoc).

The network has operated almost continuously. The only network operation failure in five years occurred in 2011. This 14 minutes and 30 seconds long failure occurred on 27

December 2011. The failures in 2011 relate mainly to exceptionally strong storms in July and December 2011. During the rest of the months there have been only two failures in seismic station OL-OS6. The seismic station had over 14 hours long power failure, which started in June. The flash memory of the station OL-OS6 was broken on 12 September 2011 and the station was out of order the rest of the year.

The operation reliability of the network has been almost as good as during the previous year. The quality of the monitoring has been mainly good in 2011, except the short but extensive periods of failures in July and December. In July the storms caused coincident failures in four to eight stations. The storm in December caused failures in wider scale. Several stations and the Olkiluoto server had a 35 hours long power failure which started on 25 December. Only four stations (OL-OS1, OL-OS2, OL-OS4 and OL-OS5) were in order. Technically the network was still in operation, although the sensitivity of the network was significantly lower than usual. The complete about 15 minutes long operation failure started on 27 December 16:15:34 when also those four stations went down.

All detected events are stored in the field stations until they are safely transmitted to the site computer. This means that even though the server was down, four stations were still in operation. Minimum number of stations needed for the event location is three. The seismic network was out of operation for 14 minutes and 30 seconds on 27 December 2011.

Altogether 1223 events have been located in 2011. The majority of the events (1064) are explosions inside the seismic ONKALO block (87 %). Altogether 159 of the accepted events have been located outside the seismic ONKALO block. Only 34 of them are located inside the seismic semi-regional area. The magnitudes of the observed explosions inside the semi-regional area range from M_L = -2.2 to M_L = 1.5 (M_L = magnitude in local Richter's scale).

The majority of the accepted events were explosions. In 2011 three excavation induced earthquakes were detected inside the ONKALO block. In addition to that there were no earthquakes inside the seismic semi-regional area in 2011. However, the seismic network at Olkiluoto recorded three tectonic earthquakes that occurred in southern Finland. The first recorded tectonic earthquakes (M_L = 2.6) occurred on 19 March 2011 in Mäntsälä about 210 km east from Olkiluoto. A swarm of tectonic earthquakes occurred in December 2011 in Kouvola, about 280 km east from Olkiluoto. Two of these earthquakes were recorded by Posiva’s network on 1 December (M_L = 2.8) and 22 December (M_L = 2.6). The earthquake detections were confirmed by the Institute of Seismology, University of Helsinki.

Three induced earthquakes were observed in 2011. The magnitude of the first event (9 February 2011) was significantly larger (M_L = -0.5) than the magnitudes of the two events (M_L = -2.0 and -1.9) that occurred on 14 May 2011. The calculated source radiuses of the events were about 10 meters. The estimated peak slip values of the earthquakes were 20 µm (in February) and 1 µm (in May).

On 9 February 2011 an excavation induced earthquake occurred at the same location but about six hours after the round blasted in ONKALO. The estimated volume change that related to the earthquake was about 1 dm^3 expansion. Because the event was in the immediate vicinity of the tunnel wall, the expansion could have produced a rock burst. Any known geologic structure could not be associated with the microearthquake observed in February.

On 14 May 2011 two small excavation induced earthquakes occurred about four minutes after the last explosion of the round blasted in ONKALO. It looks like the tremor of the round blast has triggered the microearthquakes. The earthquakes were located 20 - 25 meters in front of the round blast in the area that was not yet excavated. The microearthquakes locate inclined below the tunnel floor. The microearthquakes could be associated with the orientation of the pervasive foliation of the bedrock that dips towards SE in the ONKALO area. That is close to the dip angle between the round blast and the earthquakes and also fits also to the fault plane solutions. The estimated fault types of the earthquakes are reverse (first earthquake) and reverse left-lateral oblique (second earthquake). The slip vectors show the hanging wall has moved 1 μm upwards and towards NE.

According to seismic monitoring the rock mechanical conditions in the rock mass surrounding ONKALO have been stable in 2011. Regarding safeguarding the construction of ONKALO, the conclusions of the explosions detected inside the seismic ONKALO block are similar to those in the seismic semi-regional area. Any indications of undeclared works have not been found.

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