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Geophysical methods to detect tunnelling at a geological repository site

Applicability in safeguards

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ABSTRACT

Generating power with nuclear energy accumulates radioactive spent nuclear fuel, anticipated not to be diversified into any unknown purposes. Nuclear safeguards include bookkeeping of nuclear fuel inventories, frequent checking, and monitoring to confirm nuclear non-proliferation. Permanent isolation of radionuclides from biosphere by disposal challenges established practices, as opportunities for monitoring of individual fuel assemblies ceases. Different concepts for treatment and geological disposal of spent nuclear fuel exist. Spent nuclear fuel disposal facility is under construction in Olkiluoto in Southwest Finland. Posiva Oy has carried out multidisciplinary bedrock characterization of crystalline bedrock for siting and design of the facility. Site description involved compilation of geological models from investigations at surface level, from drillholes and from underground rock characterization facility ONKALO. Research focused on long term safety case (performance) of engineered and natural barriers in purpose to minimize risks of radionuclide release.

Nuclear safeguards include several concepts. Containment and surveillance (C/S) are tracking presence of nuclear fuel through manufacturing, energy generation, cooling, transfer, and encapsulation. Continuity of knowledge (CoK) ensures traceability and non-diversion. Design information provided by the operator to the state and European Commission (Euratom), and further to IAEA describes spent nuclear fuel handling in the facility. Design information verification (DIV) using timely or unannounced inspections, provide credible assurance on absence of any ongoing undeclared activities within the disposal facility. Safeguards by design provide information applicable for the planning of safeguards measures, e.g., surveillance during operation of disposal facility. Probability of detection of an attempt to any undeclared intrusion into the repository containment needs to be high. Detection of such preparations after site closure would require long term monitoring or repeated geophysical measurements within or at proximity of the repository. Bedrock imaging (remote sensing, geophysical surveys) would serve for verifying declarations where applicable, or for characterization of surrounding rock mass to detect undeclared activities. ASTOR working group has considered ground penetrating radar (GPR) for DIV in underground constructed premises during operation. Seismic reflection survey and electrical or electromagnetic imaging may also apply.

This report summarizes geophysical methods used in Olkiluoto, and some recent development, from which findings could be applied also for nuclear safeguards. In this report the geophysical source fields, involved physical properties, range of detection, resolution, survey geometries, and timing of measurements are reviewed for different survey methods. Useful interpretation of geophysical data may rely on comparison of results to declared repository layout, since independent understanding of the results may not be successful. Monitoring provided by an operator may enable alarm and localization of an undeclared activity in a cost-effective manner until closure of the site. Direct detection of constructed spaces, though possible, might require repeated effort, have difficulties to provide spatial coverage, and involve false positive alarms still requiring further inspection.

Key words: *spent nuclear fuel, disposal, nuclear safeguards, non-proliferation, containment, surveillance, design information verification, geophysical survey.*

PREFAFE

Detailed site investigations are needed to demonstrate the suitability of the site to be selected for a geological repository to dispose of spent nuclear fuel. The hydraulic impermeability of the hosting geological formation surrounding the repository is essential for the safety case. The impermeability may be jeopardized by inhomogeneities in the rock mass and in case of igneous rock by fractured zones with may have long extensions. While developing the site-specific geological repository for spent nuclear fuel, the performance of rock mass and engineered systems as containment and isolation barriers are to be considered during planning, design, construction, operating and closing of the repository.

The designers and rock engineering of a repository need site characterization data from different geophysical surveys, pilot drillholes ahead of tunnel front with related geophysical, geological, and hydrogeological investigations, and monitoring. Geophysical methods have developed and focused on the site-specific scientific and technical needs. Their role in safeguards have been under discussion during the development of IAEA safeguards approaches for geological disposal to detect undeclared activities.

Geophysical methods have been proposed as design information verification measures as the rock engineering needs the understanding of the host geology and its impermeability. The exploratory works can provide sets of safeguards-relevant information, but in practice only the engineered underground constructions cannot be accessed to be verified. The other application is related to containment and surveillance, i.e., detection of human intrusion. For this purpose, the extension of the containment should be clearly defined. During the operational time of a repository, this rock volume cannot be pre-defined. In addition, monitoring of the site conditions gives assurance about the natural responses of the formation and should detect unknown and unwanted phenomena in the vicinity of the repository. The Additional Protocol was introduced for this purpose to exclude undeclared activities, but it does not include the application of geophysical techniques. However, the public research for safety case and rock engineering supports the same safeguards mission to have credible understanding about the absence of undeclared activities at a geological repository.

In Finland, Posiva Oy has carried out multidisciplinary bedrock characterization for siting and design of the repository at Olkiluoto, focusing long term safety case in purpose to minimize risks of radionuclide release into natural environment. During site characterization and site selection in Finland, set of information was gathered which is having safeguards-relevancy in understanding site properties and providing baseline. International regulatory expert group has timely reviewed uncertainty of geological data, the interpretations, and expert judgements during the site investigations. These findings support also the safeguards needs to have timely conclusion about the absence of undeclared activities during the 30 years of investigations beginning from the first boreholes drilled at the Olkiluoto site. The excavation of the underground galleries began after more than 15 years of site characterisation work. The Continuity-of-Knowledge must cover the safeguards-relevant information during whole lifetime the repository.

In this report, the current understanding of the applicability of geophysical techniques for safeguards purposes is analysed. The report is prepared by the site investigation specialist Eero Heikkinen at the AFRY company. The focus is on the resolution and detection capabilities of the active electromagnetic, electric, and seismic sounding and corresponding passive monitoring at the Olkiluoto site. The report is based on literature reviews including safeguards-related research also at other geological sites and circumstances. The above-described fluctuation in definitions and safeguards terminology is affecting the review work since most of the figures and their captures are copied from earlier publications. Many of those are presented at the SAGOR or ASTOR group meetings supporting the IAEA to develop methodologies to safeguard geological Repositories since 1989. The originality is in the updates in technological details based on recent geophysical surveys at repository sites and analysis of cost-effectiveness made for STUK. At STUK this work was supervised by Olli Okko.

1 Introduction

Electricity production using nuclear power involves radioactive materials. Production accumulates spent nuclear fuel. Various concepts for spent fuel treatment and storage are considered. Disposal of spent nuclear fuel aims to permanent isolation of radionuclides from biosphere. Isolation systems should preferably be passive, thus rendering extensive monitoring systems for nuclear safety unnecessary (IAEA 2011).

In the KBS-3 concept, spent fuel assemblies as such are planned to be encapsulated in steel reinforced canisters made of copper (KBS-3), or stainless-steel canisters and placed into disposal wells or tunnels. Other types of handling and processes can apply for processed spent fuel.

Geological disposal concepts are proposed to be tailored for diverse types of geological formations. Considerations exist for sedimentary salt or claystone formation, or metamorphic or granitic crystalline bedrock. Construction method can vary from drill and blast to full face boring, or a deep borehole. A relative difficulty in implementing safeguards in geological disposal has been recognized (Richter 2004, DeMuth 2014).

Major task in safety case is isolation of spent fuel from groundwater flow, which could provide release path for radionuclides. Emplacement of canisters may take place in vertical wells in tunnels (KBS-3V) or along horizontal tunnels (KBS-3H or equal). Typically, water absorbing bentonite clay backfill is designed to buffer the hydraulic interaction between the fuel and surrounding rock mass. Portals to disposal tunnels are designed to be plugged, and tunnels and shafts finally backfilled to suppress hydraulic transport routes, and simultaneously to prevent intrusion into repository.

1.1 Nuclear safeguards to geological disposal

According to Nuclear Non-Proliferation Treaty (NPT, 1968), IAEA seeks to prevent or detect diversion of significant quantity of civil stocks of uranium and plutonium to contribute to any unknown purposes. Nuclear safeguards consider non-proliferation of nuclear materials. Measures include timely physical inventory verification, frequent inspections and containment and surveillance (C/S). These aim to increase probability of early detection and this way to deter any diversion.

In geological disposal, the spent fuel cannot be verified using traditional safeguards measures (IAEA 1998, Okko et al. 2018). Uninterrupted monitoring of individual fuel assemblies practically terminates at encapsulation. After emplacement of fuel identification or item counting of canisters and re-verification of nuclear material inventory is no longer possible. Underground engineered spaces will not be directly accessible, nor directly observed (Richter 2004). Safeguards of nuclear materials is considering means to verify declarations and nuclear material accountancy. In geological repositories the new challenge is to verify the accountancy using indirect methods by excluding undeclared activities. Applied safeguards measures should ensure credible assurance of non-diversion.

Methods instead of traditional safeguards belong to category of Containment and Surveillance (C/S) and Continuity-of-Knowledge (CoK). Geophysical methodology described in this report, does not relate to Containment and Surveillance (C/S), but to the confirmation of the host rock suitability for geological disposal and detection of tunnelling.

Once nuclear fuel is included into the material balance of the operator, there will be continuous bookkeeping and verification according to international agreements between the states and IAEA (INFCIRC/198/Add.8). Inventory change reports (ICR) are delivered monthly. Physical inventory taking (PIT) is carried out by operator currently once a year generating also physical inventory PIL & MBR reports. Bookkeeping will be maintained to unforeseen future. Physical inventory verification (PIV) is proposed to continue annually, though it is planned to base on Continuity of Knowledge for the inaccessible disposed of canisters/fuel.

The safeguards as a process should be implemented at applicable stages of the disposal, collecting information during site characterization, repository design and construction, as well as during operation. The C/S systems may include motion and radiation detectors, optical surveillance, and seals. Monitoring would also include detection of an attempt to remove any nuclear material away from repository, using portal activity sensors at transport routes. Unattended operation and remote monitoring will be applied.

Monitoring and surveillance of closed repository may continue. Confidence needs to be built there would not be diversion of nuclear materials before, during or after disposal, neither any undeclared activities at the site. At first stage C/S is targeted on encapsulation process (Mongiello 2013) and transportation of spent fuel casks but will continue during disposal and further on after closure of the repository facility. Later the containment and surveillance may be understood including different monitoring and remote sensing technologies, requiring definition of containment volume and distance of intrusion causing alarm. Containment of spent fuel can be considered effective only in case it can be verified (Finch 2009). Definition of "geological containment" is understood as the canister though the (engineered) isolation barriers (backfill) and natural barriers can contribute to long term safety functionality as well.

Continuity of knowledge (CoK) will be issued to ensure the status of nuclear material has remained unchanged, in cases surveillance is unable to produce concrete information on presence via direct observation. This applies after closure of the canister, and emplacement of the canister (Mongiello 2013), tunnel backfill and closure of the disposal tunnels. In case tracking record is not continuous, the spent fuel can be inspected and measured again to confirm the content is unchanged. After encapsulation this is not desired and after emplacement of canisters this is not possible.

Operator produces to competent national authority (STUK) and to IAEA/EC the Design Information. These declarations IAEA will verify for correctness and completeness (Design Information Verification, DIV), though for natural materials such as rock mass this is not unique. DIV can include for example laser scanning of the tunnels. DIV has not been advised to contain the bedrock volume surrounding the repository, apart from some related suggestions, for generic safeguards approaches for operating and closed deep geological repositories (IAEA 1998, Okko 2004). It is obvious that a declaration for the host rock cannot be expected to be either verifiable, correct, or complete.

The design information verification (DIV) at various stages (though mainly operational, Mongiello 2013) will be used to ensure the repository in its details will conform what operator has designed and reported. This would mean there shall not be ongoing any undeclared activities in the disposal site (absence of excavation of tunnels, rock engineering, and devices), and that the bedrock surrounding the repository is intact. Design information verification is carried out at changes of repository frequently during design, construction, and operation phases. would be even 3 – 6 times per year.

According to Additional Protocol (AP) to Safeguards, the operator produces a site declaration to national authority (state). State forwards the site declaration to IAEA. Verification methods in AP will be additional query, and complementary assess (CA) to the site, including for example environmental sampling and radiometric measurements. IAEA has thus opportunity to detect undeclared activities in all premises at the repository, including those not included in design information.

Additional protocol (AP) also includes the buildings and volumes of underground rooms, but it does not consider the stability of these premises. Posiva runs safeguards programme, where information is generated for example using laser-scanning (Pentti & Okko 2018).

Safeguards by design (Okko et al. 2018) is a process for the inspectorates IAEA/EC or STUK and the operator to communicate about appropriate safeguards-relevant information during design, construction, and operation. Detecting and preventing an undeclared intrusion into the disposal facility after disposal, or after closure of the site, may require long term monitoring or repeated checking. Design of geological repository is changing during construction due to unforeseen conditions. For this reason, the safeguards measures need to be flexible to adapt design changes (Okko et al. 2018). National authority STUK has direct access to site, and full-time presence at facility during operation.

Pre-nuclear phase of repository construction will consist of generation and verification of the as-built design data. The provided baseline information will be based on data collected during site investigations and repository construction (Okko and Rautjärvi 2004). Inspections are proving the data will correspond with the excavated rock spaces and geometric volume. Assessment of all safeguards relevant monitoring data would assure absence of undeclared safeguards-relevant activities at or near the repository (Richter 2004).

Post closure (Okko & Rautjärvi 2004) safeguards measures would provide a prominent level of assurance that the quantity of nuclear material contained in the spent nuclear fuel is transferred to the repository and undeclared removal of nuclear material, as well as undeclared breaching of integrity of a repository would be detected. The space into which repository is constructed and the immediate rock volumes contiguous to the repository boundaries cannot be directly observed. After emplacement, the inventory of the nuclear material cannot be re-verified due to backfill of disposal tunnels. In case continuity of knowledge would be lost, it cannot be restored.

Closing will last several years. Closing includes backfill of all drifts, tunnels, and shafts in repository. Boreholes, surface installations and monitoring equipment will remain until these are considered no longer necessary, and surface site will be restored.

Diversion of nuclear material from closed repository requires excavation of new or original shafts or tunnels, excavations from other mines, tunnels, or caves. The surface area including original shafts needs to be monitored to cover these activities by on-site inspections and remote monitoring. Safeguards approach includes unannounced random visual inspections applying also geophysical techniques, satellite, or airborne monitoring, active or passive seismic monitoring, environmental sampling, and information analysis. Safeguards approach does not require possibility to verify the presence of the nuclear material but the integrity of the repository site (Okko 2004).

Research and development needs have been recognized in some geophysical techniques related to safeguards (IAEA 2017). During repository operation, seismic methods may be useful. Ground Penetrating Radar (GPR) technology was considered useful for verifying the declarations in the repository environment. Even presence of a metal canister behind the bentonite backfill can be indicated with simple GPR measurement (Lee et al. 2020). Topics to be developed would be for example automated data review and interpretation of various data sources, including geophysical results. Other development issues were for example environmental sampling to detect undeclared underground processing activity. Modern safeguards would include qualitative elements in non-mechanistic way to gain credible assurance of absence of undeclared nuclear operations (Okko 2004).

A possibility for authorities to make a random inspection on how well declared construction activities correspond the actual conditions, may suppress interest in carrying out an attempt for diversion. However, any technology to be applied should not impact to repository long term disposal safety (Seidel 2007). Methods should be able to discriminate declared activities and natural conditions from abnormal (undeclared) activities. The methods should also have a low false alarm rate. Further requirements have set for using remote monitoring, automated analyses (e.g., Lee et al. 2020) and random inspections, possibility to be implemented by well-trained safeguards inspector supported by geophysics specialist, and being fast and easy to position and implement, carry short measurement time, permit monitoring of large areas, and be reliable and rugged (Seidel 2007). Methods should also be cost effective.

Fully independent IAEA safeguards at geological repository would require continuous human and instrument presence at the site during whole lifetime of repository. Maintenance of technical equipment would require technical people reached at short notice (Okko & Rautjärvi 2006). Given the pace of disposal process, emplacement of one canister each working day during several decades, it is apparent that efficiency is required. Instead, cost-effective method would be a full usage of existing systems in pre-nuclear phase including audit of national system elements and their safeguards functions. This would incorporate examination of progress reports and the as-build design, assessment of national monitoring system to be assured of absence of undeclared activities, structures, equipment, and materials of safeguards relevance. It would require IAEA access of national system elements in short notice, as well as approaching national system in case of anomalies, inconsistencies, or questions of safeguards relevance.

1.2 Monitoring for long term nuclear safety

Monitoring of measurable properties at the area hosting the repository would rely on baseline information collected during site characterization. Monitoring will use either passive source methods (not requiring implementation of active geophysical source, for example natural fields or environmental noise), or repeatable surveys, or combination of both. Functionality of monitoring would require long time series of comparison data, understanding the geological conditions, and the effect of declared construction and operation of the repository.

Monitoring using external capabilities independent of the operator would review time series of satellite imagery, to detect changes in environment, like development of roads, buildings, excess construction materials, and changes in vegetation or land use in general.

Monitoring at the neighborhood of the site would indicate changes in various environmental parameters. These may include observation of excess drainage water, changes in water flow and quality, increase in radon release due to underground construction, or changes in power consumption or traffic frequency.

Monitoring using systems and installations provided by operator, applying data collected by the operator from the site, is following changes in baseline properties, and can be compared to effect of declared activities. Definition of baseline properties require accumulation of the recording during long time before starting of operations, to describe the properties in adequate accuracy. Most safeguards-relevant methods currently carried out by the operator, belong to range of rock mechanic monitoring, and include microseismic measurements and detection, rock movement detection on ground surface and in excavated tunnels, and temperature measurements and stress field measurements in bedrock.

Microseismic monitoring in detection of unanticipated construction have been studied in several reports. Regarding spent nuclear fuel disposal project carried out by Posiva Oy in Finland, several previous desktop works were carried out in this respect. Undeclared construction work would cause noise and events in case of use of explosives, for both of which the source can be localized. Microseismic network need to be established before construction, operate throughout construction in pre-nuclear phase, and continue operation in post closure phase.

Detectability of distinct types and sources of mechanical construction noise have been reviewed at Yucca Mountain site in disposal investigations (Finch 2009), and at Gorleben test laboratory in salt formation (Altmann 2012, 2013, 2014), and at Olkiluoto (Saari & Malm 2015).

Temperature can be measured in excavated tunnels, but also in drilled boreholes at the site and the neighborhood. Temperature can be measured in groundwater contained in boreholes, using wireline sensors. Changes in bedrock or groundwater temperature may indicate undeclared underground construction, changing the temperature due to ventilation and other processes, as well as due to changes in groundwater flow.

Other monitoring methods are recognized as changes in hydraulic head. Possibilities using hydrogeological pressure field monitoring were discussed in earlier report (Pentti and Heikkinen 2017). Construction of the repository will change the hydraulic conditions at the site. Drawdown of hydraulic head will occur theoretically both as a large-scale cone of depression, detectable in piezometric wells, and in hydrogeologically defined domains, like fracture zones. In the zones even greater pressure responses can be detected to longer distances. Changes in pressure can be detected using sensors installed in an isolated section in a deep borehole. Interception of such zone by undeclared construction work would be detected and separately recognized from corresponding responses related to declared activities.

Other potentially recognizable monitoring methods might be available the hydrogeochemical conditions, where changes may appear in salinity of the groundwater (electrical conductivity of the groundwater can be measured with wireline sensors) due to upconing of saline groundwater caused by drainage water management. Changes can occur also in various other hydrogeochemical parameters, including ion strength and groundwater species, acidity, or alkalinity (due to e.g., cement), redox, oxygen or carbon dioxide content, and dissolved gas content, to mention few.

Monitoring is insensitive to amount of rock volume excavated or shape of excavated underground space. Monitoring cannot be used for design information verification in sense of reviewing the correspondence between declared excavated rock volume and its declared shape, and the one constructed (Okko & Rautjärvi 2004). Actual localization and characterization of an observed disturbance would always require more detailed checking in the field.

Monitoring will be applied at all stages of design, construction (pre-nuclear) and operation of repository to provide baseline information, ensure operational safety and facility operability, and confirm conditions are consistent with long term nuclear safety. Monitoring program should not reduce overall level of long-term safety (Okko 2004).

1.3 Active geophysical surveys

This report will summarize recent development of geophysical site characterization methods, which could have safeguards-relevancy. Observed properties of different survey methods, and their application, are discussed.

The geophysical methods are used in characterization of the bedrock volume of the site. The results are used in constructing geological description (models) of the site, which in turn is contributing to site understanding, design of the underground repository layout, and considerations of long-term safety. Knowledge can be used as a baseline for safeguards.

Geophysical techniques may be applied for verification of design information, so that the underground constructed premises and spaces are conforming what is declared.

Geophysical measurements can be used for exploring the bedrock volume surrounding the repository. Several geophysical techniques can be used to detect voids and openings in bedrock.

The results can be used either to indicate presence of undeclared excavations, or favorably as a proof of absence of such engineered spaces (Okko and Rautjärvi 2006). Direct detection of undeclared activities without prior knowledge, or without using baseline information for comparisons, would be demanding, as it should be applied in any location and circumstances, without prior knowledge on when and where a potential attempt for intrusion would take place. In worst case, detection would be necessary even without exact knowledge on geometry of the existing (once declared) underground premises.

Geophysical remote sensing through bedrock relies on contrast in limited set of physical properties which govern the potential field or wave field applied in each technique. These include specific mass (density), magnetic susceptibility, electrical conductivity and dielectric permittivity, and elastic properties. Among of these are physical parameters between the void and support structures (air, water, concrete or metal mesh liner, bolting) and host rock.

The detectability of any object in a geophysical survey is governed by number of factors, including size and distance of the object from survey, accuracy of the tools and measurement parameters of designed measurement system, density of the survey stations in the area, alignment of a survey setup, and for wave field, the frequency band of used waveform. These factors also affect to the maximum range (depth of survey) from where observations can be made, and the resolution at which objects can be detected or separated from each another.

Shortly, longest wave lengths (lowest frequencies) carry information from deepest but have the least of smaller object resolution capability. Smaller objects are detected with dense measurements, and from shallow depths, at high frequency wavefield. Small contrasts require accurate measurement tools and survey practices.

Each geophysical method has a feasible way of implementation, affected by accessibility to the target. Profile measurement or mapping on the ground level may be carried out effectively from an aircraft (staffed or unmanned, fixed wing or rotary), producing information of variation in physical property within an area. Similar information, without physical contact to the medium, can be carried at slower pace from ground level, too. This kind of information may include gamma radiation, gravity field, magnetic field, or electromagnetic field. The surveys typically carry information from the very surface or from a depth of few tens of metres in maximum, and do not imply resolution to detect tunnel sized targets from the repository depth. Low frequency or time domain electromagnetic survey can be an exception on depth penetration, but not at remarkably high resolution.

Contact onto medium is required for electrical survey (for source and receiver electrodes) and seismic reflection survey (for geophones and sources). Electrical survey can produce depth penetration to tens of metres or with lower resolution up to hundreds of metres. Electrical survey does not carry resolution of small objects to greater depths. Seismic survey can provide depth penetration to kilometres with lower resolution, and to hundreds of metres with a good or moderate resolution. Seismic reflection sounding is only technique which has at least theoretical potential to observe deep seated excavated space from ground surface. Specifically, this holds in case where no prior information of exact design of tunnels would survive.

Survey methods considered as category of “sounding,” can be applied using transmitted and back scattered wave field like seismic, ground penetrating radar (GPR) and other electromagnetic or electric soundings, which enable imaging of target objects. Other than imaging methods can be alternating either application frequency or time delay (electromagnetic soundings) or survey array geometry to adjust depth penetration (electrical sounding), resulting to a diffuse image, and lesser detection resolution than wave field-based methods.

All the similar survey methods can be implemented also from scan lines formed by a borehole in the ground, or in a tunnel or other excavated space in bedrock. These survey locations offer a possibility to make observations closer to target. Access to the volume is restricted by availability of the drillholes or tunnels.

Seismic sounding using active sources would have highest safeguards relevancy in detection of an attempt for undeclared intrusion. Several variations are possible for survey implementation from tunnels or drillholes. The methods however are slow to implement and expensive to use. Application is also requiring highly expertized tools, design, and processing to create clearly understood results. Methods may also be invasive, risking an impact to repository integrity unless carried out with great care.

There are reported recent development on tunnel or mining environment seismic methods, which may be considered in this context. Permanent seismic array for repeated measurements might also be a solution, especially if combined with seismic station network, and implemented without risking repository safety. Disproving of existence of any undeclared voids is difficult without disturbing operational safety of facility (Okko and Rautjärvi 2006).

Geophysical surveys are likely to produce number of anomalies from subsurface. Typically, these anomalies are associated with geological objects. Geological variation is abundant and anomaly causing contrasts in the same order of magnitude as the would be for the tunnel objects. Information is fuzzy in character, potentially containing indications mixed of both tunnel and non-tunnel. Verification with drilling might be required. Such checking is costly, for which reason it might not be applicable. Also drilling may compromise long term safety and thus not anticipated (Okko and Rautjärvi 2006).

The observability or detectability of the complete disposal facility at depth of 500 m, while not knowing its’ existence, has been studied with forward modeling of geophysical responses (Isaksson et al. 2010). Computing used the known contrasts between tunnel structures and crystalline bedrock. Results for Swedish Forsmark case, using the geophysical signature of bedrock in the area, were indicating that although some of the ground surface survey methods can detect weak anomaly caused by magnetic, density or conductivity properties of repository in the corresponding field, neither of these could localize the repository. Only the seismic reflection method, implemented with using an adequate accuracy, could indicate that a repository would exist in the depth. Even in this case, the detail of layout in repository would not be imaged. Reversely, for a known layout, it is unlikely that deviations from the design would be observed using ground level survey alone, nor presence of an undeclared tunnel in a proximity of existing tunnels. Detecting undeclared activities and separating these from existing premises would be more difficult, requiring higher resolution, and a comparison between baseline and repeat surveys – a knowledge of existing disposal site and tunnel geometry.

Applicability of ground penetrating radar technique was assessed based on available GPR and borehole radar surveys in Olkiluoto (Saksa et al. 2005). Further experiences on the GPR method applicability in Olkiluoto conditions have been gathered during 2005 – 2020. The formed estimate of method applicability is revised in this review. Also, other geophysical methods are considered. Scope of this report is to revise GPR applicability, and review other geophysical techniques (active seismic sounding, electrical survey, electromagnetic surveys), and engineering methods, to update the information collected during construction of the ONKALO underground characterization premises in Olkiluoto. Also, some of results and knowledge collected in co-operation with Swedish Nuclear Fuel (SKB) are referred.

1.4 Olkiluoto spent nuclear fuel repository

Spent nuclear fuel disposal facility is under construction in Olkiluoto in Southwest Finland. Posiva Oy has carried out multidisciplinary bedrock characterization for siting and design of the facility, focusing long term safety case in purpose to minimize risks of radionuclide release into natural environment. Performance of rock mass and engineered systems as release barriers have been considered.

The rock engineering needs site characterization data which include different geophysical surveys, pilot drillholes ahead of tunnel front with related geophysical, geological, and hydrogeological investigations and other related information.

Authority review of site characterization is carried out at three-year interval, reviewing suitable volumes to host repository and technical solutions, simultaneously keeping in focus the safeguards relevance (Okko and Rautjärvi 2006). International regulatory expert group (Cosgrove et al. 2003) has timely reviewed uncertainty of geological data, but also the adopted safeguards approach.

Olkiluoto site is located on an island in Baltic sea coastal area in Southwest Finland. Coastal island is surrounded by shallow sea from three sides. Hard bedrock is covered by variable thickness of shallow glacial till overburden. Groundwater saturation reaches to ground surface. The bedrock is outcropped at few percent of its' surface. Bedrock consists of banded migmatite of sedimentary origin, containing in its current composition micaceous veined gneiss melanosome (paleosome) and segregated, partially recrystallized leucosome (neosome) granitic pegmatoid inclusions and veins. Rock mass contains also varying amount of supracrustal lithologies. The bedrock has undergone polyphasic deformation ranging from several ductile deformation phases, several brittle deformation phases, and alteration. Brittle fracturing on average is sparse, being concentrated to established narrow and continuous deformation zones, defining the volumes of avoidance in emplacement of spent nuclear fuel canisters.

Hydrogeological properties defining the disposal concept have been assessed using these deformation zones as hydrogeological units, e.g., in simulations (Posiva 2011).

During site characterization and site selection in Finland, set of information was gathered which is having safeguards-relevancy in understanding site properties and providing baseline. Characterization focused on long term safety of disposal (safety case) in natural environment, regarding performance of engineered barriers, to minimize risks of radionuclide release. Long term safety considerations have been revised at three-year pace.

Further characterization of the site contains core drilling of 60 deep boreholes from ground level, with associated hydrogeological and geophysical wireline logging, ground level and drillhole geophysical surveys, and extensive geological analysis. During construction of underground rock characterization facility ONKALO since 2004, three vertical shafts of 500 m depth extent were lowered. Over 5 km of inclined access tunnel were driven during six years, with pilot holes drilled on tunnel face. Geophysical and hydrogeological surveys were conducted from pilot holes and on tunnel surfaces, and in characterization niches. All these activities have deepened and focused the understanding of the rock mass. Acquired data has been used in creating geometric models and parameter information for site description. The models and parameters have been applied for safety case, intended for reasoning the long-term nuclear safety, including engineered and natural barriers of radionuclide release.

Wide range of geophysical methods were applied and interpreted for geological characterization of bedrock. Location and geometry of zones were characterized having mechanical or hydrological interest in safety assessment. This information was reviewed for relevancy for safeguards. Typical responses received with different geophysical methods, the ranges of investigation, and the object resolution are information which have also been gained during the site investigations.

Rock mechanical information is considered to have highest relevancy. Microseismic baseline measurements were started in 2002 early during the characterization, well before construction of ONKALO started. Currently 18 stations are operational on ground level and in tunnels and drillholes in Olkiluoto (e.g., Haapalehto et al. 2020). Annual reports of microseismic events include both localization of excavation blasts, as well as natural and stress field induced microearthquakes.

Sensitivity of the network is M_L = -2.5 - -2.0 (in local Richter scale). Monitoring has provided significant level of information of level of natural seismicity in the area. Sensitive station network has provided also localization of each excavation blast. Tests were made to detect and localize seismic noise caused by raise-boring of vertical shaft (Saari & Malm 2015). Later, small effects of stress field redistribution due to tunnel construction have been detected. Results are reported in publicly available annual reports. Monitoring has indicated that there has not been detected any significant undeclared safeguard-relevant construction activities in ONKALO or its vicinity. Such statement was made also by national authority soon after starting of construction of ONKALO (Okko and Rautjärvi 2006).

Bedrock remained undisturbed until construction of underground rock characterization facility started. Monitoring programme provides information related to long term safety.

Adjustments to the content of monitoring would give signals from rock masses from safeguards-relevant neighborhood of the ONKALO.

The average rock mass has been described in close range to include the local deformation zones into geological models, using geological mapping in tunnels and pilot holes, but also applying geophysical drillhole and tunnel surface methods like seismic and GPR soundings in different scales, and electrical crosshole measurements. Work has focused on continuity of local deformation zones, to be avoided in emplacement of spent fuel capsules. Joint interpretation of the characterization results is taking place in Rock Suitability Classification (RSC) process.

During construction phase the performance of excavation and rock surface quality of constructed underground premises can be investigated with Ground Penetrating Radar (GPR). Main purpose of GPR inspection is to ensure the excavation damaged zone (EDZ) on the rock surface would not provide a continuous groundwater flow path.

The excavation has been carried out with drill and blast method. Tunnel face dimension is 4 x 5 m. Blasting is carried out in 4 m rounds, where tens of percussion drilled holes are prepared at short distances on tunnel contour and on halfway between contour and mid-point, and a larger hole for starter charge is prepared on a lower part on the centre of tunnel profile. After blasting the rock mass is loaded and hauled to surface to be stored. After excavation, the tunnel surface is mapped, scanned with 3D laser (total station), and then for working safety, reinforced using bolting, sprayed concrete, grouting, steel mesh, or cast concrete. Pre-grouting can be used when rock quality or suppression of drainage water flow requires. Support method varies along tunnel wall as it depends on conditions. Coordinated inspection is carried out to recognize used solutions for safeguards-relevancy (Okko and Rautjärvi 2006). The change of methods according to local conditions sets requirements to handle possible unexpected changes in repository layout (Okko and Rautjärvi 2004).

Excavation procedure requires generation of rock spaces for drilling, blasting, loading and transport vehicles to pass each other, similar volumes as required for treatment of spent fuel transport canisters. For the safeguards it is necessary to map and verify these spaces, and the corresponding non-treated rock walls. To carry out the design information verification the rock face needs to be documented before reinforcement using photos and laser scanning to create 3D image, and volume estimate, etc. This documentation will be inspected by national safeguards when support method for each tunnel section is accepted and reinforcement taken place.

2 Possibilities to detect an undeclared activity

2.1 General

Independent detection of undeclared tunnels or spaces is demanding because it needs to be possible without prior knowledge when and where a potential intrusion attempt would occur. A verification of presence of spent fuel is not required, but continuity of knowledge needs to be assumed from credible assurance of absence of undeclared activities within repository boundaries. The integrity of repository with its boundaries should remain. Perimeter within which other excavation activities may not be allowable, have been suggested for example 10 km; and perimeter within large construction, capable in hosting shafts or tunnel portals, 5 km (Richter 2004). On the other hand, authorities may not be anticipated in installing monitoring devices in a private property outside the repository area (Richter 2004).

Diversion paths may include direct substitution of an empty container at the surface, retrieval of a spent fuel package from underground, opening spent fuel packages underground followed by removal fuel and transport to surface, and removal of spent fuel from packages for reprocessing underground. Pathway can include removal through shafts or ramps, or any other openings from repository to surface, or clandestine tunnels excavated into repository or out from the repository to the surface or to a nearby tunnels (IAEA 2010). During operation, non-diversion may be assured with radioactivity portal monitor placed at openings suitable to material transport.

Enabling the tracking of condition of repository during construction, operation and in post closure phase, a staged approach has been proposed (Okko and Rautjärvi 2006). Initial information regarding bedrock conditions (baseline) from site understanding shall be collected. Design information shall be generated during excavation, construction, installation, and operation. Underground repository cannot be planned due to unforeseen geological and rock mechanical conditions, so safeguards measures need to be flexible to accommodate changes in design (Okko et al. 2018).

Regarding nuclear material, verification of receipts and flow of materials is required, so that there would not be possibility to use other than declared access routes, nor enter or remove any undeclared material from the underground facilities undetected. Any technology or method used in support of the safeguards should be functional and non-invasive. A method should also be cost-effective to apply. Maintaining the continuity of knowledge shall not impair safety in operation or overall level of long-term safety.

Safeguards approach will have to be site specific. Least invasive of monitoring methods would be satellite imagery or airborne photography in follow-up of changes in environment. This kind of activity can be mostly carried out remotely, with some reservations for ground truthing and inspections. Surveillance in societal development, indications on unexplained activities like energy consumption, traffic, or other, may be also carried out with minimal interference.

Concrete means to follow-up activities in bedrock volume would be based on different passive or active measurement techniques. Best established passive methods would be the seismic monitoring of the site, which would directly detect and localize undeclared attempt to excavation by drill and blast or tunnel boring machine from distances of several hundreds of metres to kilometres. Other monitoring related to rock mechanic investigations would be observations of displacements and stress field. Topographic interferometry has been used in detection of changes by tunnel construction. Extensometers and convergence measurement in tunnels can indicate changes in stress field of near environment. Temperature monitoring might indicate closely located clandestine tunnel construction.

Other considered passive techniques would be based on monitoring of hydraulic head in bedrock (Pentti and Okko 2018). Tunnel construction causes drawdown in hydraulic head. Inflow into the tunnels is reduced by grouting and lining of rock mass. An undeclared tunnel construction would be seen as interference in hydraulic pressure field. Another groundwater related source of information is associated with salinity. Variation in electrical conductivity or changes in dissolved chemical compounds can be measured to detect changes caused by groundwater pumping, for example up-coning of saline groundwater.

An existence or absence of a clandestine tunnel at the repository site of Olkiluoto is difficult to prove. Geophysical methods (seismic and electromagnetic) would require high detection capability and produce substantial number of anomalies to be verified by extensive drilling. Contrary, preparation of clandestine tunnels would change environmental conditions that may be detected indirectly.

To reach 430 m depth with truck, sloping tunnel of 1:10 inclination is required, having length of at least 5 km. Such tunnelling cannot be easily carried out in undetectable way. Excavation blasting would be detected by microseismic station network from considerable distance. Saw extraction of rock mass, or full-face tunnel boring (Fuerst and Del Nero 2018), would produce noise which also can be detected though from shorter distance than blasting. Extracted rock residue mass should be hauled and stored somewhere.

Large construction machinery would be difficult to bring in. Operation consumes energy, which might well be detected. Also, the electromagnetic interference caused by large power sources are likely to be measured from longer distances even through the rock mass. Leading the excess drainage water away, and ventilation of tunnels with exhaust air outlet will be detectable as well. The IAEA approaches are very generic. Compatibility with national Swedish proposed system were reviewed (af Ekenstam et al. 2018).

DIV including geophysical methods to detect deviations from declared design could be used instead (IAEA 1998). IAEA Board of Governors (2002, referred in af Ekenstam 2018) have stated that under integrated safeguards, geophysical methods may not be needed to detect excavations or excavation activities, but replaced by Complementary Access and information analysis (belonging to Additional Protocol). GPR may still be needed for required DIV processes like detection of undeclared tunnels, rooms and boreholes or permanent underground equipment. The latter would require for GPR to be a metallic structure, well reflecting object, when located behind rock mass.

DIV would be used during construction to verify the declared design of the repository. The IAEA may undertake inspection and monitoring activities to assure itself of the absence of undeclared chambers or tunnels, and to identify undeclared equipment. Geophysical techniques, as far as these would be feasible and effective, could be implemented (IAEA 2010). During operational phase, nuclear material will be transferred into repository for emplacement, and controlled to maintain continuity of knowledge, using containment and surveillance. DIV will continue, as-built information will be subject to inspections. Environmental sampling can be carried out. After backfilling the safeguards would be reduced to measurements that assure no intrusion occur which could result in retrieval of nuclear material. There would not be an operator present at the site after closure.

Geoscientific characterization techniques can be used either by authority or by nuclear energy operator. A continuity of knowledge is anticipated, over wide time span and depth scale. Containment of spent fuel is considered effective only in case it can be verified (Finch 2009). Different verification activities can be implemented are planning and design (baseline information), construction, operation (design information verification), and post-closure (monitoring). The construction and operation phases offer limited access into close area of the repository, to make comparisons between baseline and verifying measurements. After the site would be closed, close access is no more possible, and possibilities are focused on monitoring (Finch 2009). Passive seismic monitoring seems favorable for long term applications as it can detect a tunnel boring machine operation at distances in order of 100's of meters or kilometers away. Near term monitoring is implying more problems because construction itself is producing noise, which can mask undeclared activities (Finch 2009). Cost efficient passive seismic monitoring may be conducted using commercial sensors (Haddal et al. 2014).

2.2 Previous methodological considerations

Safeguards relevant geophysical monitoring and exploration techniques are dependent on-site properties, like geological environment, physical characteristics of rock mass, repository design, and arrangements in operation. Applicable methods have been discussed and reviewed in various projects.

Finch (2009) has reviewed application of range of monitoring and geophysical methods, listing their capabilities compared with safeguards relevancy. These included magnetic, gravity, electrical, electromagnetic, and seismic methods. Finch (2009) and Haddal et al. (2014) conclude on basis of TBM test made at Yucca Mountain site in tuffitic rock, that seismic monitoring may be most feasible for long term detection of an attempt for diversion. A full-face tunnel boring machine may be seen using sensors from distances of several kilometers. Induced noise levels are of similar range as city traffic noise. Other techniques like water jet cutting or wire saw rock extraction may cause less intense noise, which would be more difficult to detect.

Tunnel boring machine or drill and blast excavation would need a gentle, maximum 10-15% slope to enable vehicle transportation. Advance of excavation, 2.5 – 5 m/ day, would allow warning time to make detection before suspected undeclared activity reaches near the repository. Tunnel excavation activity would be energy intensive, which may enable detection of energy consumption, exhaust fumes or ventilation air, excess water from dewatering, chemical compounds (nitrogen) from blasting, electromagnetic fields caused by machinery, electrically conductive or magnetic mass of machines used in excavation, and excess rock mass to be hauled from tunnel and stored.

Altmann (2013) has compared wide range of mechanic excavation noise sources (mechanic extraction, blasts, drilling, sawing) for their energy, peak particle velocity and spectral character in Gorleben salt dome. Detection of excavation caused noise could be carried out using an underground “fence” of sensors surrounding the repository at 1 km distance from repository, within the salt dome or for example 500 m distance of the salt dome margin, placed at depth of few hundreds of metres in drillholes. Various sources cause different kind of signals. Spectra from periodic sources like vehicle engines and percussion drilling cause harmonic series, transferred to rock via acoustic to seismic coupling, seen to distances of hundreds of metres. Rock removal for example by drilling because broad spectra signal up to several kilohertz of frequency. Blasting and mechanic extraction cause largest signal level, seen to distances of one to several kilometers. TBM or road header activity detectability was not estimated. Different other sources cause weaker signal than blasting. Rock grader produced signal can be visible from distances of 200 – 500 m. Chain saw, roof cutter, picking or percussion drilling can be recorded from distances of 20 – 70 m. Detection of such activity from a tunnel face would be covered with placing a geophone or accelerometer station at each 50 m of tunnel.

Detection of acoustic events caused by undeclared activity would be based on simple amplitude criterion, which would also need definition of seismic background. During operation seismic noise of undeclared activities may be masked by those caused by declared activity. After closure, no sensors and cabling can remain in repository. Shorter distances are relevant during emplacement phase, higher energy level noise and longer distances for long term monitoring after closure.

Passive seismic monitoring requires less sensors than active seismic survey, does not require source, and it can be applied to monitor mining activities in large repository scale (Haddal et al. 2014). Passive systems may require 8 – 15 stations of 3 components, for borehole and surface sensors, with 10 – 15 years lifetime: saving data and carrying automated detection. Cost range would be in order of 100 – 400 k$. Site visits would need to be carried out annually. Full time analyst would be required to operate the system and carry necessary interpretation of detected responses. Commercial on the shelf systems are feasible in case security will be ensured (Haddal et al. 2014).

Canadian safeguards support reviewed seismic signals theoretically in cases of operating underground mines (CSSP 2002). Posiva has followed progress in tunnel excavation using microseismic network and managed also in detection and localization of raise-boring of vertical shaft, which is analogous process for tunnel boring (Saari and Lakio 2007, 2009, Saari and Malm 2015). TBM detection would require continuous recording, which is not typically used in station seismology. The moment when rock cutting head is hitting the surface produces best recordable signals, repeating frequently during the process. Nevertheless, in case seismic monitoring network is in operation, a skilled operator would always detect an attempt of intrusion using TBM due to generated continuous seismic noise, making such attempt impossible without detection (Saari and Malm 2015). After first detection of a susceptible signal, further field studies at higher sensitivity would be required to define location of the origin of signal at accuracy of few metres to some tens of metres in lateral direction. Resolution of localization would be high to distances of one kilometer, detectable at range of 1 – 1.5 km, and not feasible at greater than 2.5 km distances.

Altmann (2014) has modelled propagation of various signals and compared these to measurement data. Blast shots have S/N ratio 650-3800 when recorded underground at distances 31 – 233 m, and 20 – 130 when recorded on surface at 1060 – 1176 m distances. In mine detection would require one geophone each 50 m, after closure from surface, at 1 … 8 km distances from repository centre. Modelled signal is useful to be compared with recorded signal, to detect deviation. Altmann (2013) concludes on basis of testing in Gorleben experimental mine, that monitoring around a disposal site in rock salt could be carried out with a “fence” of seismic monitoring sensors at 500 m from salt margin, at 1 km offset from the site, to recognize any blasting or drilling related to rock mass removal. All sources of seismic signal were analyzed from different distances. Detection distances are kilometres for blasts, several hundreds of metres for heavy vehicles, and c. 100 m for weaker sources (hammer, drilling, scaling). Detection will depend on background noise level. Signals can be separated from other sources. Signal strength from even same type of source vary greatly.

The drillholes required for measurements could be prepared to safe distance from repository as not to breach the integrity of repository and thus endanger the long-term nuclear safety, and preferably placed towards potential directions of intrusion. Problems related to of this kind of drillholes include that there needs to be some instance who would propose, place, and prepare these. Also, funding would be necessary if excess drillholes would be prepared. In worst case the repository hosting volume would need to be completely encircled with such an array. Geophysical “alarm fence” around repository would consist of for example 30 boreholes at 400 m spacing, 600 m deep each, at 2 km radius from the centre of the repository. This would be significantly contradictory to requirement of cost efficient, easily implemented safeguards-relevant survey method requiring minimal special expertise involvement, but bare existence of such possibility would be adequate to suppress attempt to intentionally breach repository integrity from outside of repository perimeter.

Sensors cannot be placed or maintained at the deep disposal premises after their closure. There cannot be created hydraulic connections to the ground surface, potentially weakening integrity of disposal, so data transfer would be impossible. Neither there would be allowed foreign materials. Ground level installations are possible.

Short distances (weak sources) of detection are relevant during operational phases, applied automatically at densely placed sensors (50-100 m distances), and stronger signals after closure. Signal produced by TBM or road header type of excavation was not reviewed by Altmann (2014). Seismic monitoring would be equally feasible method also in crystalline rock and sedimentary clay stone. Acoustic emission can be used in mining activities and rock stress measurements (Finch 2009).

Station seismology has been used in monitoring seismic activity at the Olkiluoto site. The events measured to levels of ML < -2, include excavation blasts, excavation induced microseismic activity, and naturally occurring seismic events. Network capability has tested to demonstrate capability to detect and localize a TBM or raise boring type of mechanical noise (Saari and Malm 2015).

Seismic monitoring has been listed as a potential method in detection of an attempt for external intrusion (Finch 2009). Application was tested at Yucca Mountain site. Signal decay was analyzed and estimated to be adequate over reasonable distances. Other sources of information, like muck and groundwater removal (hydrogeology, satellite imagery, ventilation, power consumption) were considered as well for detection of undeclared excavation activity (Finch 2009). Tunnel preparation might be detected with electricity consumption, electromagnetic interference caused by machinery, or transport and storage of residual materials. Interference of local environmental conditions, for example in the sea water quality, may also reveal large non-reported underground construction work. A legal, purposeful excavation activity would require permitting and environmental impact assessment, which would be easily detected and understood already in design stage. Clandestine operation is unlikely to remain unnoticed.

Microseismic survey was carried out in ONK-TKU-3620 POSE project (Reyes-Montes et al. 2013), to define intensity of rock spalling during heating experiment and recovery (Valli et al. 2013). Microseismic activity related to induced deformation can be recorded within sphere of several metres. Survey can detect seismic events caused by excavation, and velocity changes due to changing stress field and water saturation, when compared between repeated measurements (Haycox and Pettitt 2009).

Possibilities to apply for safeguards purposes the long-term safety aimed monitoring system used in ONKALO was reviewed by STUK in 2017 (Pentti and Heikkinen 2017). Functionality of GPR method in Olkiluoto conditions was reported in (Saksa et al. 2005). Possibilities to apply ONKALO long term safety aimed monitoring was reviewed in 2017 (Pentti and Heikkinen 2017, Pentti and Okko 2018).

Active geophysical survey methods can be used to detect and localize undeclared constructed spaces. Most reliable way to detect new tunnels would be comparison of repeat measurements with a baseline survey conducted earlier, especially when accurate location is unknown, distances from survey location are long, targets small, contrasts in physical properties low, or naturally occurring anomaly features abundant.

Two active geophysical methods, GPR and active seismic reflection sounding, and passive seismic methods, were reviewed as examples of geophysical techniques for safeguarding final disposals in geological environment (Seidel 2007). Requirements for geophysical methods were recognized as not having an impact to repository safety envelope, being able to discriminate declared activities and baseline conditions from abnormal activities and having low false alarm rate. Further to these requirements the applied methods should be efficient, using remote monitoring, automated analyses, and random inspections; being possible to be implemented by well-trained safeguards inspector with support from specialist in geophysics. Positioning should be fast and easy, measurement time short and volume or area coverage large, unless equipment could be permanently installed. Tools to be used should carry high reliability, be rugged, and possess long meantime between failures (low need for maintenance) (Seidel 2007).

Two main objectives remained for application of geophysical methods, being verification of the design information of the geological repository (detection of undeclared tunnels and rooms) and detection of undeclared excavations to get access to the repository from outside (Seidel 2007).

GPR is considered easy to handle, high resolution, not impacting repository safety, and possible to implement by well-trained safeguards inspector (Seidel 2007). Problems were recognized to require planning of whole project and interpretation requiring expert knowledge, and limited range of detection. Modeling presented in report (Seidel 2007, Seidel et al. 2004) shows the resolution and detectability would be adequate to be able to detect presence of abnormal underground excavation near declared rooms at distances of 10 – 20 m, from different geological background (rock salt, clay stone, crystalline rock). Modeled case for 50 MHz GPR is for tunnel geometry slightly idealistic. A 50 MHz antenna is bulky to operate and requires particularly good shielding to suppress tunnel reflections from side walls, back walls, and ceiling, as well as from any metallic installations.

The GPR signal travels in medium at a single velocity waveform (depending on medium). The measurement array consists of transmitter and receiver which are located symmetrically, and each measurement trace (A-scan) is presented at the mid-point. This makes the GPR images (B-scan) easy to understand, though the actual anomaly causes necessarily do not locate precisely at line perpendicular to the measurement surface, but within a radar transmission cone ("beam"), which has aperture of several tens of degrees. More to this the anomaly form for point-like or spherical objects are hyperbolic, and for linear objects more linear in form. For inclined linear objects, the angle of inclination is not true but apparent. Mathematical process to suppress diffracted events emerging from point or spherical objects, and to image all features at correct location, is called migration.

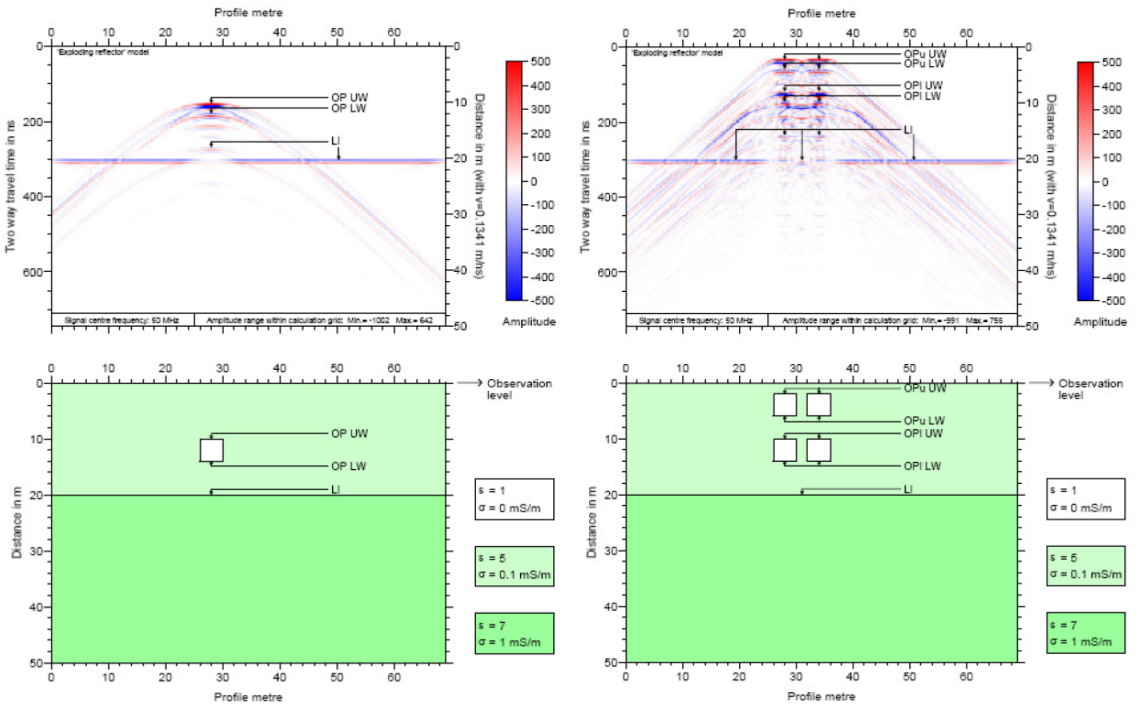

Figure 2-1. Synthetic model of GPR measurement data on a tunnel wall in geological environment having resistivity and dielectric permittivity contrast. Observability of simple model case with one (on the left) or more complex model case with several (on the right) excavated spaces is demonstrated (Seidel 2007, Seidel et al. 2004). Side flanks of reflecting events indicate hyperbolic diffracted features caused by point-like objects.

Functionality of GPR method in Olkiluoto conditions was reported by STUK in 2005 (Saksa et al. 2005). Practical results from Olkiluoto (Saksa et al. 2005) show that geological variation causes problems in form of possible false alarms, as well as high attenuation of GPR signal reduces the effective range of observation. Use of GPR would rely on using geological information and design information with GPR data to support interpretation. Non-identified objects may be of natural origin or synthetic. GPR has a partial coverage at proximity of tunnels, only partial verification of disclosure of non-reported features is possible.

An example by Seidel (2007) from unpublished test material in Konrad mine 2004, shows that in rock mass resistivity of 2 Ωm at GPR frequencies in iron ore, implies strong attenuation and GPR does not carry information from rock mass or constructed spaces. Test was carried out using 50 MHz double antenna with an 8 m offset between transmitter and receiver.

Also support structures like metal fibre reinforced concrete will be reducing the applicability of GPR method. Modeling was suggesting that spent fuel capsules may imply large enough contrast to be detected from distances of up to 10 m from parallel tunnel. Lower frequencies have higher detection capability and range but imply problems in application and interference from irregular surface and installations.

Highest resolution is obtained from borehole measurements, which however require expensive and rare equipment, expertized personnel, and a borehole for application which does not maintain the safety of repository envelope.

An idea has been promoted on application of directional borehole radar reflection sounding in multiple boreholes, for in-mine detection and localization of undeclared activities (Althaus 2013, Uchtmann and Althaus 2014). Method would be used in early-stage identification, applied at a sufficient distance, being complementary to passive seismic monitoring. Survey would rely on baseline and repeat measurements, and detection of changes. Radar would produce directional volume information within the repository boundaries. A static radar system would require permanent installation of sensors outside of the repository. Monitoring could be continued in post-closure phase. Radar waveform could be used in recognition of types of new observations, caused by tunnels or installations. Method would rely on distinction of undeclared activities from known activities and baseline conditions. A protective shield should envelope the repository.

A borehole radar method to be developed should require low effort for inspectors, low need for maintenance, and automated measurements, processing, and interpretation. Method should have no influence on repository integrity, use wireless data transfer and self-sufficient power supply. Tools should use standard antennas and be constructed of reliable components suitable to rough conditions. Detection of undeclared activities should be based on modeling. New development of tool technology would use multiple frequency measurements, high transmission power, and high-performance electronics and data storage.

In favourable conditions borehole radar could be used to distances of hundreds of metres from a measurement borehole. In Olkiluoto conditions, the attenuation in metamorphic rock suppresses the range to tens of metres, which would require high density and number of boreholes to be prepared, requiring excessive costs, and potentially risking the integrity and safety of repository. Also, the naturally occurring reflections would cause multitude of false alarms which would need to be checked or rejected to create a meaningful set of information.

An alternative technique for borehole radar, to be used to complement the passive seismic monitoring, would be seismic borehole reflection measurement. Having longer range, requirement of drillhole density would be lower. Method would still be expensive to implement and maintain, but could use combination of passive, environmental noise recording, and active surveys.

Regarding the active seismic methods, also these have sufficient resolution, do not impact repository safety, and range of detection is good. Seismic investigations, however, require expert knowledge to design the work and interpret the results, high technical effort for measurements, and cannot be done by an inspector alone (Seidel 2007).

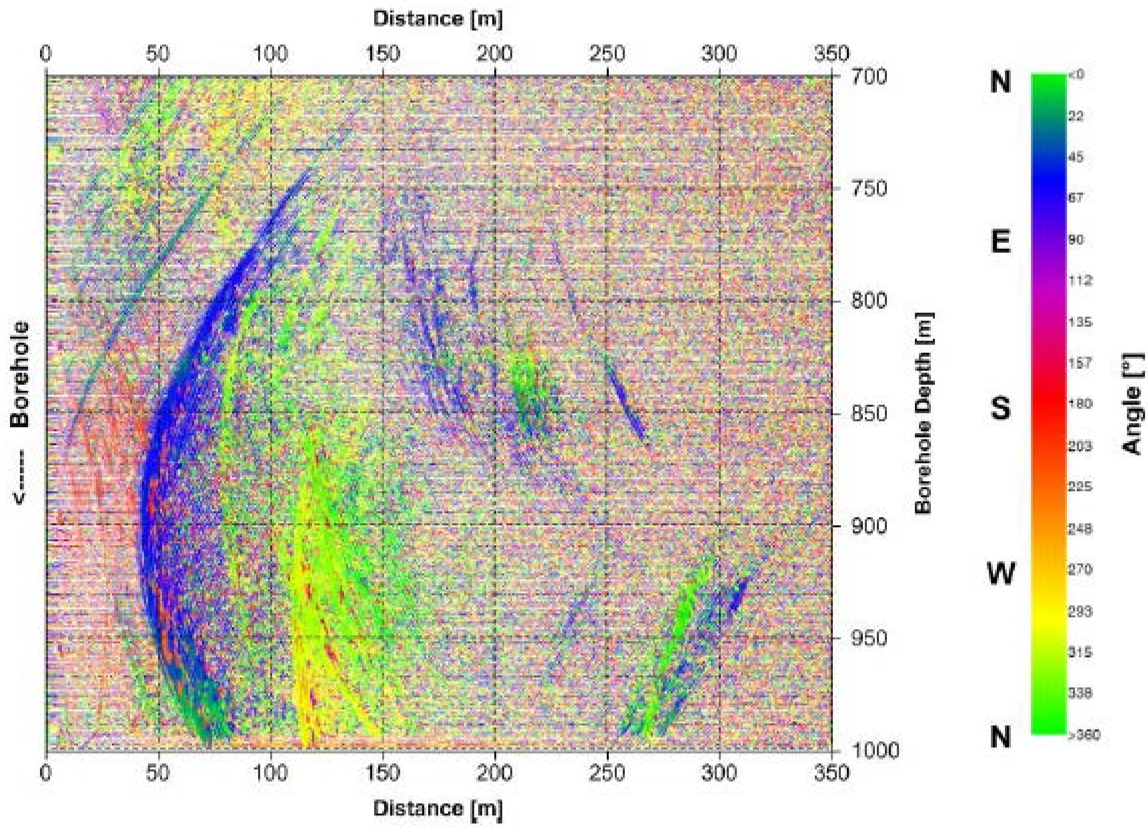

Figure 2-2. *Directional drillhole radar reflection example (Althaus 2013). Vertical axis is drillhole length. Horizontal axis shows radian distance from drillhole. Image displays backscattered radar waveform reflection amplitude. Colour coding indicates direction (azimuth angle from the measurement drillhole). Reflections can be lithological contacts, excavated tunnels or deformation zones in rock mass. In favourable conditions (inside a salt formation, granite containing fresh groundwater) low 10 – 20 MHz frequency drillhole radar can indicate reflections to two-way distances of several hundreds*

of metres from measurement drillhole. Repeat measurements would indicate undeclared activities, and their distance and direction from a borehole. Coverage of several boreholes would enable more precise localization, and enable creating a detection shield around the repository.

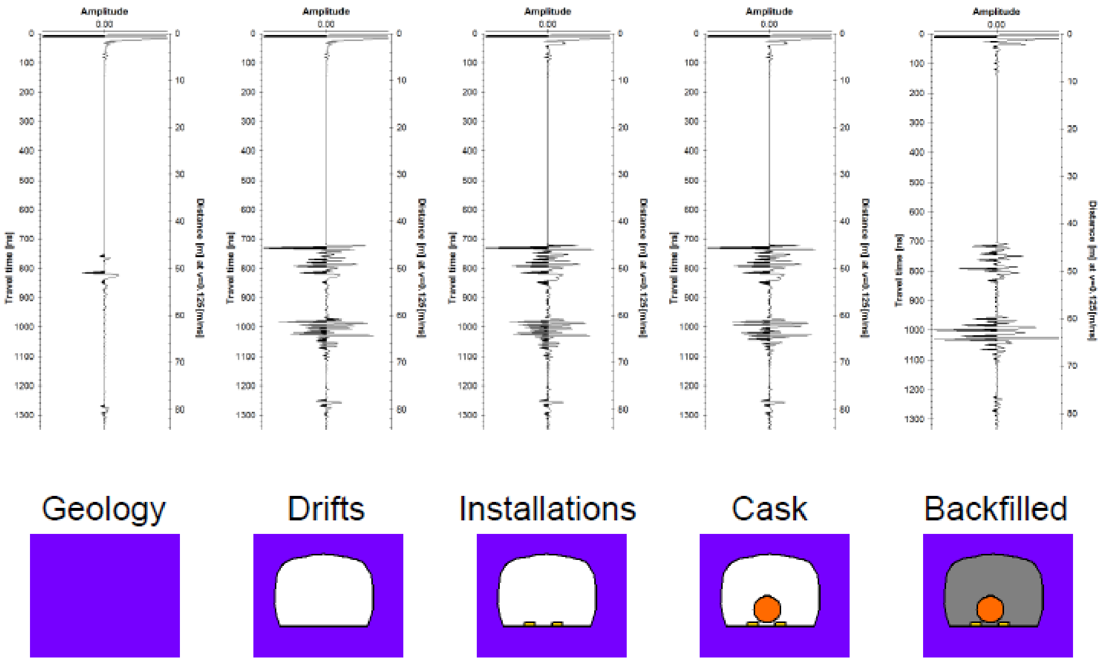

Figure 2-3. *Comparison of GPR synthetic model generated single traces containing baseline measurement (geological information), and responses from excavated tunnels, tunnels with installations, tunnels containing disposal cask, and backfilled tunnels with casks. Waveform is slightly different in each case (Uchtmann and Althaus 2014).*

The seismic signal travels in medium at several group velocities (compressional, shear and surface waves). The measurement array typically consists of multiple receivers for each source position, and a trace is produced by geometric stacking of several recordings to achieve adequate signal level. Recognition of the source of an anomaly is less straightforward as for GPR. The actual location of anomaly source may differ from what is seen in image. Directional effects of different waveforms may leave objects at specific locations unobserved for certain measurement geometries. Enhancement or suppression of different waveforms, and enhancing visibility of specific anomaly sources, would be necessary in processing.

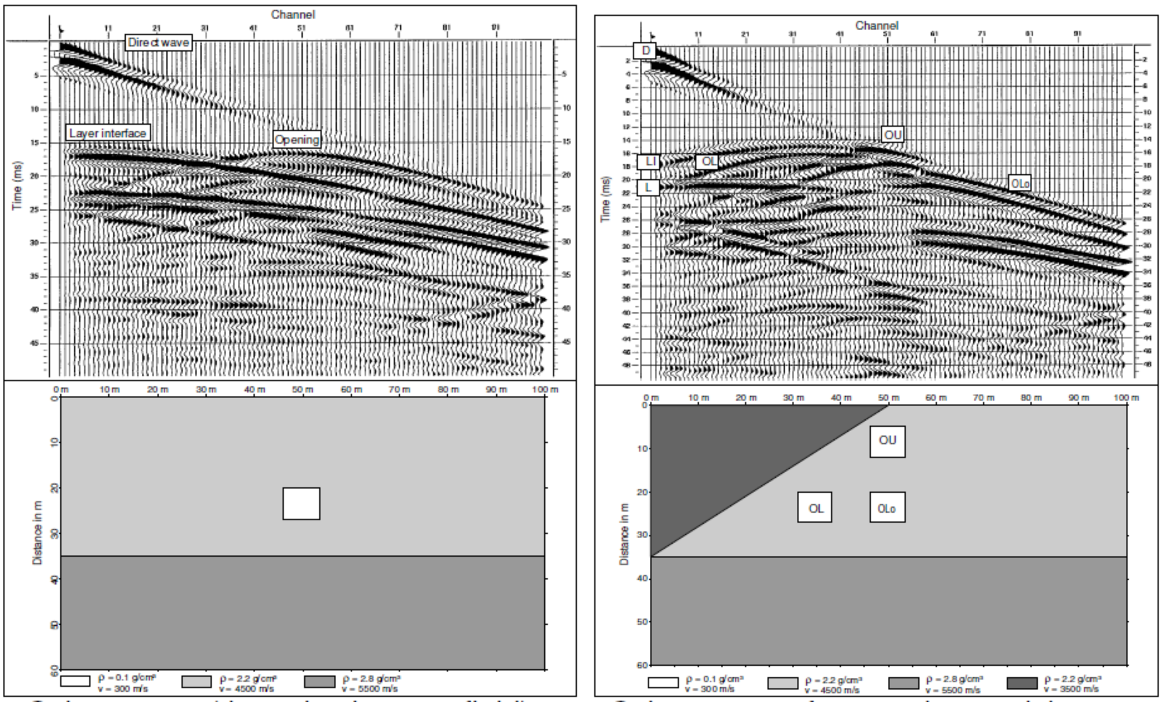

Figure 2-4. Seismograms from synthetic models of seismic measurement data on a tunnel wall in geological environment (Seidel 2007, Seidel et al. 1999) having elastic contrasts. Observability of simple model case with one (on the left) or more complex model case (on the right) with several excavated spaces is demonstrated. Several waveforms and velocities, converted waveforms, complex geology combined with measurement geometry, etc., are making the raw stacked image complicated to understand.

Field testing in a mine was presented, using high 1 m density of geophones and seismic sources on tunnel wall in a salt mine, along a 144 m line. Seismically visible targets are visualized in surface wave and shear wave reflection image up to a 100 m distance from measurement line, with a 1 m accuracy. The interpretation was based on knowledge of location of the targets (Seidel 2007, Zöllner and Schicht 2007, Schuetze et al. 2008).

In case unexpected observations would be made, these could further be checked. Measurement of the line has required two working days in tunnel conditions. Seismic methods would require technical development to be applied for safeguards purposes (with comparable ease as GPR systems), including principal tests, development of prototype and appropriate software for processing and interpretation (Seidel 2007). False alarm rate needs to be kept low. There is also a risk that not all relevant features would be detected. Results should be compared to known layout of existing tunnels or using a baseline and repeat measurement to compare changes between measurement campaigns.

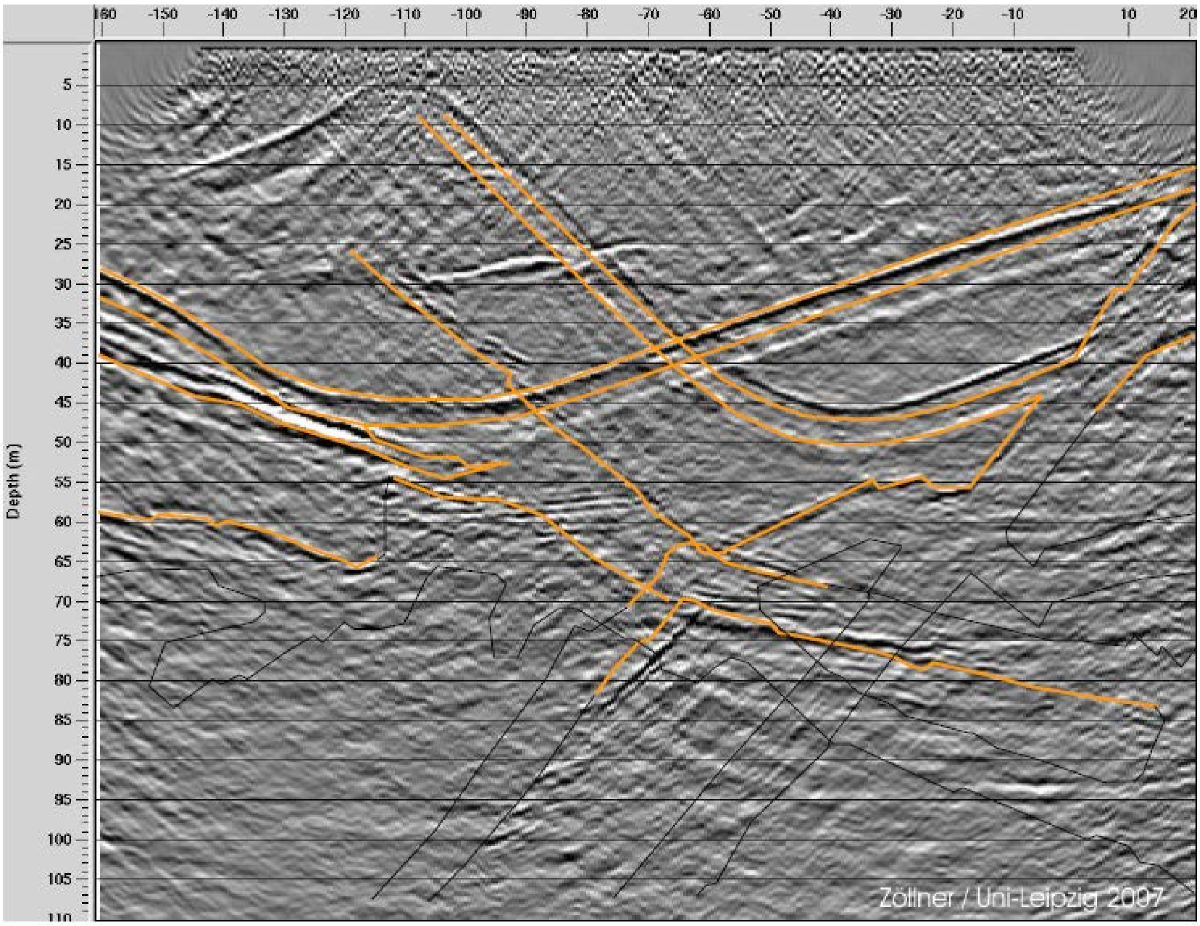

Figure 2-5. *Practical seismic example from a salt mine (Seidel 2007, Zöllner 2007). Seismic image produced with high spatial coverage of geophones and seismic sources at a target with known tunnel locations (orange and black lines, orange lines are considered as seismically visible structures). Creation of image has involved multiphase processing. Horizontal axis is survey line length in a tunnel, vertical axis is distance from the measurement tunnel. Reflection amplitude is show on grey scale image, black and white continuous lines indicate reflections from tunnel wall. Known, seismically visible tunnels are shown with orange color and other known tunnels with black color. Also, other objects (lithological contacts, faults) are seen in image. Not all visible tunnels, due to orientation generate reflections using this survey geometry.*

2.3 Capability of geophysical methods in safeguards

Detectability of engineered underground spaces using active geophysical methods would be based on contrast of physical properties of the constructed volumes to the surrounding rock mass. The contrast may be causing an anomaly in potential field (electrical, magnetic or gravity). Cause could be a density contrast, or electrical resistivity contrast between rock and air or water. Magnetic contrast to rock mass would be caused by iron containing support structures, installations, or machinery. Active survey can describe location, size, and partially form of an excavated space.

Actual construction activity instead could be observed, and localized, by monitoring a related physical wavefield, which may be electromagnetic interference from electric or diesel engines or power source, or mechanic noise from extraction of rock mass, or operating machinery.

Contrast may also be generating a reflecting boundary, seen in back scattered electromagnetic or elastic waveform. Contrasts can be generated by seismic or radar velocity between rock and air or rock and water, or by metallic installations and support structures.

Detection capability is defined, further to the contrast, by distance of the target from measurement array, and attenuation of the physical signal carrying the response from the target. Also, size of the target, comparable to the detection distance, and to properties of physical signal, are governing the observability.

In a waveform-based method like seismic or radar survey, the wavelength of transmitted and reflected wave needs to be minor compared to size of the object, to enable detection of a target. Decreased wavelength decreases the achievable range. From longer distances and longer wavelengths, the size of object needs to be larger to be detected.

Reinforcement of engineered spaces may increase detectability, like metal containing shotcrete lining or bolting may make tunnel wall more visible in electromagnetic measurements. In some cases, the electrically conductive installations may suppress observability due to wavefield attenuation.

Active seismic methods in verification of design information are likely to require highly designed survey technique and processing, high source and receiver density, high frequencies to enable detection of small objects, directional, capable of processing shear waves for better detection and resolution, but for these reasons compromising range of detection from tunnel. Methods may require preparations on tunnel wall, like drilling boreholes to install sources or receivers.

Also, other geophysical techniques have been tested in tunnel conditions, of which electrical resistivity sounding or electromagnetic sounding may have capabilities in safeguards. More limited application possibilities may be involved in magnetic surveying and gravimetric surveying, either in tunnels or in boreholes. Best application possibilities would be with repeat measurements, where baseline not containing undeclared activities, would be compared to later survey.

In Olkiluoto conditions, performance of several active geophysical methods for safeguards were reviewed (Okko 2004). Ground penetrating radar (GPR) was estimated capable to detect an undeclared void from distances of few metres behind rock face. Reference is the declared repository design, so a GPR baseline survey of full site coverage (on tunnel rock faces) is not likely needed.

Active seismic survey from ground surface was initially assessed not capable to detect undeclared tunnels or excavations at repository level (Okko 2004).

Active electromagnetic or electrical ground level surveys were initially assessed not practical for safeguards purposes (Okko 2004). Passive electromagnetic monitoring may be considered in detection and localization of power consuming installations and wiring.

Electromagnetic (or electrical) methods can be used for locating the metal canisters or waste containers (Finch 2009). Also, metallic support structures can be observed with EM or DC methods. Passive electromagnetic methods can be used in monitoring power consumption (Finch 2009). Detection of electrical or electromagnetic fields may lead to detection of undeclared activities (machinery, power feed).

Applicability of geophysical methods from the ground surface to detect existing repository were reviewed in case its presence would be unknown during the time of survey (Isaksson et al. 2010). Review was using the known contrasts of constructed tunnels and repository to the host rock in simulation of geophysical responses in measurement, and comparison the variation in the synthetic data ("anomaly") to the naturally occurring variation. Seismic reflection measurement was the only relevant technique for the purpose. Yet confirming a known design information from ground level measurements to the depth of 400 – 500 m, and even detection of deviation from the declared information, would require much higher resolution for active survey methods.

2.4 Places and timing of geophysical measurements for safeguards

Development of repository can be divided to pre-nuclear, operation and post closure time ranges. The pre-nuclear phase includes selection between candidate sites, preliminary characterization aiming for siting process, safety assessment and repository design, and construction. All these phases are producing site description information, which can be used as baseline for safety case and safeguards related investigations alike.

Geological site characterization includes drilling of several dozens of deep drillholes, which provide also access closer to the repository volume. Construction of tunnels and shafts will also provide closer access and view to the site volume, and possibility to install sensors at closer range, and different vertical levels with respect to the repository volume.

Also monitoring is necessary to be started in suitable time before construction, to understand site properties and risks, as well as to follow changes caused by construction. Seismic monitoring from ground surface is adequate to detect events of large energy, like excavation blasts, with their magnitude and location to distances of several kilometers. Possible natural and excavation induced microseismic activity can be localized and detected in cases where several stations are able to detect the same event. Smaller events to be detected will require more sensitive sensors to be installed near the repository volume, either in boreholes drilled from surface, or from tunnel. Range of detection is several hundreds of metres.

Ground surface-based measurements can be conducted in any time during lifetime of the repository, also post closure. However, the depth range of ground-based surveys, and first, their detection capability, is inadequate to observe an undeclared tunnel from depth of 400 – 500 m. Reflection seismic survey is in practice only existing active geophysical method which has the required detection power. A 2D line survey has highest resolution but needs to be placed and aligned correctly to observe tunnel. A 3D area survey has highest coverage.

Locations and timing from where and when undeclared tunnels might be observed, are from ground surface any time during and after construction of the disposal facility. Deep drillholes can be used in survey to enhance the resolution. Extending closer to target, drillholes can be used to observe smaller objects than would be possible from ground surface. Any surveys carried out from the drillholes would have shorter range, but higher resolution than from ground level. Surveys would also be directional. The location and distance of drillholes from the expected target is more critical than those of ground level-based survey.

The drillholes would be available during site description and partly during construction of the underground facility. Due to avoidance of hydraulic connections between hydraulically conductive zones and the repository volume, the drillholes located close to the facility will be permanently sealed, without possibility to leave installations behind. Neither any new drillholes would be allowed. This means the drillhole based survey opportunity near the repository would not be available after closure of the disposal facility.

In case an intrusion from outside of the repository volume would be expected, an early warning capability would be useful. Tunnel construction is expected to progress at maximum pace of 5 m /day. Observation of tunnel construction at a perimeter of 1 – 2 km from the repository would allow time to react to an attempt. In case a tunnel would be prepared from closest distance, it would be also located closer to the surface, making observation more feasible. Inclination of 10-15% would mean vertical distance of 200 – 300 m below ground level at this perimeter. This depth is still so large, that other than seismic reflection method is not capable in observing tunnel sized objects from ground surface. A drillhole measurement can be used to distances from 150-250 m from the drillhole using seismic survey, and 30 – 50 m using drillhole radar. Distances between the drillholes would need to be 300-500 m for seismic reflection survey and 50-100 m for radar survey to cover and overlap the rock volume with survey.

Distance large enough from the repository would also make it possible to prepare drillholes for installation of a network of sensors. Such perimeter installation would however be costly and require continuous operation and maintenance. Attempt to approach from deep below the repository, trying to avoid detection, would be greater, more time-consuming effort.

Tunnels and vertical shafts constructed during site description and during repository construction, are available locations which can be used also for safeguards related geophysical measurements. The tunnel or shaft surfaces can be used to place surveys to observe undeclared tunnels from closer, up to distances of few metres to few tens of metres from measurement system. Accessibility to the target during construction and during operation may have practical limitations, though. The tunnels and shafts would not be available for investigations after the backfill and closure of the site. Just like ground level based deep drillholes, the tunnels and shafts will be finally backfilled and sealed and at later stages of disposal not any more available for detection measurements. Neither any permanent data acquisition systems, or their required data transfer systems, would be very unlikely to be allowed to become constructed before backfilling and sealing.

Characterization drillholes from the tunnels can be used in detection measurements until these are not sealed. Normally during construction, the pilot holes drilled onto middle of planned tunnel before excavation, serve as data source, but are excavated away during tunnel construction.

Different survey methods have different capabilities in detection and possibilities for implementation. Waveform reflection-based methods GPR and seismic reflection can provide exact information of location and shape of an object behind tunnel wall.

Electromagnetic radio wave reflection method, Ground Penetrating Radar (GPR) is providing imaging of bedrock volume. The GPR method can be applied from tunnel surfaces or drillholes. The method can produce high resolution imaging at close 0 – 40 m range from measurement line in deep Olkiluoto bedrock conditions. In salt dome or granite, the range may reach 50 – 100 m. Results can be used to detect undeclared constructed spaces behind tunnel surfaces. GPR reflection measurement is quick to implement, cost effective, and does not require specialist driven planning or implementation, taken that serious range limitations would be respected. The GPR method does not apply in conditions where the bedrock has high electrical conductivity, or lining material used for tunnel support is electrically conductive.

The GPR in its current industry standard method, is capable to detect tunnel behind rock wall to distances of 10 m using conventional manually operated tools. Detection range depends on applied frequency and measurement system. Detection with low frequency (20 MHz) drillhole radar is possible to distances of 40 m in favorable conditions in Olkiluoto. Presence of conductive minerals or saline groundwater in rock mass suppresses this range significantly. In salt dome environment even 500 m is possible to reach. Limitations of the GPR belong it cannot be applied through metal fibre containing concrete reinforcement or concrete walls. Survey may encounter limitations due to reinforcement of tunnel walls, for example bolting, wire mesh support or metal fabric containing shotcrete lining. On the other hand, GPR does not require mechanical contact onto the measurement surface, is quick to implement, has high production rate, is easily operable, and does not require prominent level expertise in planning, operation, or interpretation. Method is also easily repeatable.

Seismic reflection imaging methods from tunnel have significantly larger distance range than GPR up to 100 m, but the design and implementation of method is slower, more expensive and requires high expertise.

The seismic reflection method is also standardized investigation technique in geotechnical, mineral exploration and oil exploration industries. Method is capable in detecting a tunnel behind rock wall to distances of more than 100 m. The method requires mechanical contact onto the measurement surface. Implementation is significantly slower and more expensive than GPR. Planning, implementation, and interpretation requires prominent level of expertise. Results are not possible to view immediately but require extensive processing.

Alternatives for GPR at similar, or slightly deeper range are other electromagnetic methods and electrical resistivity sounding (tomographic imaging), which however have less resolution than GPR and would be slower and slightly more expensive to and require expertise to implement.

Other geophysical methods than reflection surveys can be used in detection of presence of an undeclared tunnel behind rock wall. These can rely on density contrast in case of gravimetric method, magnetization contrast in case of magnetic method, and electric conductivity in case of electromagnetic profiling or electrical resistivity tomography. Each of these methods are quicker to implement than seismic reflection, slower than GPR, and can indicate presence of suspected deviation to distances of 10 – 50 m from a tunnel. Understanding the results would require comparison to synthetic model results, and preferably comparison between baseline and repeat surveys.

The existing site description data includes survey results which could be used in designing new investigations, and for comparison of repeat studies. Coverage is limited, though. Approximately 20 of the deep drillholes were measured with 3D VSP reflection seismic survey. Data can be used to compare possible new features in the rock mass within 200-300 m of drillholes if survey would be repeated. The same holds for 9 drillholes measured using drillhole radar, up to distances of 40 m from the drillholes. From ground level, two campaign of reflection seismic surveys conducted in 2005 and 2006 can be used as partial baseline in Olkiluoto. One seismic 2D reflection lines cover the length of the island and one line in crossing direction. Outside of their coverage area, no baseline survey is available for comparison.

Along access tunnel, three different campaigns of seismic reflection survey were carried out in 2007, 2009 and 2013. These surveys can be used as a baseline data in case the visibility of now constructed or future planned declared tunnels would be checked, or measurement for screening undeclared activities would be anticipated. GPR studies on tunnel wall were conducted in few locations for methodological development, assessment of applicability can be drawn on that basis. Electrical resistivity tomography was carried out at one location in a demonstration tunnel, indicating the possibility to apply that kind of survey. Some of relevant surveys have been conducted during construction of the tunnels or shafts, and their results can be utilized as a baseline for comparison, to detect any changes in responses.

Regarding other than geophysical techniques which could be applied for safeguards, the construction produces data which can be applied for safeguards. The tunnel surfaces are laser scanned immediately after construction for documentation and quality control purposes. Deeper seated areas are reinforced after excavation, using systematic bolting, wire mesh installations on ceiling, and shotcrete lining reinforcement at most of tunnel sections, though mainly not in the disposal tunnels to avoid chemical influence of the cement material. In the tunnels are frequently carried out maintenance work. Bolts and mesh installations are checked and replaced. Shotcrete is drained for water leakages and it can be repaired where necessary. Tunnel sections which do not contain lining, are checked for loose rock material which is frequently removed for personnel safety requirements. Form of the tunnel surfaces can be re-surveyed either by laser scanning or photogrammetry to compare any reported or non-reported changes on the local tunnel wall. This may help in observing potential changes, when comparing to the original scanning results.

This report is describing experiences from geophysical surveys used in rock mass characterization during excavation of the ONKALO disposal facility. Similar techniques can be applied later safeguards purposes, if required.

3 Experiences from hard rock geophysical surveys

3.1 Ground penetrating radar and drillhole radar

Ground Penetrating Radar method (GPR) is based on high frequency electromagnetic (radio) wave reflection occurring at boundaries and objects having contrast between electrical rock properties. These properties include dielectric permittivity which is defining the wave velocity within the rock mass, and electrical conductivity which is governing the attenuation of the wave field in the rock mass.

GPR signal is generated by creating a short timed (rapidly raising and lowering) impulse of high electric current into an antenna. Size and shape of the antenna define the central frequency and frequency band at which the antenna operates. Dipole antenna length is defining the frequency. Similar antenna is receiving the direct and back scattered wave field according to recording time. Transmitter and receiver antennas can be placed close to each other within same housing (monostatic, zero offset) or operated separately at specifiable mutual distance (bi-static, adjustable offset), or even in an array of several antennas. Antennas can be shielded against transmission towards other than target itself, and receipt of scattered reflections from side and above (behind) the antenna, or non-shielded, radiating to all directions on antenna transmission pattern (e.g., dipole axis). Non-shielded antennas are sensitive for interference in tunnel conditions, being more suitable for application in open outdoors terrain or using drillhole.

Alternatives for impulse radar, there are systems based on continuous waves (single frequency), and modulated stepped-frequency systems, covering wide frequency band within one tool.

Waveform is sampled at dense time intervals to form a radar trace (A-scan), to specific time after transmission. One trace at each line position is stored. Several frequently repeated traces measured at anticipated intervals on measurement line form a B-scan (GPR image). Images produced parallel on a rock surface, or from different sides of an object, can be used to form a volume description or C-scan (tomography).

At each measurement location, the boundaries having contrast of electrical properties in rock mass, create returning amplitude occurring at specific time on the trace. The time is proportional to distance to the object. Changes in GPR wave velocity modify the distance axis accordingly.

The contrasts in rock mass are related to water content in fractures. Water has high relative dielectric permittivity (ε_r = 81) compared to typical rock mass (ε_r = 5 – 8), which enables high reflected amplitudes. Other contrasts can be found at lithology contacts, contacts at electrically conductive layers (like sulphide minerals), and on boundaries of engineered structures. For safeguards relevancy, the contrasts between rock mass (ε_r = 5…8) and air (ε_r = 1), or installations in tunnel (steel, wiring, etc. which are highly conductive) are of importance.

Polarity of amplitude depends on properties of the contrast. Amplitude of the reflected event depends on strength of the contrast, distance, and extent of the target. Different shapes of reflecting boundaries cause different form of anomaly on GPR image. A continuous planar surface can be seen as a line on the image. The apparent inclination of the line depends on the true angle of the planar surface with the line of observation.

A point like or spherical object is seen as a hyperbolic trace on the GPR image (a diffracting event). Also, termination points of planar or linear objects are causing a diffractor event in the GPR image.

The GPR image is projected as a vertical depth (from floor) or perpendicular distance (from a wall). In practice the GPR signal is transmitted in a conical volume, which angle is delimited by dielectric contrast between air and rock mass. For this reason, the reflections can arrive also slightly offset from the normal to the observation surface.

Distance onto which the GPR can detect an object in rock mass, is depending on the dielectric permittivity governing the velocity (time vs. distance), the electrical conductivity of the medium (attenuation of the GPR wave field), and on the transmission power of the antenna, sensitivity of the receiver antenna, dynamic range of the measured amplitude, noise level, and frequency of the signal. Lower frequencies attenuate more slowly and penetrate to greater distances. Dynamic range of the receiver amplitude is affecting to the range through signal to noise ratio. Transmission power is connected to the rock mass through coupling onto the surface, depending on both the quality and material of the rock surface, and the antenna design.

GPR receiver is a control tool which contains computer, storage, software, display, and connections to antenna. Antenna designs are several different, depending on frequency and application purpose. High frequency conical antennas can be used in an air-coupled mode, at a distance from observation surface. This implementation allows vehicle installation and quick operation. Tools are sensitive to reflections arriving from surrounding environment. Other types of antennas are used as ground-coupled, which require short distance from the observation surface during measurement. Antenna systems can be mono-static (zero offset), containing both transmitter and receiver elements within same housing at short distances, or bi-static, having transmitter and receiver in separate units, with either fixed or adjustable offset distance. In these cases offset can be placed either in-line or broadside. Selecting different offset distances may enhance some reflection observability compared to zero-offset measurement.

Especially the monostatic antennas are often shielded against transmission and receipt of signal from other directions than the actual measurement target. This is required in tunnel environment, as the reflections of airwave from side walls, ceiling, and irregular surfaces, as well as installations, are easily making the data useless for application. Bi-static antennas, either in separate units, or assembled in a pulled array cable or in drillhole antenna system, are usually not shielded making their application in tunnel almost impossible. Drillhole antennas are radiating to all directions perpendicular to antenna length (that is, on dipole axis), and have good coupling on the surrounding rock mass, which enhances data quality and observability. Directional drillhole radar can be used to define the arrival direction of reflections based on polarity. Also, directional transmission drillhole antennas have been developed recently.

Low frequencies, which could be used to detect objects further away from tunnel wall, are using large antennas, which are difficult to manufacture properly shielded, are heavy and bulky to operate, and sensitive to irregular shape of surface between antenna and rock mass. The latter is causing severe ringing, which makes data less usable as for high frequencies. Especially surfaces aligned with observation line are difficult to detect when airwave ringing is present in data.

Measurements can be carried out with moving the antenna with vehicle or manually at walking pace, especially when measurement is directed downwards on the floor of tunnel. On the walls or ceiling, it is necessary to hold antenna firmly with a mechanical arrangement or manually.

Measurement is carried out in fractions of seconds at a single station. Measurement can be stacked to improve signal to noise ratio, with multiple recording at one location, either stopping or during slow movement. Also, multiple offset Measurement can be repeated at dense interval on measurement line, launched either with time, by operator, or using for example pulse encoder which can be attached to length measurement line tape, or rotated on the surface as antenna is moving.

Measurements need to be carried out as campaign on specific location. Application technique would consist of lines, having some degree of continuity, placed on tunnel surfaces. Lines may be placed also parallel, at separation of some metres. Measurements can be made using a vehicle moving at slow pace, or with slow walking pace, up to 1 – 2 km / h. Tunnel conditions in a construction work area causes severe limitations for accessibility, survey timing, and arrangements. For these reasons achievement with interpreted results would in an order of 2000 €/ km on tunnel surface.

Measurements are possible through paving on floor in case the material does not contain significant amount of metal residue from reinforcement. Measurements cannot be taken on wall or ceiling which is lined with metal fibre reinforced (sprayed) concrete. Nor it cannot be carried out to volumes behind a reinforced concrete wall. The banded texture of foliated rock mass causes abundance of irrelevant reflections, and in part attenuate the signal sooner than in many other lithology would.

Drillhole radar measurements could be conducted in rock mass, the range covering 5-10 m radial distance around the drillholes with 250 MHz antenna, 10-15 m with 100 MHz antenna, 20-25 m with 60 MHz antenna or 20 – 40 m with 22 MHz antenna. Using drillholes in survey is unlikely possibility, as for nuclear long-term safety there shall be avoidance of potential hydraulic connections within the repository. Maintaining drillholes around the tunnels, or drilling new holes, would not be anticipated.

Observability of a target is depending on distance, size, contrast to surrounding rock, as well as GPR wave frequency, dynamic range of the system, and transmission power. Signal to noise ratio can be enhanced to some level by improving numerical accuracy (previous 16 bit to 32 bits recently), using more powerful transmitter, and stacking (summarizing) the signal at specific location or over several offset distances (at common mid-point). Smallest targets which can be detected are linear and continuous water filled drillholes, when located in GPR transmission cone, and aligned so that reflection can arrive back to receiver antenna. Otherwise, smallest realistically detected objects have radius in order of magnitude of product of distance and wavelength. Two closely located objects cannot be separated as individual targets when located closer than a wavelength. For the lowest GPR frequencies, the resolution is in order of 1 – 3 m (Olsson et al. 1992, Sandberg et al. 1991) which is adequate for tunnel detection.

Lowest contrast remains earliest below signal to noise ratio threshold; highest amplitudes are detected from longer distances. Reflections and diffractions are obtained from surfaces facing towards the receiver antenna, located within the transmission cone. Objects aligned close perpendicular to observation surface are not observed directly, though scattering and attenuation may occur.

Accuracy of detection in distance is related to correct knowledge of GPR wave velocity. In Olkiluoto, typical average dielectric permittivity $\varepsilon_r = 6$, converts to 125 m/μs GPR velocity. Changes in lithology and variation in groundwater content may cause changes of 5 – 10 % of this range. On observability, tunnels, shafts, and galleries are large objects to be detected with GPR in case these would be in favorable location, and the properties would be appropriate. Measurement needs to be directed towards the target so that it would be located within GPR transmission cone. Tunnel would need to contain surfaces facing towards the measurement system. Contrast of rock mass and water is remarkably high enabling good observability. Contrast between rock mass and air is much smaller and may not be detected from greater distances. Low contrasts like rock mass and concrete, combined with higher attenuation due to elevated electrical conductivity, may suppress observability. Best observed would-be perpendicular intersection of tunnel at close distance, which is creating a distinct hyperbolic reflection of a spherical object. A dead-end tunnel face behind the wall may be observed equally well.

Long, parallel to observation line and discontinuous surface with weak contrast and further away, may lead to false negative observation. Regarding the effective range of GPR observation, there is no reliable way to confirm at which distance an object would not be seen even when it is there.

False positive observations may become a risk in case a survey is carried out as a single pass study. Plenty of natural lithological and fracture anomalies exist, some of which are also causing hyperbolic anomalies, and other objects linear continuous features. These are unlikely to be possible to become checked by drilling. Most reliable confirming method would be useful, using repeated survey on same positions, focusing on new features which have appeared after previous measurement round. Measurements would need to be also checked against reported tunnel layout to check visibility of existing tunnels.

The GPR is suitable with manually handled, well shielded antennas to frequencies of 250 – 400 MHz, providing fairly accurate detection and location possibility to 5 – 10 m distance from rock wall. Effectivity is based on high data production rate and continuous measurement, without need to stop and attach tools physically to tunnel surface. Measurement needs to be applied on non-reinforced, clean rock surface, with adequate continuity of survey line to image the target properly. Measurement is hampered by elevated electrical conductivity in rock mass e.g., by saline groundwater. Measurement needs to be directed towards the anticipated target. A slightly deeper penetration, 10-15 m, would be obtained with a shielded 100 MHz antenna, which is however already bulky to be operated on the wall, and the results are disturbed by ringing caused by uneven rock surface below antenna. Lower frequencies at 20 or 50 MHz would be clearly useful for greater depth range (20 – 30 m), especially when combined with recent 32 bit recording dynamic range providing better signal to noise ratio. However, these tools are large, up to 4…8 m of antenna length, and in tunnel conditions would need to develop proper directionality and shielding for both transmitter and receiver antennas, to avoid direct wave and multi-path airwave ringing in the results. Consequently, this kind of tools would be slow to operate in production.

GPR method can be used in assisting of containment and surveillance in cases where would be expected presence of undeclared tunnel near existing tunnels. Method can be used only until backfill of the disposal or central tunnels. Design information verification is also an application method, using to prove there would not be indications of undeclared excavated spaces after construction, or that the form of the tunnel face is conforming what is reported. Regarding continuity of knowledge, though it is possible to observe a capsule in backfilled disposal hole from close distance using the GPR method (neighboring disposal tunnel may be at distance limit or too distant), there would not be confirmation that the high amplitude reflection would emerge from a capsule, and that it would not have been moved and replaced meanwhile. In extremely limited cases GPR could be used in non-designed purpose for security, e.g., to detect a vehicle transport even through a wall, in a form of altered reflection amplitude.

Range of tunnel or ground surface operated GPR is not high to observe any undeclared spaces from rock mass after closure of tunnels or the whole repository. Range and accuracy are high enough to detect locations where interference of natural properties would have taken place (clandestine portals below soil layer or rock wall, covered excavations). Drillhole radar method can be used as repeat survey in case existing drillholes of minimum 56 mm diameter would be available. Data is of high quality and undisturbed by local variation in tunnel properties installation interferences. Data is usually not directional, so only distance to potential target can be derived. Directional 60 MHz RAMAC antenna has in Olkiluoto 10 – 20 m radius from drillhole, and it has capability to indicate direction from where reflection is arriving. Physically larger 22 MHz tool can provide reflections from 20 – 40 m distance from the drillhole. New development of more powerful multi-frequency tools (Althaus 2013) may bring in slightly larger range and quicker measurement, at a cost of more expensive tool and requirement for larger 85 mm or 130 mm drillhole diameter.

Deep drillholes prepared at the disposal site perimeter, at distances avoiding interference to long term safety, can be used as a campaign to observe tunnels. Measurement of each drillhole (down to 500 m depth) would require 1 day, at an approximate cost of 5000 €/day. False alarms could be suppressed by repeated survey, and comparison of results between subsequent measurements. Drillhole radar tools are not likely to be used as permanent installations due to their relative rarity and excessive cost. More likely method of application would be repeated survey rounds at pace of months or years, or on demand.

Lower frequency and higher measurement range may become feasible with shielded antennas, array of one or several transmitters and multiple simultaneous receivers at different offsets, used for stacking and mathematical suppression of air and direct waves and ground interference reflections. Measurement would be based on stopping at frequent intervals and would become much slower and more expensive than conventional GPR survey.

One possibility to apply two separate low frequency antennas would be placing a fixed transmitter in one tunnel and completing a measurement line up to 40-50 m direct distance in another tunnel. This Vertical Radar Profiling (VRP) geometry might help in suppressing tunnel interference. Each profile would indicate undeclared tunnels between two disposal tunnels, within few metres distance from measurement tunnel.

3.1.1 GPR and drillhole radar surveys for Posiva and SKB

The GPR method in its variations has been used in separate phases of site characterization and site description or construction. Preliminary stages applied GPR at 40 MHz and 100 MHz antennas for measurement of till layer thickness and partly bedrock fracturing. Later investigation trenches were surveyed with GPR to estimate fracture extensions.

Drillhole radar was applied at 22 MHz omnidirectional reflection survey to 30 – 40 m from drillhole down to 1000 m length (Figure 3-1). The tool does not indicate direction where the cause of anomaly is located. From ground surface, drillholes were measured with VRP surveys to 50 m depth using fixed surface transmitter positions. A directional 60 MHz survey was carried out to 15-25 m distances to delineate and orient fractures and other reflecting layers in rock mass.

The other investigation sites in Finland, Kivetty and Romuvaara, made it possible due to higher resistivity of bedrock, to reach range of 100 m around drillholes using 22 MHz frequency, and up to 50-60 m using 60 MHz directional drillhole radar.

SKB was using drillhole radar in Stripa mine characterization, and was able to make imaging of existing tunnels with drillhole radar measurements to distances of tens of meters (Figure 3-2, Olsson et al. 1992). There it was possible to indicate that drillhole radar is capable to detect nearby tunnels with their characteristic hyperbolic reflection or diffraction pattern. Similar survey was carried also in Grimsel test site for Nagra, showing comparable results.

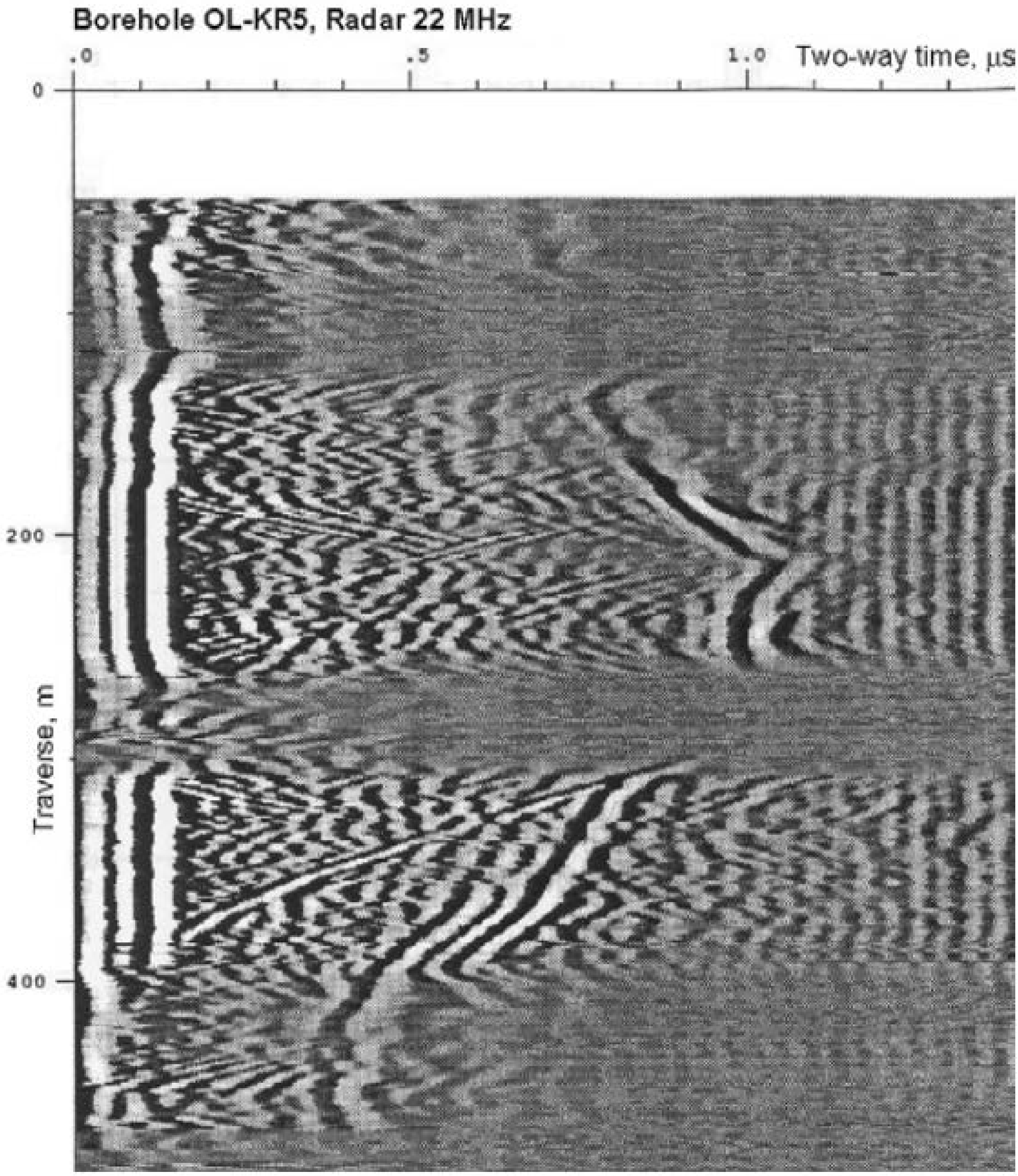

Figure 3-1. Drillhole radar single hole reflection image from Olkiluoto drillhole OL-KR5 in 1991 (Carlsten 1991, Saksa et al. 2005), 22 MHz Range of reflections, 1 microsecond, indicates roughly 60 m radial distance. Strong inclined reflection is nearby dolerite dyke. Smaller, drillhole intersecting reflections are local fractures, faults, and lithological contacts. Stronger attenuation is seen deeper (below 400 m) in drillhole. Local water bearing faults or conductive mineral bearing veins attenuate signal at some intervals (50 – 100 m, 300 m). Prominent ringing at late times is caused by wave traveling along drillhole and back between transmitter and receiver.

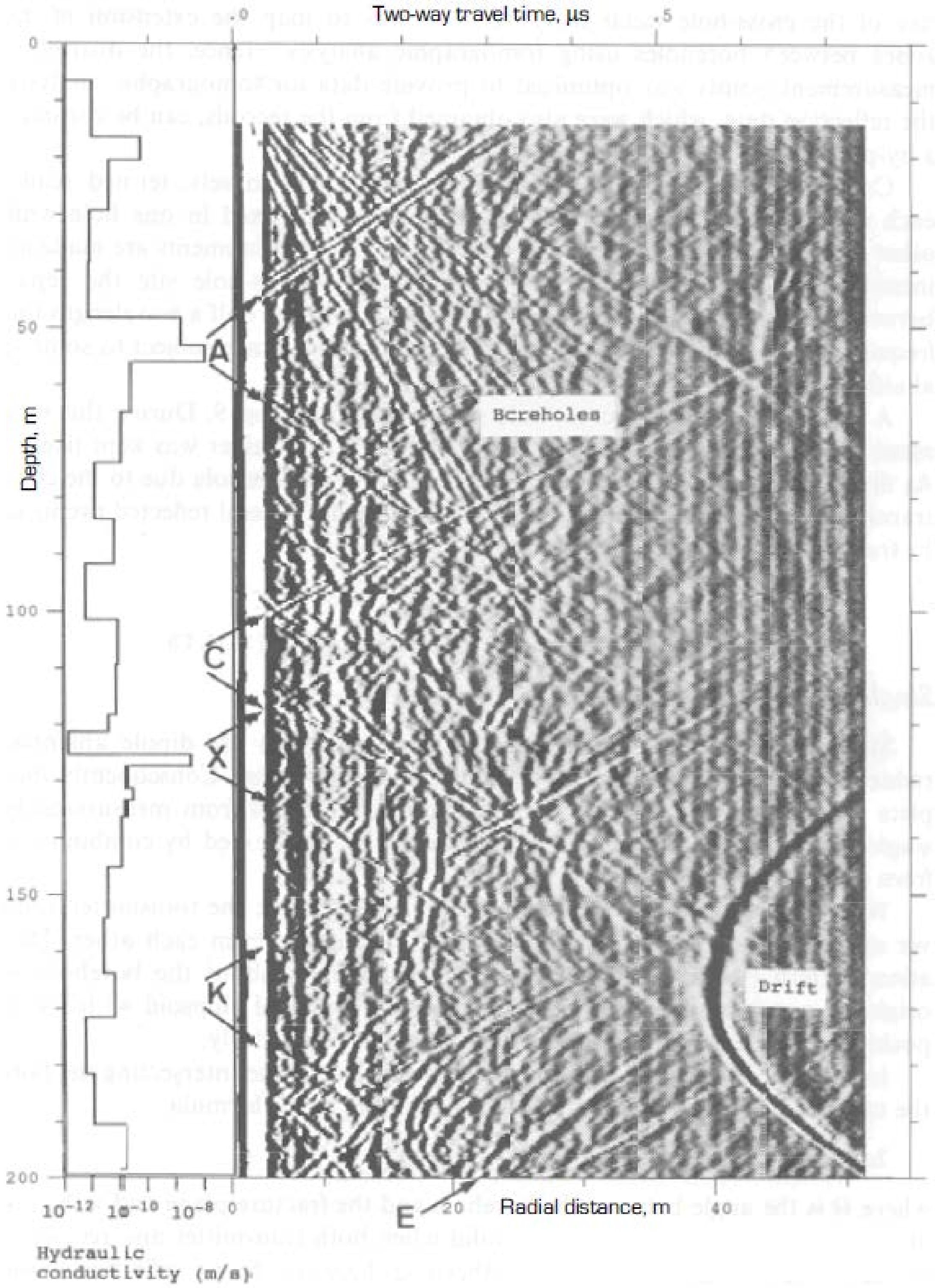

Figure 3-2. Drillhole radar single hole reflection image from Stripa mine investigations, 60 MHz drillhole radar (Olsson et al. 1992; Saksa et al. 2005). Excavated drift is clearly seen as a hyperbolic reflection at 40 m radial distance from the measurement drillhole. Other drillholes drilled from the same niche are visible as linear objects.

During construction of ONKALO access tunnel, more than 30 tunnel and niche pilot holes were used to measure omnidirectional 250 MHz drillhole radar profiles to radial distance of 5-10 m. Survey used bi-static drillhole antenna (Malå Geoscience). Purpose was to locate, delineate and measure intersection angle and continuity of fractures and other radar reflecting layers in rock mass within and near the tunnel perimeter. Results were combined with core logging data. Functionality of the method in this purpose was evaluated by Döse and Gustafsson (2011), related to Rock Suitability Classification work (Figure 3-3). In case a tunnel would be located within range of measurement, it would be observed. Range of investigation would be greater with 100 MHz or 60 MHz tools, or even with 22 MHz drillhole radar, which on the other hand are heavier to operate due to their large size. In one case (Mustonen et al. 2011) a repeat survey in remaining drillhole was indicating the parallel tunnel wall is clearly visible in drillhole radar data (Figure 3-4), though distance was 1 – 2 m in that case.

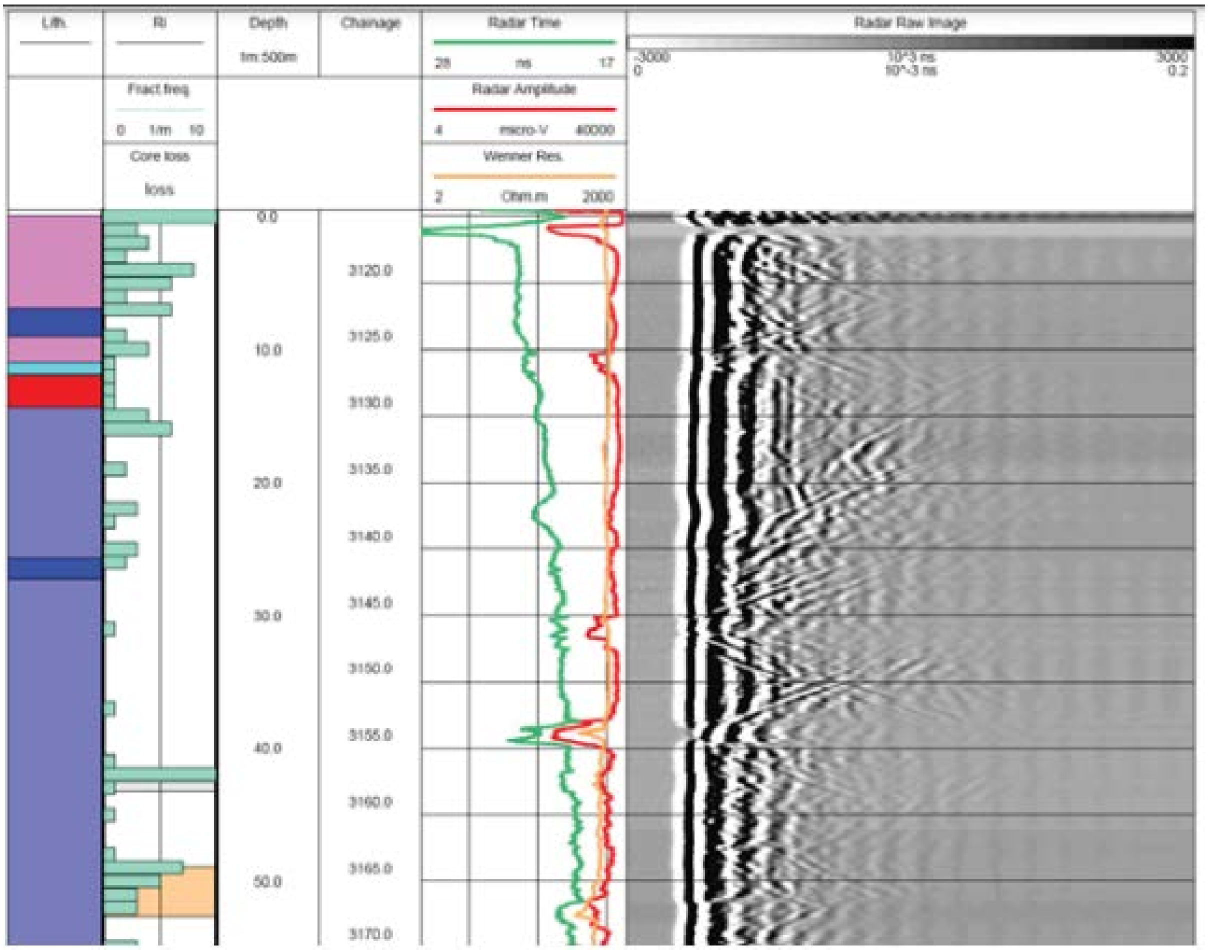

Figure 3-3. Extract of drillhole radar reflection image from pilot hole ONK-PH08 at chainage PL3115 m in ONKALO access tunnel, 250 MHz dual antenna (right). Full time scale 200 ns, reflections are obtained until 100-120 ns two-way time (7-8 m radially from drillhole). Reflectivity is associated with lithology and fractures, which contribute to GPR velocity and attenuation (Döse and Gustafsson 2011, Karttunen et al. 2009).

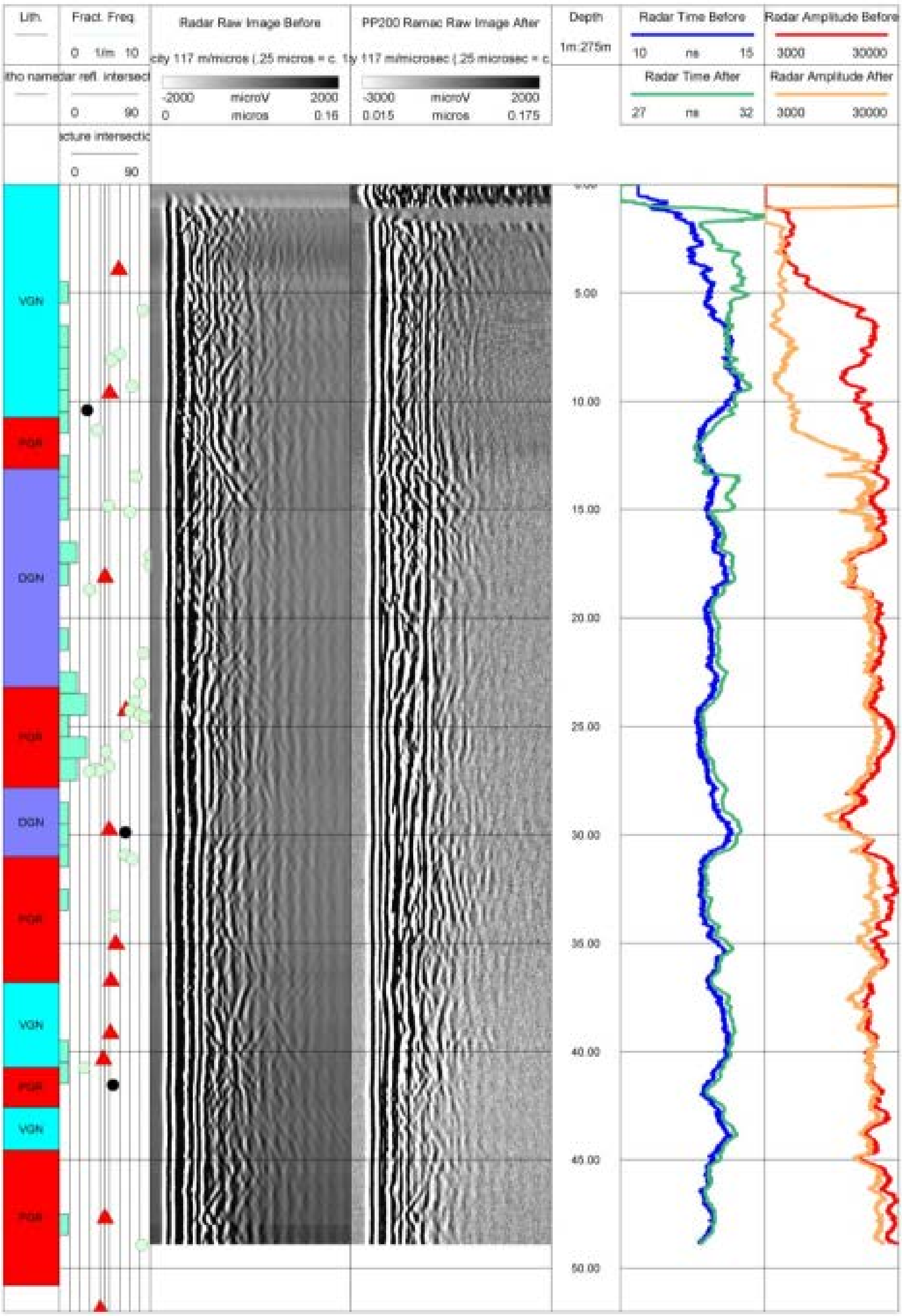

Figure 3-4. Drillhole radar images in horizontal pilot hole ONK-PP200 with 250 MHz drillhole antenna, full radial scale c. 10 m. Left image before excavation (baseline), right image after excavation of investigation niche ONK-TKU-3620. Lithology and fractures are contributing to inclined reflections, water saturation to velocity and amplitude differences near top of the hole. A parallel, discontinuous new reflector, partly masked by ringing, indicates a tunnel face approaching closer to drillhole towards the end of the hole, 1 – 2 m distance (Mustonen et al. 2011).

The surfaces of access tunnel were measured with GPR for testing the performance, then for description of the Excavation Damaged Zone, using 1.6 GHz high frequency GPR down to depth of 1 m from the surfaces (Heikkinen et al. 2020b, Figure 3-8). Results are detailed, and in case any structure would be hidden immediately behind a tunnel wall, it would be also detected. Based on testing, a GPR EDZ method (Silvast & Wiljanen 2008) was developed, where GPR measurement amplitude data would be processed in frequency domain to index values, representing EDZ layer thickness on the rock surface. Measurement can be carried out with air coupled antenna, using vehicle mounting (Figure 3-5). Later a ground coupled system has been developed (Figure 3-6). High frequency GPR has been applied also on experimental disposal hole walls and shaft walls to detect extent of fracturing. The GPR EDZ method is independent on reflection data, which could have relevancy for safeguards purposes, like baseline and repeat surveys (Figure 3-7).

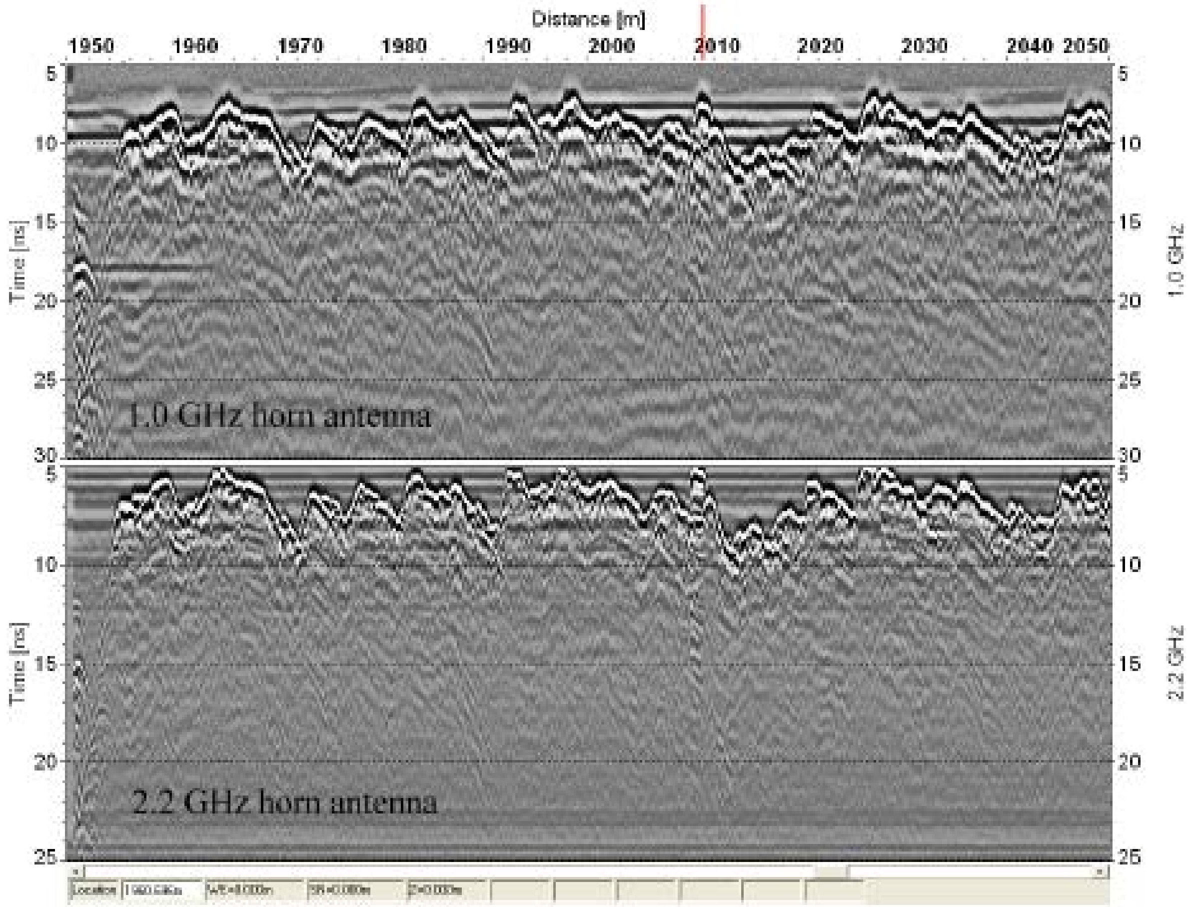

Figure 3-5. GPR images measured at ONKALO access tunnel chainage 1950 – 2050 m. Distance from the wall 0.5 – 1 m, mounted on a vehicle. Air coupled horn antennas with frequencies 1.0 GHz and 2.2 GHz, produce range of 25-30 ns corresponding 1 – 1.5 m distance in rock mass, performed without contact to the surface (Silvast & Wiljanen 2008). Steel reinforced mesh on the surface would prevent any measurement.

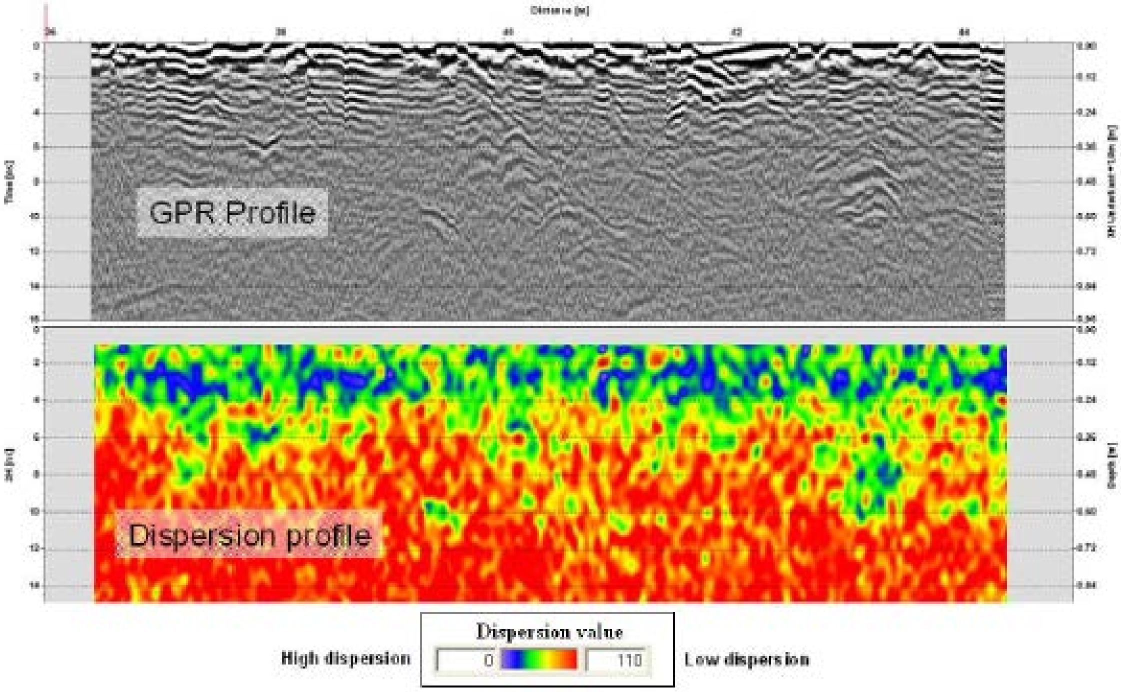

Figure 3-6. GPR EDZ measurement, GPR image of 1.6 GHZ antenna showing effect of small-scale fracturing on surface, and frequency processed GPR EDZ index data, blue colours represent increased excavation damage (Heikkinen et al. 2010b, Kantia et al. 2013). Depth range 0.9 m from surface.

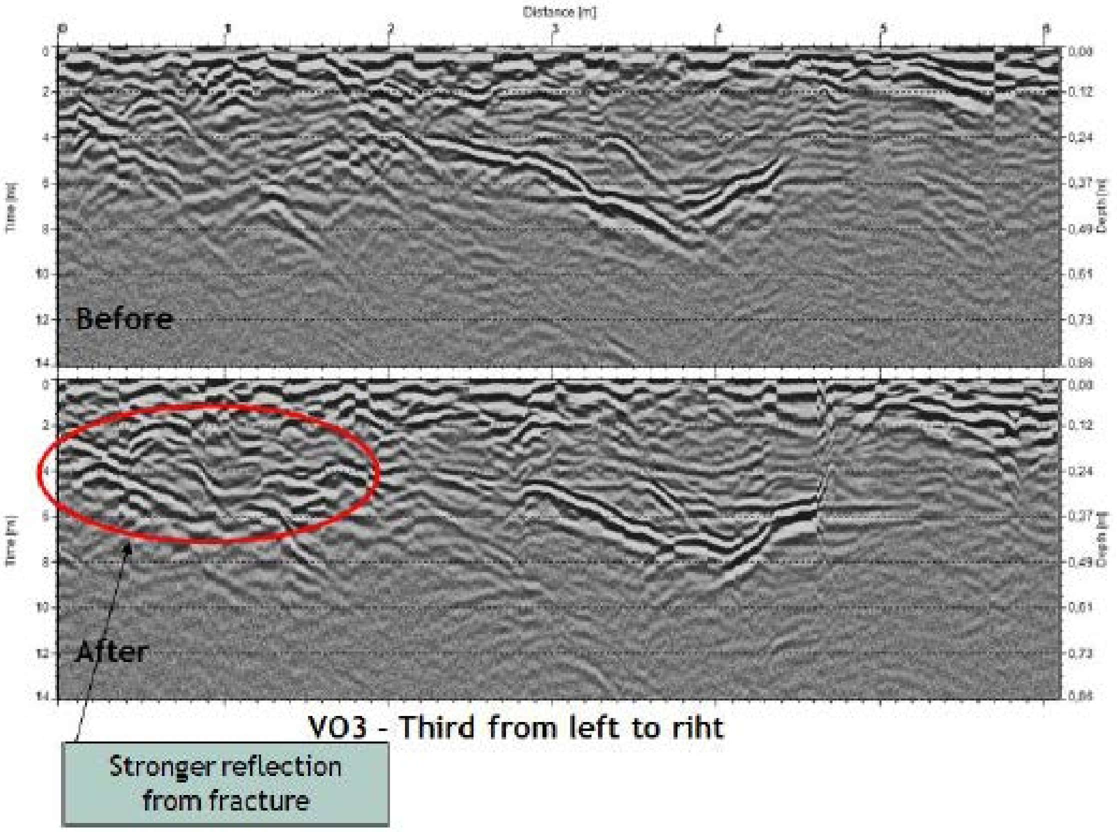

Figure 3-7. GPR EDZ repeat measurement at investigation niche PL2240 in ONKALO access tunnel, with and without water saturation. Repeat measurement can be compared to baseline (Heikkinen et al. 2010b). Depth range 0.9 m from surface.

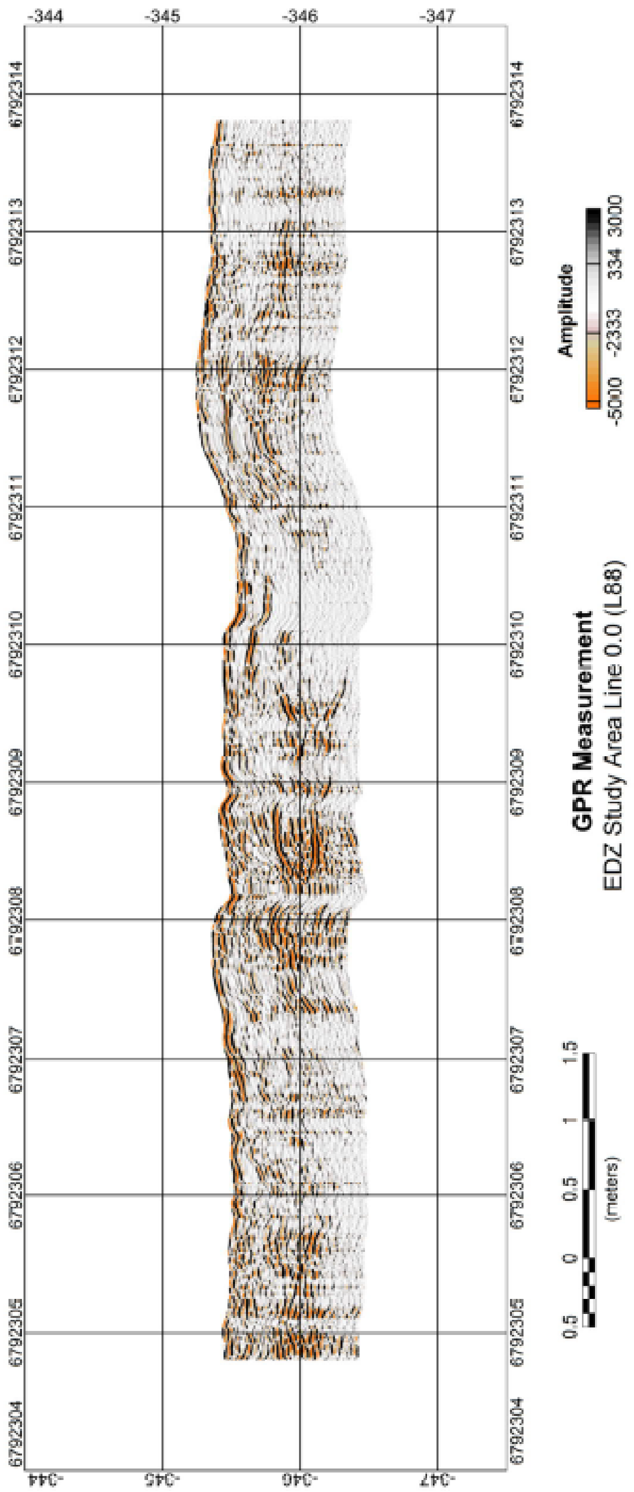

Figure 3-8. GPR measurement profile on tunnel floor at investigation niche ONK-TKU-3620, measured for EDZ characterization, draped on to form of the floor. Frequency 1.6 GHz, depth range 1.0 m (Heikkinen et al. 2020b).

Laboratory analysis and numerical simulations indicated the electrical conductivity 0.005 – 0.01 S/m at high GPR frequencies (analysis at 2 GHz) start to be at limit on wave transmission, and attenuation of 0.5 – 1 dB/m approach the level where GPR starts to be no more applicable (Heikkinen et al. 2020a).

Table 3-1. Estimated GPR range at different frequencies in Olkiluoto and other spent nuclear fuel disposal candidate sites. GPR wavefield Q (number of cycles within range of investigation) is depending on attenuation (conductivity) of the rock mass, but also measurement configuration, coupling into the medium, dynamic range of measurement system and intensity of primary signal.

Frequency	Relative dielectric permittivity	Wave-length	GPR velocity	Range in Olkiluoto	Range in non-saline crystalline rock	Notes
22 MHz	5.7	5	125	50 (Q=10)	100 (Q = 20)	
60 MHz	5.7	2	125	25 (Q=12)	50 (Q = 25)	
100 MHz	5.7	1.2	125	15 (Q=12)	25 (Q = 20)	
100 MHz DH	5.7	1.2	125	15 (Q=12)	25 (Q = 20)	
250 MHz	5.7	0.5	125	10 (Q = 20)	15	
250 MHz DH	5.7	0.5	125	10 (Q = 20)	15	
350 MHz	5.7	0.35	125	10 (Q = 30)	#N/A	32-bit, hyper stacking system
400 MHz	5.7	0.30	125	4 (Q = 12)	#N/A	
1.0 GHz air	5.7	0.12	125	1.5 (Q = 10)		
1.6MHz	5.7	0.08	125	1 (Q = 12)	#N/A	
2.6 GHz	5.7	0.04	125	0.6 (Q = 10)		

Earlier the conductivity and attenuation were estimated indirectly based on measurement data at different frequencies, and from various targets in Olkiluoto (Saksa et al. 2005). Recently more direct information on the range has been produced from the actual disposal level and actual rock mass properties, also with the applicable type of tool and antennas. In any case, the conductivity in high frequency end is high enough to cause strong attenuation, which is severely delimiting the GPR range to the class of 10 m from tunnel wall at its best. For example, saline groundwater in bedrock would further suppress the GPR range. GPR was thought to provide information on possible empty spaces behind tunnel lining. However, metal reinforced shotcrete, widely used to support tunnels for personnel safety, suppresses completely the GPR wavefield, being highly electrically conductive.

As the electrical conductivity and attenuation of GPR wave field is strongly frequency dependent (dispersive), the lower frequencies have slightly lower conductivity and that way greater penetration as cycles, and accordingly also distance. The resistivity in Olkiluoto saline water containing gneiss is low, and attenuation high. In salt formation or either dry, or fresh water containing crystalline rock, method would be more functional.

The 270 MHz antenna was used in mapping of fracture extensions in tunnel floor at investigation niche ONK-TKU-3620 (Koittola 2014, Figure 3-10), as well as the access tunnel at chainage PL3300 – PL3600 (Heikkinen andKantia 2011, Figure 3-9), to depth of 8-10 m from tunnel floor and wall. This tool was used also in demonstration area for rock suitability classification in mapping of fracture continuity in analogous way (Figure 3-11, Heikkinen and Kantia 2011). Tests were made also with 100 MHz tool (Figure 3-12, Heikkinen and Kantia 2011), with a hope of deeper penetration. However, the large size and consequent inferior quality of the signal led to almost comparable (max 15-20 m) depth range with lower frequency (theoretically with greater range). Heavy 10 kg tool is slow to be operated manually on the tunnel wall.

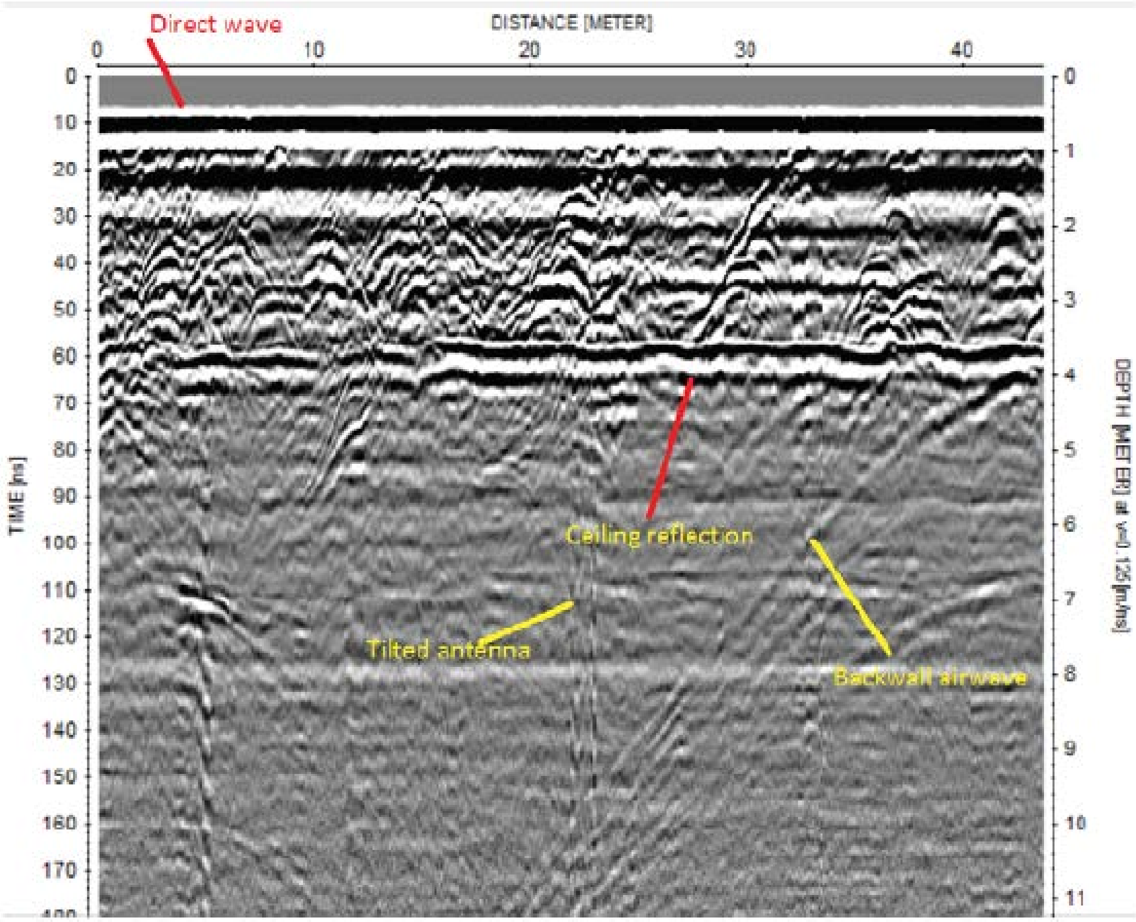

Figure 3-9. GPR image measured on tunnel floor downwards at ONK-TKU-3620, using 270 MHz GSSI tool (Heikkinen & Kantia 2011). GPR range is at order of 7-8 m. Reflections from ceiling, side walls and back wall as well as interference caused by irregular form of floor affect to results. Best range and performance are obtained with 200 – 400 MHz shielded antennas. Interference increases with larger 100 MHz antenna, gaining little to actual range.

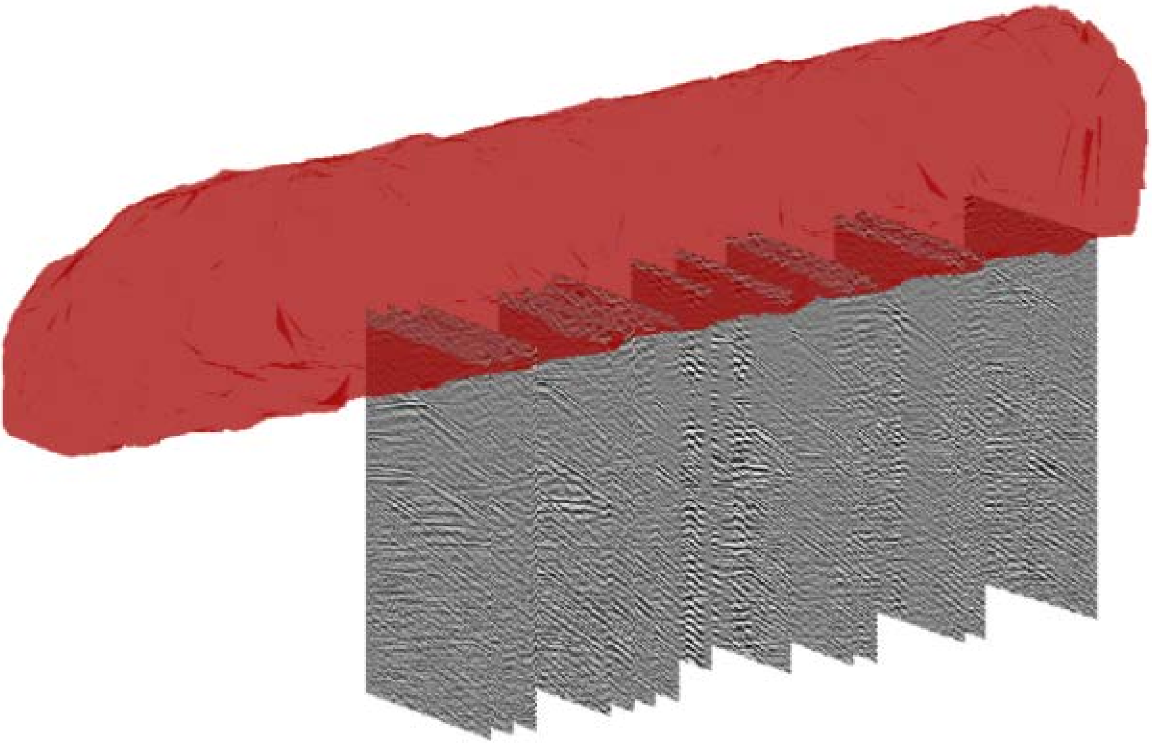

Figure 3-10. GPR images measured with 270 MHz antenna stacked in 3D on a tunnel floor. Depth range 7-8 m. Tunnel (red solid) height 5.5 m (Koittola 2014). Fractures are seen on images. A tunnel below floor could be detected.

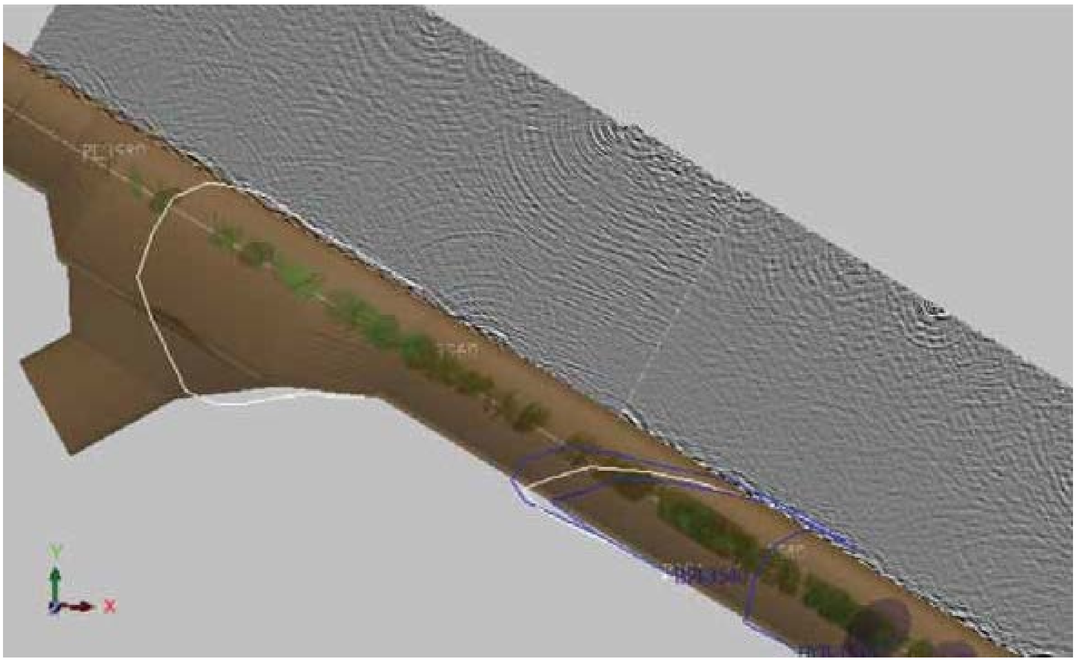

Figure 3-11. GPR image draped on tunnel wall in 3D, measured between chainage 3300 – 3600 m on right hand wall of ONKALO access tunnel, 270 MHz antenna. Range on the wall is less than 10 m (Heikkinen & Kantia 2011).

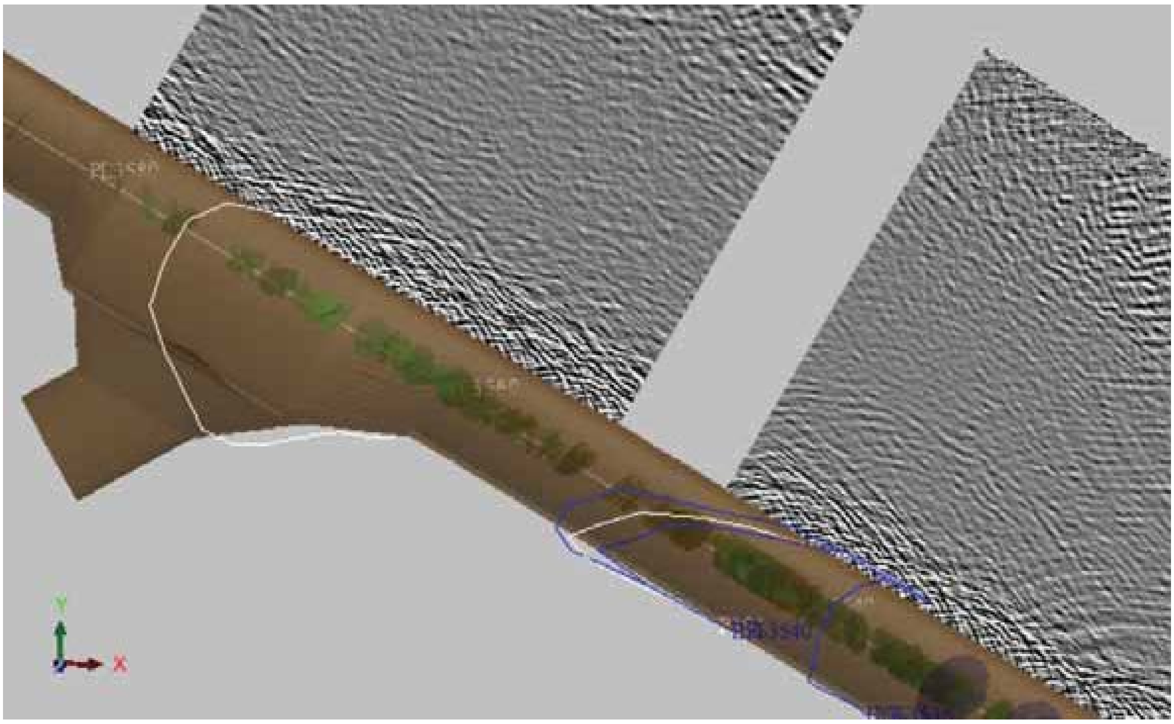

Figure 3-12. GPR image draped on tunnel wall in 3D, measured between chainage 3300 – 3600 m on right hand wall of ONKALO access tunnel, 100 MHz antenna. Range on the wall is slightly more than 15 m (Heikkinen & Kantia 2011). Interference from tunnel surfaces and installations make application of results difficult without extensive processing.

Test with 400 MHz antenna at same ONK-TKU-3620 niche (Koittola 2014) indicated depth range of 3 – 4 m. All these measurements require that the rock surface be clean and dry, and there must not be any reinforcement or shotcrete lining on the wall. Also the macadam lining on floor should be absent, because moisture, salinity and metallic fragments from shotcrete cause noisy reflections and amplitude decay near surface.

SKB tested for development of detailed investigation methods GPR survey on tunnel wall on same places as seismic survey methods and electrical resistivity tomography. GPR survey was designed to measure extensions of fractures encountered on tunnel surface (FPI's, full perimeter intersection). GPR reflection image produced with measurement using 100 MHz antenna has a range of 15-20 m (Figure 3-13) in Äspö site, which is fairly resistive. Some reflecting objects are detected, though few directly associated with tunnel mapped fractures. Non confirmed reflections may arise both from fractures or fracture zones and lithological contacts. Reflectors are seen generated also from short grouting drillholes left outside of tunnel perimeter. If a non-declared tunnel would be present behind the wall on the same elevation, within measurement range, it would likely to be observed.

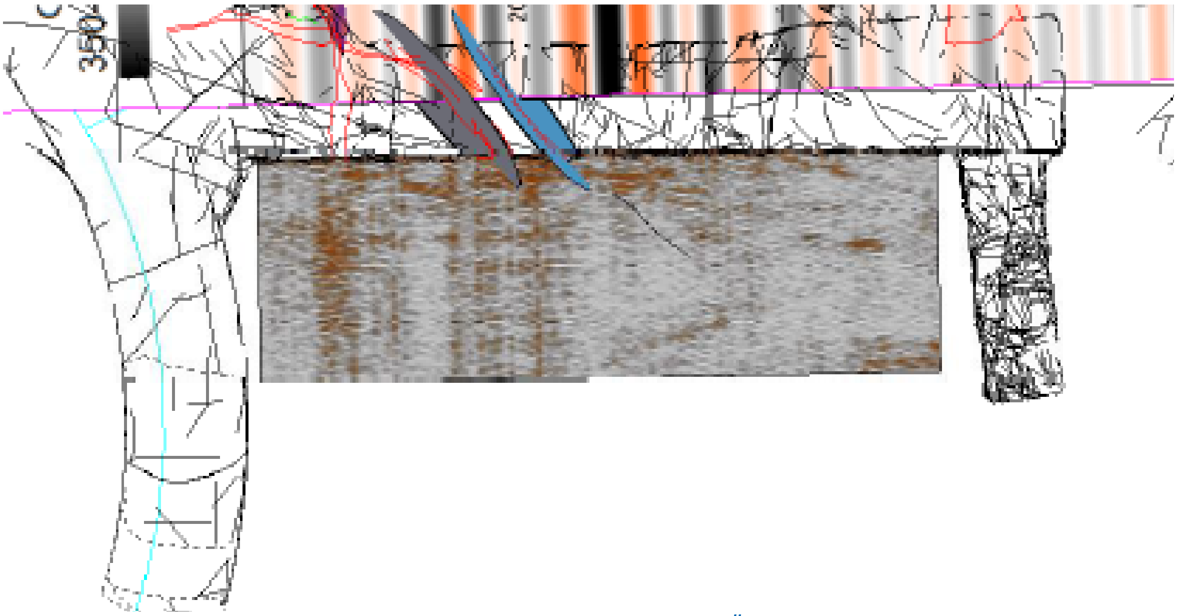

Figure 3-13. GPR survey results on tunnel TASA wall at 450 m in Äspö hard rock laboratory, Oskarshamn (modified from Cosma & Enescu 2015)*. Frequency 100 MHz enabled a 20 m depth range. Black lines inside the tunnel perimeter are mapped fractures. Disks indicate a fracture trace covering the full perimeter of tunnel, described as a geometric object with orientation. Some weak reflectors are seen, though not explained by tunnel observation. Few near tunnel reflections are due to grouting drillholes remaining on tunnel wall (filled with cement).* Black to red bar is indicating a drillhole synthetic seismogram based on sonic and density logging (not relevant to GPR results).

Applicability of the different antennas (and frequencies) require good contact on the tunnel surface. An irregular rock surface leaves an air gap between wall and antenna surface, which causes ringing in the data, which is difficult to remove and makes observations more difficult. The larger the size of the antenna (increasing with lowering frequency), the weaker is the shielding of the antenna. Also, the air gap variation and irregularities of wall are causing scattered reflections. Poor shielding also causes side reflections from irregular tunnel surfaces, electrical and lighting installations, or any other metallic objects in tunnels, opposing wall, and from the floor and ceiling. It appears that optimal resolution and range can be achieved with higher frequency antennas, which are better shielded and fit more closely to tunnel surface.

3.1.2 Other types of environment and new GPR development

DMT has constructed a more powerful 85 mm or 130 mm diameter directional borehole radar for salt dome internal characterization (Althaus 2013). Salt has exceptionally low attenuation of radar wave. Presented idea was to create a protective screen of boreholes around a repository, which could be used to detect undeclared intrusion from outside, even after closure of the site (Figure 3-14).

Development in radar technology would include high transmitter energy, massive stacking, bi-static transmitter-receiver array, stepped frequency tool, use of multiple frequencies. Also, the transmitter would be directional and shielded.

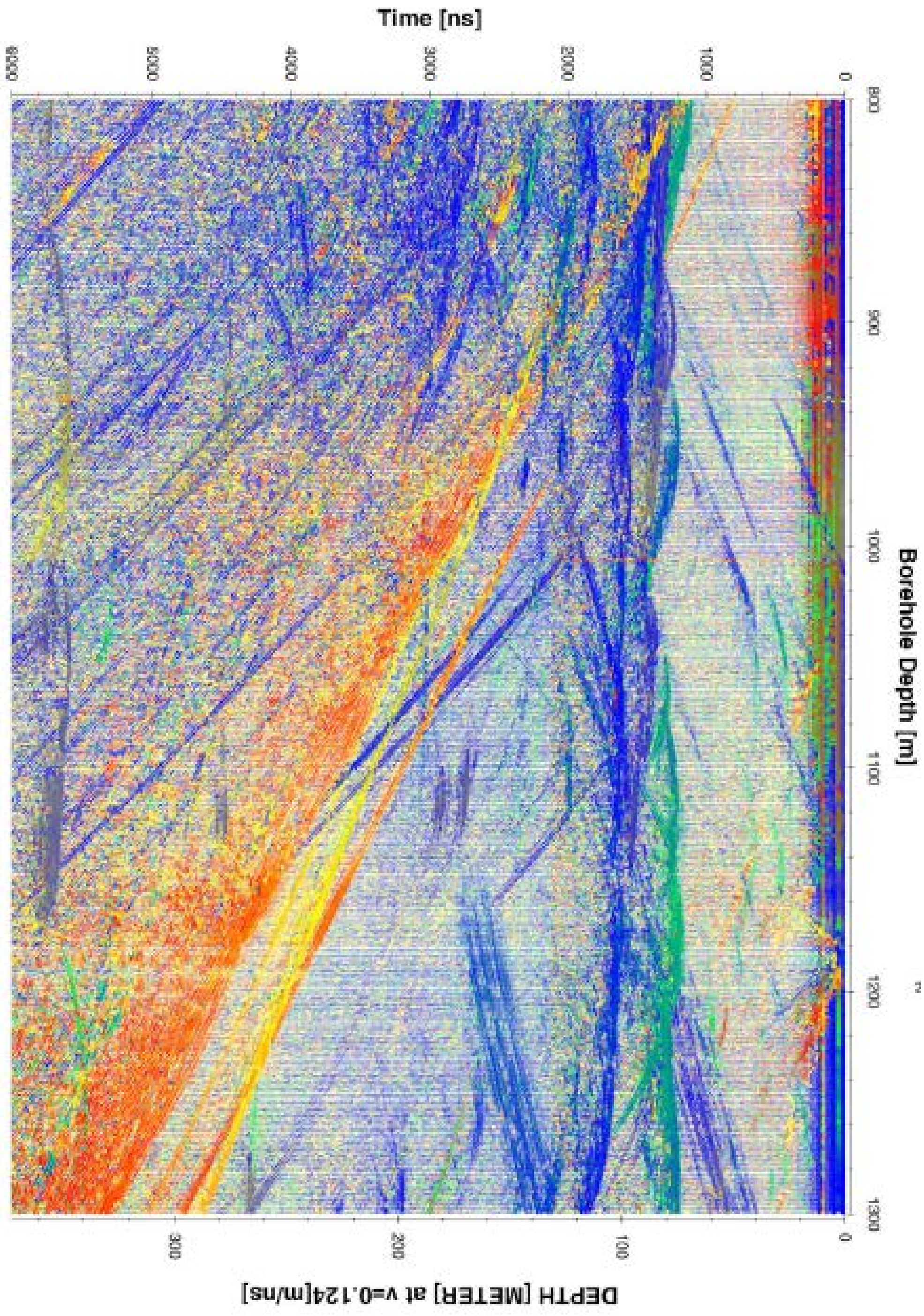

Figure 3-14. (Althaus 2013). Drillhole radar amplitude map from a single drillhole at length interval 800 – 1300 m (vertical axis). Location of a drillhole in the image is on the right. Horizontal axis on top shows time to 6000 ns. Horizontal axis on bottom indicates the distance from drillhole converted to time (370 m), assuming constant radar wave velocity. Reflected radar wave amplitude is shown as intensity in the map. Different colours are indicating the radial azimuth around the drillhole. Linear features of different elevated amplitude regions show direction and distance of boundaries in differing electrical properties, like boundary of salt formation. Reflection signature in salt is low amplitude except few inclusion caused features. Reflectivity in surrounding rock mass is higher in amplitude. A tunnel would be seen in image as a local hyperbolic diffracting event.

Application of borehole radar has been developed further than before, into comparison of baseline data and repeat measurements (Uchtmann and Althaus 2014). Application would be based on early-stage implementation, recognition of all excavated spaced in the repository volume, identification of reflections, and monitoring for changes in backfilled areas and post-closure stage. Monitoring will require static radar system installed permanently outside of the repository. Similar static arrangement might be applied also for active seismic methods, or in limited cases for other electromagnetic method than radar, or even resistivity.

Recent GPR development has increased the range of the survey method. The change of data bit depth from 16 bit (+/- 32 000 integer) to 32 bits (millions in floating point) has made the relative noise smaller and increased the depth range 30%. Another development to GPR technology is related to recording of traces (the A-scan). Historically the GPR scan has been constructed from time lapse sampling oscilloscope type of readings, which have been repeated with small time increments to finally construct a complete scan, consisting for example from 1000 samples at 0.2 ns time interval. Currently a hyper stacking GPR system can record each trace at single pass, and then use dozens of traces to stack data further into a single trace with much higher signal to noise ratio than before, and with enhanced depth range from tunnel wall. Still, the GSSI 350 MHz HS tool appears to have a maximum depth penetration in ONKALO rock mass of 10 – 12 m.

3.2 Seismic investigations

Seismic measurements are a group of active geophysical methods, which uses seismic waveform interaction in rock mass for characterization of geological geometry and physical properties. Active seismic surveys can be used to detect structural features with sharp contrasts, to verifying repository design, and monitoring rock stress fields (Haddal et al. 2014). Active surveys require many sensors and active source.

Active seismic survey uses an artificial source of elastic waves, and measures backscattered wave field. Method is based on transmission, reflection, refraction and diffraction of elastic waveforms within geological medium. Measurable properties are travel times and amplitudes of backscattered seismic waveforms. Travel time and amplitude of waveforms are depending on both geometry (distances) and elastic properties in the medium. Boundaries of different elastic physical properties cause reflections, refraction, diffractions, and waveform conversions. These properties are bulk density of geological medium, related to mineral composition, as well as seismic velocities (initially governed by Lamé parameters and density) which in turn are related to mineral composition, texture, porosity, and stress field. Boundaries can be caused by geological structures like lithological contacts, fractures, and fracture zones, and engineered (constructed) structures like tunnels. Sharp elastic contrasts may be created in potential clandestine tunnels, like bedrock face on tunnel surface (Finch 2009).

Source of seismic signal can be active or passive. Sources can range from explosive charges to mechanical impact or vibrating frequency sweep sources. Active sources are ranging from mechanic impact from a hammer or drop weight, sweep with a variable frequency vibrating source, or small explosion using detonator fuse or small explosive charge. Passive signals can include application and correlation of natural signal sources like wind, waves and microearthquakes, as well as synthetic noise as traffic and industry as the seismic source. Mechanical environmental noise and its autocorrelation can be applied as a source, especially in longer term recording.

Source of seismic energy needs to be coupled into the medium to be investigated. Impact generates different seismic waveforms, which travel in the medium with their characteristic phase velocities. Velocity of each waveform is governed by elastic properties of the rock mass (Lame properties and bulk density) and stress field. Compressional P wave front has highest phase velocity. P wave is transmitting through all materials. Shear S velocity is traveling at slower velocity, proportional to P velocity, and does not penetrate fluids. Different forms of surface waves generate and travel on surfaces on the medium on ground level, tunnels, drillholes and fracture surfaces.

Back scattered seismic amplitude according to time are recorded with accelerometer or geophone sensors, which need to be attached onto investigated material. Recently possibilities for applying fibre optic (DAS) sensors as receivers have emerged. Recording is carried out with accelerometers or geophones, or using optical fibre sensors, depending on frequency range.

Detection of a target within rock mass is based on seismic reflection or refraction sounding or imaging. A survey line would consist of multiple, overlapping recording stations and source locations. Measurements are most often carried out by geometric stacking of several records, for example centered at a common midpoint (CMP stack), at several different source-receiver distances (offsets).

Each implemented source signal is recorded with several (even tens of) sensors on a survey line or on an array. Sensors are located at varying offset distances from the source location. Seismic wave reflections within rock mass are weak due to geometric spreading and attenuation, for which reason it is necessary to geometrically stack (summarize) the recorded traces. Typical way of stacking consists of common mid-point calculation of signals received from variable offsets. Range of other processing steps, including frequency filtering and arrival time geometric adjustments (normal moveout, static corrections) are also required for proper alignment of reflected events in the processed image. For weak reflections, multiple stack fold is often necessary. Before actual stacking, several filtering and direct and surface wave suppression steps are always necessary.

Measurements can be carried out on a 2D survey line on ground surface, along drillhole, or in tunnel. The surveys from drillholes or tunnels are directional and can be arranged as a side-view geometry. An array of in-line receivers at several lines, and sources on several crossing lines, can be used to form a (downwards viewing) 3D reflection survey on ground surface.

From tunnel or drillhole geometry, possibility to run 3D survey is geometrically more limited. Using offset sources from receiver lines or drillholes, it is possible to run a limited 2D or 3D reflection view for resolving location and orientation of a planar or linear reflecting target, usually interpreted as a combination of several survey lines. In tunnel environment, also emerging tunnel waves need to be suppressed preferably already with measurement array or using advanced processing (Enescu et al. 2014).

Observability of targets, and depth range of the seismic method, depends on applied frequency range. Surface based investigations may apply frequency range of 20 – 200 Hz, being able to carry imaging to depth of several kilometers and resolving targets at size of some tens of metres. High frequency surveys from tunnels and drillholes, at 100 – 1000 Hz, can be used to image rock mass to distances of 100 – 200 m, and detect objects in size of metres. Thickness of a layer to be observed can be tens of centimeters. The radius of a planar object, or distance between two objects, needs to be in order of product of wavelength (velocity divided by frequency) and distance. Lower frequency range has depth or distance penetration of several kilometres, mid-frequencies tens to hundreds of metres, and highest frequency range some metres to tens of metres. Detection of a target depends on frequency and thus wavelength, largest range, and lower frequency band, with 5500 - 6000 m/s P wave velocity, show wavelengths of 20 – 100 m; mid-range 5-10 m, and highest frequencies tens of centimeters.

Observability of a boundary is fractions of wavelength, detection of an object and separation of two closely located objects in order of wavelength. Bedrock often shows an optimal frequency band which penetrates the rock mass best and carries most information. The frequency band, and relevant waveforms, would need to be considered for example with numerical modeling tests with related processing methods. The sensor density for sources and receivers needs to be dense to recover the reflected or scattered signal well. For a 500 Hz frequency (10 m wavelength), sensors should be placed in order of 2 m distance.

Normally in spent nuclear fuel site characterization, and in rock engineering where fractures and fracture zones are the main target, the used seismic processing techniques are designed for detection and enhancing of continuous reflections from extensive fractures and lithological boundaries.

A tunnel would be different kind of targets compared to continuous fracture surfaces. Depending on the orientation of a target tunnel or gallery, compared to the measurement array, a perpendicular tunnel may be seen only as a diffractor. These are easily removed in standard seismic processing or migration. Thus, a specific diffracting or scattering source processing would be necessary. A tunnel parallel to measurement array would be seen as limited linear reflector, which may again be easily removed as a multiple reflection and would be sensitive to directionality of wave field. Tunnel scattering event might be best observed from single shot gather before processing, or while composing a processed image, requiring special processing techniques.

Tunnel target itself may also generate multiple types of scattered wave fields, starting from ringing tunnel waves along the tunnel surface, then reflected P and S waves, depending on contrast of air or water with the rock mass, and a range of converted wave forms. Observability issues, and processing design would be best resolved using pre-survey modeling and test measurements for tunnel detectability.

Tunnel seismic investigations can use different migration schemes and spectroscopy (Tzavaras et al. 2008) to focus the imaging to actual reflection or diffraction point. Detection on a tunnel using seismic methods may be enabled by full waveform imaging (Smith et al. 2017). Common problems in conventional analysis, based on first arrivals, or reflection interpretation, are poor signal-to-noise ratio, lack of separation of body waves and surface waves, and rapid attenuation of higher frequency seismic energy in shallow surface. Elastic full waveform inversion of densely placed sources in a 3D field array, show location of a tunnel as an elongated low S-wave velocity anomaly.

Survey is partially directional. Different waveforms emerge best at different offsets, like P wave at normal incidence to the reflecting boundary, and S waves at wider angles best.

Compressional waves reflect towards the measurement line best from surfaces at reflection angles of 0° … 25° from surface (near offset). Shear wave reflectivity maximum is at 45° offset and can be observed starting from 25° reflection angles. Especially underground and drillhole surveys may be useful to be applied with 2-component or 3-component receivers. Reflections however can arrive from offline and locating of actual position may require external knowledge to constrain.

Typical survey timing on surface has consisted of 0.5 – 1 km of 2-D line in day, requiring minimum 100 – 200 geophones attached on a line, with a cost range of 10 000 – 30 000 €/ km processed and interpreted. A drop-weigh source and land streamer receiver array are more efficient to deploy. Practical production rate of sources is at order of 100 stations in a day. A 3D survey is more demanding in preparations, will require 300 – 1000 geophones installed in a field, and being able to produce a square kilometer in few weeks' time, at minimum 1 000 000 €/ km^2 cost range. Drillhole reflection measurements, using several source locations on ground surface or in tunnel, and repeatedly moving a receiver array along the drillhole after deploying all source stations, has required working time of one week for each 500 m long drillhole and 10 sources, 50 000 € each drillhole. Using more receivers to cover longer drillhole lengths at each shot or recording a whole drillhole length at once using a fibre optic DAS, would make the field time shorter at a cost of more expensive measurement tools.

Tunnel seismic work has required attaching geophones into tunnel surface, deploying sources in prepared short drillholes, or both. Placing either sources or receivers 1 – 2 m away from tunnel surface would help reducing ringing and tunnel-based surface waves in the results. Using 100 geophone stations, preparation of a 100 - 200 m long dense geophone line on tunnel surface may require one day. Deploying corresponding source locations would require another day, then moving on similar length day more each 100 m.

Typical cost profile for a single, full coverage 2D seismic imaging on a tunnel wall has been at an order of 100 000 € /line. Lower density of sources at high receiver density, or reversely low density of receivers using a high amount of densely located sources, may produce adequate data to locate undeclared tunnels to 50 - 100 m distances from survey line, achievable at slightly lower costs. According to Seidel (2007), Zöllner (2007) has demonstrated dense receiver and source array capability to image nearby tunnels. Time required to produce measurements for 144 m line in two sections required two days. Adding more efficiency would require development work (Seidel 2007) in measurements and processing.

Repeating such survey, at higher resolution, might help by comparison of results to detect the existing (intentional) tunnels, and separating new tunnels that would not be allowed. Because the coverage of existing measurement line data is limited, possibilities to directly detect a tunnel with local high resolution seismic line or several lines would be useful. Typical CMP stack binning size on 2D line can be in order of 5 m, which is corresponding the size of tunnel profile. Higher resolution would mean higher density of sensors, and slower, more costly survey. Processing technique would need to be designed to enhance specific tunnel related observations. Direction of survey line would be optimally near perpendicular to potential tunnel traverse. Seismic line survey on ground level can be run on any time, also after closure of the disposal facility.

Applying a land streamer receiving array and using sources in short drillholes would enable quicker downward viewing survey. Fast drop weight type of survey on tunnel floor, would require more sparsely placed receivers attached in a drillhole, or advanced processing to suppress ringing, cyclic tunnel waves from the results. Running a side viewing survey on wall of tunnel would require an oriented (side hitting) hammer source, small explosive sources, or a vibrating source on a same wall as where the receivers are attached. Possibilities are also to use tunnel construction and operation generated noise in and accumulating signal in passive mode recording. leaving sensors for measurements over specific period.

In each case, processing and interpretation would require design and modeling to be able to visualize the results in proper way, after which systematic processing could be run in brief time. A single campaign would require research and trial processing of several weeks before results are available.

Seismic survey can be recorded using industry standard seismograph tools and geophones and processed with existing processing software. However, design of tunnel survey will require planning prior the survey. Amount and size of tools require that there will be arranged a quiet period in tunnel sections during the work, at least for installation of receivers.

In seismic survey results, geological variation like lithological contacts, veins, and inclusions, as well as different kind of deformation zones like fractures, are causing abundance of anomalies in reflection images. Separating these natural reflecting or diffracting objects from synthetic, undeclared tunnels, would require at first place dedicated processing of results to indicate cause of the observation. Comparable way as in GPR results, a parallel tunnel to the measurement line may be observed as a linear, continuous feature, as an intersecting tunnel would be seen as hyperbolic event in raw, stacked data, and point like event in a migrated data. In case an anomaly would be observed, decision should be made can its origin be resolved with more accurate and focused further measurement or would a confirming drilling be required. A baseline and repeat survey using similar measurement and source array, or semi-continuous measurement using a permanent measurement array and repeated sources at specific time periods, would enable comparison between results to follow up changes, avoiding need to check unexplained observations. Especially the underground survey geometry requires thorough planning to avoid false positive alarms, but also possibilities to leave out possibility for false negative result (not observing an existing undeclared tunnel, located too far, or a dead zone with respect to measurement geometry).

Seismic survey in a tunnel can be conducted any time the tunnel is still open, before backfilling and closure. Near the tunnels, surveys can be used for verification of repository design. With professionally designed acquisition (angular coverage, components), it may be possible to detect changes in rock stress fields. Passive recording systems can be used in measuring noise and events from activities related in excavation. Actual geometric properties need support from active measurements with more dense receiver arrays. Seismic response from bedrock and tunnels are complicated compared to single wave form, zero offset GRP responses (Chapter 3.1). Figure 2-4 in previous section displays a synthetic example of seismic 2D line measurement over a model containing tunnel and a lithological contact (Seidel et al. 1999). Direct wave, hyperbolic reflection and multiples from a tunnel, and reflections from a layer interface overlap, and make visibility of each object difficult even without presence of noise and multiple natural objects. Adding more boundaries and tunnels also add the difficulties in understanding the results.

Existing and backfilled tunnels and their environment can be surveyed from neighboring still open tunnels. Feasible distances from tunnel range at 100 – 200 m in case long survey lines can be deployed. Resolution is not high enough to view the disposal facility construction details from ground surface after closure of the facility, even against design data. Resolution would be better using existing drillholes for such surveys, until sealing of the drillholes. Active seismic survey can display reflections from tunnel openings (Seidel et al. 1999), though the more complicated a geological setting will be, more difficult the recognition of tunnel related features would become (Figure 2-4). More advanced processing techniques combined with knowledge of existing tunnels will help in understanding the seismic images. A repeat survey may be required to recognize features that have not existed during previous measurement.

After closure of the site, only possibilities to apply seismic reflection survey for safeguards would be to carry combined surface and drillhole based reflection measurements at the perimeter of disposal facility environment, to detect a new tunnel in case such would be in preparation. Active surveys at frequent intervals would become expensive. Automated acquisition of environmental noise with permanent receiver installation, assisted with possible active source campaigns at least in beginning, and processing to display only changes occurring in subsurface, may appear a possible though tedious method. On a circle, on repository perimeter, would need to be equipped with DAS or equal seismic receiver on ground level and in drillholes at c. 500 m interval, down to depth of minimum 500 m. Active source locations would need to be dense, with spacing of few metres. Also, drillhole based sources would be useful. System would rely on continuous data acquisition and automated processing.

3.2.1 Seismic surveys for Posiva and SKB

The active seismic surveys in Olkiluoto crystalline rock have applied frequency ranges from 30 Hz to 200-300 Hz from ground surface and deep drillholes, up to 1000-2000 Hz from tunnel surfaces, and as high as 100 kHz in short drillholes.

Historical seismic measurement methods from Olkiluoto which could be used as future technique for safeguards purposes, include drillhole 3D VSP reflection in c. 20 deep drillholes, moving source seismic profiling, 2D surface seismic profiling (HIRE), 3D reflection seismic imaging, tunnel seismic survey, and cross drillhole or cross tunnel seismic reflection or tomographic imaging. Other applicable methods might be tunnel seismic profiling carried out during construction, or repeat measurement using similar survey array.

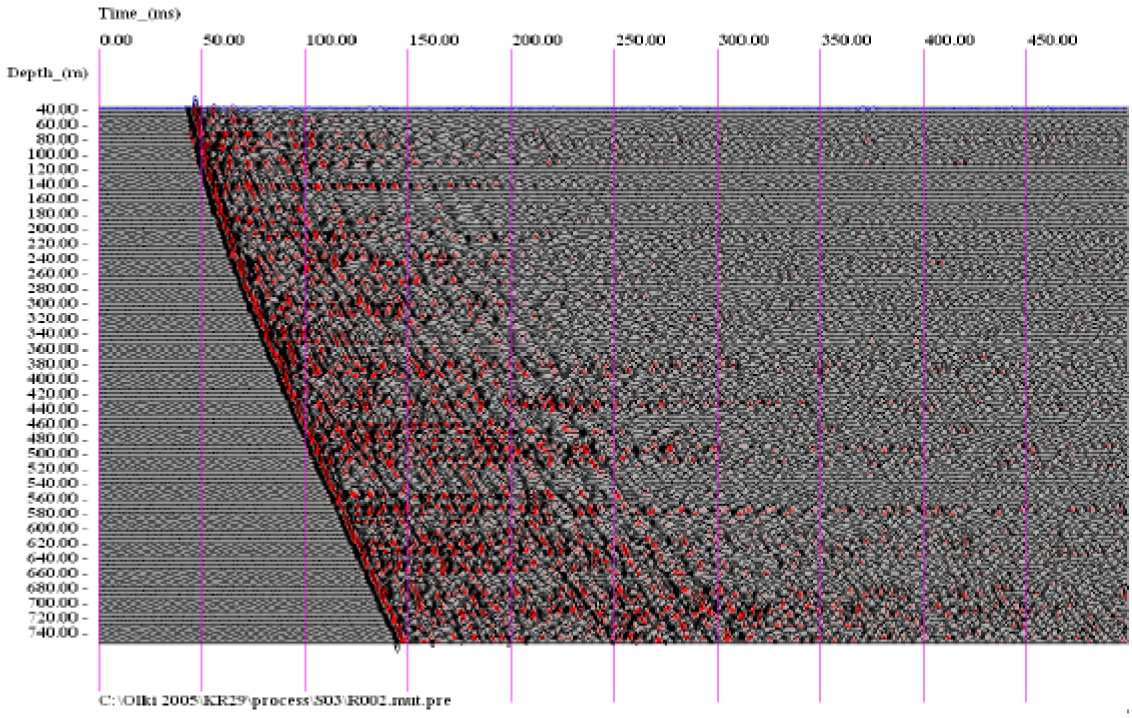

Figure 3-15. Seismic 3D VSP reflection image, drillhole OL-KR29 (Enescu et al. 2007). Seismic waveforms from ground surface source station were recorded using 3C receiver in drillhole at 5 m interval. Image contains reflected energy from distances of several hundreds of meters from drillhole, which may be used to detect tunnels at close range (best using baseline and repeat survey). Source position needs to be selected optimally for detection from different directions from drillhole. Two way arrival time 400 millisecond corresponds radial distance 1200 m from source via reflector to receiver.

Two-dimensional seismic line measurement (Kukkonen et al. 2010, Figure 3-16), can be used to detect reflecting objects. A deep seismic sounding of 31 km was carried out in 2008 using Olkiluoto road connections. Vibroseis source point interval was 25 – 50 m, and receiver station interval 12.5 m. Comparison between baseline and repeat survey would be essential to detect undeclared tunnels, as well as enhancing resolution.

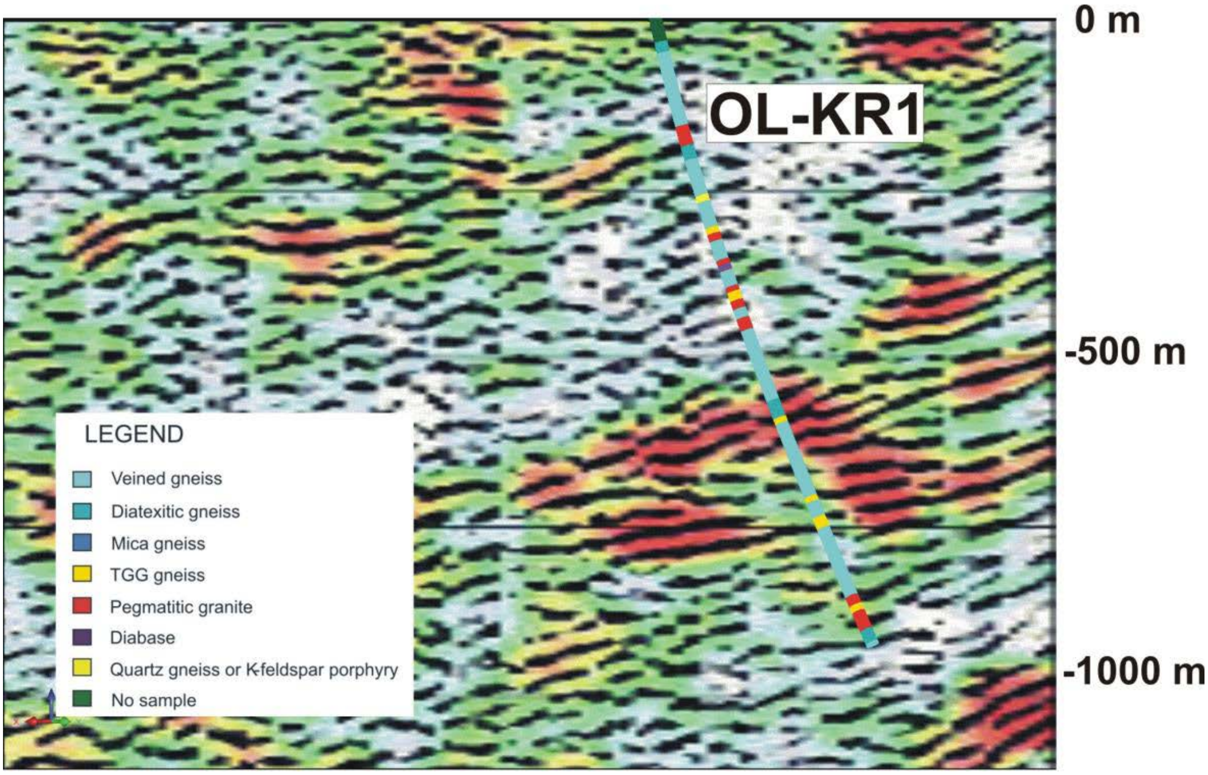

Figure 3-16. Projection of the drillhole OL-KR1 on seismic profile V1, view from NE (Kukkonen et al. 2010). Processing enhances gently dipping, continuous linear events.

In Olkiluoto, short geotechnical refraction lines with 2.5 m CDP distance can be used for reflection processing (Öhman et al. 2006, 2008, Figure 3-17), but their resolution is limited. Application requires minimum stack fold of 20 - 30. Strong diffracting events may be an indication of undeclared activity in an area, detectable in favourable conditions down to depth of 500 m.

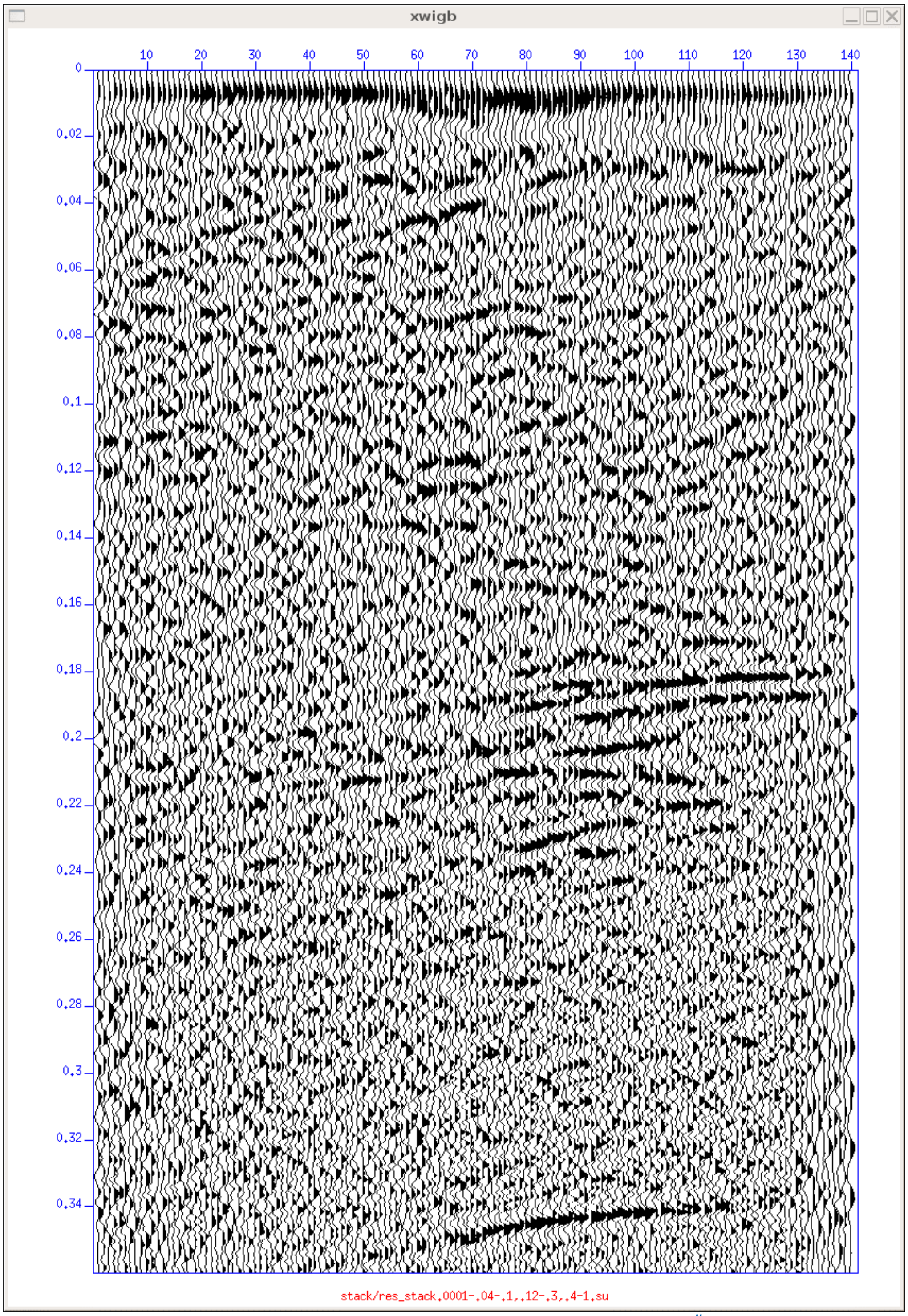

Figure 3-17. Reflection processing of densely acquired geotechnical refraction seismic line (Öhman et al. 2008). Reflections at 0.2 ms time (500 m depth) are distinct. Stack fold is 30, CDP bin 2.5 m. A 3D survey is not so sensitive to direction of tunnel as 2D line, so any direction might be observed. However the area coverage is smaller, and the whole of Olkiluoto island is not covered with 3D seismic surveys. This makes comparison to previous data impossible in part of the area. Detectability considerations of different object sizes at various depths were discussed before survey implementation, using synthetic calculations (Saksa et al. 2007).

Size of a survey area in 2006 was 600 x 650 m. The bin size of 3D stacking in 2006 was 12 m (Juhlin and Cosma 2007) for receiver line interval 60 m and receiver interval 24 m, and source crossline interval 100 m, source interval 10 m. In 2007 another area was measured at slightly modified, larger measurement array (Cosma et al. 2008b). Compared to 2D seismic line, coverage is small but resolution clearly higher (Figure 3-18). A rule of thumb for proper imaging would require three times as long lines as desired depth extent, with high stack fold and dense CDP binning (5 m or denser).

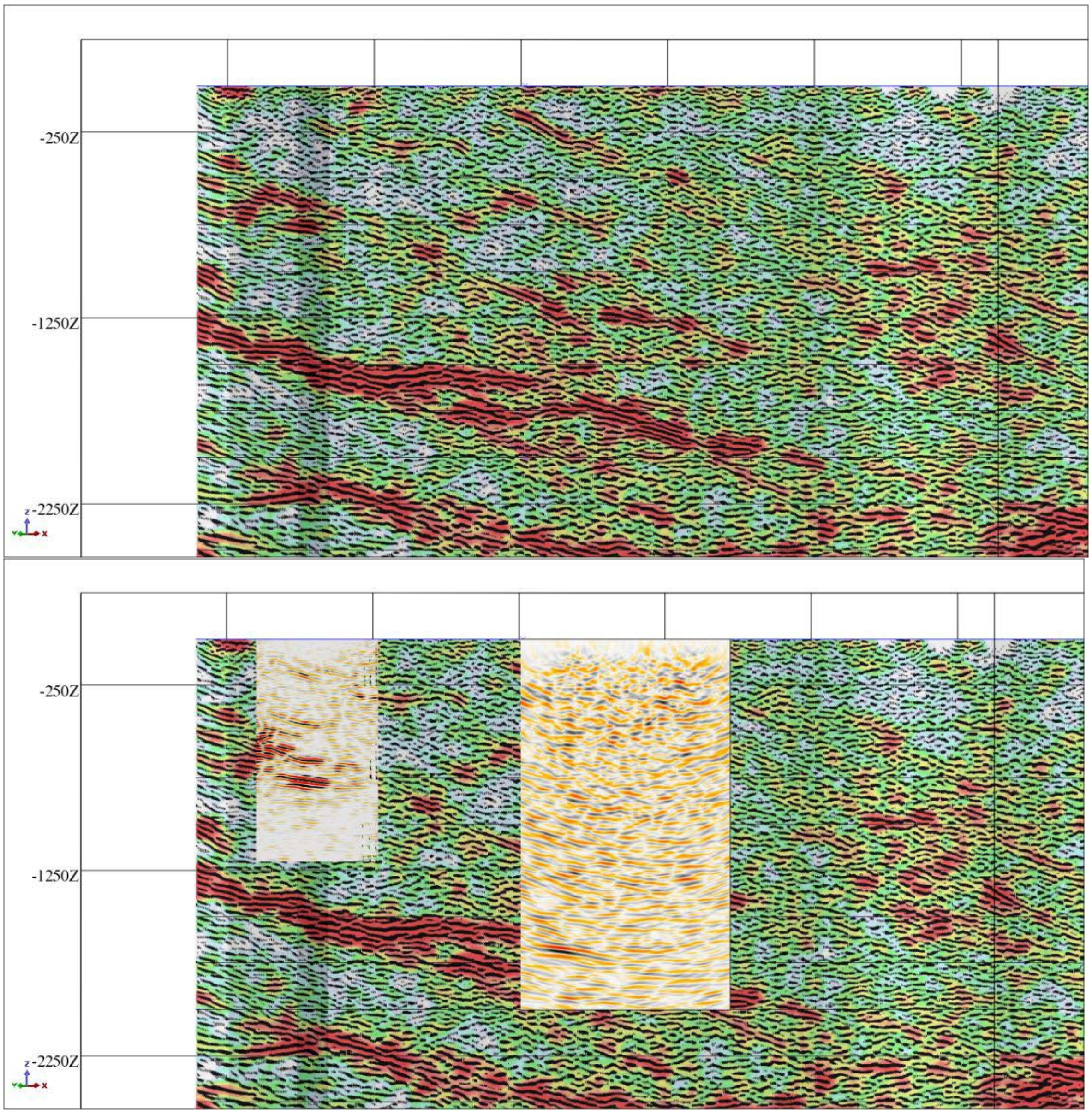

Figure 3-18. Comparison of HIRE 2D seismic data (above, Kukkonen et al. 2010) with 3D seismic results from 2006 (Juhlin and Cosma 2007) and 2007 (Cosma et al. 2008, below). Resolution with denser measurements and different source is significantly higher.

Fold was highly variable. This means that observing a tunnel reflection and separating from the results tunnels which are close to each another, like 20-25 m, may become difficult. In direct observations, features deviating from known tunnel layout may still be checked. Useful would be to make a survey denser, so that bin size would be in order of 2 - 5 m, allowing closer separation. Design of processing so that diffracting events would be imaged best, would be useful. There may be more area limitations for a full 3D survey than for 2D, but this kind of technique would be available even after closure of repository.

A detailed 3D seismic survey was carried out in Forsmark 2016 on a small 320 x 406 m area, with aim to image reflecting events to depth of 500 m from surface (Lundberg et al. 2018, Figure 3-19). Receiver spacing was 4 m on 24 lines, receiver line spacing 14 m. Shots were placed at 16 m interval online, and crossline interval was 14 m. In processing the CDP bin size was 2 m in inline and 7 m in crossline direction. Static correction was based on velocity tomography at 4 x 4 x 2 m cell size. Shallow boreholes were used as control for bedrock depth. Earlier two parallel 2D lines of 300 m in length were surveyed at 2 m geophone and 6 m shot spacing (Brojerdi et al. 2014). Reflection interpretations are focused on the upper 250 m of rock volume. Most interpreted events are found at 60 – 80 m depth level. It may not be likely to detect a tunnel from deeper levels even using these detailed active seismic surveys. A longer line length and designed processing scheme would be required to reach to greater depth.

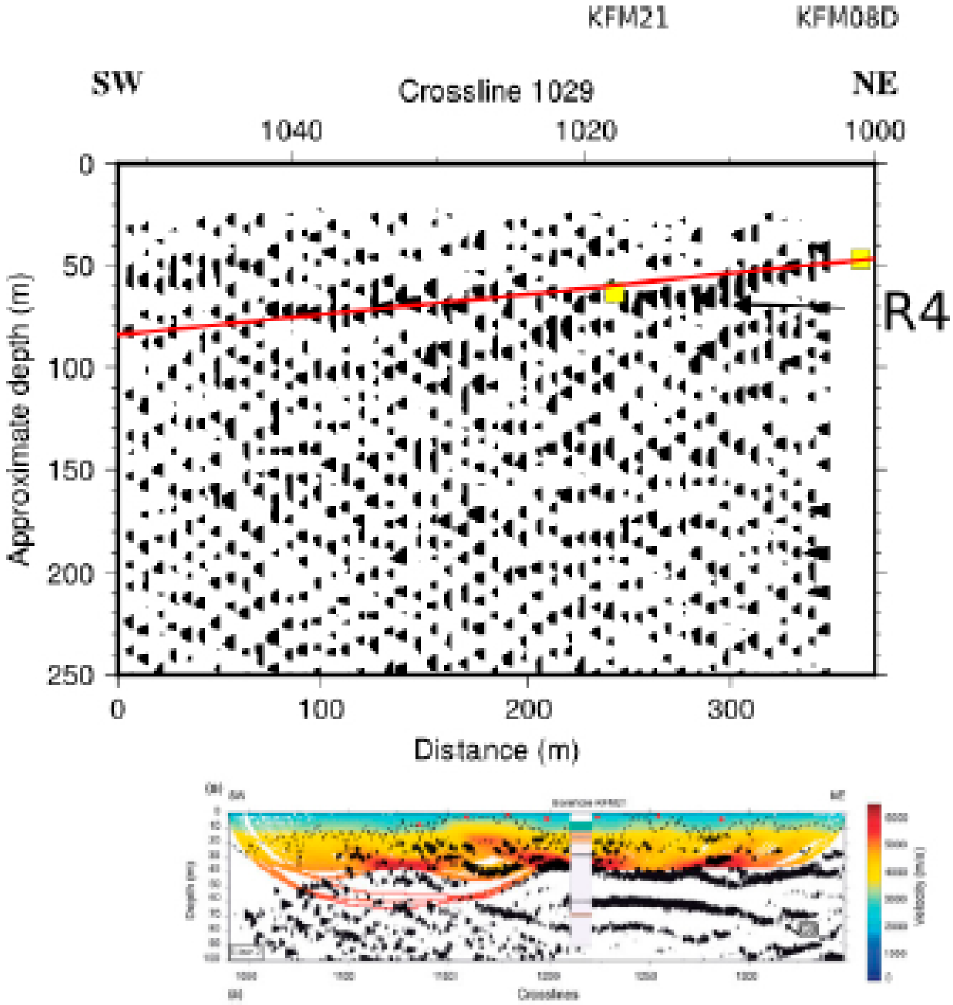

Figure 3-19. Comparison of 3D reflection image (above, Lundberg et al. 2018) using 7 m CDP distance and a 2D line (below, Brojerdi et al. 2014) with 1 m CDP distance, from same location.

Surface to drillhole reflection seismic survey (also called as 3D VSP) can make imaging around drillhole at 100 – 300 m radial distance range (Cosma et al. 2003, Enescu et al. 2007, Figure 3-20). Number of fixed sources is limited. Location of a source will affect to observability. Resolution is higher than with surface array, which need to operate from greater distance, and are affected by near surface effects of attenuation and scattering. Because recording is carried out using 3C geophones, the results are directionally sensitive which would enable localization. Processing using common model from several drillholes, and focusing processing into a limited volume at a time, would further enhance the interpretation (Figure 3-21).

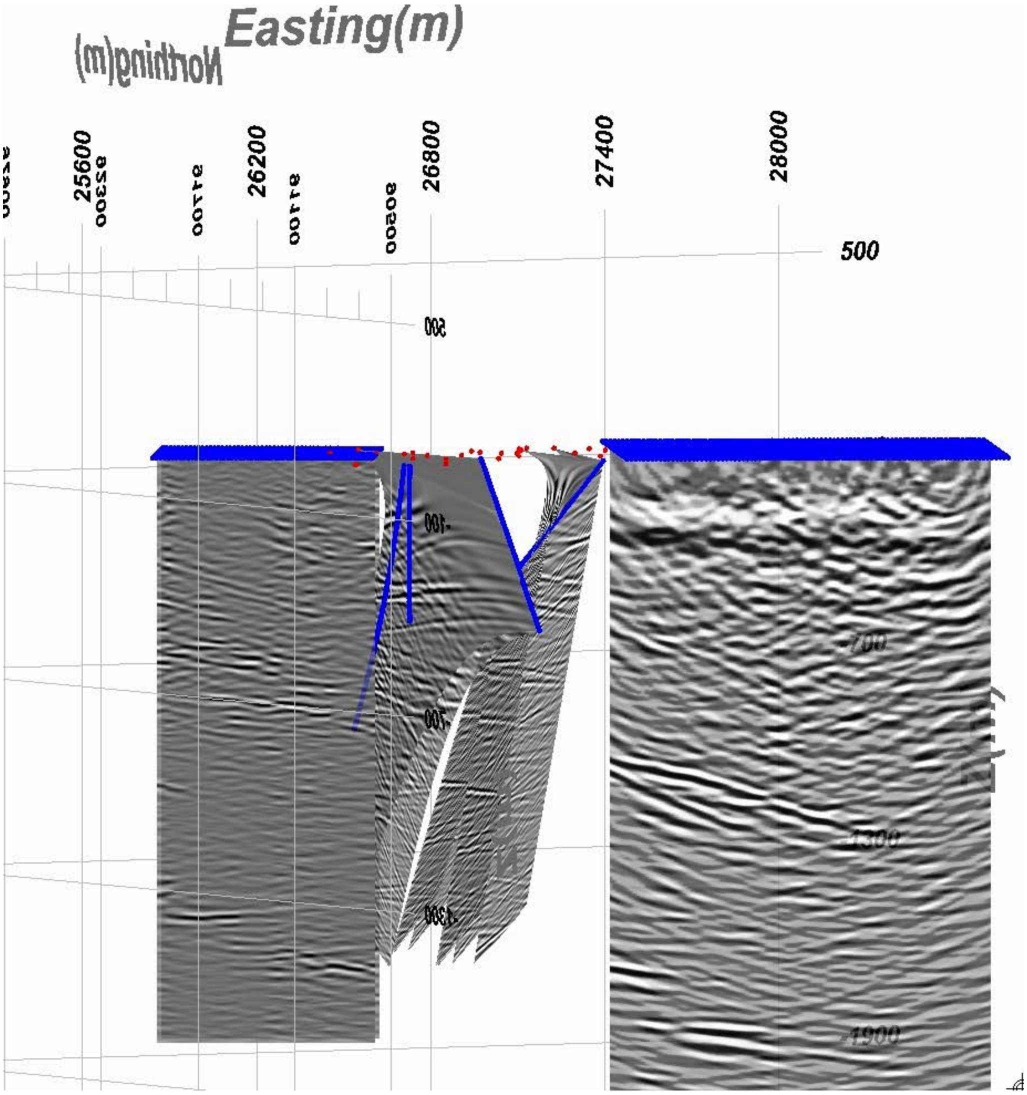

Figure 3-20. Comparison of 2006 seismic 3D results (left, Juhlin and Cosma 2007) with 2007 3D results (Cosma et al. 2008b, right) and to 3D VSP migrated sections (Cosma et al. 2007).

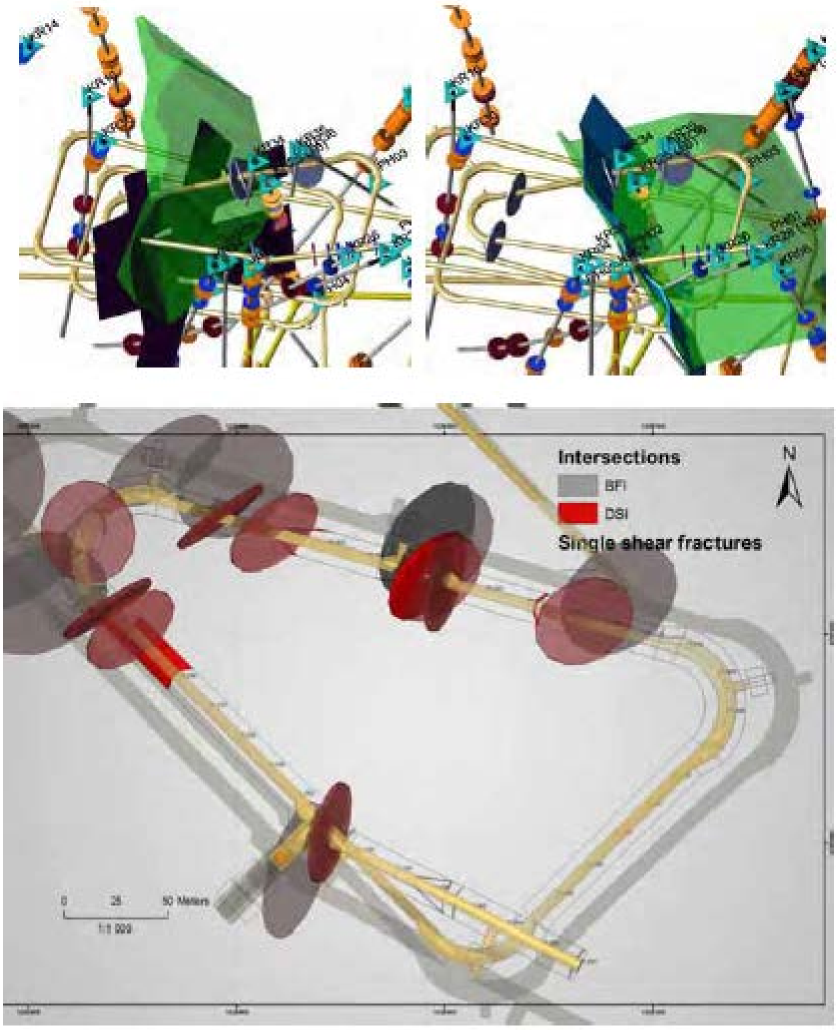

Figure 3-21. Interpretation and verification of tunnel intersecting reflectors from 2005 seismic drillhole 3D VSP survey near ONKALO volume (Enescu et al. 2007).

A variation of the 3D VSP is a moving source seismic profiling (MSP) where a survey can be carried out with fixed receiver station in a drillhole, and densely repeated sources on a ground level line (Enescu et al. 2004). Another variation, horizontal seismic profiling (HSP, Cosma et al. 2003) uses geophone line recording on ground or hydrophone recording on lake or sea bottom, and fixed source points around the survey line at different directions. These surveys are available at limited coverage for comparison and possible repeat surveys. The VSP and MSP would require non-sealed drillholes available for measurements, or permanently installed receivers in sealed drillholes. HSP can be run as a variation of 2D seismic line, with limited number of source stations, which also brings in directional sensitivity.

Two cases of drillhole seismic surveys exist. A single hole reflection survey is a radially sensitive measurement where elastic source is moving along the drillhole with the recording stations. Survey range is, depending on frequency range and power of the source, in order of 50 – 100 m around a drillhole (Figure 3-22). Crosshole seismic tomography can be run between two closely (30 – 200 m apart) located drillholes

(Enescu et al. 2003, 2004). Finding a geological or other explanation for reflecting or diffracting events is a demanding task containing uncertainties (Heikkinen et al. 2004). Comparison of baseline and repeat surveys would be most certain means to obtain positive alarm of potential intrusion attempt.

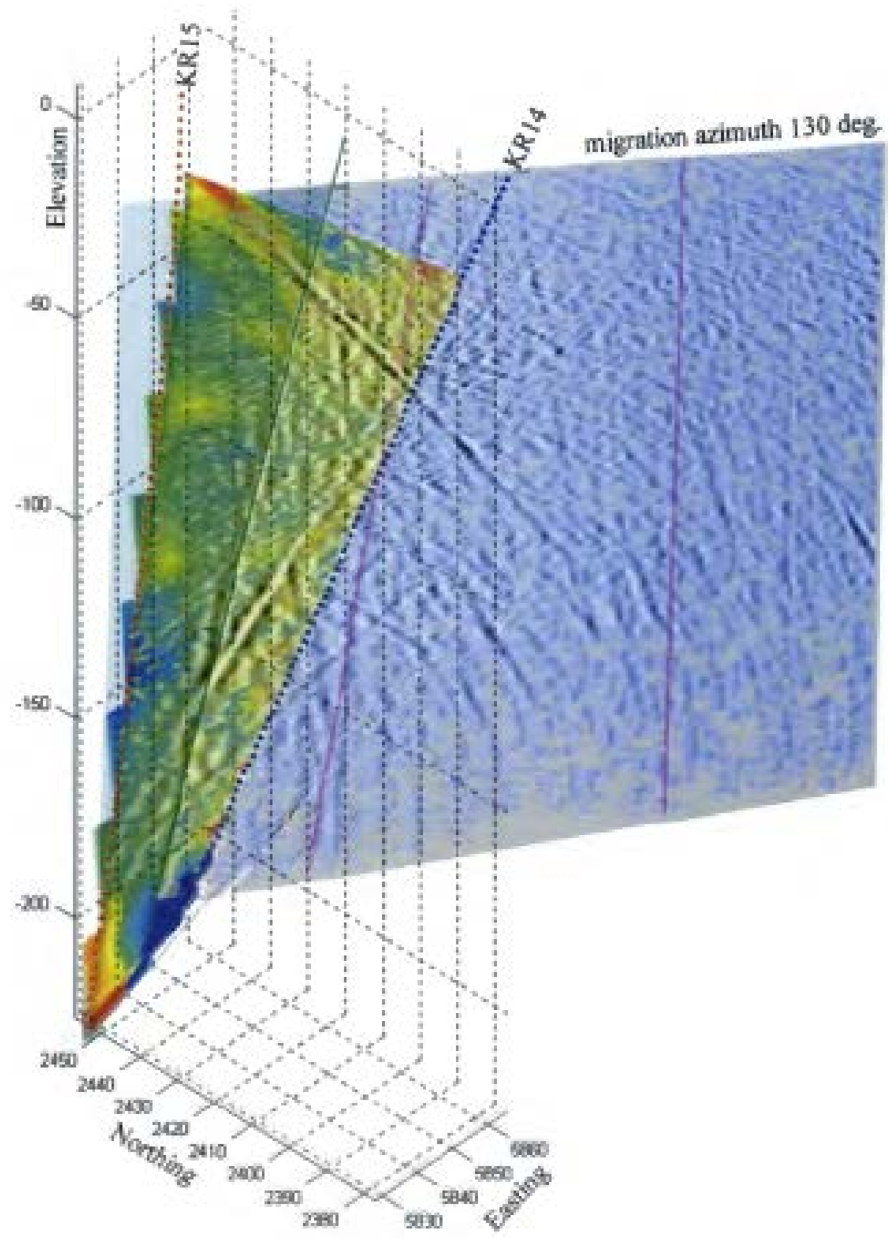

Figure 3-22. Drillhole reflection and crosshole tomographic sections overlain, from drillholes OL-KR14 and OL-KR15 in Olkiluoto (Enescu et al. 2003). Survey can be directional, and is able to provide reflection data to over 100 m from drillhole. Recognition of a tunnel may be most feasible from a shot gather, or require a modified processing scheme, also likely to require comparison between baseline and repeat surveys.

A velocity or attenuation tomogram may be used to image velocity anomalies caused by a tunnel located between the drillholes. Reflection data can be used in indicating the location of a tunnel as a support for tomography. Single hole reflection array can be used also from drillholes drilled from a tunnel, or as a measurement conducted using the tunnel instead. Also, the crosshole tomographic survey can be run between two holes drilled from tunnel, between tunnel and drillhole, or between two tunnel sections. Again, timing of single hole measurements or crosshole measurements is not possible after the drillholes need to be sealed. Also, along tunnel or cross-tunnel surveys must be abandoned after the tunnels would be backfilled and sealed.

Tunnel seismic surveys have ranged from a 100 m long 2D line to a single 3C line of 300 m along tunnel, and two different tunnel and drillhole arrays consisting of several 80 – 200 m long 3C line segments and drillhole intervals.

A single 2-component line, surveyed in 2007, was viewing on the side of the tunnel and downwards to 100 – 150 m from the tunnel (Figure 3-23). Purpose was to resolve location of continuous fractures and local fracture zones. A 2C receiver configuration left possibility to resolve the location of reflectors either towards horizontal, inclined, or vertical plane. Both P and S wave migrates sections were produced. Percussion drilling was demonstrated a feasible seismic source. Survey with preparations took five working days. Receiver stations were attached into shallow drillholes on the tunnel wall (Cosma et al. 2008a).

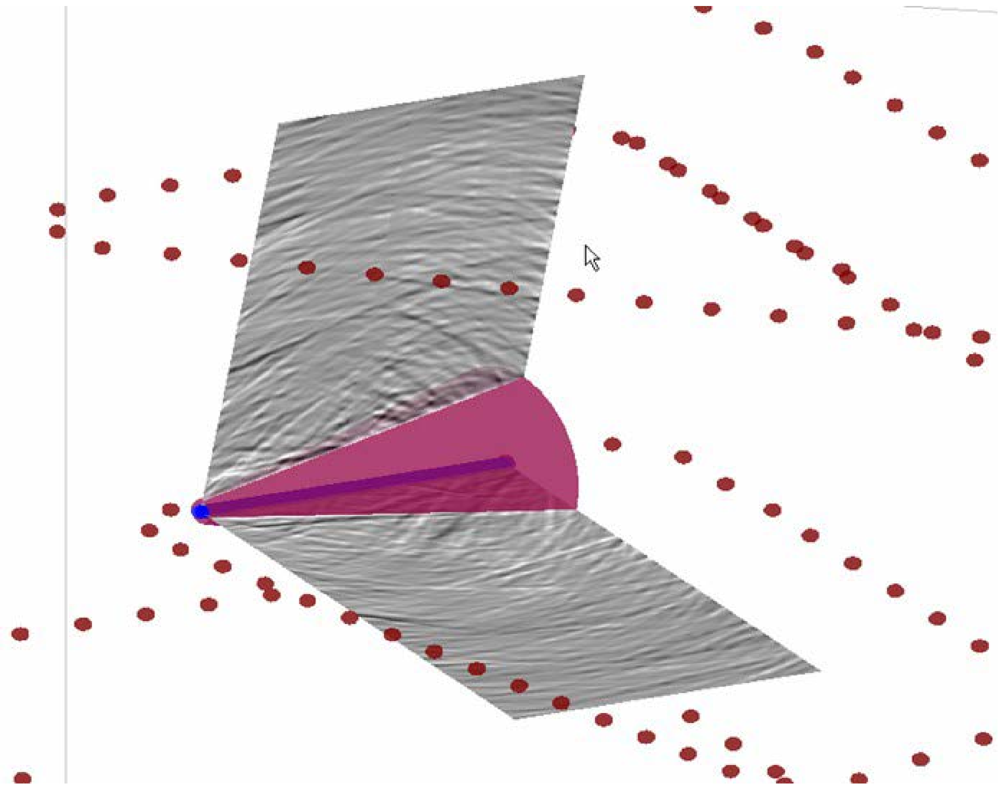

Figure 3-23. Tunnel seismic sections measured in Olkiluoto 2007 (Cosma et al. 2008a).

A single 3-component receiver line of 300 m, surveyed in 2009 produced several inclined sections of migrated P and S wave reflection images, reaching to 250 m from tunnel, and placed at 15 degrees angle intervals from vertical up to vertical down

(Cosma et al. 2011, Sireni 2011, Sireni et al. 2011). Survey took 8 – 10 days in the field. Receivers were attached in percussion drilled shallow holes in the tunnel wall. Results indicate a remarkably high resolution. Similar reflection measurements have been used also earlier to produce information from fractures and nearby tunnels (Figure 3-24, Blümling et al. 1990).

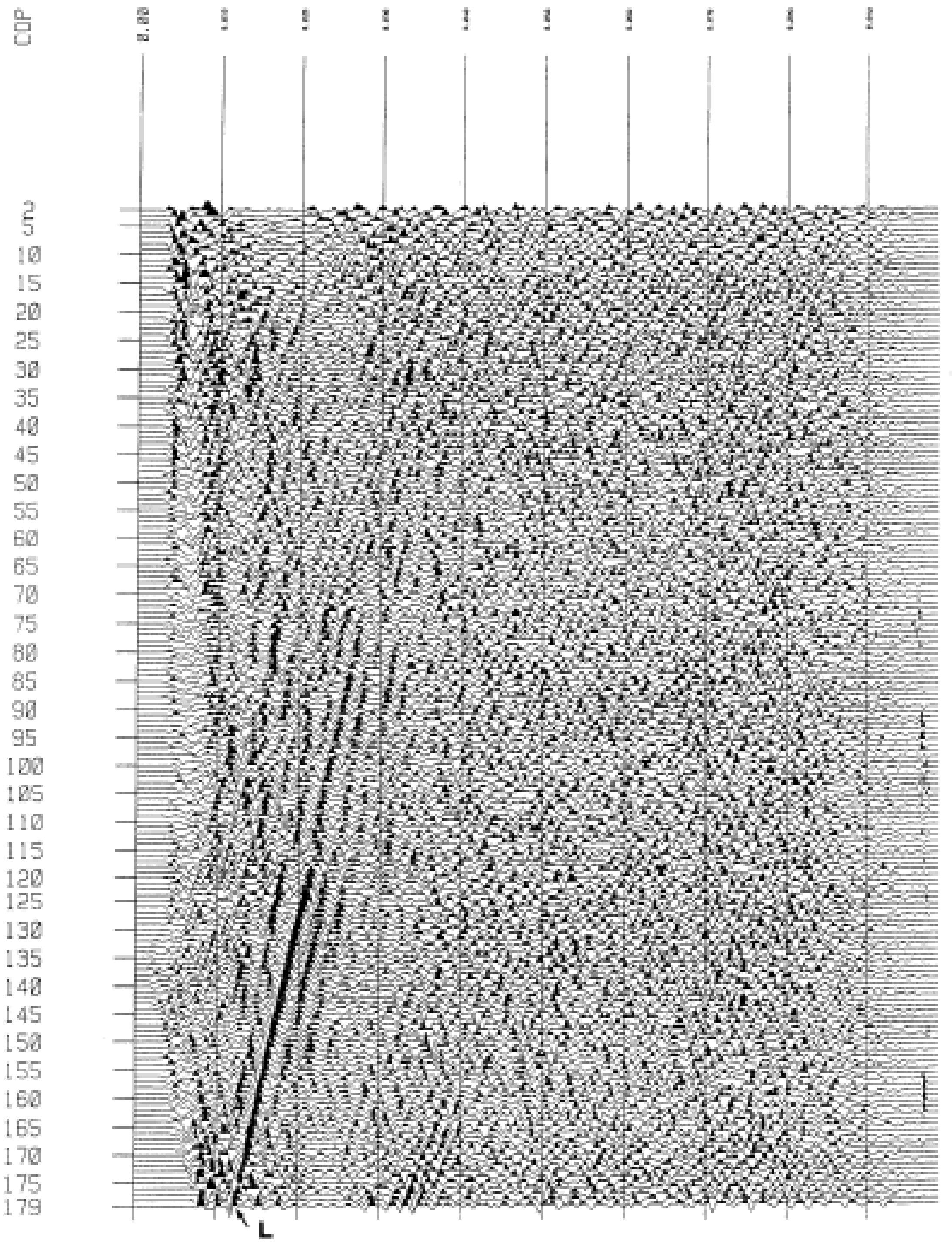

Figure 3-24. Stacked tunnel seismic data showing a clear reflection from other tunnel (shown with "L"), from Blümling et al. (1990).

Higher frequency (100 kHz) crosshole and single hole seismic surveys were conducted at excavation damage zone (EDZ) study niche (Enescu and Cosma 2010). A drillhole profile along length of planned niche (short tunnel section) was surveyed from drillholes at 2 m separation, 50 m long, before excavation with crosshole tomographic and reflection survey, and repeated at tunnel contour between tunnel wall and remaining drillhole. Clear indication of lowered velocity near tunnel, and fracture caused reflections near the tunnel surface, as well as the surface itself, were detected from the results (Figure 3-25). Another, tomographic survey was carried out on tunnel floor in pairs of 1.3 m deep vertical drillholes. Velocity tomograms indicated lowered velocity zone on the tunnel surfaces, related to stress field release and generation of some new fractures on the tunnel surface (EDZ). The 100 kHz surveys are capable in detecting small scale variation and changes due to excavation, but the range is limited to few meters.

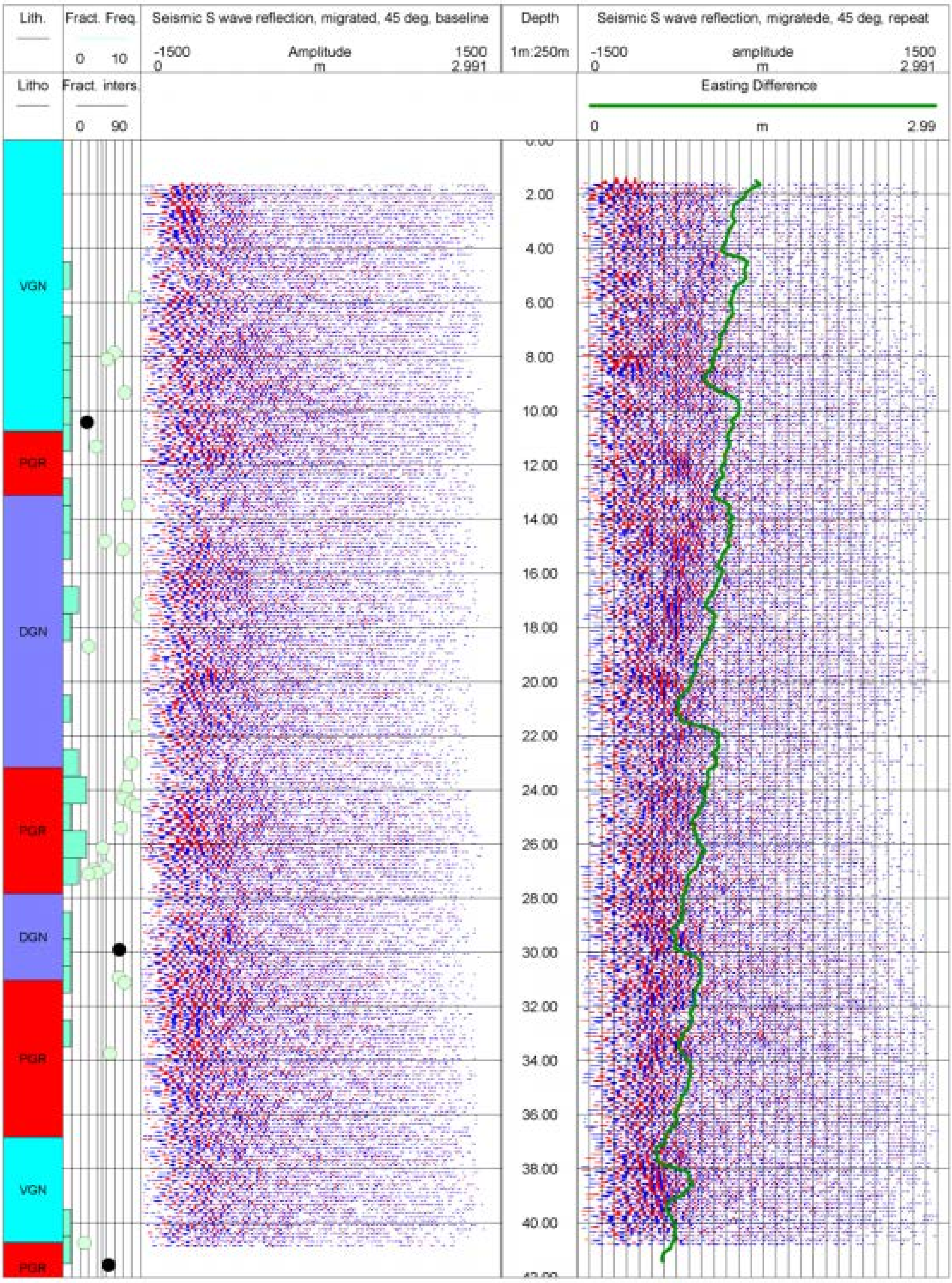

Figure 3-25. Baseline (left) and repeat (right) directional single hole S wave reflection survey from drillhole ONK-PP200 on the side of investigation niche ONK-TKU-3620, showing a tunnel wall near the observation hole (Enescu and Cosma, 2010, Mustonen et al. 2010). Full distance scale 3 m. Before excavation, the local reflections are caused by lithological contacts, fractures, and fracture zones. Tunnel perimeter is shown on green line. Fractures are focused onto the tunnel surface, which itself is also reflecting.

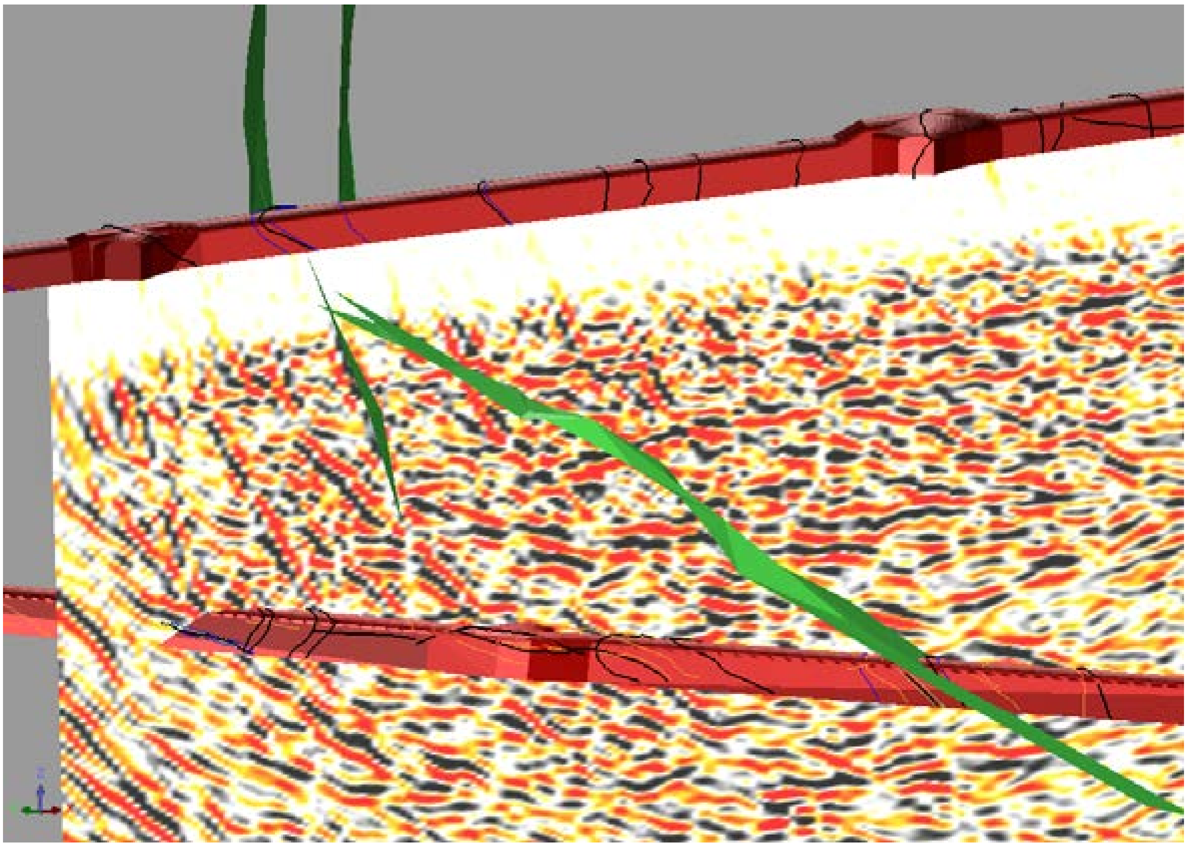

Figure 3-26. Migrated seismic image attached on ONKALO tunnel, survey 2009 (Cosma et al. 2011, Sireni 2011). Resolution is high. Migrated sections can be projected towards different azimuth around the tunnel.

Two different seismic reflection works included 2-component receivers on tunnel wall, seismic source on tunnel wall and in drillholes, and several P and S wave migrated reflection profiles, imaging the bedrock around the study area in horizontal plane towards different directions (Figure 3-26, Figure 3-28) and distances of 150 m (Cosma and Enescu 2014, 2015, Enescu et al. 2014). Processing included some cross tunnel, drillhole to tunnel, and crosshole tomographic sections (Figure 3-29).

One survey was carried out for SKB in Oskarshamn Äspö underground research laboratory (Figure 3-27). The other was taken in ONKALO at demonstration area tunnels and pilot holes. Purpose of the surveys was to develop techniques to detect fracture zones and extensive fractures from tunnels and drillholes prior to excavation, and to define extension length of observed fractures. Comparing the different geophysical measurements from same tunnel section indicate that seismic reflection survey has greatest range and detection power from available methods (Figure 3-13, Figure 3-30 and Figure 3-40). Investigations designed for fracture zone characterization would need to modify to detect a tunnel.

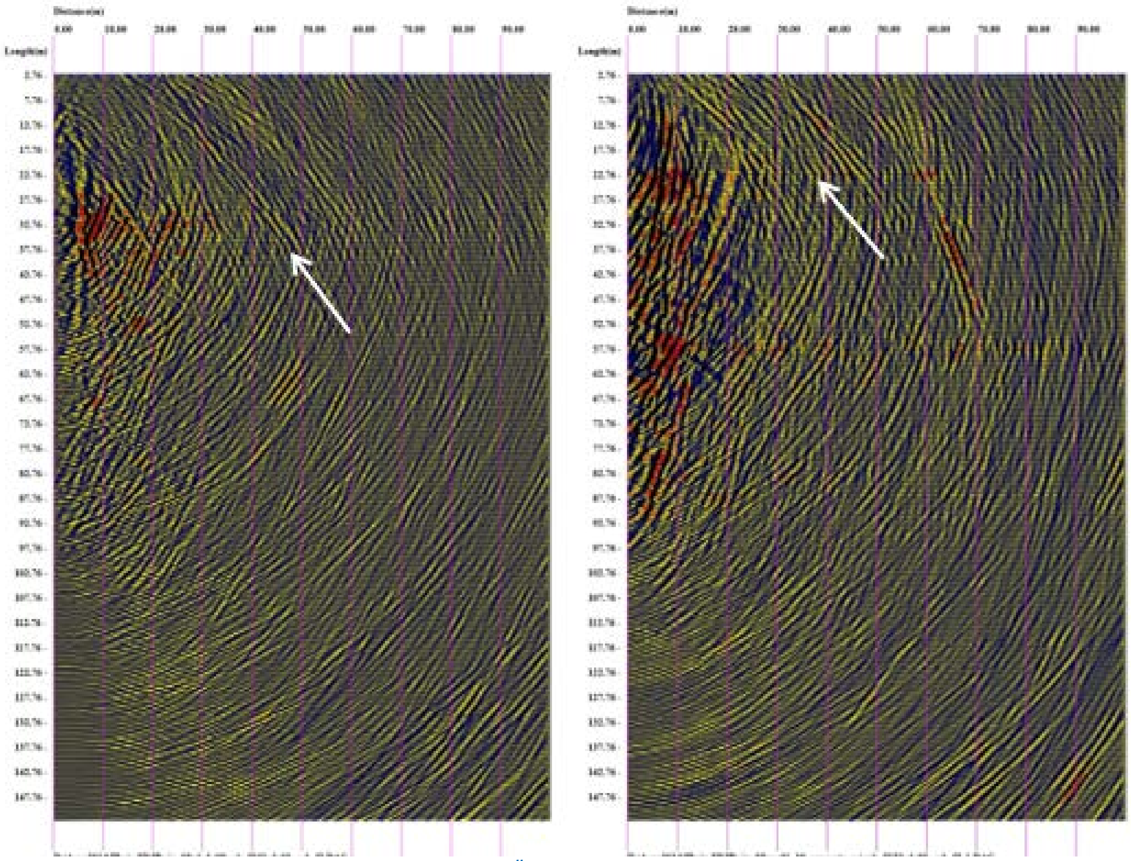

Figure 3-27. Cross tunnel reflection measurement in Äspö 2014 (Cosma and Enescu 2014). White arrow indicates reflection from other tunnel.

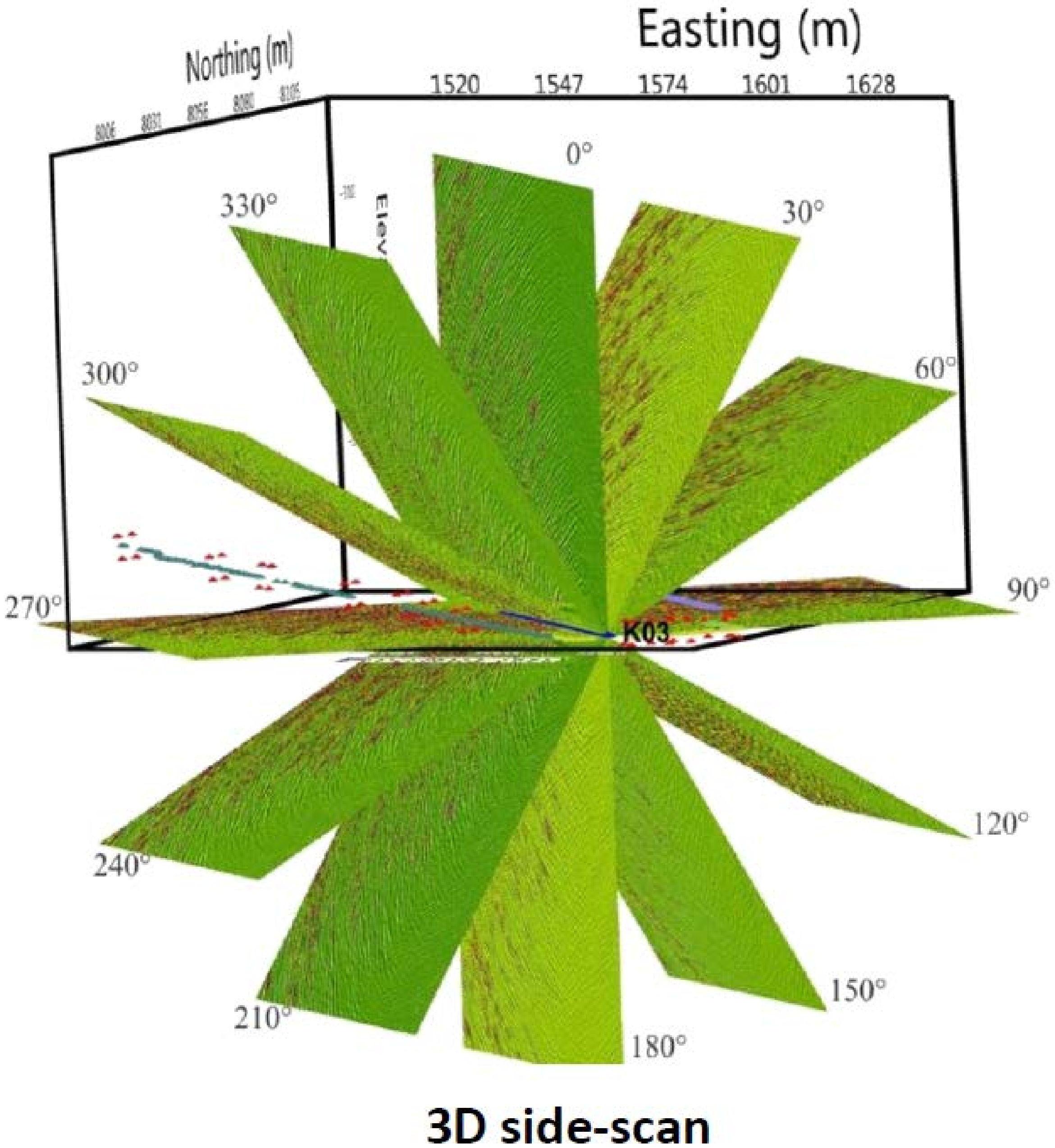

Figure 3-28. Side scan 3D seismic survey from a tunnel (Cosma and Enescu 2015). Directional imaging can be obtained with multicomponent receivers and using several source station lines within the investigation volume.

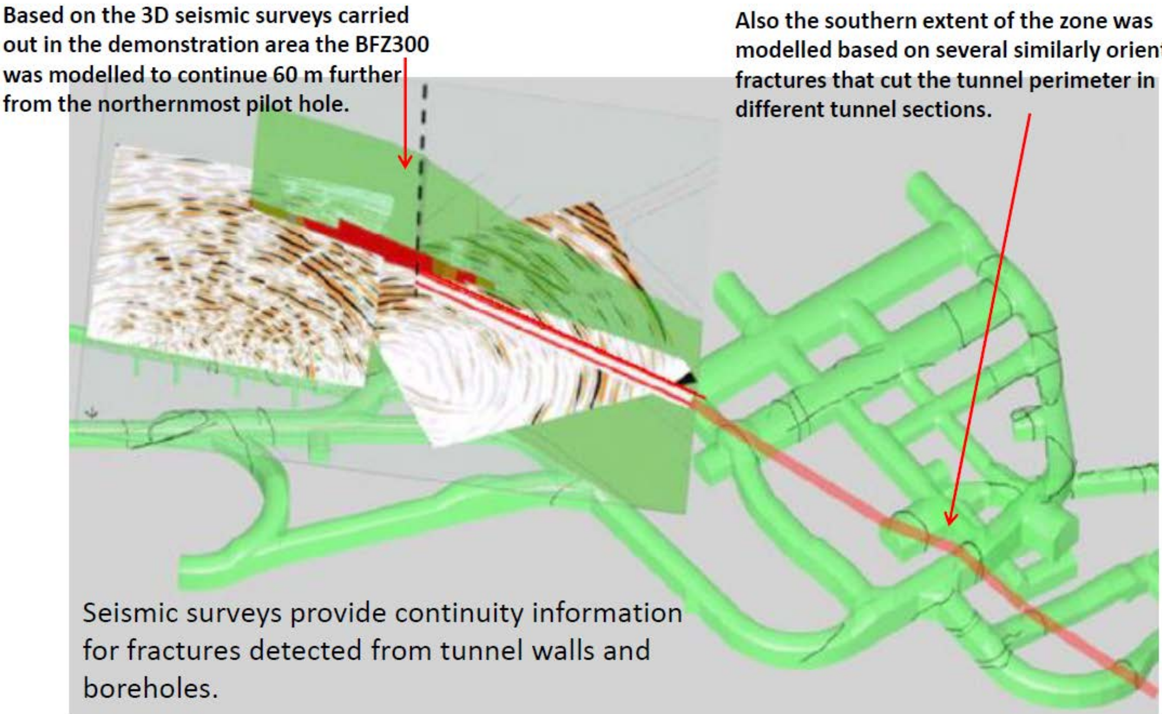

Figure 3-29. A directional seismic 3D reflection survey from tunnel may be applied in detection of undeclared excavation at 100-150 m distances (Cosma and Enescu 2015). Repeat survey to compare baseline, and specialized processing method to enhance small object detectability, would be needed.

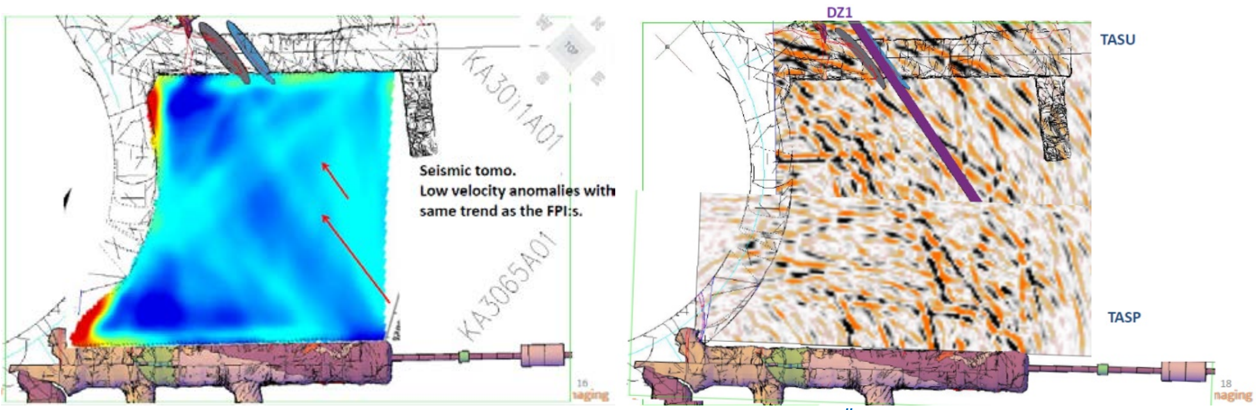

Figure 3-30. Comparison of tunnel seismic investigations from same location in Äspö Hard Rock Laboratory. left seismic crosshole/cross tunnel tomography and lower right seismic reflection survey.

Surveys were preceded by numerical synthetic modeling of tunnel wave suppression and processing, and optimal observability of fractures in reflection images, as well as for design of processing techniques. Modeling indicated that strong surface waves are generated on tunnel surface, intersecting fractures, and lithological contacts on tunnel surface, and ends of tunnels. To suppress the tunnel wave in survey, the receivers were placed and cemented in 0.5 m deep drillholes. Further measures were taken to process data to avoid tunnel wave caused ringing in migrated sections. Optimal receiver and source distances, and processing steps, were defined on basis of modeling, which were intended for detection of continuous linear features (fractures), their orientation, and termination. Processing included oriented migration to enhance one orientation set of reflectors at a time. Similar designed processing for detection and localization of tunnel generated diffraction events might be useful in designing safeguards monitoring, as a normal seismic processing method would suppress the diffractors from being seen in the results.

3.2.2 Development in seismic survey techniques

Forward to tunnel seismic techniques with sparse seismic source and receiver arrangement have been advised by Nagra 1990 (Blümling et al. 1990), and applied for tunnel construction surveys either with conventional seismic recording (Krüger et al. 2010, Figure 3-31) or correlating recorded TBM signal (Chwatal et al. 2011, Figure 3-32).

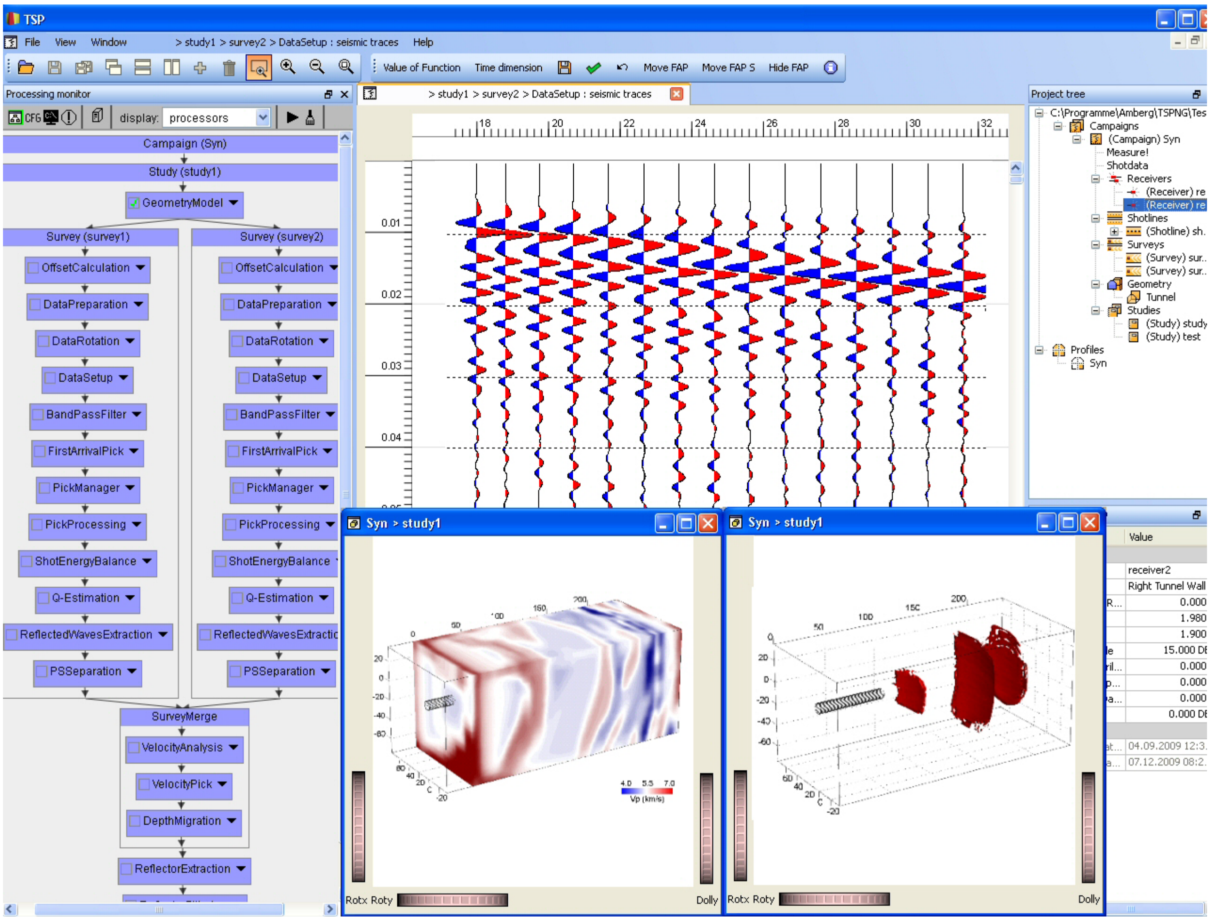

Figure 3-31. Tunnel Seismic Profiling (TSP) procedure by Amberg (Krüger et al 2010). Limited seismic recording near tunnel face is carried out during excavation break.

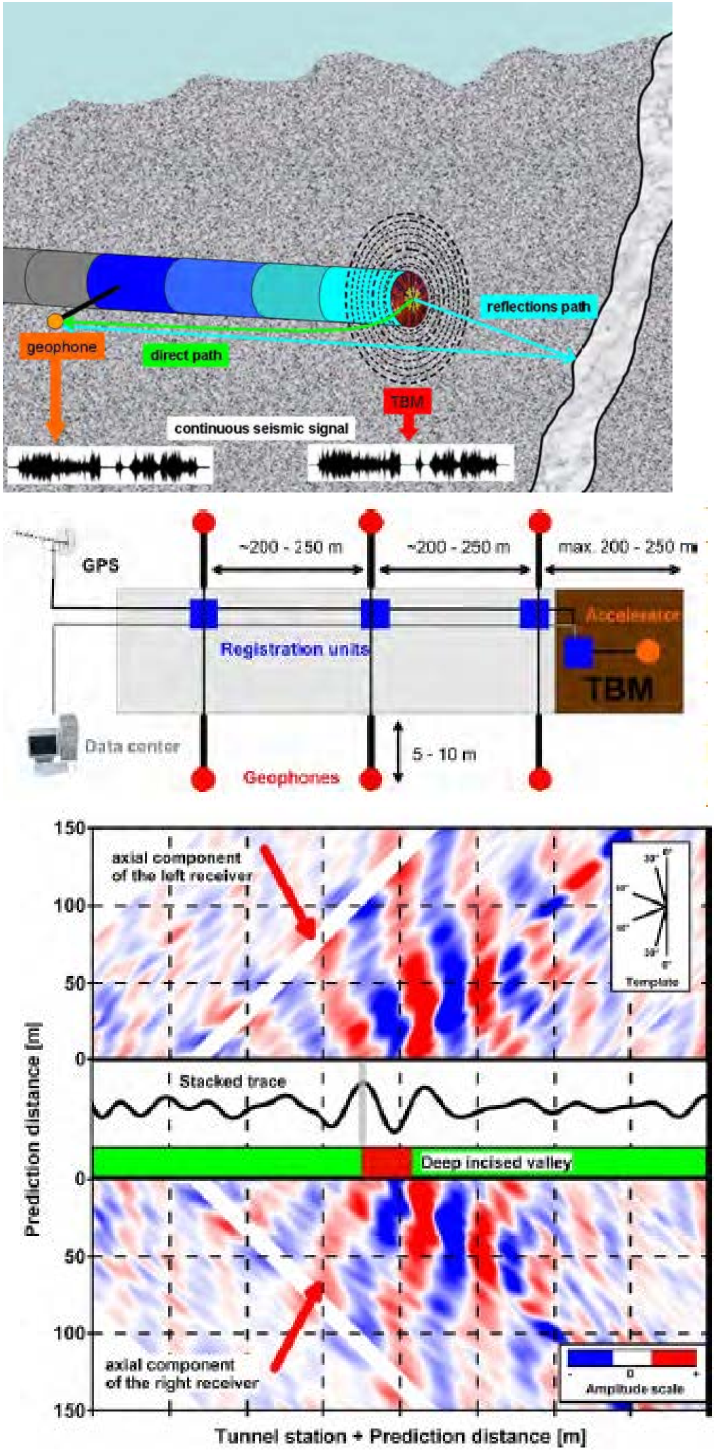

Figure 3-32. TBM signal recording using 3C geophone stations in shallow (5-10 m) drillholes maximum 100-150 m in front of a tunnel face. TBM pilot signal recorded from boring machine is correlated to geophone recording to produce seismic reflection data, processed further to imaging (Chwatal et al. 2011). Survey is repeated at 200-250 m interval. Baseline survey could be produced using tunnel excavation as a source, then a repeat survey carried out using similar array to ensure absence of deviatory activities.

Ideas range from placing receivers onto tunnel wall, tunnel floor, or in short drillholes on the tunnel surface; and using either small explosives, mechanical source, tunnel boring machine (TBM) noise (Chwatal et al. 2011), or other, as a source either on tunnel wall, on drillholes drilled to the side of the tunnel, or the TBM face as the tool penetrates through the rock. Recording of seismic sections is carried out at frequent intervals (daily/weekly), and processed in a standardized manner at fast pace to determine location and orientation of fracture zones in the front of the tunnel, to distances of 100 – 150 m. This kind of survey approach may well be used also for safeguards checking from tunnel surfaces until the tunnels are open (not backfilled).

Some practical conditions may be required for tunnel seismic survey. Simply mounting receivers on tunnel surface or macadam bed on floor, and using explosive, impact, or vibrating source on same surface, is likely to cause severe ringing in recorded data, called tunnel wave. Suppression of tunnel wave will require either the sources or receivers placed away from the tunnel surface. Distance could range from 1 – 3 m. Survey can be organized in a reciprocal manner. Either it is possible to use standard 24 or 48 channel seismograph or equaling tool system, mounting geophones or accelerometers on the tunnel surface, and applying several sources at different directions and lengths along the receiver line. Or, mounting several multicomponent receivers in different directions and length along a source line, which would be implemented either as TBM locations, drill and blast excavation blasting or probing hole percussion signal, or purpose made source stations along the tunnel surfaces. Critical is to have several, separated tunnel seismic profiles either as a single receiver-multiple sources, or single source-multiple receiver gathers. Result would be a combination of different migrated sections, where energy is stacked onto locations where reflectors reside.

Optimal seismic survey to detect 3-10 m size of tunnel like objects from distance, may consist of 100-1000 Hz frequency, and either dense receiver or dense source lines, with selected number or sources or receivers to produce seismic profiles for spatial 3D migration. Seismic survey has also potential to detect possible empty spaces behind a tunnel wall or tunnel lining.

Recent development in seismic acquisition techniques (Koivisto et al. 2018) have included using sparse active source arrays (Singh et al. 2019), combination of surface and borehole or tunnel measurement arrays to enhance directionality and resolution, and application of passive recording systems of ambient noise from different types of source signal (Afonin et al. 2018, Chamarczuk et al. 2018), or using fibre optic sensors (DAS, Distributed Acoustic Sensing) for simultaneous dense recording of a complete drillhole at a time (Riedel et al. 2018), or wireless sensors to provide dense and cost effective recording in poorly accessible conditions (Heinonen et al. 2018). Enhancement of processing may also include interferometry to correlate signal in receivers to create dense virtual sources (Figure 3-33, Väkevä et al. 2018a, b, Väkevä 2019, Chamarczuk et al. 2018), for better and higher resolution imaging. Combination of the new active and passive or monitoring methods could provide possibility for both design information verification and post closure detection of undeclared tunnels (Figure 3-35). Permanently installed borehole DAS receiver (Figure 3-34), repeated recording of ambient noise with interferometric processing, and frequently repeated active sources on ground surface may enable high resolution for safeguards monitoring.

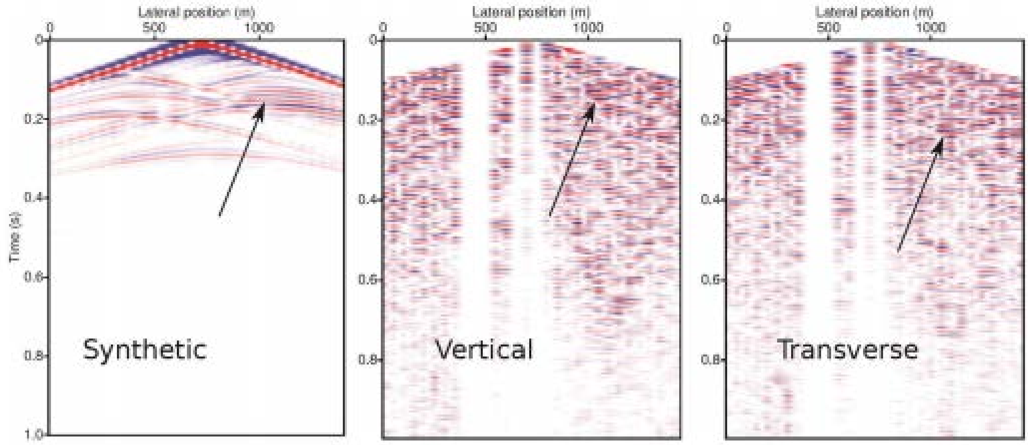

Figure 3-33. Passive seismic recordings with virtual sources processed by interferometry (Väkevä et al. 2018), left active synthetic shot gather, real data middle vertical (P/SV) and right transverse (SH) wave field processed from one day noise recording (45 3C seismometers).

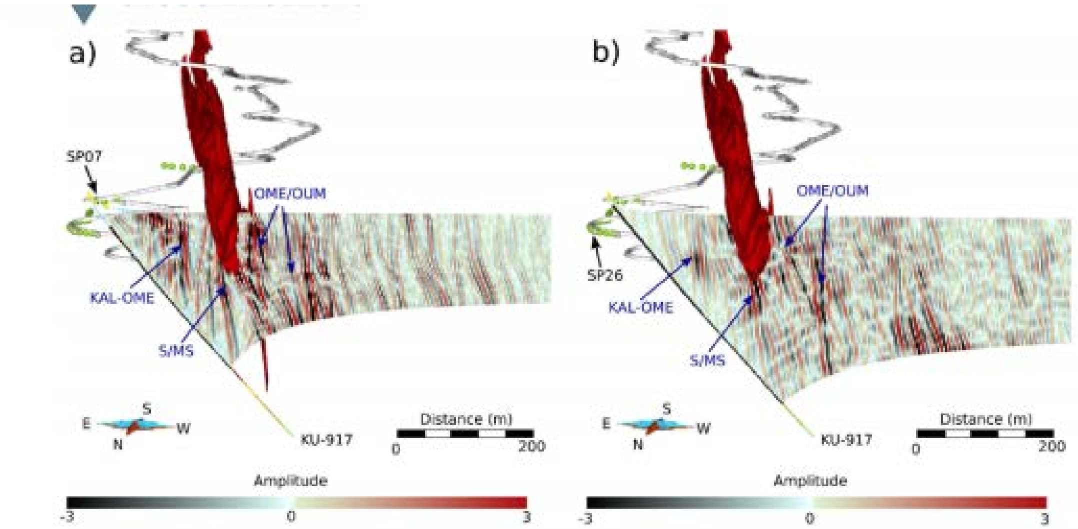

Figure 3-34. Comparison of 3C VSP recording with conventional borehole receivers (left) and DAS optical fibre receiver in same drillhole, different source position (Riedel et al. 2018). DAS provides opportunity to make recording at once for all receiver locations, whereas traditional survey requires moving sensors and repeating shots. DAS includes only one component, traditional survey can provide three-component recording, enabling better visibility of reflectors in different direction. DAS can be installed as a permanent recording system.

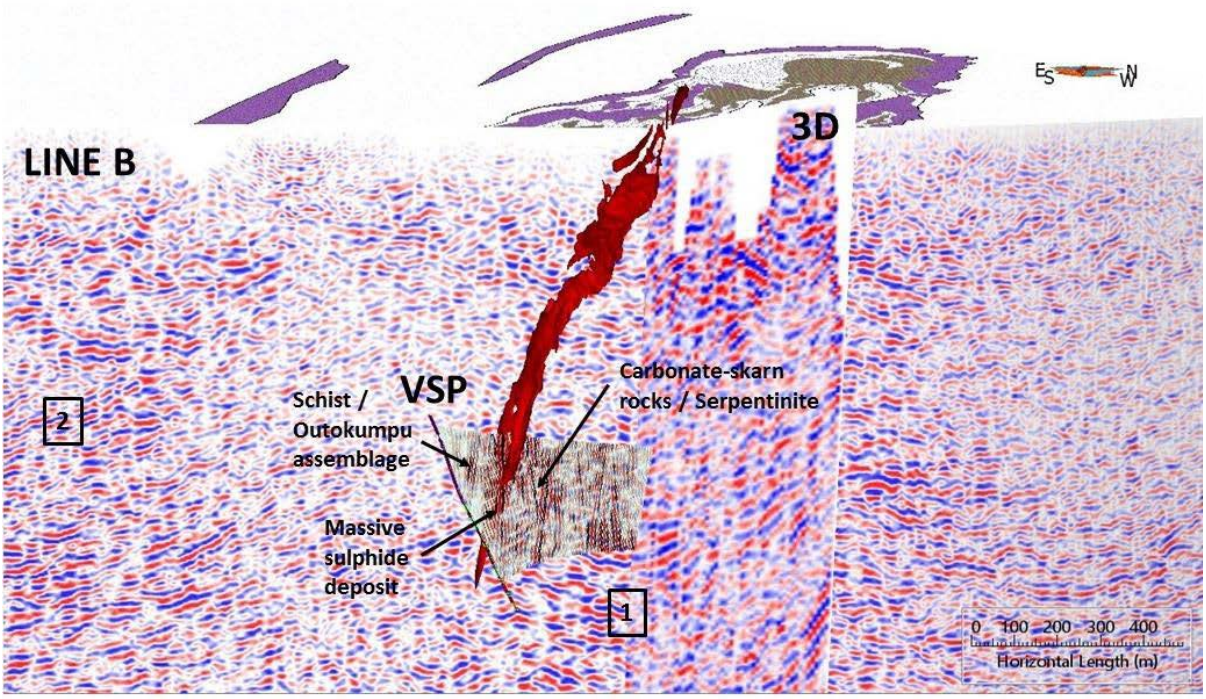

Figure 3-35. A composite of seismic imaging at different scales and geometries, combining dense passive seismic recording, sparsely applied Vibroseis sources, tunnel seismic recording, and borehole DAS recording into subsurface imaging in mining environment (Koivisto et al. 2018).

Surrounded by sea areas, the Olkiluoto area would be favourable for higher production rate and better coupling of seismic signal using underwater array for acquisition. An acoustic seismic survey (Alvi and Virtasalo 2016) can be used in definition of soil thickness and soil types, bedrock topography and fracture zone ground interception data. A hydrophone streamer and towed seismic source would enable efficient high-resolution survey on seabed.

3.3 Electrical measurements

Electrical resistivity methods are based on measurement of variation of specific resistivity (inverse of electrical conductivity) in subsurface. Direct current or low frequency alternating current is generating an electric field in the ground, where the measurable voltage is proportional to source current intensity, inverse distance from the source, and resistivity of material.

It has been considered for nuclear safeguards that resistivity survey can be used for locating the metal canisters or waste containers (Finch 2009). Also, metallic tunnel support structures could be observed. Passive detection of electrical fields may enable detection of undeclared activities (machinery, power feed).

The resistivity in natural materials has broad range of variation. Silicate and quartz containing minerals are highly resistive (insulators). Pure groundwater as itself is weakly conductive (low resistivity). Increase in electrolyte content is further lowering the resistivity of water. Groundwater content due to porous space and fractures is lowering the resistivity of the bulk rock mass.

Presence of electrically conductive minerals within rock mass or on fracture surfaces are lowering the resistivity to further extent. Weakly conductive minerals include different clay materials due to their texture and water content. Higher conductivity is found in metal sulphides and graphite. Apart of occurrence of water and conductive minerals, also texture in rock mass is affecting to the resistivity.

Regarding the constructed tunnel environment, application of resistivity methods would be based on resistivity contrast of the tunnel and the surrounding rock mass. In purpose of detect air or water filled cavities from ground surface using resistivity measurement, elevated or lowered resistivity has been applied as an indicator of a cavity. A high resistivity air filled cavity is more difficult to observe from background, than any conductive material containing object from resistive background mass. Tunnel may be detected with resistivity measurement due to metal containing support structures or installations, which will be lowering the resistivity.

Electrical resistivity measurement requires a galvanic connection to the investigated medium. Two electrodes at a time are used to inject a short pulse of electric current into the medium. Polarity of the current pulse is alternated to suppress polarization effects in the medium and electrodes.

Amplitude of the pulse, and distance of the electrodes, will define the form and intensity of generated electric field. In case the second (return current) electrode is effectively at great distance from the target, symmetric field of an electric pole source is generated. Shorter distances between the two electrodes are handled as dipole source.

The voltage difference (potential) generated by the current pulse (compared to the off-injection time) is measured synchronized with the current pulses, using two other electrodes at a time than the current circuit electrodes. The primary measurement data is a resistance value, voltage difference divided by the current difference. This is converted to apparent resistivity of surrounding material by using a geometric coefficient, which is depending on mutual distances of each of the four involved current and potential electrodes. Also, the voltage transient decay after closing the current injection can be measured to describe the so-called induced polarization effect, where electrolyte content, grain size of medium, texture, and presence of electrically conductive minerals is causing a transient electrical field.

One measurement station contains influence of the complete spherical volume surrounding the measurement system, from a distance proportional to the size of the current injection dipole.

To carry electrical resistivity imaging in the subsurface, a set of repeated measurements need to be carried out. Multiple opportunities for geometries exist. A resistivity profiling is using a fixed length of current injection dipole, joined with a fixed length of a voltage measurement dipole, placed at a constant location and distance from each other. The complete measurement system would move on a line, to provide profile display of variation in resistivity. Length of the electrode system would define the range of investigation (typically, 15-20 % of maximum length of the array). Profiling can be carried out also keeping the current sources at permanent position (further away from the target area) and measuring profile of the voltage with moving measurement dipole.

Electrical resistivity sounding at an individual location would consist of a series of expanded current injection arrays, centered on the measurement station, and measuring the voltage at the same location. Increasing the size of the array will be increasing the range of investigation, though at the cost of lowering resolution with increasing distances. Multiply repeated measurement stations on a profile, or on a surface area, are producing a resistivity imaging ("tomography") profile, which can be used for detecting a resistivity low or resistivity high targets from surrounding volume. The effective range where an object can be detected, is defined by the size of the measurement array, and the size of the objects which can be detected, is defined by distances between measurement stations, the closest distances between pair of current electrodes and distances between the pair of measurement electrodes. Size of an object comparable to a tunnel of 5 m in cross section, would require distances between electrodes to be in order, or less than, the distance of 5 m. A measurement system may be able to detect a tunnel containing conductive materials to distances of 20-30 m from the measurement line in favourable conditions in resistive environment.

Measurements can be carried out also along a drillhole or a tunnel with radial symmetry. In a tunnel, measurement systems with size less than 2 - 3 times of the tunnel diameter can be used as directional. Longer arrays start to become viewing radially to all directions. Survey can be carried out also between two closely located drillholes or tunnel sections as a crosshole (tomographic) survey, imaging objects located between the survey drillholes or tunnels. Measurement can be carried out also with grounding a current electrode to a conductive body and measuring the electrical field generated by this body as an object (mise-á-la-masse survey), locating the presence and continuity of the grounded object by the shape of modified electric potential field.

Measurement is carried out by a computerized resistivity meter, containing either separate or integrated current transmitter and a voltage receiver tool. Most efficient manner to carry out a resistivity survey is to apply a multiple electrode cable array, where the receiver is changing the current injection positions one by one, and measuring meanwhile all relevant voltage recording stations, either one at a time, or up to 10 at single recording. Electrode positions in a cable can vary from 32…40 connectors to 80-100, or even more. A composite of such recordings would be presented as apparent resistivity pseudo-section, according to length and depth (or distance) from measurement line. An inversion processing would be used to carry imaging into a resistivity length and depth (or distance) section, where the correct resistivity parameter values are imaged at their actual location. Further interpretation may be possible by carrying out forward modeling with synthetic model computing, and comparing the measured data and inversion computed images with corresponding results obtained with the model, then changing the models until reasonable match would be obtained.

Measurement and inversion can be carried out on a profile in 2D, where objects are assumed to be located on below the measurement system, and side effects may interfere with the result. Optimal observation of a target would require location of a measurement line right at the location for limited size of an object, and near perpendicular to an elongated object. A target parallel to the measurement line would be harder to detect and understood as a planar (layer like) object.

There is usually found plenty of natural causes of anomalous resistivity objects which can be masking the anticipated observation of a tunnel. To avoid or suppress possibility of false positive alarm, and to enhance possibility to detect weak indications, a repeat survey using same measurement array several times at same location, might become useful application technique. Survey could be used in indicating the presence (or absence) of significantly changed electrical conductivity near the existing (and accessible) tunnels. Survey may be able to detect some indications of spent fuel canisters located on a neighbouring tunnel at 20 m distance but is not capable to indicate absence of a capsule at its expected location.

Typical measurement time on a ground or tunnel surface, for a 80-100 electrode cable array would consist of 2 hours of recording. One of a cable spread like this could cover a 400-500 m of tunnel length in a general, geotechnical application of 5 m electrode spacing, imaging to distance of 30-50 m from the survey line. Extension of a survey moving ½ or ¼ of a cable system ahead on the line would take 1 hours each. Constructing and dismantling, as well as moving a line or line segment would require 1 hours. Typically, production with this kind of array would be 600-800 m in a day. More detailed survey at 1 m electrode spacing on tunnel floor or wall would cover a 80 – 100 m line, to depth of 15 – 20 m, and achieve a 150 – 200 m of line per day. Daily cost of 3–4-person crew and tools may require 2000 €/day. Processing of each daily line segment requires 1 – 2 hours of expert work. Drillhole and crosshole surveys are much slower to implement and processing and interpretation will be more demanding than for the surface or tunnel-based survey.

Electrical survey can be applied along the existing tunnels before closure of the tunnel. Resolution is adequate to observe undeclared conductive objects located in resistive environment to maximum distances of few tens of metres, with some geometric limitations of direction and relative tunnel orientation. Tunnels or shafts with related installations might be possible to become detected with similar restrictions from drillholes, until sealing of the deep drillholes. From ground surface the resistivity survey methods can be expected to observe targets of size of a tunnel down to depth of no more than some tens of metres. Due to near surface variation of resistivity and natural causes of elevated conductivity in rock mass, it is unlikely to avoid false positive alarms without baseline and repeat survey.

3.3.1 Electrical surveys carried out in Olkiluoto and in Äspö

Electrical surveys for different purposes were carried out in several phases, both in ONKALO, and in Äspö HRL. Early stage in characterization, several tens of sounding stations were placed to detect effect of increasing salinity in bedrock groundwater, reaching to depth of 100-150 m from ground surface (Lehtimäki 1990; Heikkinen et al. 1992). The results were showing also lateral variation of resistivity by fracture zones and conductive mineral occurrences. More detailed and continuous imaging of bedrock resistivity was carried out on three lines, one along the length of the island (length 3 km) and two in crossing direction, using a pole pole measurement array. Spacing of measurement stations (current electrode location) was 50 m along the line, and the resistivity was measured at 50 m interval on spread distances to 500 m from current electrode (Figure 3-36, Heikkinen et al. 2004). The results were combined to pseudo-sections and inverted to true resistivity vertical cross sections. Theoretically the survey depth range was c. 200 m. Reviewing the results together with electromagnetic frequency sounding results, and with drillhole core logging and resistivity wireline logging results, it was observed that the firstly met electrically conductive, laterally continuous layer up to 100-150 m depth was correctly imaged in its position. The thickness of the layer, or presence of similar deeper seated separate layers was not possible to determine. Inversion interpretation was attempted with constrained inversion using drillhole logging profiles. However, the different array geometries are difficult to combine in inversion process. The local resolution might be enhanced with combining ground level and surface to drillhole pole-pole array results in inversion. Observation of a tunnel sized object from deeper in the rock mass, independent from other supporting information, may not be feasible even with this kind of survey.

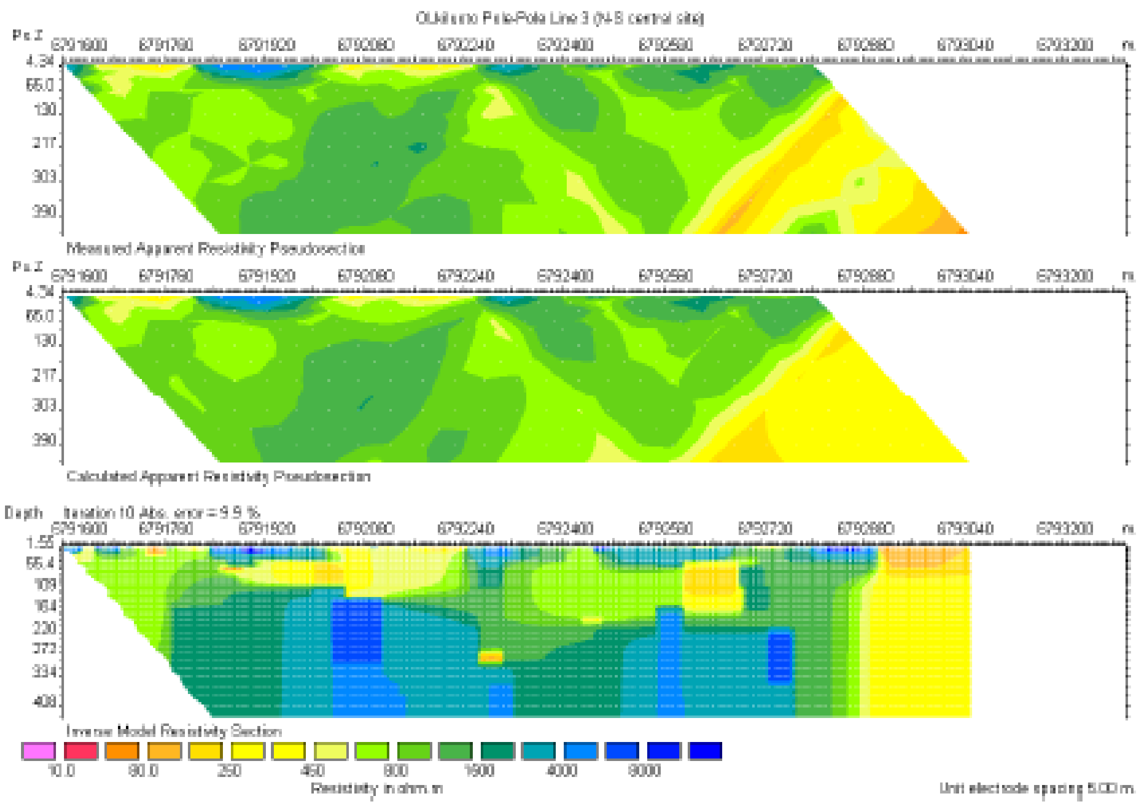

Figure 3-36. Electrical resistivity tomography ground level survey in Olkiluoto, 1.5 km long N-S line. Interval of measurement stations 50 m, spacing of current source locations 50 m to distances of 500 m. Measured resistivity pseudo-section on top, results of computer inversion of resistivity in the middle, and obtained vertical cross-section model on the bottom. Inversion was constrained with borehole data (Heikkinen et al. 2004). Though section extends to depth of 400 m, resolution is limited to upper surface of first significant conductive body at depth of 100-200 m. Detection of a steel reinforced tunnel deeper than that would be unlikely.

Crosshole and drillhole to surface mise-á-la-masse surveys were carried out in several campaigns in deep holes drilled from ground surface (Ahokas et al. 2014). Current source was grounded in a drillhole into an electrically conductive interval, which was detected by wireline resistivity logging. Measurement of electrical potential was performed in the same drillhole and in several neighbouring drillholes, and on ground surface lines, at 5 m measurement interval. Results were used for interpretation of electrical connections between the drillholes through deformation zones, or through electrically conductive minerals containing layers. This kind of survey would not be directly applicable in safeguards. An alternative, fully covering crosshole electrical tomography, may serve as method for tunnel detection, but as a baseline and repeat survey implementation. After sealing of deep drillholes this kind of approach would not be possible. In drillholes located further away from the disposal volume, a permanent electrode installation would be possible, to carry repeated tomography.

A detailed electrical resistivity tomography survey was carried out for characterization of Excavation Damaged Zone (EDZ) at ONK-TKU-3620 (Heikkinen et al. 2020a, Figure 3-37). Electrode spacing was 0.1 m or 0.2 m in a survey array of 80 electrodes, producing a 8 m long section reaching to depth of 1 m. In total 11 parallel profiles were measured. The more intensely fractured layer on the tunnel floor, and some natural fractures in the rock mass were possible to be detected from the results. It seems that this detail of survey, or slightly coarser resolution, 0.5 – 1 m electrode spacing to reach high resolution until 5 – 20 m of depth, along 40 – 80 m of line length, may be applicable to detect electrically conductive objects behind the tunnel surfaces. Method can be applied also to view behind the conductive metal fibre reinforced concrete on the wall, or macadam cover on the floor. both of which would suppress GPR performance.

Mise-a-la-masse survey was conducted in Hydco niche on the right-hand side of ONKALO access tunnel (ONK-TKU-3760), grounding with a source electrode at fractures in one drillhole at a time and measuring potential field densely (0.1 m spacing) in another drillhole located 2 m apart (Ahokas et al. 2011). Survey was carried out also between the drillhole and the nearby tunnel at 1 m measurement interval. Grounded electrically conductive installation or support structure could be detected on basis of changes in electrical potential field.

Similar survey was conducted between demonstration tunnel pilot holes at 20 m drillhole distance, grounding source electrodes onto fractures in one drillhole, and measuring electrical potential field on tunnel surface at 1 m spacing and in the other drillhole at 0.1 m spacing (Ahokas et al. 2015). Using a sparse location of source electrodes, does not allow detailed observation of other objects from underground. However, it allows following continuation of electrically conductive objects when grounded with current source. One measurement campaign in ONKALO for mise-à-la-masse, included also a drillhole pair at 20 m drillhole distance measured with electrical crosshole tomography (Figure 3-38), and one tunnel floor which was surveyed with electrical resistivity tomography downwards to 20 m depth (Heikkinen et al. 2017).

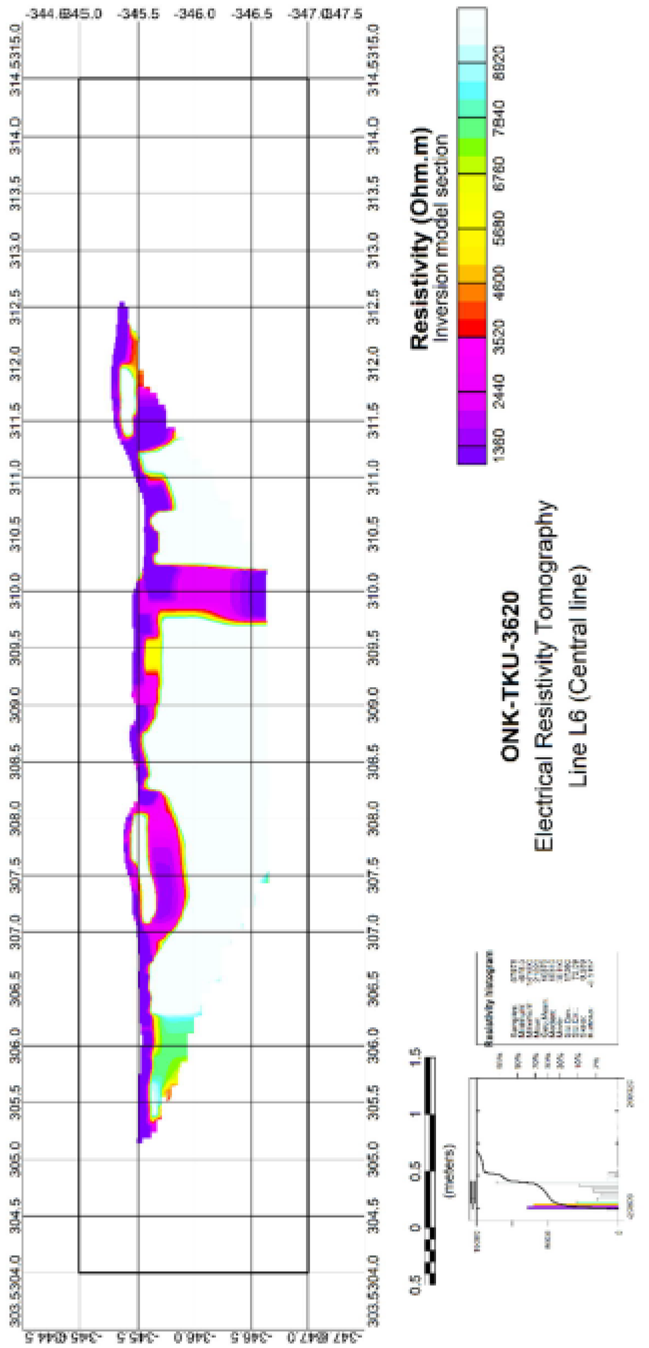

Figure 3-37. Electrical resistivity tomography on tunnel floor at 8 m line, results of inversion modeling considering the form of tunnel surface. Lower electrical resistivity indicates presence of fractures. Method could be applied to detect cavities and conductive installations behind rock surfaces (Heikkinen et al. 2020a).

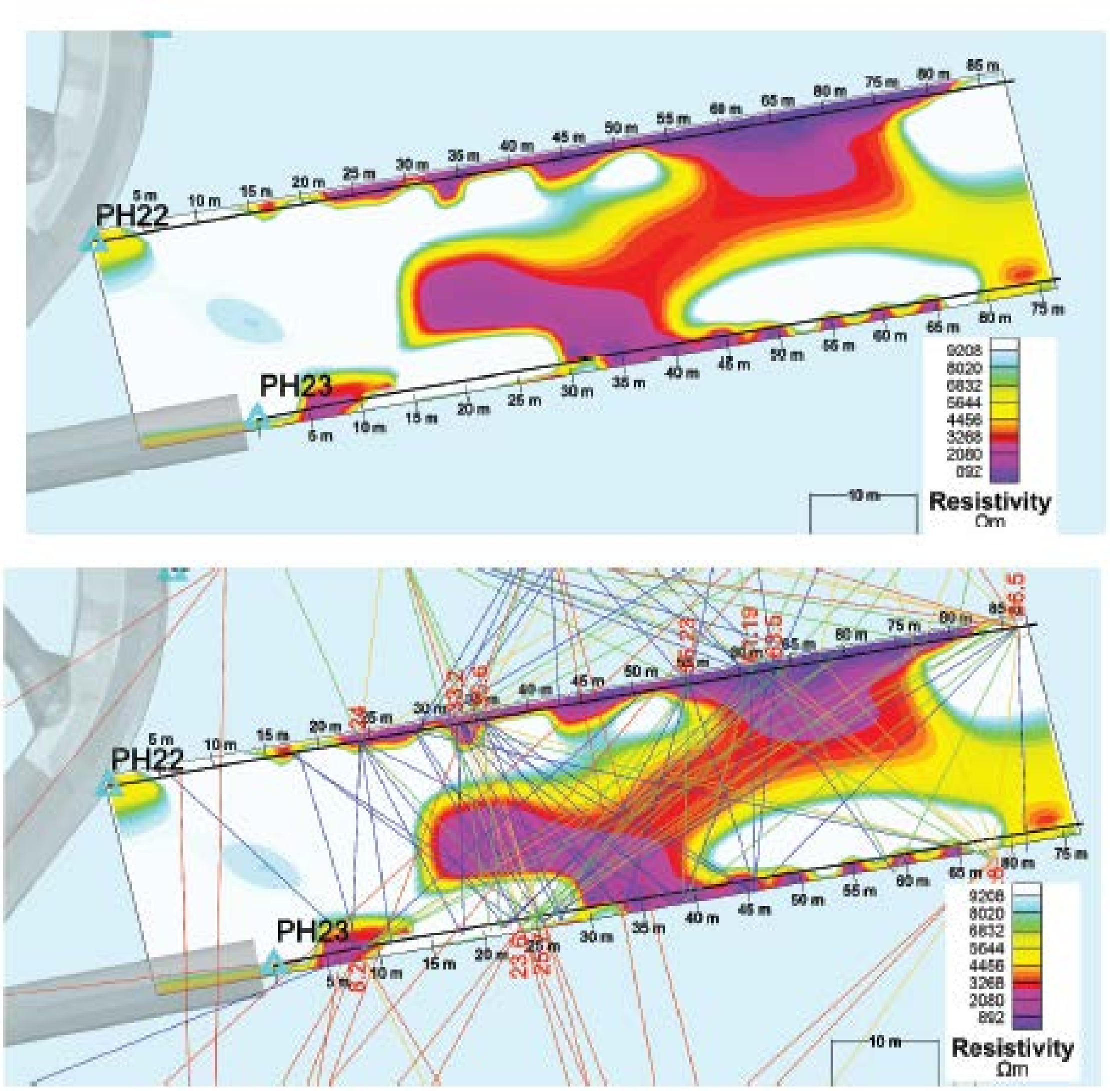

Figure 3-38. Crosshole electrical resistivity tomography between drillholes ONK-PH22 and ONK-PH23 (Heikkinen et al. 2017). Drillholes are parallel, horizontal, and located 20 m apart each another. Pole-pole electrical survey was carried out at 1 m current electrode spacing in one drillhole and 0.1 m potential electrode spacing in the other drillhole, and inverted to tomographic image (above). Mise-à-la-masse survey was used in following electrical connections (lines) along fractures between drillholes (below), partly coinciding with tomographic image. An object of deviating resistivity (low or high) located between the drillholes could be detected.

Crosshole mise-à-la-masse survey was conducted in three vertical shaft characterization holes at a 100 m vertical length. Drillholes were located c. 3 m distances of each other. Fractures and veins containing conductive minerals were imaged in the rock mass (Heikkinen et al. 2010a).

Highly detailed mise-á-la-masse surveys were carried out between pairs of eight drillholes surrounding an experimental disposal well ONK-EH3 in investigation niche ONK-TKU-3620 (Heikkinen et al. 2013). Survey included mise-à-la-masse measurements and electrical tomography to line up fracture connections around the experimental hole, partly caused, or explaining, damages caused by thermal spalling experiment.

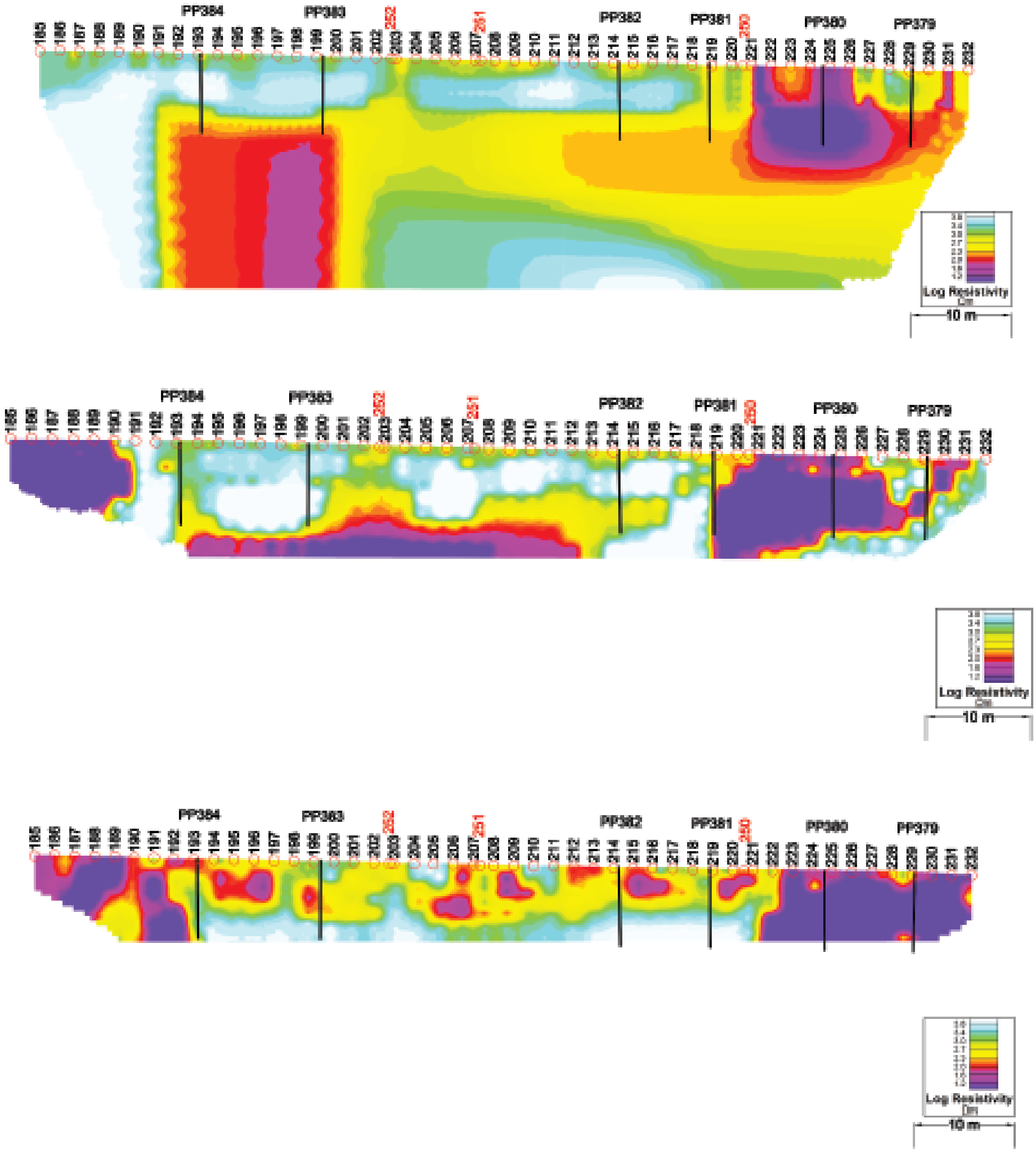

Figure 3-39. Electrical resistivity tomography carried out on tunnel floor at demonstration tunnel ONK-DT2 /Heikkinen et al. 2017), line length 92 m. Current electrodes were located at 2 m interval on the floor, and electrical potential was measured at 2 m interval to distance of 40 m. The results were compiled and inverted for three geometries: acquisition pole-pole geometry (top) with deepest 20 m depth range, and superposition of results to pole-dipole (middle) to ten meters and multigradient (bottom) to depth of 6-7 m and highest resolution. Disposal well pilot holes (8 m) are indicated with vertical lines. Conductive locations are shown on red colours. A tunnel near rock surface could be detected, though also natural resistivity variation would contribute to the results.

Higher coverage of electrical survey was used in Äspö for cross-tunnel and along tunnel electrical tomography for designing detailed underground characterization methods, and during a revised campaign using single-hole electrical survey, crosshole electrical tomography, and drillhole to tunnel electrical tomography. All these measurements also included mise-a-la-masse interpretation of grounded electrical conductors (Cosma and Enescu 2015).

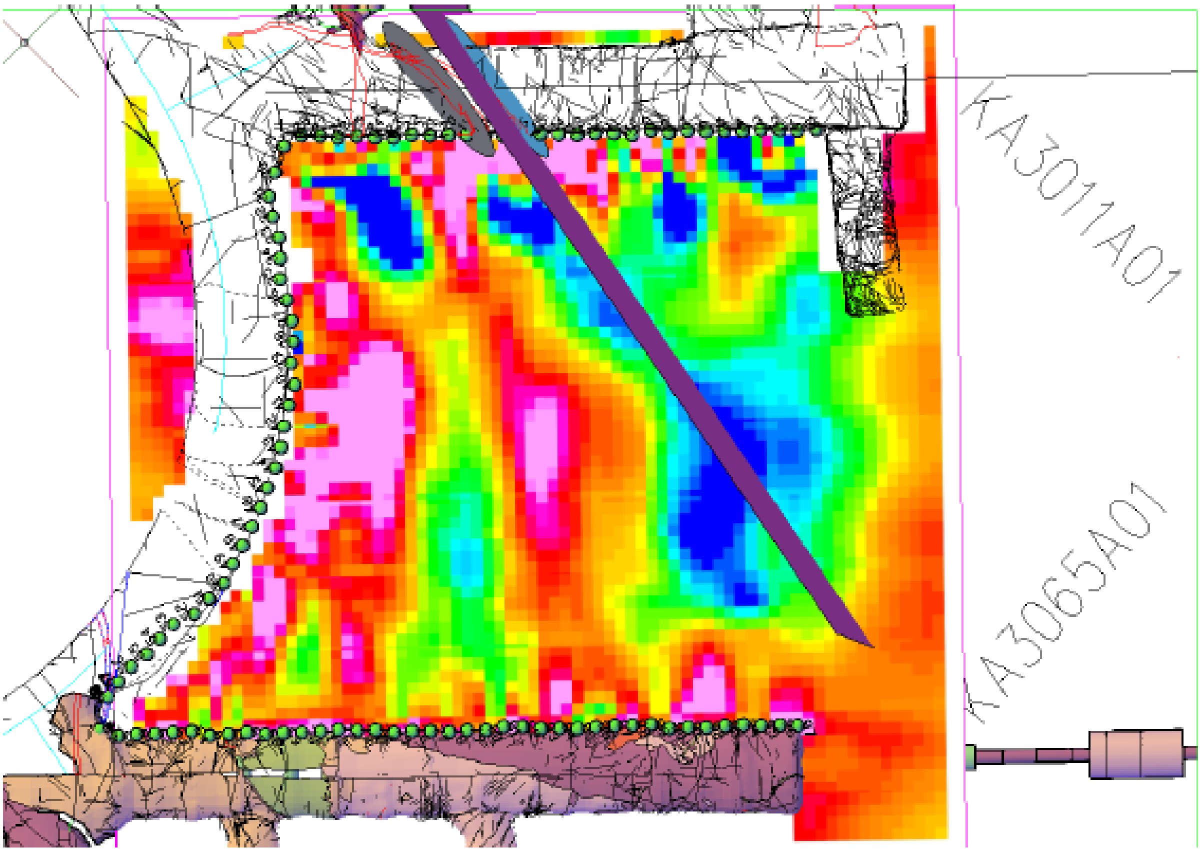

Figure 3-40. Electrical resistivity tomography carried out on tunnel wall on three sides of a 100 x 100 m rock block in Äspö HRL (Thunehed et al., Geovista, presented in Cosma & Enescu 2015). Electrically conductive locations are coinciding with modeled minor faults and tunnel crosscutting fractures.

A series of crosshole tomographic sections was carried out in vertical holes, placed at 1 m distance from each another, to characterize electrically conductive features around an experimental disposal hole. Main purpose was to carry out mise-a-la-masse survey on fractures grounded with active electrode, measuring potential field in neighbouring drillholes on profile. Fairly dense pole-pole data was used to compute downhole pole-dipole crosshole data and used in tomographic inversion. Conductive bodies were aligned with survey.

The electrical potential (mise-a-la-masse) and electrical resistivity tomography were used for measurement of continuity of electrically conductive structures, like fractures and sulphide veins.

The surveys could be applied, with some limitations, to detect also tunnels at close distance from measurement line in tunnel or drillhole. Survey would need a multielectrode measurement system, to place measurement electrodes densely and on adequate long spread, to also obtain depth range.

In case a tunnel would be lined with electrically conductive, metal reinforced shotcrete, or bolted or wire mesh lined for supporting, this would enhance observability with electrical tomography. A tunnel without lining, and being air filled, would be resistive and not so easily observed. The electrical tomography in observing a tunnel would be efficient to distances of 10-20 m away from observation line. Survey could be applied to detect an undeclared tunnel near a disposal tunnel, or a disposal well, before emplacement of the capsule, or soon after emplacement. Possibilities to install a low-cost permanent electrode positions on tunnel surfaces would enable frequent repeat measurements to detect possible new, undeclared tunnels. Only cables, transmitter and receiver would need to be brought with crew during survey.

After backfilling of tunnel, the possibility to apply the method at close range and high resolution will cease.

3.4 Electromagnetic survey

Electromagnetic measurements can apply either natural magnetotelluric fields or artificial sources. Similarly, as for the resistivity method, the electrical conductivity in subsurface, or its inverse resistivity, are affecting to the measurable results. Electromagnetic wave field generates secondary field components proportional to conductivity of the medium, which can be observed with receiver tool.

Conductivity of rock materials has broad range of variation. Most rock forming silicate minerals are insulating, and conductivity mostly associates to metal ion containing sulphides and graphite. Weak conductivity can be observed in fractured rock mass due to increased water content, and due to clay minerals.

Electromagnetic methods can be used for locating the metal canisters or waste containers (Finch 2009). Also, metallic support structures can be observed with EM methods. Electromagnetic (wave field) survey can be applied to detect metallic reinforcement related to tunnels, based on their large contrast to surrounding mostly resistive rock mass. An exception in Olkiluoto is local graphite and pyrrhotite bearing fracture zones, shear zones and layers (veins), which also are conductive.

Electromagnetic measurement does not require physical contact onto surveyed medium. Methods using artificial source, may apply the energy into the surrounding ground either by magnetic dipole source, created with a strong alternating current injected into wire loop, or a long-grounded wire. Size of a loop can be small, or large. Intensity of the primary field is proportional to surface area of the wire loop, circles of wire in the loop, and amplitude of electrical current.

In frequency domain measurements the current is injected at one or several known frequencies. Measurement coil is tuned to the measured frequency. Measurement is carried out during on-time of the transmission. Receiver is located at a known distance and it is aligned with the transmitter, either on co-planar or co-axial orientation. Transmitter and receiver are synchronized. In absence of any conductors, receiver response will be zero, and in presence of conductive bodies, the receiver amplitude of in-phase field (at same phase as source field) and quadrature field (90 degrees phase shift to source field) are increasing. Distance range of observation depends on the distance of transmitter and receiver, on the power of transmitted primary field, and mostly on the frequency of measurement. High frequencies have shortest measurement range and highest location resolution. Low frequencies have greatest range. Measurement is carried out as densely measured stations on a profile, repeating measurement on each station. On profile form, closely located conductive objects can be seen as specific anomaly forms, usually cross-over or double maximum. Conductivity and distance of a conductor can be defined from the results. Using multicomponent receiver, it would be possible to also estimate direction to a conductive object.

In time domain measurements the current is injected as a short impulse of known pulse form. Measurement is carried out during off time of the transmitter. Transmitter and receiver are synchronized very accurately. Receiver coil or magnetometer is measuring a transient decay of secondary field intensity, normalized with primary field and with distance. Receiver is aligned with transmitter. Different geometric arrays can be used. Transmission can be carried out using a large, fixed loop, where measurements are taken along lines or along a drillhole within and near the loop. Or a local smaller loop can be used as a source and measurement carried out as coaxial array, receiver in the middle of transmitter loop, or as a dipole-dipole (Slingram) array where receiver is located at fixed distance from transmitter. In both cases the entire system moves along a measurement line. Each measurement station forms a sounding, where slope of the time decay curve shows conductivity of the target, but also physical extent, and distance to the target. Measurement profile formed by several soundings on a line can be used to further characterize orientation and location of the target. Using multicomponent receiver, also direction to the target can be estimated.

Electromagnetic measurements can be carried out with portable frequency domain tools as a line measurement on quick pace, up to 2 – 3 km line coverage during a day. Time domain survey may operate at slightly slower pace, depending on transmitter technique. In tunnel measurement, size of measurement array would be limited. As the measurement system would detect all possible conductive objects near the survey line, the probability of false positive alarm is high. Also, natural conductive bodies probable cause multiple anomalies. For this reason, also the electromagnetic survey methods would apply best as baseline and repeat survey, where results from each measurement time would be compared to detect any undeclared activity.

Whole of the area in Olkiluoto was covered in early site investigations with airborne EM measurement, and later ground level survey, using dense line and station spacing. Results were used to create a ground level electrical conductivity map, used in interpretation of lithological and deformation properties and geometry on surface. The survey methods which were applied have a depth penetration of few tens of metres. If repeated, this kind of surveys could reveal near surface synthetic (clandestine) installations, as these are causing interference in the results. Airborne or ground level EM line surveys with portable tools have little contribution to deep repository safeguards but may be applied effectively on wide surface areas to detect exceptional, previously unknown installations. Largest depth penetration is associated with time domain electromagnetic survey, which can be operated airborne or ground level. This method has not been used in Olkiluoto.

During early site investigations, a frequency domain electromagnetic sounding tool Gefinex 400 Sampo was used to measure several hundreds of sounding stations at different transmitter receiver spacing distances (Heikkinen et al. 2014). The tool operates at 1 – 20 000 Hz frequency range. Survey was covering the rock mass to depth of 1 km, indicating variation of electrical conductivity caused by fracture zones, presence of saline groundwater, and electrically conductive layers. Later the method has been applied in repeat measurements on fixed measurement stations for monitoring, to detect conductivity changes (increases) due to expected up-coning of saline water interface in the rock mass, caused by pumping of excess water from tunnels (Korhonen 2018).

The detection resolution is estimated to be inadequate from ground level to produce reliable information of tunnel sized objects even with repeated and controlled surveys. Drillhole receiver for this specific system, which might have higher resolution in detection at closer distance, is not widely available. Method has been severely interfered by power lines in the area.

Transient electromagnetic survey methods from ground surface have not been widely implemented in Olkiluoto area. Though these methods might have benefit on highly conductive object detection and depth penetration, the time domain survey technique is even more disturbed by power line interference, and to greater distances than the frequency domain survey. Transient electromagnetic survey could be carried out in drillholes and even in a tunnel using a large ground surface loop as transmitter.

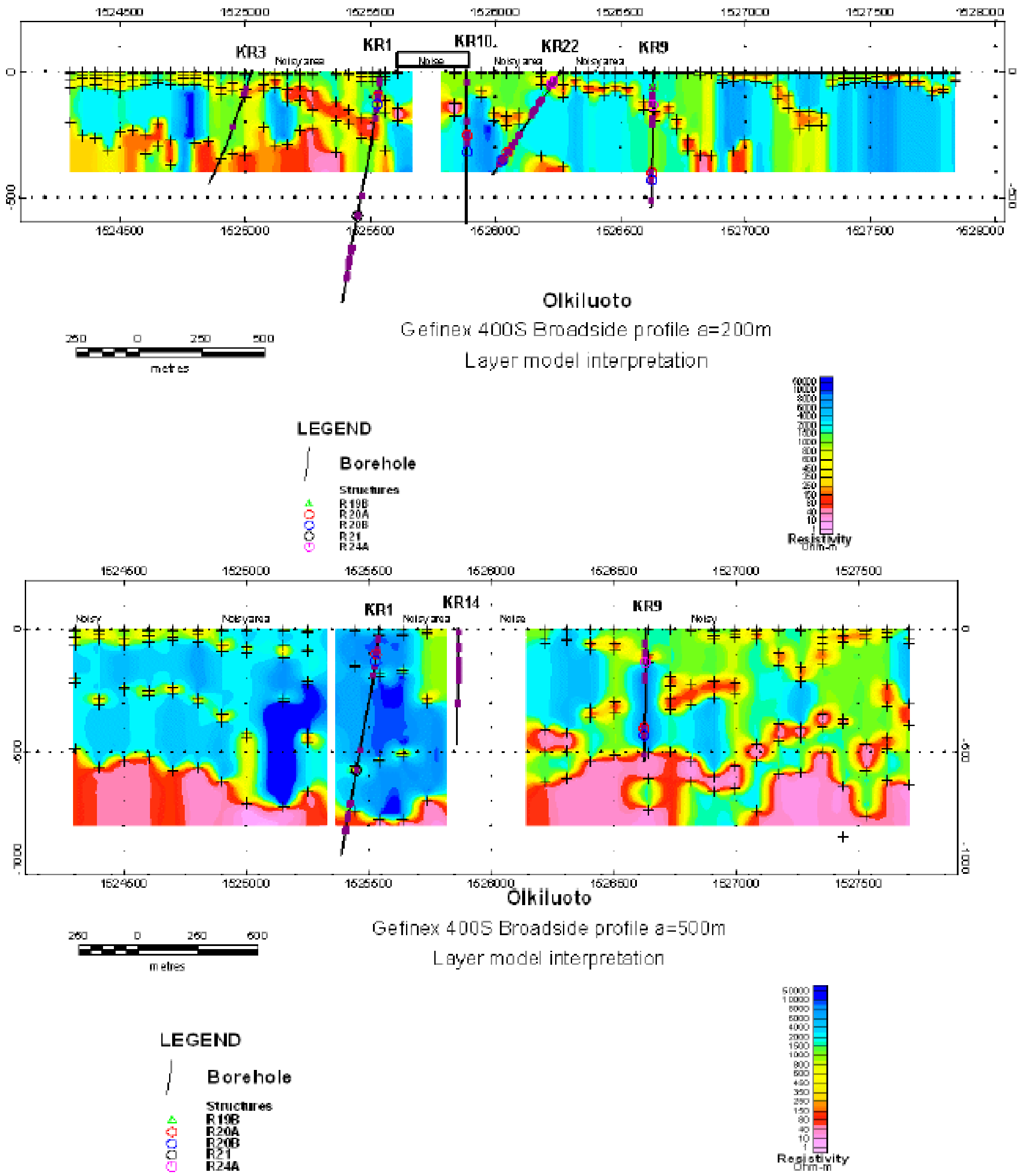

Figure 3-41. Interpreted compilation of 1-D soundings in Olkiluoto using frequency domain electromagnetic tool Gefinex 400S SAMPO (Heikkinen et al. 2004). Two different measurement arrays on a same line are presented (slightly different length coverage). The 200 m transmitter-receiver spacing has better resolution, depth range to 200-300 m. The 500 m transmitter receiver spacing improves depth penetration to 600-700 m with a tradeoff of weaker resolution. Upper surface of deeper conductive body is detected. Separation of natural and artificial conductive bodies would require repeat surveys.

Crosshole electromagnetic frequency domain method, FARA, or EMRE, a radiowave shadowing method, has been carried out at three pairs of drillholes in Olkiluoto down to depth of 500 m. Distances between drillholes was 100 – 150 m at measurement interval. Method produces at high frequencies a crosshole tomographic image (Korpisalo et al.

2008). Frequency range of 300 – 1250 kHz is not capable to function as radar reflection survey, though both dielectric permittivity and conductivity will contribute to results. The results display a conductivity image between drillholes. Image may include features located off-plane. Whether a survey could geometrically identify a tunnel sized object between drillholes but not intersected by either of holes, is uncertain. A new conductive object might cause some differences between baseline and repeat survey.

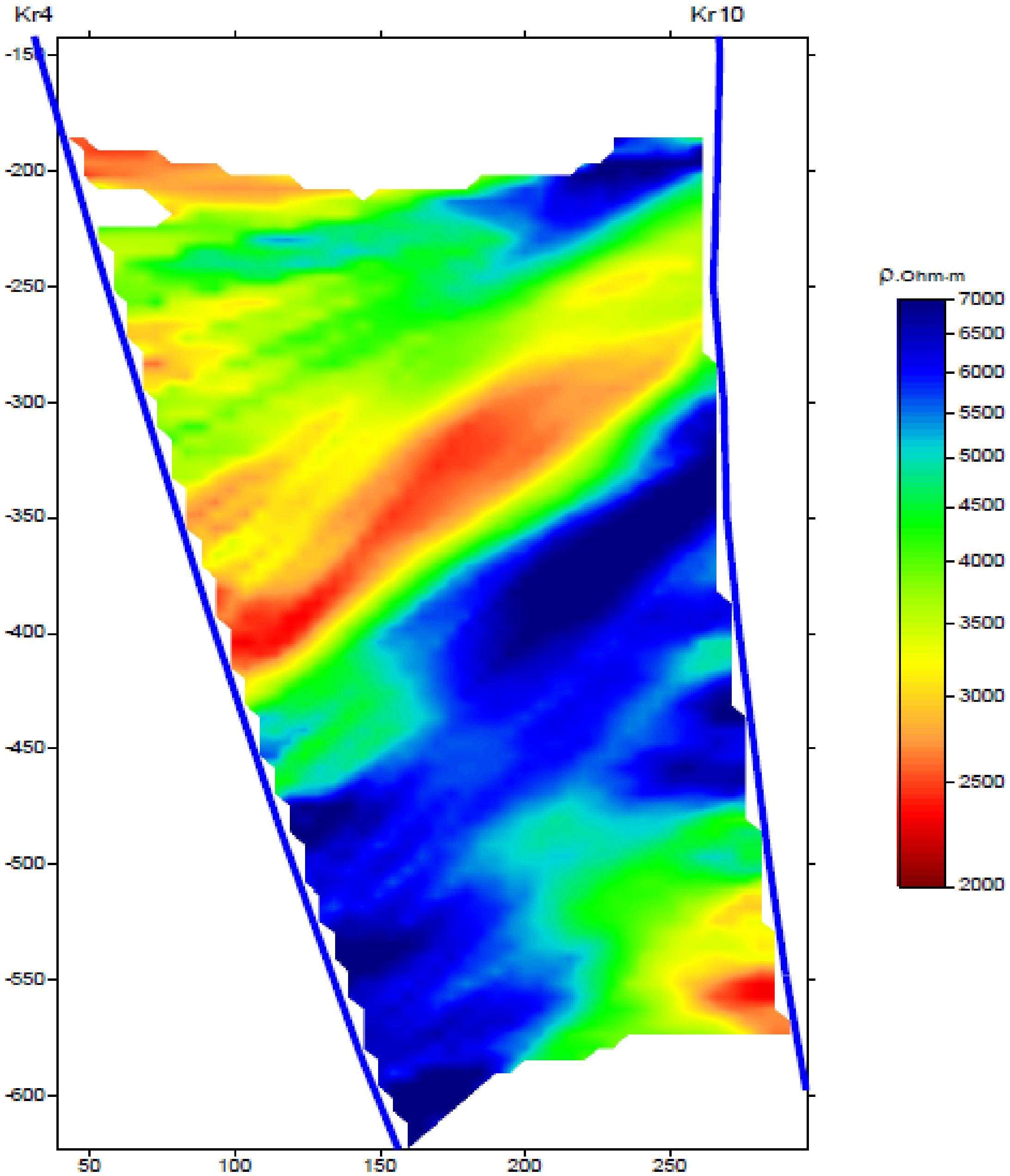

Figure 3-42. Electromagnetic radiowave imaging at 1250 kHz frequency. Amplitude is converted to resistivity (Korpisalo et al. 2008). Changes in image could be associated with undeclared activities.

In Olkiluoto, no tunnel electromagnetic survey has been carried out. Possibilities are, that such method might be applied to detect possible undeclared tunnels near existing ones. Because all nearby metallic objects, installations and natural conductive bodies cause anomalies in the measurement data, the application manner would be repeated survey to be compared to baseline data.

Frequency domain EM survey, for example Slingram (horizontal loop EM), can be carried out in tunnels. Typical slingram tool like MaxMin II, may use comparably short transmitter to receiver spacing, and high frequencies. Measurement would detect presence of metallic objects to distances of 10 – 30 m from the tunnel. A multicomponent Slingram (like Iris Promis 10) can also display direction to the conductive body. Drillhole slingram tools have been developed (e.g., GTK SlimBoris), but are not commercially available.

Time domain EM survey, using for example Geonics Protem, would be based on transmitted EM pulses, and recorded transient decays of the EM field induced into the conductive bodies. Currents induced into tunnel lining would cause a secondary field, detectable to distances of tens of meters from tunnel or drillhole. Implementation can use a large and powerful ground surface based current loop (vertical magnetic dipole), and measurement of the secondary responses either in drillholes (before their sealing) or in tunnels (before backfill). Ground level-based measurement is not sensitive enough to detect deeply seated small objects from other variation.

Another alternative for TDEM survey is to carry a local loop source together with receiver, at constant distance (Slingram-type of array) or using central loop array and measure the responses locally. Combination of resistivity and induced polarization on near surface, and magnetotelluric survey on deeper part (Titan-24 or Spartan, Quantec 2021), especially when supplemented with a drillhole measurement, may enable high enough resolution.

All electromagnetic soundings would benefit on comparison between a pre-survey and repeat measurement. Responses can be modeled prior to considerations, using forward modeling. Recent development of techniques (Duncan 2017) is likely to bring in new applications.

3.5 Magnetic survey

Magnetic measurements are based on observation of natural magnetic field. The Earth has a magnetic field associated with the internal geological processes of the globe. Orientation and intensity of the field is varying according to location. Typical values in latitudes of Finland (in Olkiluoto) are 51 000 nano-Tesla (nT) intensity, declination c. 5 degrees to east from geographic North, and inclination towards 75 degrees from horizontal.

Small scale variation of the field intensity and field orientation can be caused by local conditions. This variation may range from few tens of nanoTeslas to several thousands. Local field orientation may also be altered due to local anomaly sources. The magnetic field induces secondary field in paramagnetic minerals. Ferrimagnetic minerals possess their own magnetization, contributing to the local field. A tunnel with steel reinforcement on the wall and ceiling, or large construction vehicles placed into a tunnel, may appear as magnetic sources in external Earth magnetic field.

Magnetic field is a potential field, where the intensity of a specific source of magnetic interference is decaying according to distance from the source. The magnetic field intensity related to the source is proportional to the amount and distribution of magnetized material in the medium, the shape, and volume of the object. Effect of homogeneously distributed magnetized substance in rock mass can be understood as a geometric object, which would cause a specific anomaly form on a line or surface area measurement. Shape of an anomaly on a line can be used in localizing an object and defining its orientation and form. Historically, magnetic methods have been applied also to detection of submarine vessels and mines, unexploded ordnance, and other manufactured objects, even in archaeology.

Magnetic field intensity can be measured with widely available tools, ranging from ferrite-coil construction (fluxgate) to proton-precession and more precise cesium-vapor operated or squid magnetometers. Method of application of magnetic measurement, is a line survey with densely located measurement stations. Depending on application, either specific field component, total field, or orientation of total field and different components, can be measured. Numerical accuracy requirement is depending on the application purpose. Geotechnical and ore exploration purposes record the field at accuracies of 0.1 nT.

Magnetic survey is quick to implement. With continuous recording of 10 values per second, survey can be carried out installed in a vehicle, or walking pace, several kilometers in day. Magnetic measurements can be carried out also in drillholes, until these would be sealed. Some sensor types are cheap, so that these could be installed into a permanent monitoring network, enabling recognition of undeclared activities at some areas within repository volume. Alternatively, drillhole based survey or monitoring may be carried out from ground surface or drillholes placed further away from the repository boundary.

Method of application of safeguards, would rely on detection of magnetized metallic objects, which could range from support installations to construction machinery. A large drill rig or tunnel boring machine may cause interference in natural magnetic field, detectable to distances of tens of meters through the rock mass. Human constructed objects would also cause deviation into the orientation of magnetic field, because of high content of magnetizable iron in the materials. Due to abundance of natural anomaly causes, and anomalies already existing due to declared tunnels, method would be based on baseline and repeat surveys, where only the changes in the result would be inspected in more detail.

Olkiluoto has been covered by both airborne magnetic survey and with dense ground level measurement. Results have been used for mapping of lithological and deformation zone locations and geometry. Magnetic properties in rock mass have been measured by wireline logging. Observations on 3-component magnetic field variation have associated with drillhole imaging surveys. Even small metallic objects have found to cause interference in magnetic field orientation to distances of few metres. Tunnel based magnetic surveys have not been carried out. Magnetic surveys may be applied on ground surface for effective detection of unexpected features. Surveys can be run also with UAV's.

In case of bolting or steel fibre reinforcement in tunnels, magnetic survey has some capabilities on detecting undeclared tunnels from close distance. Magnetic total field measurement would indicate magnetic field high and low anomalies due to metallic object to distances of some metres to tens of metres. Distance to the object can be resolved using forward modeling. Three component magnetic measurement would help in also resolving location, or direction towards, the object. Again, a comparison measurement and a repeat survey, with mutual comparison, would be most useful technique to detect any changes occurred between the surveys.

Downhole magnetometry, or three component magnetometry, can be used in ground level based deep drillholes, and tunnel based drillholes until these are sealed. Tunnel based magnetometry can be carried out until backfill, but not after that.

3.6 Gravimetry

Gravimetric measurements are based on observation of natural earth's gravitational acceleration. Gravimetric field ranges on earth surface at 9.81 m/s^2, which is referred as one Gal (Galilei). Instantaneous gravimetric potential field varies at latitude, and due to tidal effects. Density of rock mass causes local variation in the gravimetric potential field, which can be measured using sensitive accelerometer-based tools. Relevant variation is at range of microGal to milliGal.

Typical rock forming silicate minerals have densities ranging at 2500 – 3000 kg/m^3. For crystalline lithologies this also produces the density of rock mass. Significant fracturing or porosity and associated water content may decrease the density. Sedimentary rocks have slightly lower densities due to their lower consolidation. Sulphidic and oxidic ore minerals (magnetite) as well as mafic silicate lithologies have higher densities than granitic rock types. Gravimetry has been applied for cavity and void detection from ground surface measurements in karstic areas, and in past mining areas for detection of risk of collapse and other hazards.

Gravity field intensity due to an anomalous object is depending on the contrast (amount and volume of the object), size, shape, and distance from the object. Gravimetric field can be measured as a total field, gradient, or using a tensor measurement tool, a tensor field which is capable on also indicating the direction to the anomaly source. Gravimetric survey can be carried out also in drillholes, using downhole sensor with wireline logging (Nind et al. 2013). Possibilities would be using the measurement technique from drillholes located further away from the repository boundary.

Any excavated spaces within rock mass have significant density contrast to the surrounding rock mass. Air filled (density close to zero) or water filled (density 1000 kg/m^3) would be clearly detectable by gravimetric measurement from a short distance of some tens of metres.

Gravimetric measurement requires stationary recording of results over some tens of seconds to minutes at each station. Measurement technique would be recording gravity value at stations along line in tunnel. Pace of measurements would be 1 – 2 km in a day.

Because of already existing tunnels and natural anomaly sources will cause variation in gravimetric field, most applicable method would be baseline and repeat measurement and comparison of the results. Observation of changes in results can be made directly but understanding the results would require comparisons to synthetic modeling.

Microgravity surveys are frequently used in past mining areas and in karst areas to detect voids and underground tunnels which may become hazardous for surface structures. Detection distance of a 3 – 5 m diameter tunnel is delimited to few tens of meters in maximum. Gravimetric survey would be based on density contrast between rock mass (2720 kg/m^3) compared to density of air (0 kg/m^3) or water (1000 kg/m^3).

Gravimetric method has not been used in Olkiluoto as systematic survey technique. Candidate areas containing mafic lithology occurrences (Syyry and Romuvaara) included gravity survey lines in preliminary investigation phase.

From ground surface to depth of 420 m the gravimetric method is not feasible in detection of tunnels. From existing deep drillholes, using drillhole gravimeter logging technique, detection could be carried out from closer distance. This again would not be possible after drillholes become sealed. Drillholes made from the tunnel, closer to the target area, may be used in comparable way, until their closure. More standard gravimetric measurement can be carried out in tunnels, with similar detection capability. This is possible until backfill of the tunnels.

Any gravimetric measurement would benefit of a baseline measurement, onto which the repeat survey would be compared. This is because the possible responses would be small.

3.7 Radiometric survey

Radiometric measurements include detection of gamma radiation, beta particles, alpha particles, and neutrons. Gamma radiation is measured with scintillometer sensors. Method is applied in geotechnical, geological and mine exploration tasks. Measurements can be used also as radioactivity safety monitoring in industrial and transportation activities, for example to prevent illegal trafficking of radioactivity containing materials. Scintillometers can be based on NaI(Tl) or CsI(Tl) crystal sensors and can be used in producing a full gamma radiation energy spectrum, to recognize radionuclides. Crystals are sensitive to mechanic failure and would require comparably large volumes and surface areas to be effectively used as portal sensor in transport monitoring.

Alternative sensors, which provide large volume and surface area, are based on plastic Polyvinyl Toluene (PVT) material, are more cost effective in manufacturing, robust in demanding conditions, and can be used in larger volume, surface area and mass in effective count rate screening. Though measurement is based on windowed calculation of spectrum, it can be adjusted to provide alarm on specific radionuclide. Tools are widely used in industrial and cargo applications, at metal foundries using recycled raw materials, at airports, terminals, and border crossing.

Corresponding sensors, with different functional principle are available also for detection of beta particles, alpha particles, and neutrons.

In safeguards application, radioactivity portal sensors may be effectively used for monitoring that radioactive materials, or indications of contamination due to diversion attempt, would not depart from repository. Testing of spent fuel itself for gamma spectrum may enable identification of the type of fuel (Hellesen and Grape 2018).

It is unlikely that a geophysical mapping type of application of radiometric sensors would be useful, unless expected a case of fallout or contamination spreading during declared (or undeclared) transportation.

3.8 Temperature

Temperature in rock mass can be measured with sensors placed in tunnels and drillholes. An effective method to measure large amount of temperature scan line, is to use an optical fibre thermal sensor, based on Raman spectroscopy. Fibre optics sensors can be hundreds of metres long and return temperature value for example at one metre interval. In case drillholes would be available for installation of such sensor, even minor changes in temperature due to construction and excavation would be detected to distances of metres to tens of metres. Effect is slow to emerge, requiring months or years to become visible, though.

Observations have shown that the ventilation air is changing temperature in and around tunnel compared to the temperature occurring in the ambient rock mass in Olkiluoto (Pentti 2017). Accurate temperature logging in deep drillholes were observing these temperature changes to distances of several metres from the tunnel. However, repeat surveys for temperature are unlikely to be possible after sealing of the drillholes. Temperature has been discussed in more detail in report (Pentti 2017).

Temperature field created by disposal of the spent fuel canisters, can be also measured and any deviations from the expected behavior might be observed in long term monitoring.

Thermal monitoring can be used to detect decay heat. It needs to be calibrated against initial conditions (Finch 2009). The baseline conditions of temperature distribution in Olkiluoto are well characterized (Haapalehto et al. 2020).

3.9 Groundwater pressure

Pressure in groundwater can be measured with either a pressure sensor installed within a packer isolated interval in drillhole, or using a vibrating wire piezometer, which needs to be cemented into the packer section. Inflatable packers can be used in non-sealead drillholes, and there is a possibility to carry maintenance or replacement of the sensor and packer system. Piezometer can be applied also in sealed drillhole, though it needs a communication and power source link from surface, which may not be allowed in any drillholes near the repository. Once failing for any reason, the piezometer only can be abandoned, as there is no possibility for replacement or maintenance. Service life can be long, but still limited.

Pressure field is easily reacting to change in hydrogeological conditions. Intrusion to a hydraulically conductive fracture zone with some degree of continuity, is lowering the pressure, which will be visible either immediately or after some time delay, over long distances in bedrock. Even small transient changes in pressure field would be indicative. Localization of an event is not straightforward, though. A deterministic fracture zone model and hydrogeological simulations based on the observation would be method in understanding the observations.

Excavated tunnel space will be draining the groundwater from surrounding rock mass, causing groundwater pressure level to approach atmospheric level close to the tunnel, and being significantly lowered in fractures and fracture zones directly or indirectly connected to the tunnel. Permanent hydrogeological pressure stations in deep drillholes (multi-packer installations) or in ONKALO (PVA stations) can be used to detect intrusion about tunnels. Groundwater pressure is discussed more detail in report (Pentti 2017).

3.10 Laser scanning or photogrammetry

Laser scanning is producing a millimeter scale accurate point cloud, including also RGB compiled photo assemblage, from a tunnel surface. Method is widely used in engineering, tunnel excavation, and mining. Survey of one measurement station covers few meters of tunnel length at a time. Advantage of stationary scanning is the opportunity to carry reliable staking for the survey. Also mobile, vehicle based multiple sensor laser and photo scanners are under frequent application in urban environment, traffic corridor, and infrastructure documentation. Survey can progress at quicker, slow driving pace, and carries the required localization while measuring, using necessary fixed-point indicators installed beforehand. Under development are also UAV or drone-based laser scanning methods, which would collect the point cloud during movement of the drone, localization would be run by using Simultaneous Location and Measurement (SLAM) processing technique.

Alternative for laser scanning using active source, slower to operate, is application of photogrammetric survey. Partially overlapping series of high-resolution photographs are taken from slightly different viewing angles, and processing after recognition and indication of fixed stations, seeks for substantial number of common points from the images, and computes then a 3D point cloud and triangulation from the results. Results need to be tied onto staking belonging to the design information. Also, photogrammetry can be run by drones or vehicle. In tunnel, photogrammetry survey requires organized and even illumination of the tunnel surface. Development of photogrammetry or video imaging assisted with active laser survey has been also underway recently, combining the accuracy and high pace of production.

During ONKALO construction in Olkiluoto, each excavated tunnel section, after few blasting rounds, are measured with laser scanning using total station. Obtained point cloud is used for quality control of the excavation, to detect under- or over excavation. After scanning, the rock surface is bolted for support, and on access tunnels lined with shotcrete and in disposal tunnels the ceiling is supported with wire mesh attached on the bolts. Photogrammetric surveys have been used for mapping of specific investigation niches, for example for the POSE investigations in ONK-TKU-3620 (Koittola 2014, Figure 3-43). Results have been used in geological mapping and documentation of changes, as well as in numerical stress field simulation as a 3D surface model.

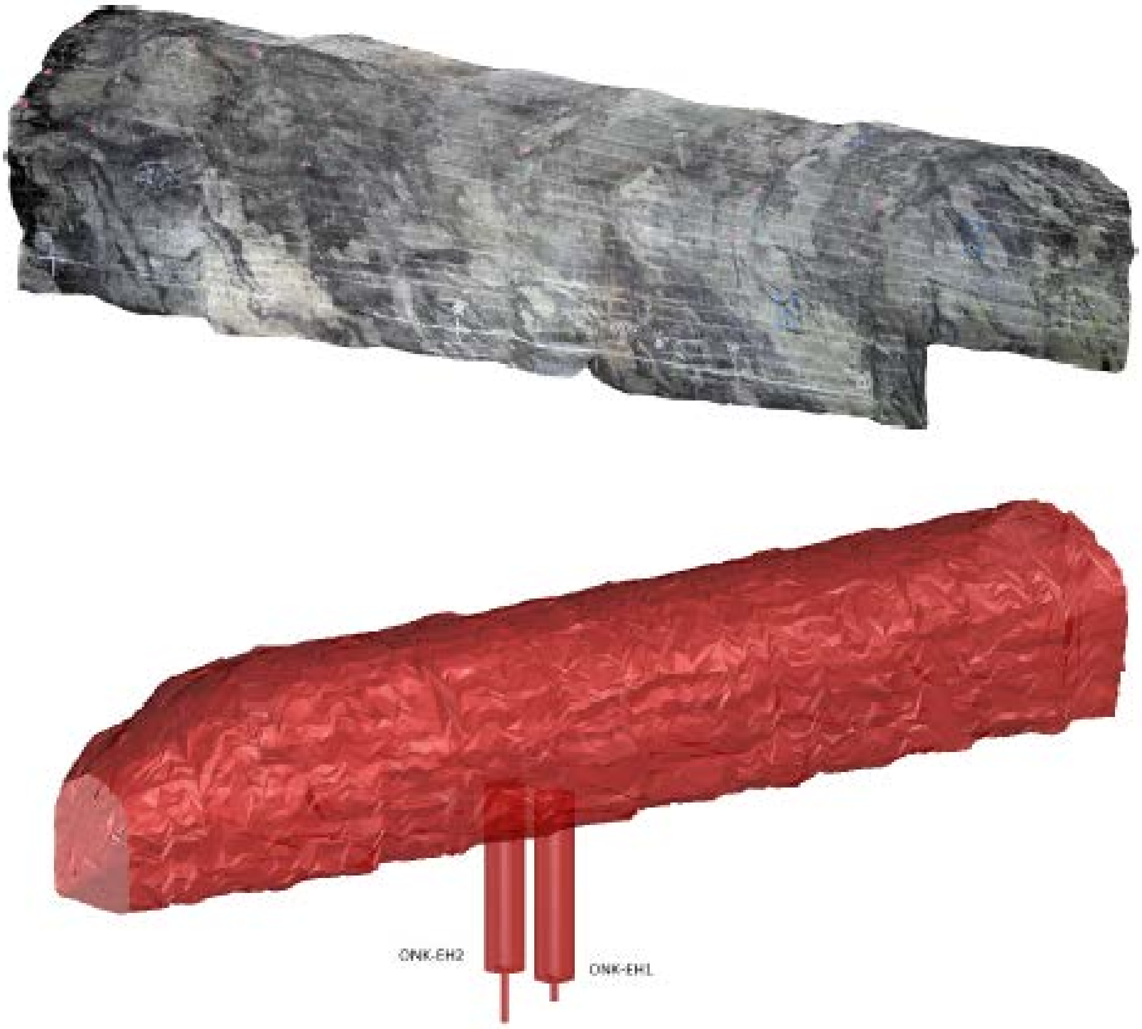

Figure 3-43. Photogrammetric imaging of ONK-TKU-3620 investigation niche. Technique uses partially overlapping high resolution images and tie points to compute a 3D point cloud which can be rendered to a 3D image (top) and 3D surface or solid model.

Known laser scanning or photogrammetric techniques can be used to resurvey the tunnels, to make comparisons on the reported initial surface, and changes in the surface, due to potential undeclared tunnels or spaces. Resurvey can be run using drone, vehicle, reconstruction of photos into point cloud, or using laser scanning. Photogrammetry can be used also to measure hyperspectral data to recognize differences in moisture (near infrared absorption) and temperature on the tunnel wall, or differences and changes in the materials on tunnel surfaces.

3.11 Nuclear magnetic resonance

Nuclear magnetic resonance (NMR) is technology which has developed in hydrocarbon exploration for measuring water or hydrocarbon content in porous space. Also, medical application in form of magnetic imaging is in active usage. From ground level, NMR have been used for groundwater resources exploration. NMR operates either with excitation of strong local magnetic field, turning the field on and off in rapid sequence, or with high intensity transient electromagnetic field. A transient magnetic field of specific high frequencies (associated with emissions from proton displacement), can be measured. The intensity and time decay of secondary field is used as measurement of water (or proton) content in the medium.

Nuclear magnetic resonance measurements (NMR) in drillholes have been recently developed available to slim (76 mm) drillhole diameter. A drillhole measurement can be used to measure water saturation immediately around the drillhole (Freedman and Heaton 2004). In case groundwater would be drained from unexpected locations in bedrock otherwise, being saturated with groundwater, the NMR method would be used to produce an indication of potential intrusion nearby. Again, survey cannot be conducted after closure of drillholes. Deep drillholes prepared to a further distance from repository volume, may be used for detecting volumes drained from groundwater due to a clandestine tunnel. A pre-measurement and comparison to repeat surveys would be best way to also apply this technique.

3.12 Muography

Muons induced by cosmic radiation in upper atmosphere can penetrate bedrock to depth of several hundreds of meters (Holma and Kuusiniemi 2018). Muon flux is inversely proportional to density of the medium above the recording station. Placing sensors below a target of interest, muon flux can be used in tomographic imaging of density variation in the medium located above. Imaging applies information collected from muons arriving from slightly varying directions, and multiple observation stations. Measurement requires long times to collect adequate number of muons into the sensors. Method is especially efficient in detecting presence of high-density material, even in a closed container, as the muons penetrate through any medium. Technique has been used to render imaging of interior of pyramids and other synthetic structures, and for example volcanoes. Applications have also been created for transillumination of cargo consignment to reveal trafficking of materials.

At a level of interest of repository volumes in the bedrock, a muon flow tomography can be used to map volumes of different densities. Lower density in an excavated, undeclared tunnel space would be detected with muography, using appropriate survey geometry. Limitations to application of the technique would be required density of sensors and need to install sensors below the level of disposal tunnels, where there is no accessibility other than existing deep drillholes.

Deep drillholes will be sealed and there is no possibility to leave there any permanent installations. In case sensors could be left in the bedrock, muography monitoring would be carried out as time lapse comparison tomographic surveys with specific time steps. Resolution is adequate to detect the presence of spent nuclear fuel canisters, and possible undeclared tunnels, required the sensor density is high.

Another applicable muographic method in nuclear safeguards would be using imaging at a gate to inspect that any specific material (of declared size and having relevant specific density) is entering the repository, and that no corresponding material would leave the specified repository area.

4 Discussion

Olkiluoto site monitoring has collected data which can be used for safeguards purposes. Current monitoring practices may be modified, or readily include data to provide also safeguards applicable information (Pentti and Okko 2018). Monitoring is likely to take place during construction of the repository, operational phase, during closure and at post closure phase. The reasons for monitoring will be ensuring safe operation and effective isolation of spent fuel from biosphere and ensuring contained nuclear materials would not be diverted to unknown purposes or nuclear explosives (Okko and Rautjärvi 2006). Practices can be further modified to conform information needs.

Currently microseismic monitoring (18 stations) is one of passive geophysical methods considered suitable for nuclear safeguards application in deep geological storage of spent nuclear fuel. Seismic monitoring in Olkiluoto is already running by the operator. It has adequate operational history proving detection and localization capability of excavation blasts to distances of several kilometers and within the repository construction area using traditional seismic event localization. Technique is based on recording and storage of events triggered on amplitudes exceeding criteria coherently on at least three stations. Method has been tested also in detection and localization of raise-boring, a vertical equivalent for application of tunnel boring machine. Correlation of coherent noise envelope emerging on continuous, low energy level, would require recording and storage of complete time series, at least until processing would have been completed. Micro-seismic monitoring has also been used in detection of seismic events, either natural tectonic and stress-field originated, or events induced by ongoing excavation and stress-field redistribution.

Seismic monitoring is safeguard-relevant, and it can be continued over long time periods. On the other hand, this method, or any other locally applied sensor-based monitoring method, is excessive cost, demanding to implement, and requires expertise involvement. Method might be remotely controlled. There would remain questions to be resolved, regarding how long the monitoring and maintenance of measurement array would be carried out (not indefinitely long), and who would be the responsible party to carry the activity (operator, state, or international agencies).

The construction and operation phases offer limited access into close area of the repository, to make comparisons between baseline and verifying measurements. During construction and operation of the repository, maintenance work is necessary for operational safety. Maintenance may include annual scaling off loose rock slabs from walls and ceiling, inspection and renewal corroded or loosened reinforcement bolts and mesh at 10 - 20-year interval, and maintenance of shotcrete lining or drainage between liner and bedrock surface. Also access route draining of groundwater seepage is likely to require maintenance activity for pumping, settling pools, and leading the excess water. These activities are likely to cause changes in shape of the wall, require reporting (declaration), and confirming measurements with laser scanning using either total station, or vehicle or drone-based scanning or photogrammetry, can be applied to monitor immediate changes on tunnel surface. These can include hyperspectral measurements of temperature, moisture, or other indicators of undeclared activities.

Measurements may join also near infrared or temperature observations. Some of the activities will also cause mechanic noise, which will produce events in seismic network, and would require explanation. Spontaneous post-excavation microearthquakes, in case occurring immediately near the tunnels, would need to be controlled and explained in design information verification as well.

Similar development of monitoring, based on continuous gathering of data, may be applied to detect changes in groundwater pressure level (hydraulic head). Hydraulic pressure field can be used to detect an intrusion to repository volume, especially when compared to land use monitoring information.

Instrumentation of drillholes with sensors require special expertise in selection of the monitored drillhole intervals of fault interception. The hydraulic sensors need to be installed in packed off sections in drillholes, typically intercepting defined hydrogeological zones in bedrock. These drillhole installed sensors can be used during disposal operation. In case the holes would be permanently sealed during closure of the repository, alternatives may remain to install sensors into purpose-made drillholes, preferably outside of the repository volume, to detect undeclared intrusion after closure.

Installation of piezometer or pressure sensors require also skilled personnel, as well as maintenance or replacement of such systems. Though monitoring, data storage and management, and analysis can be carried out also remotely, there remains question also on hydrogeological monitoring, that who shall have responsibility on the operation, and over how prolonged period. It might be feasible to suggest that operator would monitor recovery of groundwater saturation within the repository over some specified time after closure. Understanding the pressure field responses may also need special expertise, both in form of classifying the different form and amplitude of events, but also explaining their origin, requiring reference to numerical simulations. Hydraulic monitoring does not enable localization of events. After sealing of deep drillholes, monitoring cannot be continued, and sensors maintained within the perimeter of repository volume (to be defined).

Measuring or monitoring temperature changes, or changes in groundwater pressure field, may be one applicable technique. A proven technology to detect post excavation microseismic activity, or direct excavation attempt, is the passive seismic monitoring network. Efficient application of any of these monitoring techniques would require maintaining a sensor network at least in part of the repository if possible. For use of temperature monitoring in safeguards surveillance, a drillhole needs to be close (20 – 25 m) to an undeclared engineered space, be available for measurements, and adequate time must be passed after excavation to make the thermal effect detectable. A continuous monitoring of temperature would require permanent installation of thermal sensors, like optical fibre, into a drillhole.

Actively operated geophysical characterization methods are capable in localizing activities in the bedrock, considering their limitations with respect to range, resolution, and involved contrast in the physical parameters on where application of each method is based on. Several techniques exist. Most of these have limitations related to survey range and resolution. Applicability would be best at close range from existing tunnel surfaces. Standard processing techniques are not adequate to be successful in tunnel detection.

Comparison of baseline and repeat measurements might be best practice to detect undeclared tunnels. Selection of methods, measurement parameters, design of field survey, and processing practices as well as using the results are likely to demand highly experienced specialist personnel. Potentially a set of instructions, including how-to description on applicability, would be useful.

These methods may be implemented for design information verification during construction of the repository, in ensuring that there would not be deviatory activities from and within the repository, potentially carried out by the operator. Depending on method, application may be either continuous, applied systematically and frequently, or applied on demand at specific locations. Possibilities would be also to use geophysical methods in proofing of absence of attempt for external intrusion, again by operator or by a non-specified party. This kind of monitoring can be based on GPR or its drillhole application at close range, seismic reflection methods to gain further range and resolution, or various passive potential field (thermal, magnetic or gravity) or diffuse active source field methods (electrical or electromagnetic). Other possible tunnel or drillhole based close range methods, which are not applied in ONKALO characterization, but might be used in 10 m range to detect tunnels, are gravimetric survey (density contrast, does not require metal reinforcement), magnetic survey (requires steel structures), electromagnetic frequency or time domain survey (requires electrically conductive reinforcement), or surface wave seismic methods (passive or active; Fedin et al. (2020) demonstrated that surface waveforms may be used to detect cavities within rock mass to distances of tens of metres). Each of these methods would benefit of prior forward modeling, pre-survey for baseline to be compared with repeat survey, and then modeling or inversion to deduce location of potential changes in tunnel surface. However, resolution and depth extent of either refraction seismics or ERT are not adequate to detect an unanticipated tunnel excavation deeper than few tens of metres from surface. Method combination might be applied from tunnel, during operation stage (before closure of the site).

Application of any of these methods from tunnels will cease on closure of the repository. Electrical tomography can be used either as cross-tunnel or crosshole measurement, or as resistivity tomography sounding from tunnel surface to different directions (downwards or sideways) and might be used to detect a steel reinforced tunnels to distances of 10 to 20 m from the tunnel.

Best resolution to detect undeclared underground spaces from underground would be from the tunnels during operation and before the backfill of tunnels. Range of detailed observation is short (with GPR 0 - 10 m, using seismics 100 m). Other possibility is to use existing ground level based deep drillholes or tunnel based drillholes which are closer to target. The drillholes will be sealed for long term nuclear safety reasons soon, even before startup of operation, or latest before backfilling and closure. Location of existing drillholes is limited regarding survey coverage and can be used only at some selected locations.

GPR measurement can be used from exposed rock surfaces to distances of 10 m using 250 – 400 MHz tools. The currently available 32-bit data dynamic, and modern hyperstacking (introduced by GSSI brand), are enhancing signal to noise ratio, detectability, and range up to 30-50% compared to past performance. Lower frequency has theoretically better depth penetration, but large size of antenna causes ringing from irregular rock surface, and weaker shielding of antenna causes further problems with tunnel reflections, for which reasons the 250-400 MHz frequencies seem optimal to rock characterization and to tunnel detection. Metal reinforced tunnels would be more easily detected than non-reinforced.

Review considered different borehole, ground, and tunnel investigation methods, considering the Olkiluoto bedrock conditions. During the time, it was recognized that GPR would imply severe limitations even in Olkiluoto crystalline bedrock conditions. In favourable situation, without presence of strongly attenuating minerals which occur sporadically in layers in Olkiluoto migmatite, the range with GPR is limited to some metres to few tens of metres with lowest applicable frequencies. Also, it was concluded that application of the method would require expertise on the target, and on processing, though the GPR method itself consists of industry standards, is well documented, non-intrusive, quick to implement and possible to run by non-expert though well-trained inspection personnel. GPR can be used in detection of underground excavated spaces in certain conditions, but contain also ambiguity in results, and may lead either to false alarms, or may not detect the anticipated undeclared activities even when existing. Apart of range of investigation, limitations are set by unfavorable survey geometry (dead angles), and bedrock conditions: strong attenuation due to conductive bedrock, abundant natural reflecting or diffracting events masking the anticipated target, and sensitivity to tunnel related interferences like metallic objects, electrical installations, uneven surface, and support structures which may suppress the GPR wave in total. Most applicable the GPR method would be in salt formations, dry or fresh water saturated non-conductive ("granitic" or metamorphic) bedrock. Least favorable conditions include sedimentary rock mass, presence of abundant porosity and water content, especially with saline water, otherwise conductive bedrock due to mineral content, or metal containing support structures. Only partial coverage for verification is possible.

Seismic methods have largest distance penetration from the tunnel surface (up to 100 m), and these can be applied both on lining, and from exposed rock surface. Detection of tunnels, which are creating diffracting events, would be requiring separately designed processing, compared to current survey techniques. For example, a permanent array of optical fibre, or geophones, might be applied to accumulate seismic noise as a source, and using interferometry, collect adequate level of accuracy to carry time lapse tomography to follow potential changes in subsurface. Seismic methods use established source and receiver techniques. The survey geometries and processing, focusing on specific target and directions, set demand for expertise. Survey requires multiple source and receiver stations in direct contact into the investigated medium. Preparation of source and receiver locations, assembling the sensors, running the survey, and moving to following location require more time, personnel and costs compared to GPR survey.

After the tunnels are backfilled and drillholes sealed, remaining possibility for monitoring would be active seismic 2D or 3D survey from ground level (with limited resolution from that distance), permanent seismic monitoring network (passive method), or groundwater pressure monitoring. It is unlikely that any permanent measurement systems could be installed and left operational in the storage premises after their backfill and closure.

After closure of the disposal site and backfill of the tunnels, the possibilities for design information verification are limited. Monitoring will provide data from undeclared activities, using seismic monitoring network and hydrogeological monitoring network on their remaining part. Sealing of boreholes for long term safety will lead to abandoning at least some of downhole stations. Alternative for existing operator driven monitoring systems would be an authority established monitoring or detection array, which would be installed outside of the repository volume, to not to disturb the performance of repository. Passive monitoring systems can be supplemented with active surveys, either repeated as campaigns or using permanently installed multiple sensor arrays. Most functionable remote sensing technique would be seismic reflection sounding, either from ground level, or to obtain higher resolution, supported by borehole sensors.

Ground based 2D or 3D seismic survey would be an only available active geophysical method to monitor underground tunnels immediately above the repository, after backfilling and closure of the disposal facility, though the resolution without drillhole data down to depth of 420 m may not be adequate in separation of new objects from existing ones. Detection of external undeclared activities after closure of the repository would be based on drillhole or ground level-based sensor network or repeated surveys. After sealing of the drillholes located close to the repository, drillholes located only further distance from the repository perimeter can be used for investigations. Simultaneously also the volume, or length of perimeter to be surveyed, would increase. Ground surface-based surveys alone are not likely to have adequate range and resolution to detect and localize undeclared activities but would require support from drillhole based sensors or measurements. Surveys can be carried out as campaigns, systematically at frequent time intervals, or again when required. Survey network would either be constructed ready before closure, and maintained, or prepared just before taking actual survey first time (saving resources). Survey network may partly apply a permanently installed, continuously operated and remotely controlled measurement system, and partly on-demand applied measurements.

An early warning detection system used after closure of repository would rely on passive seismic network in detection of excavation activities, and some combination of campaigns or permanently installed geophysical detection network to support localization. This network would need to be installed long distance outside of the disposal site volume, both not to disturb the integrity of repository, and to provide indication of intrusion in time to react to an attempt.

Seismic reflection method can be run from ground surface, and resolution can be enhanced with drillhole receivers, which can provide information at 100 - 200 m range radially around the drillholes. Passive seismic recording systems, applying environmental noise, may be used as a signal at least partly to support application of active source. Receivers on ground level and in drillholes can be based on optical fibre sensors, which provide spatial high coverage and permanently installed monitoring system for both active and passive source application. To enable complete coverage for seismic drillhole survey, drillholes should not be located further than 300 - 400 m apart.

Drillhole radar has shorter, 20 – 40 m range around drillholes in Olkiluoto. Drillhole radar cannot be applied as permanent array of sensors, due to excessive cost of actively operated antennas and receiver system, and low availability of services on commercial basis. Application of drillhole radar would require drillholes located at 50 – 100 m range from each another to enable complete coverage in tunnel detection, making the workload and cost of survey even higher than for seismic survey.

Combination of actively run survey campaigns and passive continuous measurements can be carried out with various other measurement techniques and geophysical source fields. Magnetic field sensors are cheap, so these could be distributed at 5 - 20 m interval on length of a drillhole and connected to data retrieval system. Any notable change in magnetic field intensity near a drillhole would be considered as indication of an undeclared activity. Magnetic field sensors or electromagnetic coil receivers can be applied also in detection of electromagnetic secondary field, caused by a highly conductive metallic object near the sensor, induced in an active field of electromagnetic source. The source can be for example a long-grounded cable, or a large diameter wire loop, where a strong electrical impulse or an alternating current sweep would be transmitted. Recording of the field close to the target would make detection more feasible. Depth level, distance, and direction of cause of an anomaly could be defined from data.

Similar opportunity, though with slightly higher costs, would enable monitoring of temperature along drillhole. Optical fibre thermal sensor would retrieve instantaneously temperature profile from the full length of a drillhole. Temperature changes due to constructed tunnel in the nearby bedrock volume are a slow, diffuse process, which means the indication would not be as immediate as with magnetic, electromagnetic or gravity methods.

Each of these methods can be implemented also by running a single receiver measurement (logging) at frequent intervals along each drillhole. This would require mobilizing tools and measurement crew to the site each time the measurement would be carried out. Due to scarce availability of drillhole gravimetric sensors and commercial services, also drillhole gravimetry would require running as repeated campaigns.

Combination of different methods from same investigation area, for example survey line, can be useful for interpretation. Examples of useful combined application of resistivity and seismic survey have been demonstrated for example in geotechnical investigations (Ronczka et al. 2017). Partially depending on methods and sensor technology, several different surveys can be run in same drillholes and even using same kind of sensor technology (magnetic and electromagnetic, thermal, and seismic), only the active source technology and receiver tool would be different. With permanent installations, either all relevant sensors would need to be installed in a drillhole chain at same time, different drillholes prepared for separate sensors, or space be separated for supplementary survey run.

Each of possible geophysical technique would benefit or require use of baseline survey, where the repeat measurements would be compared. Forward modeling to understand relevant responses would be necessary. Any active survey technique needs to be supported by land use analysis and for example hydrogeological and seismic network monitoring. Existing surveys using active measurement techniques do not have a complete coverage of baseline investigations covering the whole of the site. To be used for comparisons, such baseline data should need to be produced for more limited coverage near the target area, or at the implementation of a monitoring (alarm) network. This means that application of any of the methods for design information verification, would rely on comparing of the reported layout of tunnels to measurement observations, or to carry out several survey campaigns during time, where the previous (first) survey results would serve as baseline.

In case an undeclared activity or deviation from design information would be detected, a procedure would be needed how to handle the occurrence. Alarm threshold for each observation class would be necessary to be defined. Should the event require counterchecking to revive trust on absence of deviatory activities, specific detailed inspection in the tunnel, or other, remains to be designed. Inspections may rely on already available monitoring network, using for example the ongoing excavation and construction work as a source of seismic signal. Would the existing microseismic network be adequate for receiver station coverage or requiring to be supplemented by denser receiver array, remains a topic for further considerations. Application of construction work as a seismic source is an existing technology. Example of feasible survey and processing technique are presented by Nagra (Blümling et al. 1990), Tsavaras et al. (2008), Amberg (Krüger et al. 2009) and Pöyry (Chwatal et al. 2011) in their different applications.

Active geophysical survey can be used at different geometries and in various stages of disposal as remote sensing of the rock volume surrounding the repository. GPR can be applied for DIV during operation, at close 0 – 10 m range from tunnel wall and floor, to detect undeclared engineered spaces. GPR reflection measurement is quick to implement, cost effective, and does not require specialist driven planning or implementation, taken that serious range limitations will be considered. Alternatives for GPR at similar, or slightly deeper range are other electromagnetic methods and electrical sounding (tomography), which have less resolution. Seismic reflection methods from tunnel have significantly larger distance range up to 100 m, but the design and implementation of method is slower, more expensive and requires high expertise. Each of the methods would rely on repeat surveys to detect undeclared activities. Application of any of the tunnel-based measurements near the target is not possible after backfilling and closure of the site because measurement requires access to the close distance from target on tunnel surfaces.

An early warning detection system outside of the repository would rely on passive seismic network in detection of excavation activities, and some combination of campaigns or permanently installed geophysical detection network. This network would need to be installed outside of the disposal site volume. Borehole radar has short, 20 – 40 m range around boreholes. Seismic reflection method can be run from ground surface, and resolution can be enhanced with borehole receivers, which can provide information at 100-200 m range around the boreholes. Passive recording systems, applying environmental noise, may be used as a signal at least partly to support application of active source. Each of possible geophysical technique would benefit or require use of baseline survey, where the repeat measurements would be compared.

Table 4-1. Remote sensing active geophysical methods and their application possibilities for safeguards.

Method	***Stage***	***Maximum range (in Olkiluoto)***	***Time for usage / 100 m***	***Cost range/ 100 m***	***Note***
Ground penetrating radar (GPR)	Construction, operation, DIV	5 – 10 m from tunnel surfaces	½ days	1 - 2 k€	Already considered as a method. Frequencies 100 MHz to 2.6 GHz. Lower frequencies require development in tunnel application. Range limited by rock mass electrical conductivity. Not applicable through shotcrete. Baseline relying on design information.
Drillhole radar	Construction, operation, DIV	5-10-20-50 m from drillhole depending on frequency and conditions	1 day	2-5 k€/ 10-20 k€	Unique non-commercial tools, development potential. 20…250 MHz. Underground drillholes may not be available.
	Post closure	20-50 m from drillhole in Olkiluoto	1/2 day	10-20 k€	20/60 MHz. Drilling of new holes min. 100 €/m.
Gravity	Construction, operation, DIV post closure, surveillance	Tens of metres (30-80 m) from tunnel or drillhole	1 h	1 k€	Detection of voids. May benefit of baseline survey and comparison to repeat.
Magnetic	Construction, operation, DIV. post closure	Tens of metres, from tunnel or drillhole, directional	1 h	1 k€	Detection of magnetic support structures or excavation machinery.
Electromagnetic (frequency or time domain)	Construction, operation, DIV.	Tens of metres from tunnel or drillhole, directional	1 h	1 k€	Detection of conductive support structures or excavation machinery
	Post closure	Tens of metres from drillhole, directional	1 day per drillhole	5 k€/ drilhole	Detection of conductive support structures or excavation machinery. Large (powerful) source on surface, time domain drillhole measurement
Resistivity sounding (ERT)	Construction, operation (DIV)	20-30 m from tunnel surface	1 day	4 k€	Detection of conductive support structures. Weaker resolution than with reflection methods
	Post closure from surface	c. 100 m max	½ day	2 k€	Resolution can be enhanced with drillhole recording or crosshole array.

Seismic refraction and surface wave measurement	Construction, operation	c. 20 m	1 days/ 100 m line	>10 k€/100 m tunnel line	Land streamer or attaching sensors to surfaces. May use surface waves, P and S waves
Seismic reflection	Construction, operation (DIV)	c. 100 m	3-5 days/ 100 m line complete imaging 1 day/ 100 m VSP geometry	>100 k€/ 100 m tunnel line 2 – 3 k€/ VSP survey few sources	Sensors and sources need to be attached on surfaces to get proper signal, either sources or receivers 1-2 m offset from tunnel surface to avoid ringing. Land streamer downwards may be tested. Sparse source array (VSP) more cost effective (full waveform)
	Post closure 2D lines from surface	400-1000 m	1-3 days/ km depending on resolution	30-100 k€/line km	Would be enhanced by borehole recording, best survey geometry is crossing tunnel trend.
	Post closure 3D from surface	400-1000 m	30 days	500-1000 k€ campaign/ 0.5 sq-km	Larger area and entity, directional information
	Post closure from drillhole	200 m radius around drillhole	5 days/ drillhole, acquisition rate may develop using optical fibre sensors	50 k€ /drillhole, drilling 100 €/m	Directional reflection survey using surface sources, limited coverage. Can be used as combination of 2D/3D ground survey. Permanent, dense receiver installation using optical fibre.

5 Summary

Nuclear safeguards are requested to timely confirm non-diversion of any significant quantity of nuclear (fissionable) materials from civil inventories for preparation of nuclear explosives or to any other unknown purposes. Traditional safeguards measures have included bookkeeping of nuclear materials, frequent checking, and uninterrupted monitoring. Geological disposal of spent nuclear fuel is setting challenge to these measures.

After applying containment and surveillance (C/S) for tracking the route of fuel to emplacement and keeping continuity of knowledge (CoK) there will be no direct control of the materials or that of the containers. Therefore, indirect methods have been proposed to safeguard the repository. The “Role of Geophysics” in safeguarding geological repositories has been discussed over the years, since they provide information about the suitability for disposal, i.e., fracturing in the site geology. These methods can also confirm the absence of undeclared tunnels or rock spaces at the site-dependent detection range of a specific method. They also can detect deviations from the reported repository design. In addition, repeated surveys or monitoring can reveal changes in the rock mass and thus provide alarms about undeclared activities.

The design information delivered by operator and verified accordingly may offer an opportunity to provide credible assurance on absence of undeclared activities in the facility. Frequent design information verification (DIV) works as confidence building on that during operation, there would be no breaching of integrity of repository boundaries. Definition of such a boundary is one of critical future questions. After closure of repository, maintenance of a historical information on repository would become an issue. Any comparisons would be based on existing information about the layout.

Monitoring at the repository provides concrete means to detect possibility of undeclared activities. Possibility of early detection is likely to deter an attempt to diversion of spent fuel. The microseismic monitoring will serve in detecting and localizing excavation by drill and blast method, and noise generated by full face boring machinery. Other monitoring measures like hydraulic head measurement, electrical energy application monitoring, etc. can provide warning on occurrence of undeclared activity. Monitoring, however, does not provide information on shape and size of excavations related to potential undeclared underground activities.

Geophysical surveys during spent nuclear fuel disposal site characterization would initially serve as source of geotechnical data, used for geological description, related geometric models, and parameter data. The data can be further used in site understanding and for baseline information in later safeguards-relevant similar activities. Geophysical surveys can be used in design information verification best in case the interpretations would be compared to known design, which would be verified before bedrock support means like steel bolt or mesh, or concrete liner installation. Ground penetrating radar (GPR) from tunnel surfaces using 100 – 400 MHz frequency would apply from areas which are not covered by a liner, and in Olkiluoto conditions could be applied to distances of 5 – 10 m from rock face. GPR is a cost effective, rapid and a method easily implemented by small crew of personnel, using industry standard tools, and not requiring highly skilled operator in design and implementation. Lower 20 – 60 MHz frequency drillhole radar has greater range of investigation. Deeper penetrating (lower 10 – 50 MHz frequency band) GPR application is sensitive to interference from tunnel surfaces and installations and would need development work to be used successfully.

Reflection seismic soundings using different survey geometries can be used also at areas which are covered by metal reinforced concrete liner or other support structure. However, designing and running seismic survey in tunnel conditions, and making an interpretation of the results, is a demanding expert task, and tools, though commercially available, are both bulky and demanding to be handled properly. Measurements for a 100 – 300 m tunnel section with preparations can take time of working week and cost several tens to several hundreds of thousands of euros. However, properly conducted seismic reflection survey can be used to detect an undeclared tunnel to distances of more than 100 m from the survey location. Seismic survey needs a contact to investigated medium. Coverage of the survey needs to be carefully considered in design and processing. Interference from tunnel generated waveforms would need also special attention to be suppressed from the results. Critical issue would be also considerations on false or true alarm threshold: what is seen in imaging and deemed potentially deviatory, and what could not be detected.

Other geophysical survey techniques with moderate resolution and depth range, capable to detect tunnel or void, or related machinery and installations, would be gravimetric profile measurement, magnetic profile measurement, electrical sounding or electromagnetic profile measurement or sounding. Each of these methods is slower and more costly than GPR, imply lower resolution, but deeper penetration, and would be more cost effective than a full seismic survey. These surveys have smaller range of investigation and less resolution than seismic reflection method. Neither of these surveys can detect actual location of a tunnel directly but require forward modeling to resolve and understand the results. To avoid risk of false alarm caused by anomalies from existing tunnels or natural, already existing sources, a baseline and repeat type of survey would be most feasible.

Any of these methods cannot be applied effectively after the closure of the repository from greater distances, as the distance compared to size of potential objects would be too long, and thereafter resolution of the adjacent objects too poor to detect would there be new objects compared to existing data.

Some of the geophysical methods can be applied remotely but from close range (that is, neighboring tunnel section), to indicate presence of anomalous object associated with emplaced capsule, though a favorable indicative electrical, GPR or seismic anomaly cannot be considered as a proof of presence of capsule. Also, a false negative observation, that there would not be an undeclared tunnel near the disposal volume, cannot be completely certain in any circumstances.

In case the design information verification shows relevant differences to layout and construction data declared by operator, application of geophysical methods would require more complete coverage of surveys and checking of possible multiple sources of unknown anomalies by drilling (which may not be allowed as being a potential risk for repository integrity). Most if not all of anomalies would be of natural bedrock origin. Alternative for relying on fuzzy interpretations would be repeat surveys, checking for the details in results remaining unaltered between baseline and repeat.

After closure and backfill of the repository, the geophysical methods may support the monitoring by assisting in control of avoiding breaching the boundary of repository (to be defined), if so desired. Potential design of alarm network of surveys around the repository would be costly and demanding exercise, though even such possibility would limit any attempt to diversion. Because for example the shortest length of tunnel towards the repository at 1:10 inclination would require over 4 km distance to be constructed by drill and blast or tunnel boring machine, and lasting several years, preparations for such activity, and operation would be recognized by surveillance of different activities and environmental conditions.

Tunnel preparation might be detected with electricity consumption, electromagnetic interference caused by machinery, or transport and storage of residual materials. Interference of local environmental conditions, for example in the sea water quality, may also reveal large non-reported underground construction work. A legal, purposeful excavation activity would require permitting and environmental impact assessment, which would be easily detected and understood already in design stage. Clandestine operation is unlikely to remain unnoticed.

In case these are not adequate proofing for what, geophysical soundings may detect the prepared tunnel, or absence thereof, by ground surface based seismic, electrical, or electromagnetic methods while closer than 50 – 100 m to the ground surface. Deeper than that, and closer to the repository boundary, implementation of geophysical surveys would require cross drillhole or drillhole to surface surveys and instrumentation. Instrumentation can be constructed to be permanent and data acquisition and processing at least partly automatized.

Seismic surveys between drillholes and between surface and drillholes have best detection capabilities, because the range is longest, radially up to 200 m from drillhole, the boreholes can be instrumented with optical fibre as elastic wave field receiver, and environmental noise can be partly used as source signal. Together with interferometric data processing and supplementing with timely repeated active source campaigns, survey could be applied for long term safeguards approach post repository closure. Other drillhole based detection of changes, like thermal, magnetic, or hydrogeological, are cheaper to implement and operate, though having shorter range and lower accuracy, and would need repeat surveys or permanently installed multiple sensors. Gravimetric survey, drillhole radar and electromagnetic surveys would require repeated drillhole measurements at specific time intervals or on demand, as installation of multiple permanent sensors of excessive cost and limited commercial availability would not be cost effective and feasible.

Any other method than seismic survey, like drillhole radar in Olkiluoto conditions, would require closer drillhole spacing in surveillance network and significantly adding up related preparing and operational costs. Range of drillhole radar would not exceed 50 m around the drillhole. Other geological environments, like salt formations, or electrically highly resistive granitic host rock, would be more favorable for drillhole radar to apply. Similar 50 m range for indicative detection and localization of changes in rock volume would be achieved by drillhole magnetometry for magnetized (iron containing) machinery or tunnel reinforcement, thermal logging for construction and ventilation caused temperature changes, drillhole electromagnetic sounding to detect electrically conductive tools and installations, or drillhole gravity to detection of voids. Hydrogeological groundwater pressure monitoring can be used to sense attempt of intrusion from even longer distances.

The drillholes required for measurements could be prepared to safe distance from repository as not to breach the integrity of repository and thus endanger the long-term nuclear safety, and preferably placed towards potential directions of intrusion. Problems related to of this kind of drillholes include that there needs to be some instance who would propose, place, and prepare these. Also, funding would be necessary if excess drillholes would be prepared. In worst case the repository hosting volume would need to be completely encircled with such an array. Geophysical “alarm fence” around repository would consist of for example 30 boreholes at 400 m spacing, 600 m deep each, at 2 km radius from the centre of the repository. This would be significantly contradictory to requirement of cost efficient, easily implemented safeguards-relevant survey method requiring minimal special expertise involvement, but bare existence of such possibility would be adequate to suppress attempt to intentionally breach repository integrity from outside of repository perimeter.

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