**Hard Rock High Resolution 3D Seismic Investigations at Olkiluoto, Finland**

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**Main objectives**

Verify continuity of the main seismic responsive features to 1 km depth and attain sufficient confidence in the geologic model of the Olkiluoto site, to support the plans for the construction of the final disposal repository for nuclear waste in Finland.

**New aspects covered**

First high resolution 3D seismic survey in Finland. Correlation and verification of a range of geophysical investigation methods and results, from borehole logs, through VSP to 3D surface seismics.

**Extended abstract**

Olkiluoto was selected as the site for the final disposal of nuclear waste in Finland. Currently, ONKALO, the access tunnel and underground research facility is being built at Olkiluoto. Since 1987, comprehensive geological and geophysical investigations have been performed at Olkiluoto for the detailed characterization of the disposal site area. Various seismic surveys were done, from surface and boreholes (Enescu et al. 2004), over a period of more than 10 years. A pilot high resolution 3D reflection seismic survey was acquired, for the first time in Finland, in 2006. High quality data led to very promising results, hence 3D seismic investigations were continued in 2007, over a larger area (Cosma et al. 2007). The 3D reflection seismic method proved instrumental for determining the geometry of rock features and ultimately building a geometrical model of the investigated rock volume, consistent with previous geophysical determinations in the area. Reflectors ranging from 100 m down to at least 3 km were imaged with accuracies of less than 10 m.
Introduction

Olkiluoto was selected as the site for the final disposal of nuclear waste in Finland. Currently, ONKALO, the access tunnel and underground research facility is being built at Olkiluoto. Since 1987, comprehensive geological and geophysical investigations have been performed at Olkiluoto for the detailed characterization of the disposal site area. Various seismic surveys were done, from surface and boreholes (Enescu et al. 2004), over a period of more than 10 years. A pilot high resolution 3D reflection seismic survey was acquired, for the first time in Finland, in 2006. High quality data led to very promising results, hence 3D seismic investigations were continued in 2007, over a larger area (Cosma et al. 2007). The 3D reflection seismic method proved instrumental for determining the geometry of rock features and ultimately building a geometrical model of the investigated rock volume, consistent with previous geophysical determinations in the area. Reflectors ranging from 100 m down to at least 3 km were imaged. Zones or changes in the elastic properties of the bedrock, i.e. lithological changes or fracture zones, greater than about a meter in thickness could be imaged.

Objective

The main objective of the Olkiluoto site investigations and related research, over the years, has been to attain sufficient confidence in the plans for the final disposal operations. The investigations focused on the identification of bedrock volumes suited for the final disposal of nuclear waste and on the detailed definition of the properties of these volumes. Geophysics, and seismics in particular, has had a significant contribution to the detailed characterization of the planned repository host rock (Cosma et al. 2007).

Background

The Olkiluoto bedrock consists of multiphase deformed and fractured high-grade metamorphic rocks of various gneissic composition and igneous rocks including abundant pegmatitic granites. Ductile shear zones, brittle fault and fracture zones, and alteration domains are present at different scales cutting the fresh host rocks. Rock is covered by glacial till. Results from almost twenty years of site investigations at Olkiluoto have been recently gathered in four geological sub-models: lithological, ductile deformation, brittle deformation and alteration site models. (Paulamäki et al. 2006)

Several kinds of seismic investigations, from surface and from boreholes, have been used for mapping lithological contacts and structural features at Olkiluoto. Emphasis has been placed on mapping the continuity of such features between the investigation boreholes. 3D seismic investigations are especially suitable for this. A study of different 2D and 3D seismic high-resolution reflection surveys in crystalline environments has been done (Saksa et al. 2006) to evaluate the most suitable surveying methodology applicable at Olkiluoto. The main purpose of the pilot 3D survey has been to verify the performance of the 3D reflection seismic method in crystalline Finnish bedrock, in order to establish a suitable methodology for possible later surveys in the area and to produce a detailed image of the bedrock properties, while locating in space gently dipping features, their continuity and possible faulting.

3D Data Acquisition

The planned survey layout has been translated in the field by cutting lines for geophone installation and source paths. Stations were precision leveled using GPS. The fieldwork was carried out by Vibrometric and Uppsala University personnel. The seismic source was a VIBSIST-1000, using a hydraulic rock breaker, delivering ~2000-2500 J/impact, mounted on an excavator. Seismic signals were produced as a series of pulses, according to a specific pre-
programmed sequence. Impacts were repeated at a variable rate, from 200 to 800 impacts per minute (Juhlin and Cosma 2007).

A subsurface area of about 650 m x 600 m was covered by the survey using a fixed receiver array (see Figure 1). 469 sources were recorded from 270 active geophones (Juhlin and Cosma 2007). The survey is considered a pilot study since the size of the subsurface area is small compared to the depth of investigation (1500 m) and the highly variable fold within the survey. Fold has proven to be a key parameter in obtaining high quality images of the subsurface.

![Figure 1](image)

Figure 1. Location of source points (red) and receivers (blue) for the 3D template (left). The 3D survey fold for 12 x 12 m CDP bins ranges from 30 to 180 (right).

Station and geophone location accuracy was better than 0.5m. Receiver line and station spacings were 60m and 24m respectively. The source line and geophone spacing was 100m and 10m respectively. At every source location several ~30s long sweeps were recorded from every geophone using the digital Sercel 408UL seismograph. The stack bin was 12 x 12 m and nominal fold varied from 30 to 180 (Figure 1).

**Data Processing**

Carefully designed processing steps were kept as simple as possible, to minimize the potential for artifacts on the results. Refraction and residual statics and choice of temporal filter had the largest influence. Estimation of the static corrections was demanding due to high velocity contrast and a noisy environment. The stack was relatively insensitive to the velocity used. DMO helped significantly in imaging dipping reflections. Low frequencies dominate on raw source gathers, masking potential reflections. After refraction statics the receiver gathers become considerably more coherent. P-wave velocity of 5400 m/s was used in refraction static corrections. Spectral whitening and band pass filtering removed much of the low frequency noise, but the air blast remained and amplitudes were still quite variable from trace to trace. Application of an air blast attenuation filter and trace balancing reduces this variability. Pre-stack automatic gain control (AGC) improved the results. After stacking, deconvolution was applied to sharpen the signal and 3D migration was done using DMO velocities to reduce diffracted energy. Depth conversion using DMO velocities was also done. The frequency range was 80-250 Hz. The processing results, in form of a 3D reflection cube is shown in Figure 2 a) and b) (Juhlin and Cosma, 2007).
Results

The 3D pilot seismic survey has shown that it is possible to acquire high-resolution seismic data in the Olkiluoto area. Reflectors from about 100 m down to at least 3 km were imaged. Mainly two groups of reflections were observed: (1) sub-horizontal zones of reflectivity at 200-300 ms (600-900 m), 450-550 ms (1350-1650 m) and 900-1000 ms (2700-3000 m), and (2) more distinct, but weaker reflections corresponding to structures striking nearly in the West - East direction and dipping 25º to 30 º to the South. The former group contains stronger and more undulating reflections, some of which may be offset, suggesting faulting. Dips greater than 40º are not present in this 3D cube due to the template design, the processing scheme and the small area covered (Juhlin and Cosma, 2007).

In the 3D cube, reflecting boundary data have been checked, as quality control with drillhole data to lithological contacts and shear or fault zones. A good match has been found, in terms of their location and orientation, between the mapped reflector planes and same features derived from the 3D VSP investigations, as shown in Figure 3 (Cosma et al. 2007). Marked reflectivity indications in borehole logging data appear precisely at the observed reflection positions in the 3D seismic cube, as it can be observed from Figures 4 and 5.

Processed 3D data has been transferred to Posiva’s geological modeling system and has already been used for refining the construction of the geological Olkiluoto site model.

Conclusions

The 3D pilot seismic survey done in 2006 at Olkiluoto was successful, with good quality data and results. The method proved cost effective with respect to resolution and imaged volume. Significant knowledge on the continuity of geological structures was gained in the process. The objectives of the pilot survey were met. Based on the results of this work it has been decided to continue with 3D seismic investigations in 2007, using a modified acquisition template. However, due to cost optimization, sub-optimal bin size was used. Stack fold greater than 30 is considered adequate for 3D seismic imaging at Olkiluoto (Juhlin and Cosma, 2007).
Figure 3. Inline and crossline slices through the 3D cube together with a 3D migrated VSP profile. Note a very good match of sub-horizontal reflectors mapped by the two independent investigations. ONKALO tunnel is shown with orange dotted line.

Figure 4. The apparent reflectivity in drillhole KR1 matches well with reflectors mapped in the 3D cube.

Figure 5. P-wave velocity variation in drillhole KR1 matches well with reflectors mapped in the 3D cube.

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References


