

## HIGH RESOLUTION REFLECTION SEISMICS INTEGRATED WITH DEEP DRILL HOLE DATA IN OUTOKUMPU, FINLAND

by  
*Suvi Heinonen<sup>1)\*</sup>, Ilmo T. Kukkonen<sup>2)</sup>, Pekka J. Heikkinen<sup>1)</sup> and  
Douglas R. Schmitt<sup>3)</sup>*

**Heinonen, S., Kukkonen, I. T., Heikkinen, P. J. & Schmitt, D. R. 2011.** High resolution reflection seismics integrated with deep drill hole data in Outokumpu, Finland. *Geological Survey of Finland, Special Paper 51*, 105–118, 8 figures and 3 tables.

The Outokumpu area, located in eastern Finland, is well known for its Precambrian Cu-Zn-Co-Ni-Ag-Au sulphide deposits hosted by ophiolite-derived altered ultramafic rocks. In 2004–2005, a 2.5 km deep research borehole was drilled on the south-east side of the main ore belt. The ophiolite-related Outokumpu-assemblage rocks were penetrated at depths of 1.3–1.5 km. The other main lithologies observed in the Outokumpu Deep Drill Hole were mica schist with biotite-gneiss layers (upper 2 km) underlain by pegmatitic granite. In May 2006, high resolution reflection seismic data with 4 m receiver spacing were acquired at the drilling site along two crooked lines to further refine the geological model of the area. The Outokumpu Deep Drilling Project provided an excellent opportunity to correlate high resolution seismic data with drilling results. The main emphasis in the processing of the reflection seismic data was put on static corrections. Substantial topographic variation and a significant velocity contrast between the glacially deposited overburden and the bedrock caused severe travel time variations in the near surface. Results achieved using static corrections carried out with the standard refraction method and using a tomographic approach were compared. Sonic velocity and density logs were used to calculate acoustic impedances and a synthetic seismogram, and theoretical calculations were compared with reflectivity observed in the seismic section. The results indicate that the host rocks of the Outokumpu type deposits are bright reflector packages that can be observed with reflection seismic techniques. The pegmatitic granite shows only weak reflection contrast with the mica schist, but it can be delineated as homogeneous, transparent domains, whereas the mica schist is internally more heterogeneous. A fracture zone at the depth of 967 m can be observed as a sharp sub-horizontal reflector.

Keywords (GeoRef Thesaurus, AGI): seismic methods, reflection methods, data processing, deep drilling, boreholes, well-logging, metamorphic rocks, physical properties, Outokumpu, Finland

<sup>1)</sup> *Institute of Seismology, P.O. Box 68, FI-00014 University of Helsinki, Finland*

<sup>2)</sup> *Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland*

<sup>3)</sup> *Institute for Geophysical Research, Department of Physics, University of Alberta, T6G 2J1 Edmonton, Canada*

\* *E-mail: suvi.heinonen@helsinki.fi*

## INTRODUCTION

In 2004–2005, a deep drill hole (2516 m) was drilled by the Geological Survey of Finland (GTK) in Outokumpu, eastern Finland (Figure 1). The Outokumpu Deep Drilling Project (2004–2010) was a part of the International Continental Scientific Drilling Program (ICDP). Outokumpu is a classical ore province in the eastern part of Finland that is well known for its sulphide deposits with economic grades of Cu, Zn, Co, Ni, Ag and Au. Sulphide deposits were mined from 1913 to 1988 (e.g. Peltonen et al. 2008). The origins of the deep structures related to the ore belt are still disputed, and one of the aims of the Outokumpu Deep Drilling Project was to further study the geology and physical properties of the rocks in the area (Kukkonen et al. 2006).

Seismic reflection sounding is a powerful tool to reveal subsurface structures at up to tens of kilometres depth. Even though the method is better suited to imaging subhorizontal structures of sedimentary areas, it has also proven to be effective in mapping the crustal structures of geologically more complicated areas (e.g. Juhlin et al. 2003, Roberts et al. 2003, Malehmir et al. 2007). The deep crustal structures of Finland were imaged by the FIRE (Finnish Reflection Experiment 2001–2006) project before the deep borehole was drilled. FIRE also included a high-resolution seismic survey in Outokumpu and the results of these soundings (Koivisto 2004, Kukkonen et al. 2006) were used to position the deep drill hole site.

The main drilling target was the uppermost unit of several semi-continuous bright reflectors dominating the upper crustal part of the seismic section (see Figure 2). The main lithology in the

deep drill hole was mica gneiss, and at the depth of the reflector the drill hole penetrated ophiolitic rocks of the Outokumpu assemblage. At the drilling site, the drilled reflector is in a subhorizontal position, but regionally it seems to form the upper part of an antiform structure (Kukkonen et al. 2006). In May 2006, another seismic survey was carried out near the scientific drill hole. In this survey, the geophone and source spacing was 4 m and 20 m, respectively, thus giving even higher resolution than the previous FIRE soundings with a receiver and source spacing of 12.5 m and 50 m, respectively. A vertical seismic profile (VSP) and surface seismic profiles were acquired by a group consisting of students and staff of the University of Alberta, University of Helsinki, Geological Survey of Finland (GTK) and the operational support group of ICDP. One of the aims of the survey was to acquire structural data for the upper crustal bright reflectors observed in the FIRE seismic soundings, directly linking these results to the deep drill hole that at its closest approach is about 400 m from the nearest FIRE survey line, OKU1 (Figure 1).

A detailed analysis of tomographic surface model used for static corrections of the Outokumpu data was reported by Schinjs et al. (2009). VSP results will be presented separately. In this article, we present the results of the processing and interpretation of the 2006 high resolution seismic reflection data from Outokumpu. The lithological interpretation of the data is based on the information obtained from the deep drill hole.

## RESEARCH SITE AND PREVIOUS SEISMIC SOUNDINGS

Outokumpu is a former mining town in North Karelia, eastern Finland. The Outokumpu area is located in the North Karelia Schist Belt, mainly comprising metasedimentary rocks (Figure 1). The area is situated in a large overthrust unit located to the east of the suture zone between the Archaean Karelian craton and the Savo Belt, a Paleoproterozoic Svecofennian island arc complex (e.g. Lehtinen et al. 2005). The main rock type within the research area is homogeneous, turbiditic mica schist with black schist interlayers. The rocks of the Archaean basement are TTG (tonalite-trondhjemite-granodiorite) gneisses and granitoids. Altered ultramafic mantle peridotite

bodies of the Paleoproterozoic Jormua-Outokumpu thrust zone extend over an area of ~5000 km<sup>2</sup> in eastern Finland. This ophiolite complex is not uniform, but consists of hundreds of massifs and fragments. Outokumpu Cu-Co-Zn-Ni-Ag-Au-sulphide deposits are hosted by this allochthonous overthrust complex. Outokumpu-type ores have an unusual lithological association and have gone through intense polyphase deformation and medium- to high-grade metamorphism as well as strong remobilization (Peltonen et al. 2008). The topography of the area is subdued and mildly undulating. Metamorphic bedrock is covered by Quaternary glacial sands and gravels. This over-

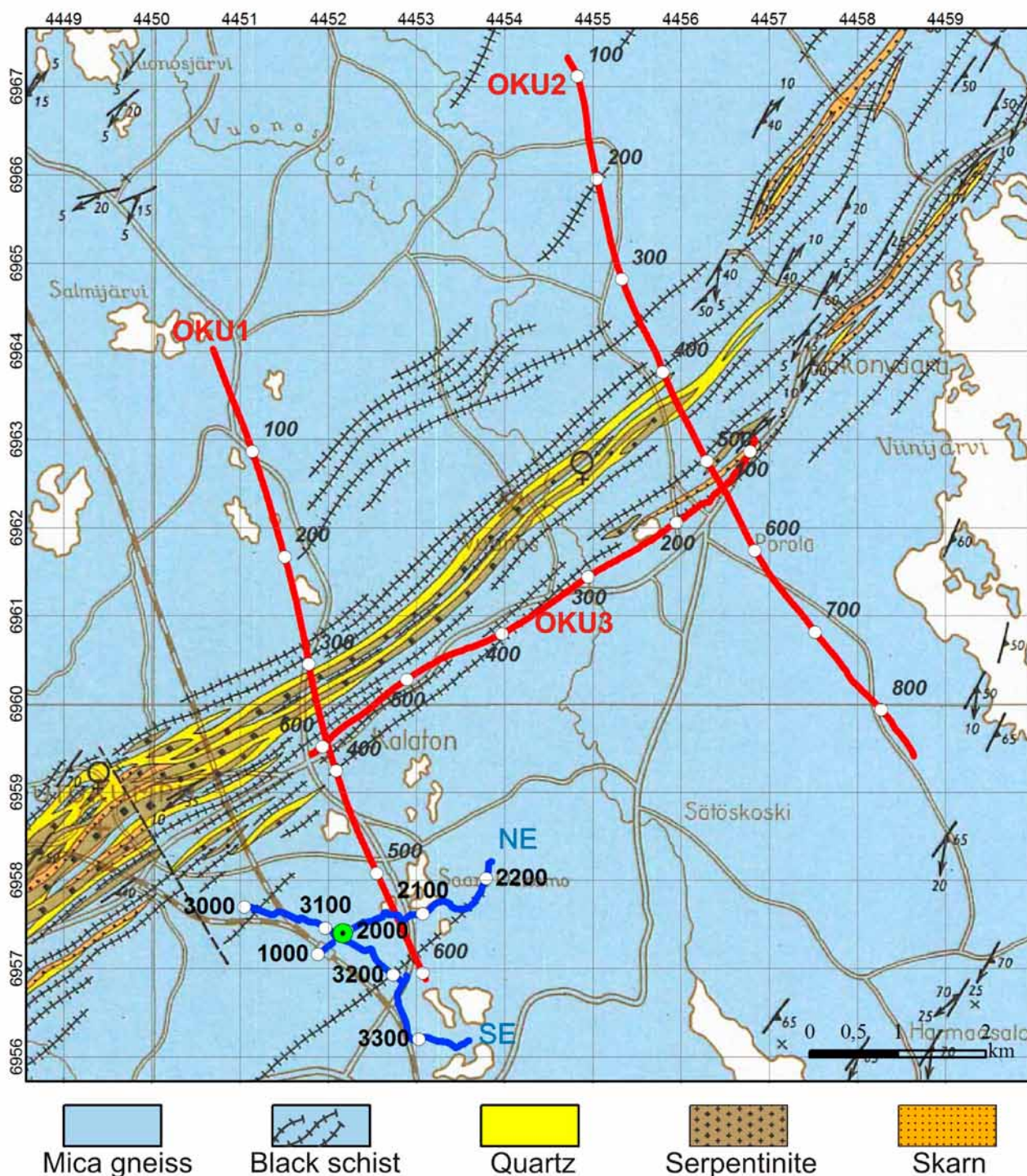


Figure 1. Survey lines of the May 2006 (blue lines) and FIRE seismic soundings (red lines) with CMP numbers shown on the geological map of Outokumpu (Huhma 1971). The location of the Outokumpu Deep Drill Hole is marked with a green circle.

burden varies primarily with the topography and is up to tens of metres thick; at the Outokumpu drill site there are 33 m of unconsolidated glacial materials.

As part of the FIRE project (Kukkonen et al. 2006), a high resolution reflection seismic survey was conducted in Outokumpu. These soundings comprised three lines (OKU1, OKU2 and OKU3) with total length of more than 30 km.

One of the lines was parallel and two perpendicular to the main ore belt (red lines in Figure 1). The seismic vibrator source was used to generate a signal with frequencies between 30–150 Hz. Receiver group and shot-point spacings were 25 m and 50 m, respectively. In the FIRE soundings, several strongly reflective units were detected, especially at depths of 1–3 km. At OKU3, running along the strike of the main ore belt, this reflectivity

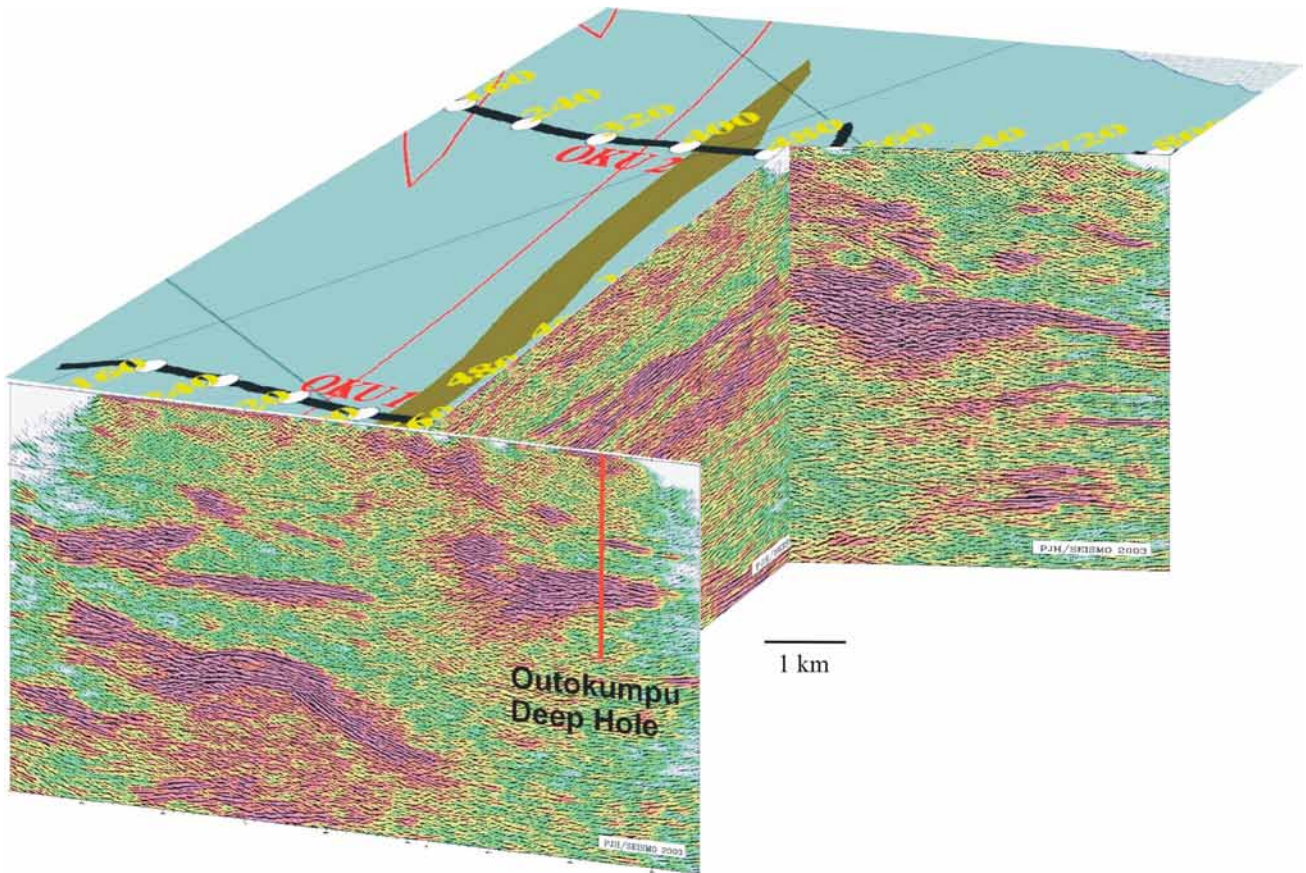


Figure 2. Reflection seismic profiles of OKU soundings and the location of the Outokumpu Deep Drill Hole in a 3D view. The background colours of wiggle traces present amplitude variations on a decibel scale with red hues indicating high values. There is no vertical exaggeration. The north is at left (see map in Figure 1).

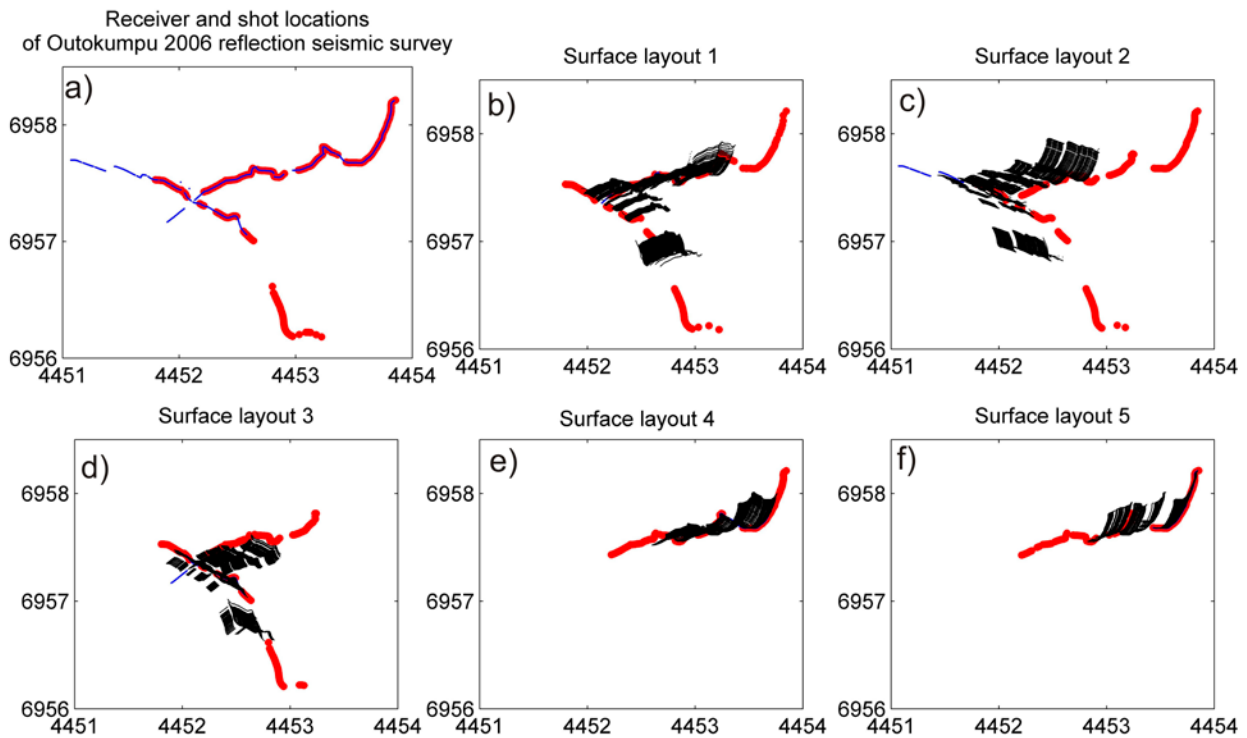


Figure 3. The shot point (red) and receiver (blue) locations of the Outokumpu 2006 survey are shown in a) at top left. The reflection seismic survey was carried out in five parts and the layout for each measurement configuration is presented in figures b–f. The calculated CMPs are plotted with black. The NE survey line has a uniform distribution of near- and far-offset data, but the SE survey line lacks the uniform CMP coverage.

was apparently horizontal and could be followed all the way between OKU1 and OKU2 (Figure 2). The reflectivity is probably caused by massive pieces of ophiolite-derived rocks in the mica

schist country rocks. These units appear to form a discontinuous belt, which emerges at the surface about 2 km northwest of the drill hole site and dips gently towards the southeast (Figure 2).

## DATA ACQUISITION

In May 2006, high-resolution reflection seismic data were acquired at Outokumpu (blue lines in Figure 1). A linear seismic vibrator sweep with a frequency band 15–250 Hz and a sweep duration of 8 s was produced with a 2720 ton force IVI Minivib™. The rough topography, surface waters and local culture forced existing gravel roads to be used as survey lines, and this resulted in a crooked line geometry. Both of the recording lines were about 2 km long, one of the lines radiates to the northeast (NE) and the other to the southeast (SE) azimuth from the borehole. The nominal shot-point interval was 20 m, although the local infrastructure and rough terrain caused gaps in the shot coverage, especially in the SE line. In order to increase the data fold along the SE line, a shot-point spacing of 10 m was used where vibrating was possible. A recording station spacing of 4 m with 216 active channels was used along both lines, giving the maximum spread length of 864 m. The measurement configurations for reflection

seismic survey together with CMP locations are plotted in Figure 3. Because of technical problems and time constraints, geophones could not be deployed along the far eastern end of the SE seismic line. The limited amount of data resulted in an insufficient fold for a conventional good quality reflection seismic stack, and processing and interpretation of the SE line are therefore not discussed further in this publication. The crossover point of OKU1 and the NE survey line (Figure 1) enables examination of the geological structures in 3D, even though the resolution of the surveys is different.

The spacing between the geophones sets the limit for the spatial resolution of the reflection seismic survey. The Fresnel zone, also used in classical physical optics, can be used to estimate the lateral resolution of the unmigrated seismic reflection data (Eaton 1991). At Outokumpu, the reflection response of the seismic signal was still detectable in frequencies as high as 200 Hz

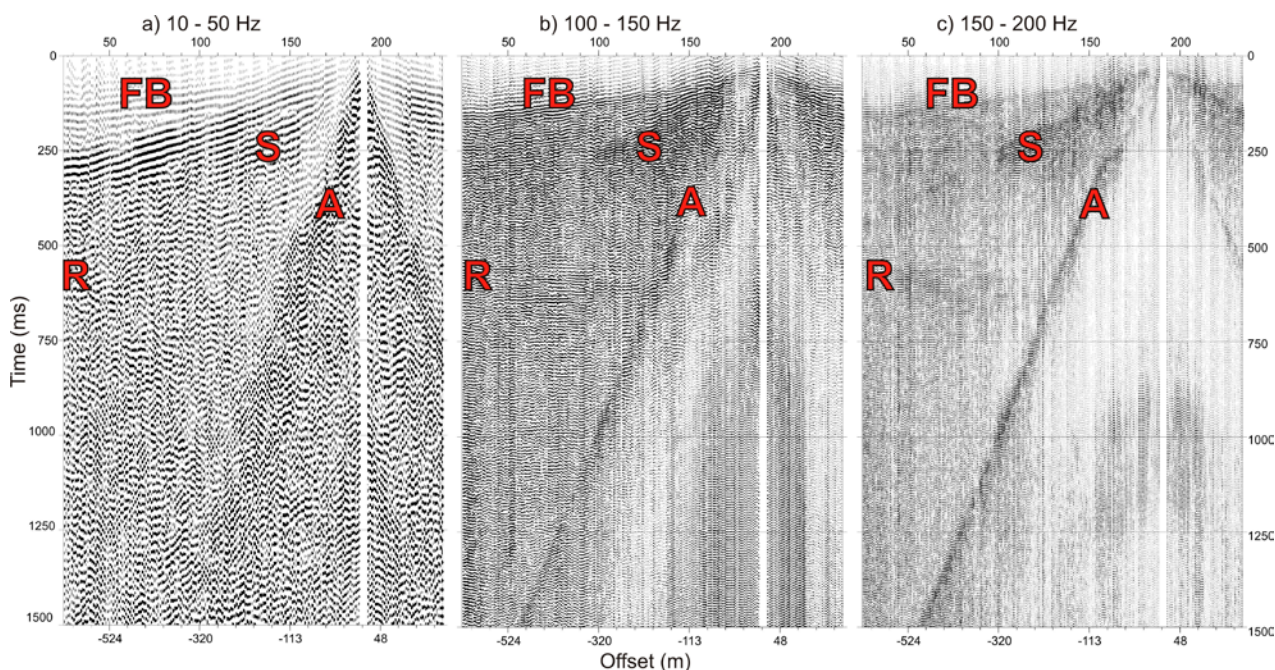


Figure 4. Unprocessed field record 2028 of the NE line (Figure 1) and the signal responses in different frequency bands: a) 10–50 Hz b) 100–150 Hz and c) 150–200 Hz. Seismic data were filtered with an Ormsby bandpass filter applying 10 Hz linear ramps. Reflection (R) between 500–750 ms is the most prominent reflector in the frequency band 100–150 Hz. The airwave (A) and surface wave (S) weaken the response at short offsets. The first arrivals (FB) are ambiguous at some locations.

(Figure 4), and thus we can expect to resolve bodies with diameters of approximately 235 m at a depth of 1 km assuming an average velocity of 5500 m/s. Smaller units might still be detectable, but they behave like a point sources. Malehmir et al. (2009) pointed out that if a reflective unit is of the same size as the dominant seismic wavelength, both diffractions and reflections occur. In addition to geometrical dimensions, the petrophysical properties of the rock unit also influence the re-

flectivity. The amplitude of the seismic reflection signal corresponds to the difference between the acoustic impedances (i.e. velocity-density product,  $Z$ , [ $\text{g}/\text{cm}^2\text{s}$ ]) of the rocks. In general, if the signal-to-noise ratio is good, the reflections are observable when the reflection coefficient is greater than 0.06 (Salisbury et al. 2000). This corresponds to a difference of about  $2.5 \cdot 10^5 \text{ g}/\text{cm}^2$  in acoustic impedance.

## PROCESSING OF THE DATA

The quality of reflection seismic data is primarily affected by field parameters and local conditions in the survey area. A crooked line geometry causes special challenges in the data processing and interpretation, as the reflection points are scattered over a wide area. In recent publications (e.g. Malehmir et al. 2009), sophisticated processing techniques and flows have been presented to overcome these challenges. The processing of the Outokumpu data was performed on the smoothed CMP line so that the processing line was as straight as possible but still close to the survey line. Special attention was paid to refraction static corrections; otherwise, a conventional processing flow (Table 2) was used in GEDCO Vista 7.0 software to produce the results presented here.

As in most reflection seismic data acquired in hard rock environments, the signal-to-noise ratio of Outokumpu data is rather low. In particular, strong ground roll causes severe problems and is usually attenuated by FK filtering, deconvolution and frequency filtering. Due to the dispersive character of the surface waves in the Outokumpu data, muting had to be used, as no other method produced satisfactory damping of these noise waves. Airwave muting also removed a substantial amount of near-offset data. This resulted in a decreased quality of the shallow part of the stack. The automatic gain control (AGC) and amplitude scaling proportional to  $t^{1.6}$  ( $t$  is time) were used to increase the amplitudes of the late parts of the seismic record, and a Butterworth bandpass filter was used to filter out the high and low frequency noise. The filter was kept broad, as the seismic reflections included very high frequencies (Figure 4). The signal response from the reflector at 500 ms TWT (two-way travel time) is most prominent at relatively high frequencies (150–200 Hz). At low frequencies, the noise dominates the data. At high frequencies (>200 Hz), the signal only penetrates the uppermost part of the ground,

and useful information on subsurface structures is not obtained. Spiking deconvolution was an important step in amplitude processing of the Outokumpu reflection seismic data. After deconvolution (operator length 70 ms), the number of multiple reflections was reduced and the shape of the reflection signal became sharper.

In Outokumpu, the topography is undulating and the glacially deposited overburden varies in thickness. The rough topography and variation in properties of the near-surface layer (thickness, density, seismic P-wave velocity) cause substantial time delays in the seismic signal, and static corrections were essential in producing a good quality stack of Outokumpu data. The velocity contrast between the overburden and bedrock is significant (~2500 m/s and ~5400 m/s, respectively). Careful static corrections are crucial in order to maintain the high frequency content of the seismic signal through the processing, especially stacking. The importance of the static corrections for hard rock surveys has been demonstrated in numerous articles (e.g. Bergman et al. 2002).

Spencer et al. (1993) used a tomographic model to calculate the time delays caused by near-surface layers, as refraction static methods failed to satisfactorily resolve static problems. At Outokumpu, static corrections for the reflection seismic data were carried out using a travel time inversion model of near-surface layers obtained from the VSP data. A detailed description of the method is provided by Schijns et al. (2009). The three-layered model employed the algorithm by Zelt (1992) with modified input parameters. The first layer of the model corresponds to the topmost glaciofluvial sand and till, and the second to a layer of glacial till. The overburden is underlain by mica schist representing the third layer of the model. Each layer has a varying thickness with laterally changing seismic velocity. Calculating static corrections using this method proved to be slightly

Table 1. Acquisition parameters.

Number of channels	216
Spread length	864 m
Receiver spacing	4 m
Geophone type	OYO Geospace™ 14 Hz (single)
Shot spacing	20 m
Source type	IVI Minivib™
Sweep	15-250 Hz, 8s
Sample rate	1 ms

Table 2. The main steps of processing the reflection seismic data from the Outokumpu survey in May 2006.

Sorting of SEG-Y files from 3 different measurement configurations
Reading of data to Gedco Vista 7.0 software and combining of SEG-Y files
Trace kill
Adding of geometry
Butterworth bandpass filter (30-50-230-250)
Amplitude decay correction ( $t^{1.5}$ )
Automatic Gain Control, AGC (500 ms)
Spiking deconvolution (operator length 70 ms)
Surgical mute of airwave and surface waves
NMO corrections
Static corrections to the final datum (Schijns et al. 2009)
Trace mix (5 traces)
CMP stacking
Stolt Migration
Time-to-depth conversion (5400 m/s)

better compared to results obtained by using a refraction static procedure of GEDCO Vista 7.0 software. The software employs the Hagerdoon's method in static calculations. Better continuity of the reflectors was obtained by using the near surface model (see Shijns et al. 2009).

Velocity analysis is challenging in hard rock terrains, where rocks are typically metamorphic and anisotropic and velocity varies both in lateral and vertical directions. Even though velocities are often uniformly high in crystalline crust (Milkereit et al. 1998), incorrect velocity values can easily lead to imperfect stacking and misinterpretation of subsurface structures. Velocity and density changes are independent of each other, and in some cases the cause of reflectivity is not the change in velocity but in density (Milkereit et al. 1998). As in the

pegmatite of the Outokumpu Deep Drill Hole, velocity and density may also change in opposite directions. This results in a lack of reflection contrast, although the geological contrast between the rock units is strong. Short offsets and high velocities made velocity analysis of the Outokumpu data unambiguous. Semblance analysis, constant velocity stacking and hyperbola fitting were simultaneously used for velocity analysis. VSP and sonic log data were used as a reference in order to obtain more reliable velocity estimates for normal move-out (NMO) corrections and migration.

After careful amplitude, static and NMO corrections, a five-channel trace mix was used to improve the coherency of adjacent traces before stacking. Post-stack Stolt migration was used to move reflectors to their real subsurface positions.

## DRILL HOLE DATA

The deep research borehole of Outokumpu was drilled in 2004–2005 by the Geological Survey of Finland (GTK) using the company NEDRA, Jaroslavl, Russia as the drilling contractor. The drill site is about 2 km to the south-east of the main ore belt, but the pre-drilling seismic sections suggested that the reflectors related to the ore belt continue to the drill site with a gentle dip. The diameter of the 2516 m deep drill hole is 220 mm. The hole tilts first towards the northwest and then to southwest in the shape of a loose spiral. The deviation from the vertical is usually only a few degrees, with the maximum deviation being 9.5°. The end point of the drilling was achieved about 250 m to the west-northwest of the starting point. The bottom of the drill hole is at depth of 2497 m in a vertical direction and the length of the hole is 2516 m.

The most common rocks in the Outokumpu hole are mica schist (1594.9 m), pegmatitic gran-

ite (462.1 m) and ophiolite-derived rock types of the Outokumpu assemblage, namely serpentinite, skarn and quartz rocks. The total thickness of biotite gneiss interlayers in mica schist is 169.6 m. Serpentinite (81.3 m), diopside skarns (29.8 m), quartz-feldspar schist (46.1 m) and black schist (38.9 m) are represented in about 10% of drill cores. The rock units of the hole according to Västi (2005) are presented in Figure 5. Ophiolite-related, altered ultramafic rocks and black schist are typical host rocks for the Outokumpu-type Cu-Co-Zn deposits. Pegmatitic granite observed at the bottom part of the drill hole was also observed earlier in the mines at Outokumpu, and it is present on geological maps to the NW of Outokumpu (Huhma 1971), but it was not expected to be as abundant as the results from the Outokumpu Deep Drill Hole indicated. The pegmatitic granite is likely to have penetrated deep faults and fractures of the Outokumpu area during the late

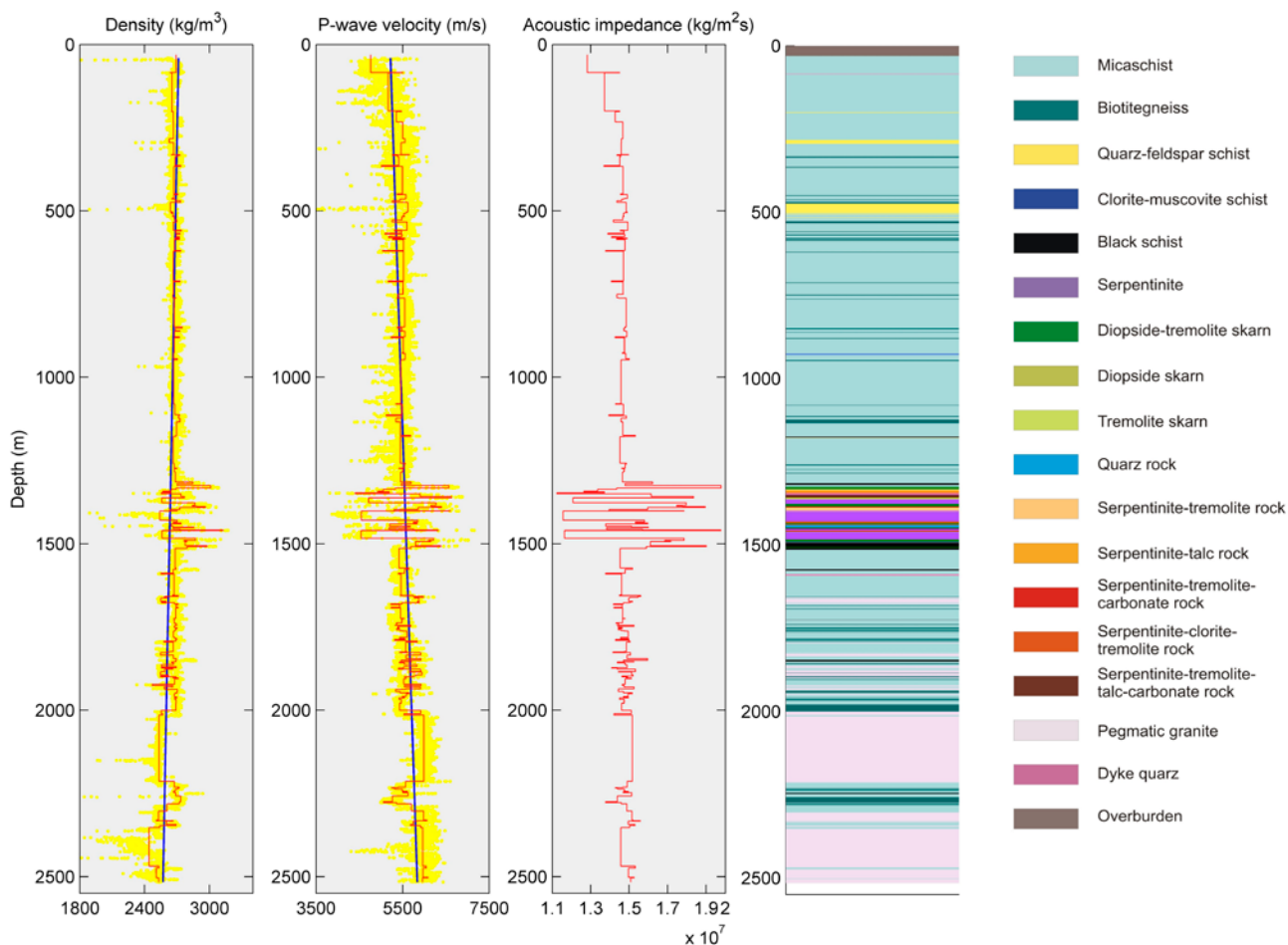


Figure 5. Densities and sonic log velocities measured in the Outokumpu Deep Drill Hole are presented in yellow. For each rock layer, a median density, P-wave velocity and acoustic impedance is calculated (red lines). The ophiolite-derived Outokumpu-assemblage of rocks at ~1.5 km depth has varying acoustic properties differing considerably from those of the country rock, mica schist. The lithological column is based on Västi (2005).

Table 3. Average physical properties of rocks from the Outokumpu Deep Drill Hole based on the logging data.

Rock Unit	Density (kg/m <sup>3</sup> )	P-wave velocity (m/s)	Acoustic Impedance (kg/m <sup>2</sup> s)	Total length (m) (number of data points)
Mica schist	2670	5477	1.462·10 <sup>7</sup>	1594.9 (7929)
Biotite gneiss	2700	5366	1.448·10 <sup>7</sup>	169.6 (845)
Quartz-feldspar schist	2631	5603	1.474·10 <sup>7</sup>	46.1 (232)
Clorite-muscovite schist	2668	5497	1.467·10 <sup>7</sup>	2.2 (11)
Black schist	2766	5749	1.590·10 <sup>7</sup>	38.9 (195)
Serpentinite	2570	4622	1.188·10 <sup>7</sup>	81.3 (409)
Diopside skarn	2929	6545	1.917·10 <sup>7</sup>	3.0 (15)
Tremolite skarn	2758	6607	1.822·10 <sup>7</sup>	4.9 (24)
Diopside-tremolite skarn	2854	6274	1.791·10 <sup>7</sup>	29.8 (147)
Serpentine-tremolite rock	2744	5818	1.597·10 <sup>7</sup>	12.1 (60)
serpentinite-talc rock	2651	5174	1.371·10 <sup>7</sup>	9.2 (45)
Serpentinite-tremolite-talc-carbonate rock	2734	5908	1.615·10 <sup>7</sup>	7.7 (39)
Serpentinite-tremolite carbonate	2814	6076	1.709·10 <sup>7</sup>	5.7 (29)
Serpentinite-clorite-tremolite rock	2721	5822	1.584·10 <sup>7</sup>	7.7 (39)
Quartz rock	2664	5314	1.416·10 <sup>7</sup>	7.2 (36)
Pegmatic granite	2531	5954	1.507·10 <sup>7</sup>	462.1 (2309)
Dyke quartz	2570	5500	1.414·10 <sup>7</sup>	2.5 (12)

stage of Svecofennian orogeny, and it is related to the Maarianvaara granite outcropping to the northwest of the study area (Huhma 1971).

Sonic log and  $\gamma$ - $\gamma$  density down-hole measurements with a 20 cm recording interval were made by NEDRA. The median density and P-wave velocity from logging and the calculated acoustic impedances are presented in Figure 5. Median presentation was chosen because the effect of single erroneous measurement values is insignificant, unlike when calculating arithmetic averages. The upper 1320 m of the drill hole mainly consists of mica schist and no dramatic change in acoustic impedance is present. In the depth ranges of 1315–1320 m and 1506–1514 m, black schist layers envelope the Outokumpu-association rocks. The internal structure of the ophiolite-derived rocks is dominated by alternating layers of serpentinite (low P-wave velocity and density) and skarn rocks (high P-wave velocity and density) resulting in rapid and strong variations in acoustic impedance, which is likely to cause a complex

reflectivity pattern. P-waves travel faster in the pegmatic granite than in the mica schist, but as the density change is reversed, the difference in acoustic impedance is not significant. The vertical velocity contrasts are influenced by the schistosity and layering-induced velocity anisotropy of the mica schist (Kern et al. 2009) as the mica schist is horizontally oriented in the drilled section. In Figure 6, densities and P-wave velocities measured from the Outokumpu Deep Drill Hole are presented in a density-velocity graph and in Table 3 the average values for each rock type observed in the borehole are provided. From Figure 6 and Table 3 it can be seen that layers of Outokumpu assemblage rocks (serpentinite and skarn rocks) are likely to cause strong seismic reflections when adjacent to any other rock units present in the deep drill hole. Reflections additionally occur inside the Outokumpu assemblage, as the acoustic impedance also varies dramatically inside the layer.

## INTEGRATED INTERPRETATION OF THE SEISMIC AND BOREHOLE DATA

In the interpretation of seismic data from the shallow crystalline crust, appropriate borehole information is often lacking (Milkereit et al. 1998). At Outokumpu, the information on the *in situ* densities and velocities of the rocks makes it pos-

sible to correlate reflectors of the seismic data with specific rock units as well as known fracture zones. Velocities and densities derived from full wave sonic and gamma-gamma logs, respectively, were used to calculate the acoustic impedances of

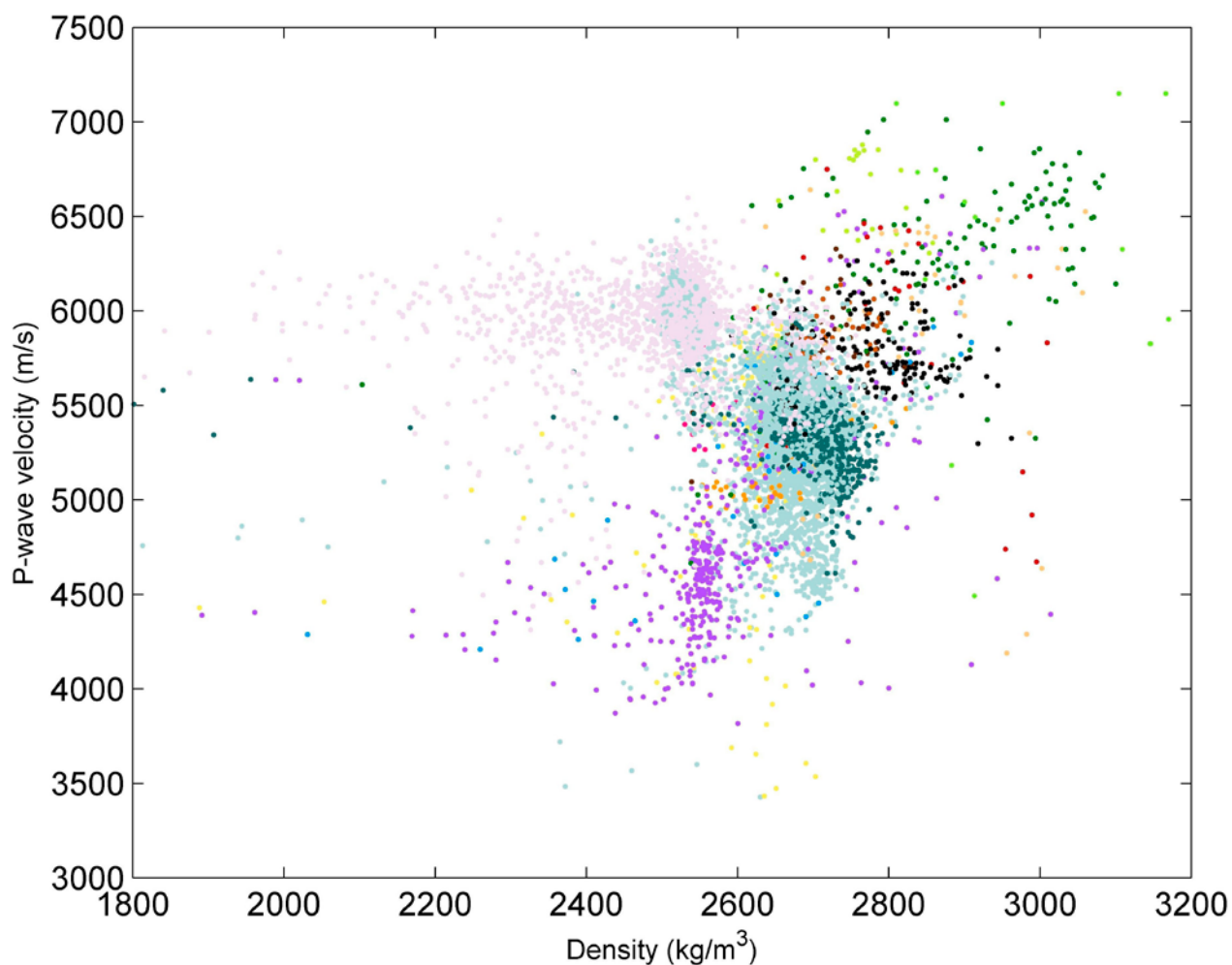


Figure 6. Down-hole measurements of different rock types of the Outokumpu Deep Drill Hole plotted in a density – P-wave velocity field. Colour coding is the same as in Figure 5. Rock types forming distinct clusters are expected to generate reflections in seismic soundings. The serpentinites of the Outokumpu-assemblage (lilac symbols) form a group with low acoustic impedance, whereas skarn rocks (green) have high acoustic impedances. Both rock types cause reflections when adjacent to mica schist (blue) or pegmatitic granite (pink).

the different rock units found in the Outokumpu Deep Drill Hole. It is clear from these calculations, and also from the seismic sections, that the Outokumpu association rocks generate a strong, complicated reflection pattern.

Reflection coefficients calculated from the logging data correspond well with the reflectivity of the NE seismic reflection line. However, the correlation between seismic and borehole data is not perfect, partly because the local infrastructure prevented soundings exactly over the drill site and the data coverage is poor at the end of the line. The western end of the CMP stack of the NE line is about 80 m from the deep drill hole site (cf. Figure 5). However, it is inarguable that the most prominent reflection at the depth of 1.3–1.5 km is caused by the rocks of Outokumpu assemblage. The interlayers of rocks with different physical

properties cause a complicated reflection pattern. In Figure 7, a trace (CMP no.80) derived from the seismic profile is compared with a synthetic seismogram calculated from sonic and density logging data. The edge of the seismic profile suffers from poor fold and near-surface problems (see Figure 8). Thus, the trace 40 m away from the edge is chosen for comparison. The two seismograms show a good correlation. In both, the reflection at the depth of 500 m is present, as well as the complicated reflection package caused by the Outokumpu assemblage. In the seismic profile of the NE line, no prominent reflections are observed at 500 m depth. The spike in the seismograms might be caused by the quartz-feldspar schist interlayer observed in the drill hole. This interlayer might be too discontinuous to form reflections to the wide range of CMP gathers. On the other hand, well

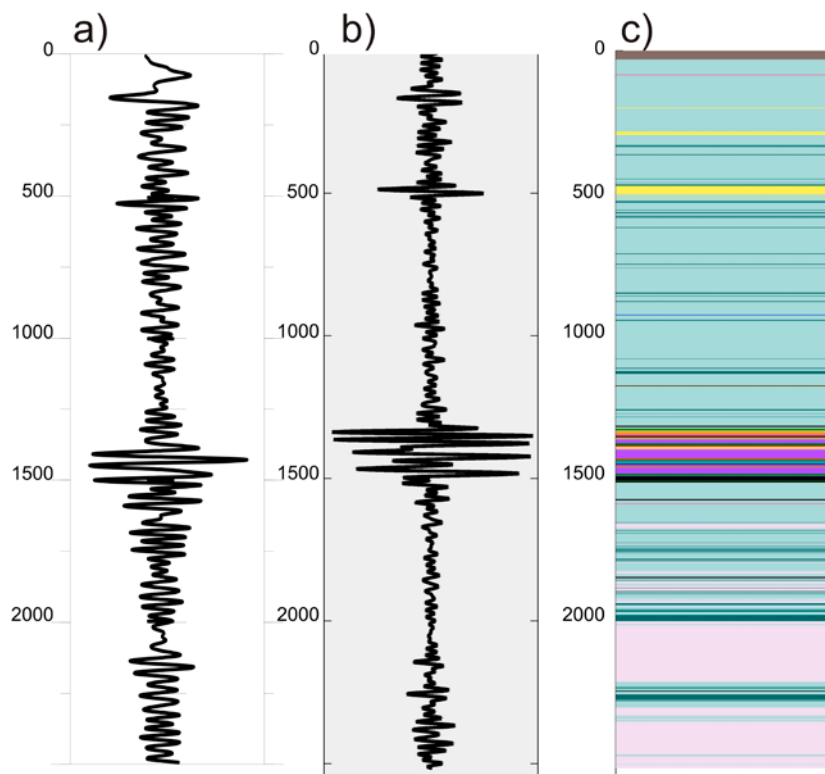


Figure 7. A trace (CMP number 80) derived from the migrated, depth converted seismic section of the NE survey line (a) has similar features to those of the synthetic seismogram calculated from drill hole logging data (b). The lithological column (c) shows that the strong reflector correlates with the rocks of the Outokumpu assemblage. They appear to generate complicated reflections in both experimental and synthetic seismograms. A feature at the depth of 500 m is also present in both seismograms, although the seismic stack does not show continuous reflections at this depth. It is possible that this reflection is caused by the quartz-feldspar schist interlayer in the mica schist, which is not continuous enough to be seen in other CMP locations, but well-developed fracturing is also related to this depth.

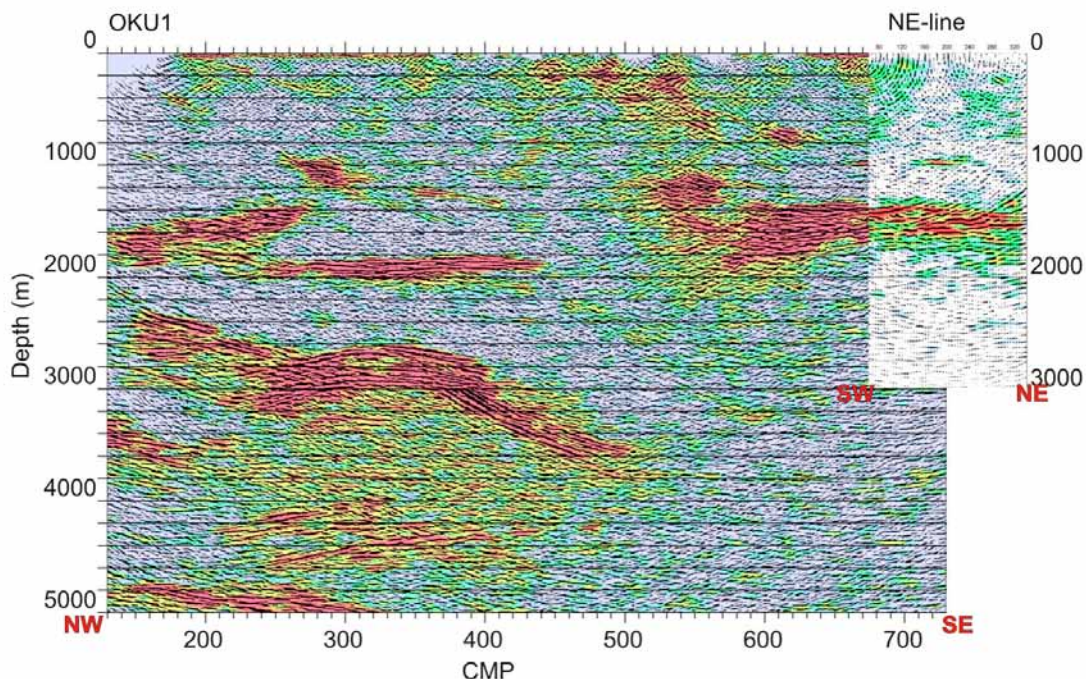


Figure 8. Comparison of the migrated stacks of the FIRE OKU1 line (data from Koivisto 2004, Kukkonen et al. 2006) and the NE line of the present study. The seismic lines are almost perpendicular to each other (see Figure 1). The new seismic soundings carried out at Outokumpu in May 2006 on the NE line (small section) provide a detailed image of the strong reflector at the drill site at 1.3–1.5 km depth and confirm that the reflector is the same as that observed in OKU1. Drilling data show that the reflector represents the ophiolite-derived Outokumpu-type rock assemblage. The reflector is not a continuous layer, but consists of fragments with different dips.

developed fracturing is also observed at this depth (Tarvainen 2006).

A minor depth mismatch is present between the synthetic seismogram and the trace derived from seismic profile. This might be due to the constant velocity (5400 m/s) used for depth conversion or because of a real change in the geological structure. The higher resolution of the May 2006 survey provides a more detailed image of reflectivity caused by rocks of the Outokumpu assemblage already observed in FIRE soundings. The Outokumpu-assemblage rocks do not form a simple planar structure, but have a complicated structure with dipping and horizontal components. The intricate reflectivity associated with the Outokumpu assemblage is probably caused by polyphase deformation that the area has undergone.

Above the Outokumpu assemblage (<1.3 km), a few thin layers of gneissic metasediments and felsic dykes in mica schist exist. Although the acoustic properties differ enough to produce a detectable reflection, the rock layers are too thin to be observed. The continuity of these individual layers is also uncertain. The reflection coefficient between the mica schist and the pegmatitic granite (main contact at about 2 km depth) is also large enough to cause a detectable reflection in favourable signal-to-noise conditions. However, this lithological contact can be observed as a change in the texture of reflectivity in the seismic section rather than clear reflections. The pegmatitic granite is more homogeneous internally and tends to appear as transparent to weakly reflective domains. It is also worth noting that in both the synthetic seismogram and trace derived from seismic section there is not a reflector at the depth of lithology change from mica schist to pegmatite. Instead, there is a lack of reflectivity, and possibly phase reversals at the depth of 2000 m.

Bergman et al. (2002) concluded in their study that hydraulic conductivity observed in fractured crystalline rocks in boreholes correlates with seismic reflectivity. In Outokumpu, a prominent reflection at the depth of about 1 km is unlikely to be caused by a lithological change, but by a prominent fracture zone located in the drill hole at about 967 m. This fracture is also one of the sources of the saline fluids entering the borehole and a target of extensive hydrogeological sampling (Ahonen et al. 2008). This could also be

interpreted from the sharp, straight shape of the reflector (Figure 8).

The NE survey line is a direct link between the borehole data and the FIRE reflection seismic data previously collected in the area. The lithologies associated with the known Outokumpu ore belt dip gently to the southeast. However, the reflector is not continuous but consists of several fragments (Figure 7) similar to the ophiolite complex on the surface, and thins to the above-mentioned fracture zone at 967 m.

Kern et al. (2009) concluded that crystallographic preferred orientation (CPO) and microstructural characteristics (i.e. schistosity) cause seismic anisotropy that should be accounted for when interpreting the seismic reflection data. A significant amount of anisotropy was measured on mica schist (and biotite gneiss) samples of the Outokumpu drill hole. In most samples, the maximum and minimum velocities were measured parallel and perpendicular to the foliation, respectively. Seismic anisotropy is likely to affect the reflection coefficient at the contacts between pegmatic granite and mica schist at depths exceeding about 1650 m, where these contacts occur, because the anisotropy has an effect on acoustic impedance depending on the propagation direction of the seismic wave. However, the Outokumpu data consist of relatively short offsets (< 1000 m). Thus, it is unlikely that the anisotropy has a significant effect on seismic profiles, as the incidence angles do not vary significantly at the depths of the reflective units (> 1000 m).

The use of more sophisticated processing techniques might improve the quality of the reflection seismic stack of the Outokumpu NE line. A crooked measurement line and complicated, dipping geological structures would be better imaged and interpreted by using cross-dip analysis (e.g. Malehmir et al. 2009) to evaluate to dip of the reflector perpendicular to the line. Even though the conventional processing of the SE reflection seismic line of the 2006 Outokumpu survey was not successful, these data could be employed in pseudo-3D processing. 3D modelling of Outokumpu, employing all the reflection seismic data as well as other available geophysical data, would provide new insights into this geologically interesting area.

## CONCLUSIONS

Attenuation of the high frequencies used in the 2006 Outokumpu survey was low and frequencies as high as ~200 Hz were present in the reflection signal. The high surface noise levels reduced the quality of the seismic data on the shallow parts of the seismic section. Static corrections are an essential component in the processing of high resolution reflection seismic data acquired in hardrock environments. In our work, a tomographic near-surface model was used to calculate the static corrections for the reflection seismic data from Outokumpu. The quality of the seismic section obtained proved to be slightly superior to the one based on a regular refraction static method. There is a good correlation between the seismic section and the lithologies as well as the geophysical properties observed in the Outokum-

pu Deep Drill Hole. The strongest reflectors at a depth of 1.3–1.5 km are related to the Outokumpu assemblage, which is an internally complicated unit showing both dipping and horizontal reflections. The result suggests that seismic reflection surveys could be used for directly detecting potential host rocks of the massive sulphide deposits in the Outokumpu area. Pegmatitic granite shows very little reflectivity, and can be interpreted from the seismic section because of its internal transparency to seismic waves, particularly when present at larger scales. A major fracture within mica schist at a depth of ~1 km is also visible in the final stack. Even though the fracture zone is thin, it causes such a drastic change in seismic velocity and density of the rock that the observable reflections are produced.

## ACKNOWLEDGEMENTS

The well-grounded criticism and suggestions by the referees Don White and Alireza Malehmir helped to improve this research. This project was supported by the ICDP (International Continental Scientific Drilling Program). Evan Bianco, Damien Meillieux, Heather Schijns, Marek Welz and Len Tober from University of Alberta, Erkki Ruokanen and Hannu Repo from GTK and Jo-

hanna Keskinen, Marianne Malm, Pasi Lindblom and Kari Komminaho from the University of Helsinki participated in the field work in May 2006. Jochem Kueck, Christian Carnein and Karl Bohn from ICDP provided operational support for drill hole logging. The research visit of Suvi Heinonen to the University of Alberta was supported by the Renlund Foundation.

## REFERENCES

- Ahonen, L., Itävaara, M. & Kukkonen, I. 2008. Outokumpu deep borehole: Site for deepbiosphere, gas and isotope studies in crystalline rock. The 7th International Symposium for Subsurface Microbiology. November 16–21, Shizuoka, Japan.
- Bergman, B., Juhlin, C. & Palm, H. 2002. High-resolution reflection seismic imaging of the upper crust at Laxemar, southeastern Sweden. *Tectonophysics* 355 (1–4), 201–213.
- Huhma, A. 1971. Outokumpu. Geological Map of Finland 1:100 000, Pre-Quaternary Rocks, Sheet 4222. Geological survey of Finland.
- Juhlin, C. & Palm, H. 2003. Experience from shallow reflection seismic over granitic rocks in Sweden. In: Eaton, D. W., Milkereit, B. & Salisbury, M. H. (eds.) *Hardrock Seismic Exploration*. Tulsa: SEG, 70–89.
- Kern, H., Mengel, K., Strauss, K. W., Ivankina, T. T., Nikitin, A. N. & Kukkonen, I. T. 2009. Elastic wave velocities, chemistry and modal mineralogy of crustal rocks sampled by Outokumpu scientific drill hole; Evidence from lab measurements and modelling. *Physics of the Earth and Planetary Interiors* 175 (3–4), 151–166.
- Koivisto, E. 2004. Korkean erotuskyvyn seismisen heijastusluotausaineiston prosessointi: Outokummun OKU2-linja. Master's thesis, University of Helsinki, Physics Department. 88 p. (in Finnish)
- Kukkonen, I. T. & Lahtinen, R. (eds.) 2006. Finnish reflection experiment: FIRE 2001–2005. Geological Survey of Finland, Special Paper 43. 247 p.
- Kukkonen, I. T., Heikkinen, P., Ekdahl, E., Hjelt, S.-E., Yliniemi, J., Jalkanen, E. & FIRE Working Group 2006. Acquisition and geophysical characteristics of reflection seismic data on FIRE transects, Fennoscandian Shield. In: Kukkonen, I. T. & Lahtinen, R. (eds.) *Finnish Reflection Experiment 2001–2005*. Geological Survey of Finland, Special Paper 43, 13–43 + 11 appendices.
- Lehtinen, M., Nurmi, P. A. & Rämö, O. T. 2005. Precambrian geology of Finland. Key to the evolution of the Fennoscandian shield. Elsevier B.V, p. 736.
- Malehmir, A., Tryggvason, A., Lickorishand, H. & Weihed, P. 2007. Regional structural profiles in the western part of the Palaeoproterozoic Skellefte Ore District, northern Sweden. *Precambrian Research* 159 (1–2), 1–18.

- Malehmir, A., Schmelzbach, C., Bongajum, E., Bellefleur, G., Juhlin, C. & Tryggvason, A. 2009.** 3D constraints on possible deep >2.5 km massive sulphide mineralization from 2D crooked-line seismic reflection data in Kristineberg mining area, northern Sweden. *Tectonophysics* 479, 223–240.
- Milkereit, B. & Eaton, D. 1998.** Imaging and interpreting the shallow crystalline crust. *Tectonophysics* 286 (1–4), 5–18.
- Peltonen, P., Kontinen, A., Huhma, H. & Kuronen, U. 2008.** Outokumpu revisited: New mineral deposit model for mantle peridotite-associated Cu-Co-Zn-Ni-Ag-Au sulphide deposits. *Ore Geology Reviews* 33 (3–4), 559–617.
- Roberts, B., Zaleski, E., Perron G., Adam E., Petrie, L. & Salisbury, M. 2003.** Seismic Exploration of the Manitowadge Greenstone Belt, Ontario; A Case History. In: Eaton, D. W., Milkereit, B. & Salisbury, M. H. (eds.) *Hardrock Seismic Exploration*. Tulsa: SEG, 70–89.
- Salisbury, M. H., Milkereit, B., Ascough, G., Adair, R., Matthews, L., Schmitt, D. R., Mwenifumbo, J., Eaton, D. W. & Wu, J. 2000.** Physical properties and seismic imaging of massive sulphides. *Geophysics* 65, 1882–1889.
- Schijns, H., Heinonen, S., Schmitt, D. R., Heikkinen, P. J. & Kukkonen, I. T. 2009.** Seismic refraction traveltime inversion for static corrections in a glaciated shield rock environment: a case study. *Geophysical Prospecting* 57, 997–1008.
- Spencer, C., Thurlow, G., Wright, J., White, D., Carroll, P., Milkereit, B. & Reed, L. 1993.** A vibroseis reflection seismic survey at the Buchans Mine in central Newfoundland. *Geophysics* 58, 154–166.
- Tarvainen, A.-M. 2006.** Identification of water-bearing structures in the Outokumpu Deep Drill Hole by geophysical well logging. Master's thesis (technology), Helsinki University of Technology, Department of Civil and Environmental Engineering, 93 p. (in Finnish with English abstract)
- Västi, K. 2005.** Syväkairausraportti (Geological log). Geological Survey of Finland, unpublished report M52.5/4222/04/R2500. 14 p. (in Finnish)
- Zelt, C. A. & Smith, R. B. 1992.** Seismic traveltime inversion for 2-D crustal velocity structure. *Geophysical Journal International* 108, 16–34.