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Authors

Ilmo Kukkonen, Pekka Heikkinen, Suvi Heinonen, Jukka Laitinen, Peter Sorjonen-Ward & HIRE Working Group of the Geological Survey of Finland

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HIRE Seismic Reflection Survey in the Outokumpu-Polvijärvi Cu-Co-Zn mining and exploration area, Eastern Finland

Abstract

A seismic reflection survey comprising eight Vibroseis lines (total length of 78.5 km) and one explosion seismic line (length 3.5 km) was carried out in the Outokumpu-Polvijärvi Cu-Co-Zn mining and exploration area, eastern Finland, in August 2002 and September, 2008. The surveys were conducted as parts of the projects HIRE (High Resolution Reflection Seismics for Ore Exploration 2007-2010) and FIRE (Finnish Reflection Experiment 2003-2006) of the Geological Survey of Finland (GTK). The HIRE survey in Outokumpu-Polvijärvi area was done in co-operation with Kylylahti Copper Oy and Mondo Minerals Oy.

The seismic surveys in the Outokumpu-Polvijärvi area revealed that the upper crust has very strong reflectors. Reflectivity can often be attributed to ophiolite-derived rocks of the Outokumpu nappe, namely serpentinite, skarn rock and quartz rock, as well as black schist. In addition to the ophiolitic rock type assemblage, strong reflectivity is associated with Proterozoic epicontinental rocks and mafic sills covering the Archaean basement and probably with Archaean mafic rocks.

Correlating the reflectors between survey lines, and using surface geology, airborne magnetic maps and drilling data, 3D models of the deep structures of the Outokumpu ore belt were constructed. In the Outokumpu belt, three major reflective packages representing ophiolitic rock types can be identified between Keretti and Kylylahti, namely, the Keretti, Horsmanaho and Deep hole reflectors.

A major fault structure, the Outokumpu fault, was interpreted from the seismic results. The fault is running immediately along the NW contact of ore belt contact and dips about 60° SE. The fault truncates the structures of the main ore belt. On the NW side of the ore belt, strong reflectivity is also present in the uppermost five kilometres. A group of reflectors is interpreted to represent ophiolitic rock types and correlated to those in the main ore belt, although located 1-2 km deeper. Towards the NE along the belt, these reflectors also seem to become thinner but they also meet the surface at locations where black schist and skarn rock occur.

In the Kylylahti area, the reflectors of the main ore belt converge into a tectonically disturbed volume which extends to about 3 km depth, and the Kylylahti reflector shows subvertical contacts and disturbances by deep faults. The Kylylahti ore deposit is not directly imaged with seismic reflections. This is attributed to the small size of the deposit in comparison to seismic wavelengths as well as the subvertical vertical dip of the deposit.

About 10 km to the NW of the Outokumpu ore belt Archaean rocks and Proterozoic sills and cover rocks outcrop in the Saarivaara area and they can be followed along reflector dips to the depth of about 4-6 km under the Outokumpu belt. This also gives the thickness of the allochthonous rocks of the Outokumpu nappe beneath the ore belt. The Sotkuma Archaean gneiss is interpreted as a slice of Archaean rocks and it does not represent a true basement window.

The seismic data indicates several potentially interesting structures for further deep exploration of Outokumpu type sulphide deposits. Such structures can be found, for instance, (1) beneath and to the SE of the Keretti area at the depth of 1-2 km, (2) in the the thick parts of the Keretti reflector along the main ore belt (one of the them at Horsmanaho, at depths >800 m), (3) the Kylylahti reflector extending to about 3 km depth, and (4) the reflectors on the NW side of the Outokumpu fault.

Keywords

Seismic reflection surveys, massive sulphide deposits, Cu-Co-Zn deposits, Outokumpu, Keretti, Kylylahti, Fennoscandian Shield

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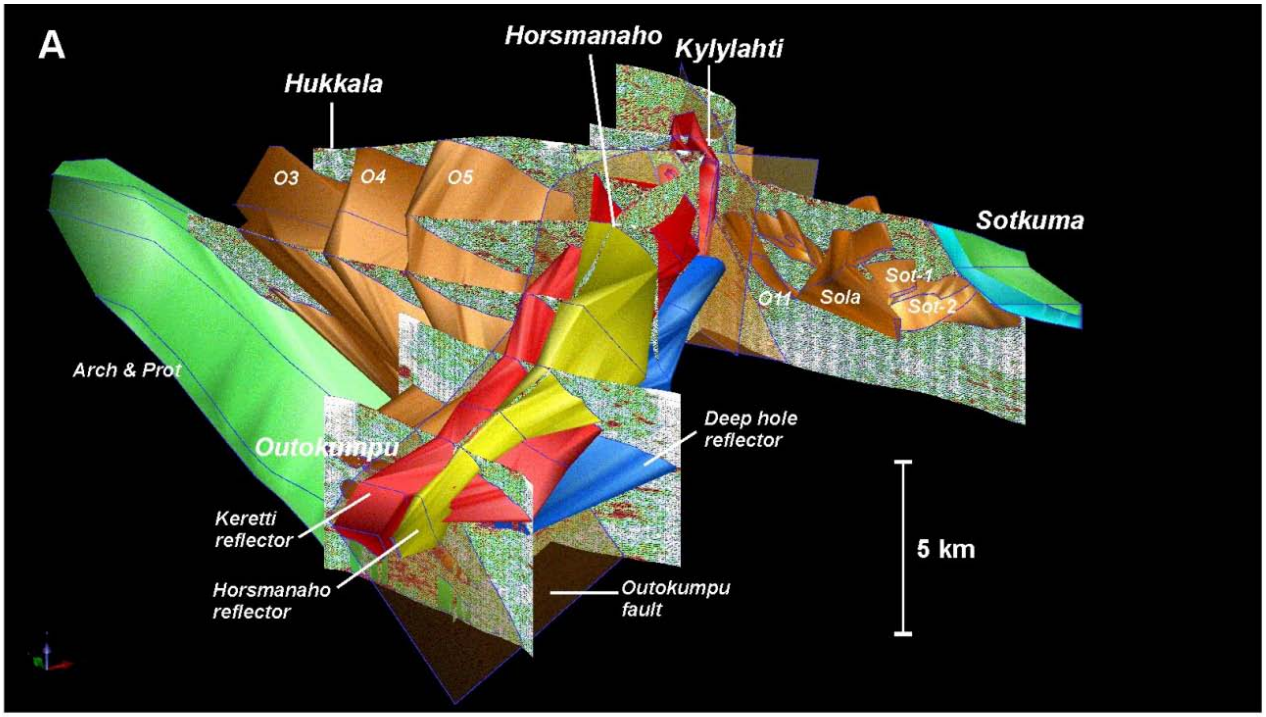

HIRE Seismic Reflection Survey in the Outokumpu-Polvijärvi Cu-Co-Zn Mining and Exploration Area, Eastern Finland

Ilmo Kukkonen[1], Pekka Heikkinen[2], Suvi Heinonen[2], Jukka Laitinen[1], Peter Sorjonen-Ward[3] & HIRE Working Group of the Geological Survey of Finland

[1]Geological Survey of Finland, P.O.Box 96, FI-02151 Espoo, Finland, e-mail ilmo.kukkonen@gtk.fi
[2]Institute of Seismology, P.O.Box 68, Fi-00014 University of Helsinki, Finland

[3]Geological Survey of Finland, P.O. Box 1237, FI-70211 Kuopio, Finland

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1. INTRODUCTION

A seismic reflection survey comprising eight Vibroseis lines (total length of 78.5 km) and one explosion seismic line (length 3.5 km) was carried out in the Outokumpu-Polvijärvi Cu-Co-Zn mining and exploration area, in eastern Finland, in August 2002 and September 2008. The surveys were conducted as parts of the projects HIRE (High Resolution Reflection Seismics for Ore Exploration 2007-2010; Kukkonen et al., 2011) and FIRE (Finnish Reflection Experiment 2003-2006; Kukkonen and Lahtinen, 2006).of the Geological Survey of Finland (GTK). The HIRE survey in Outokumpu-Polvijärvi area was done in co-operation with Kylylahti Copper and Mondo Minerals.

In the FIRE project, the main attention was in crustal scale structures of the different geotectonic units of the central parts of the Fennoscandian shield. In addition to crustal research, high resolution surveys were conducted in two ore targets to obtain experience on applying seismic reflection methods for structural studies in exploration areas. The targets were the Suhanko PGE deposit in Ranua, northern Finland (Iljina and Salmirinne, 2011) and the Outokumpu ore belt. The results from Outokumpu are reported and used in the present study.

The general aims of the HIRE project are (1) to introduce reflection surveys as an exploration tool for the Precambrian crystalline bedrock of Finland, (2) to apply 3D visualization and modelling techniques in interpretation, and (3) to improve the structural data base on the most important mineral resource provinces in Finland. The HIRE targets comprise exploration and mining camps in very diverse geological environments. Targets include Cu, Ni, PGE, Zn, and Au deposits, most of them economic, as well as the Finnish site for nuclear waste disposal. The surveys are carried out in co-operation with the companies owning the exploration and mining claims in the survey areas.

The aims of the survey in Outokumpu were to delineate the upper crustal structures of the ore belt, and to correlate the reflectors with drilling data and other geophysical data.

The survey was carried out by the Geological Survey of Finland using SFUE Vniigeofizika, Moscow, Russia, as the seismic contractor. The HIRE project is partly funded from the debt conversion agreement between Finland and Russia. The Outokumpu survey was agreed between GTK and Kylylahti Copper Oy, and between GTK and Mondo Minerals Oy based on the offers by GTK dated Feb 5, 2008.

The surveys comprised vibroseismic soundings along roads and one off-road explosion seismic line. The data was acquired in August, 2002, (FIRE lines OKU1-OKU3) and in June-August, 2008 (HIRE lines V1-V8 & E1).

2. BRIEF GEOLOGICAL DESCRIPTION OF THE OUTOKUMPU AREA AND ORE DEPOSITS

The Outokumpu ore belt comprises Paleoroterozoic turbiditic deep-water sediments and ophiolitic slices of upper mantle rocks from oceanic lithosphere which together form the allochthonous Outokumpu nappe which was thrusted from south-southwest onto the Archaean basement (Park et al., 1984; Koistinen, 1981; Peltonen et al., 2008) (Figure 1). The ophiolitic rocks are 1.96 Ga old, and the thrusting has taken place at about 1.9 Ga ago (Säntti et al., 2006; Peltonen et al., 2008). The ophiolitic rocks were involved into the thrusting from a narrow oceanic basin opened on the western margin of the Archaean complex at about 2.0 - 1.96 Ga.

Folding and deformation of the ophiolitic rock slices in the Svecokarelian orogeny was thorough, and Gaal et al. (1975), Koistinen (1981) and Park et al. (1984) suggest up to five-six different deformation phases in the Palaeoproteroic evolution of the Outokumpu area and eastern Finland in general. Following the thrusting, the first deformation phase by a southeast-northwest compression resulted in isoclinal recumbent F1 folding which was also responsible for the deformation-related thickening of the Outokumpu ore (Koistinen, 1981). The second phase of folding (F2) produced buckling of the F1 folds into steeper but open antiforms and synforms with N and NNE trending axes. The later deformation phases produced mainly N, NNE and NE trending upright folds.

As a result of the deformation history, the mantle derived rocks are present in complicated folded structures not showing any original magmatic textures, and split into numerous pieces distributed in the upper crust. Metamorphic grade increases from east to west with peak temperatures of about 500 - 775°C and pressures of 3-5 kbar. Metamorphic alteration has changed the originally depleted upper mantle rocks into serpentinite, skarn-carbonate rock and quartz rock (Säntti et al., 2006; Peltonen et al., 2008).

The sulphide ore deposits are polymetallic (Cu-Co-Zn-Ni-Ag-Au) semi-massive to massive sulphide ores systematically hosted by the ophiolite-derived rock assemblage, the serpentinite – skarn rock – quartz rock association. These assemblages are typically enveloped by iron sulphide and graphite-bearing black schist and they swim in the turbiditic mica schist. The sulfide ore bodies are most often hosted by quartz rock, but may sometimes be hosted by skarn or serpentinite due to mobilization in post-mineralization times. The deposits form thin, narrow and sharply bounded sheets, lenses or rods. The mineralogy of the ore comprises pyrite, chalcopyrite, sphalerite, pyrrhotite, pentlandite and quartz (Peltola, 1998; Peltonen et al., 2008).

The biggest deposit known so far was the already mined Outokumpu deposit (~29 Mton) which was about 4 km long, 50-350 m wide and about 10 m thick body in a sub-horizontal position and located at about 200 m below the surface. The rock assemblage that hosted the main ore deposit is about 10 km long and up to 1 km thick body with a tubular cross section.

Several models for the genesis of the Outokumpu ore have been presented during the one hundred years of investigations (see a summary of these by Peltonen et al., 2008). The perhaps most up-to-date model suggests that the ore was formed in two main phases. First, there was the deposition of a Cu-rich ‘proto-ore’ in serpentinized oceanic ultramafic rocks at 1.95 Ga from high-T, low-pH hydrothermal fluids resulting in accumulations of Cu-Zn-Co-Ag-Au sulphides. Second, Ni was derived from chemical interaction of peridotite and adjacent black schist during obduction and alteration of the ultramafic rocks. Silicate Ni was released from the ultramafic rock and redeposited as Ni sulphides, and later syntectonic mixing of the sulphides resulted in the present ore composition (Peltonen et al., 2008).

The study area, the Outokumpu ore belt, has hosted three major metal mines during 1913 -1988. The Outokumpu and Vuonos mines achieved a total production of 28.5 Mt @ 3.8% Cu, 0.2% Co, 0.1% Ni, 1.1% Zn and 25.3% S (Parkkinen, 1997; Papunen, 1987; Peltonen et al., 2008), whereas the Luikonlahti mine produced 7.5 Mt of ore @ 1.0% Cu, 0.1% Co, 0.5% Zn, 0.1% Ni and 16.5% S (Parkkinen, 1997; Kontinen et al., 2006). Presently a new mine is constructed at the northern end of the Outokumpu belt, where the Kylylahti mine has resources of 8.4 Mt @1.3% Cu, 0.2% Co, 0.2% Ni, 0.5% Zn and 0.7 g/t Au (Altona Mining, 2011).

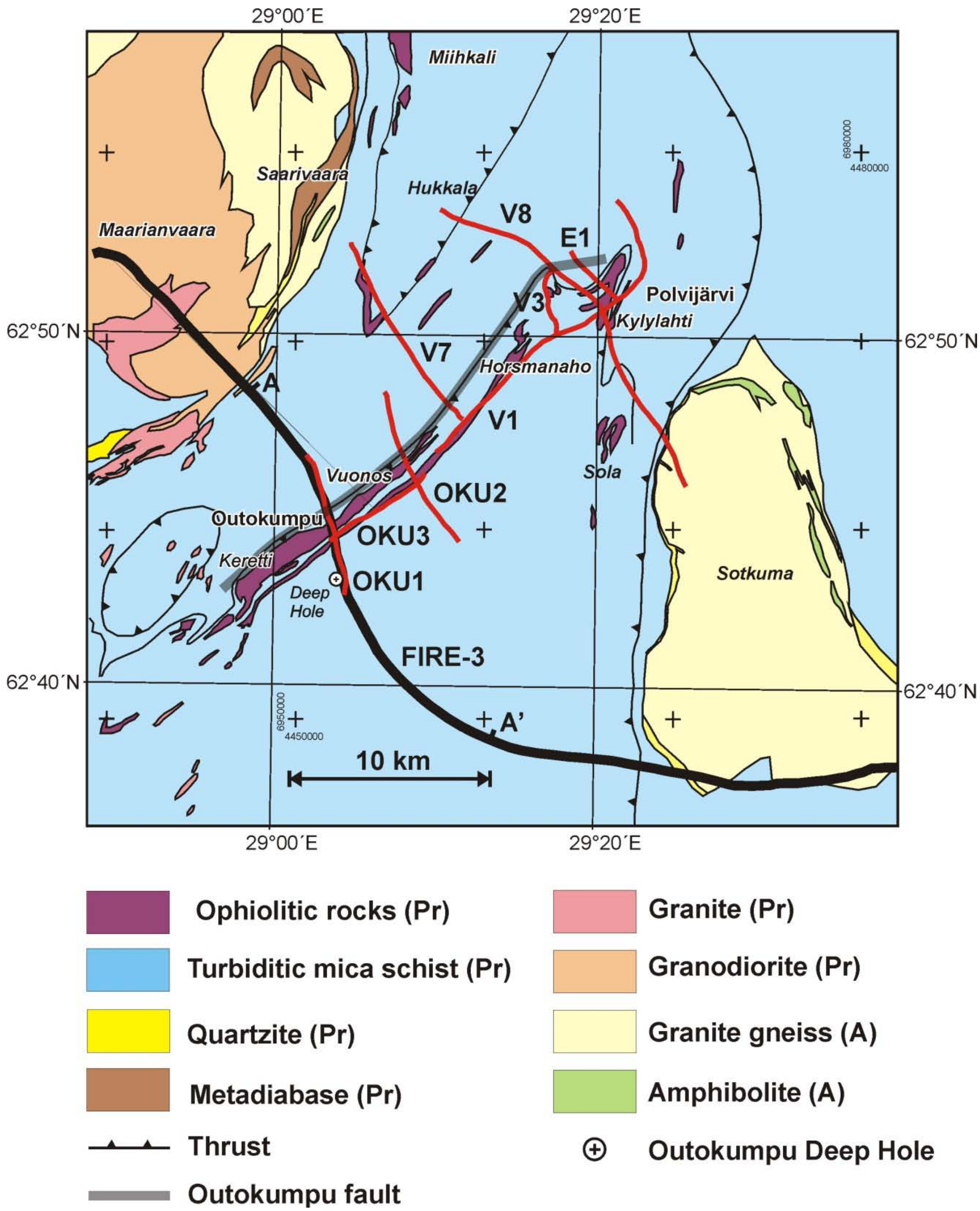


Figure 1. *Geological overview of the Outokumpu ore belt and the HIRE and FIRE seismic surveys in the area. Geology simplified from the digital bedrock map of Finland by GTK (DigiKP200).*

3. SURVEY METHOD

The acquisition of the FIRE OKU1-OKU3 lines was done using the Vibroseis method with three 15.4-ton Geosvip vibrators as a group and applying a maximum dynamic load of c. 9 t/vibrator. The shooting geometry was split-spread, excluding the ends of lines where asymmetric shooting was applied. The number of active channels was 312-474. The channel/geophone group interval was 25 m and the source point interval 50 m. Thus, the nominal fold was high varying from 78 to 119. In practice, this number was slightly reduced, because all shooting points could not be used due to vicinity of buildings or other structures. The applied input sweep was linear, 12 s long with the frequency band 20 - 130 Hz. The listening time was 12s + 6 s. The final correlated signals are 6 s with a depth extent of up to about 18 km. The sampling interval was 1 ms. At each shot point the seismogram was stacked 8 times before saving of data. The applied recording system was an INPUT/OUTPUT II.

The HIRE surveys (lines V1-V8) were also done using Vibroseis sources running on roads. One off-road explosion line (E1) was surveyed in the Kylylahti area with 250 g charges of dynamite detonated in 2.5 m deep boreholes at 50 m intervals. CMP method was applied with symmetrical split-spread geometry (at ends of lines asymmetric shooting). The number of active recording channels was 402, source point interval 50 m (locally 25 m) and the channel interval was 12.5 m giving a nominal fold of 50 - 100. The maximum offset between source and receivers was 2,502 m in case of symmetrical geometry and at ends of lines in asymmetric geometry up to 5,025 m. The sweep was a 16 s linear upsweep with a frequency band of 30-165 Hz, and the total listening time was 16 s + 6 s. The final correlated signal length is 6 s. The number of sweeps/source point was six. The sweeps were stacked and the stacked data were saved. The applied recording system was INPUT/OUTPUT IV. The acquisition parameters have been compiled into Table 1.

Geodetic positioning of the lines was done with GPS (positioning and erecting poles at drilling sites of shooting holes), and immediately before the acquisition with 25 m steel rope (line layout, recording station poles). Horizontal positioning was done with differential GPS to an accuracy of at least ±2 m, and elevations were determined with levelling to an accuracy of at least ± 0.5 m.

The survey parameters are shown in Tables 1 and 2 (Zamoshnyaya and Suleimanov, 2003; Zamoshnyaya, 2008).

Table 1. Survey parameters of the FIRE Vibroseis lines OKU1, OKU2 & OKU3

Recording system	telemetric system I/O SYS 2, 480 channels, 84 6-channel field units
Seismic source	vibrator SV-14-150
Control system	PELTON
Geophone type	GS-20DX (Fres = 10 Hz)
The number of geophones in the group	12
Geophone group length, m	25
Vibrator group length, m	25
Geophone group interval, m	25
Shot interval, m	50
Acquisition geometry	stationary spread
Common midpoint fold	increasing to the profile center, maximum values: 120 on OKU 1, 150 on OKU 2, 110 on OKU 3
Spread length, m	10400 on OKU 1, 11825 on OKU 2, 7775 on OKU 3
Minimum source-to-geophone distance, m	12.5
The number of active channels	417 - OKU 1 474 - OKU 2 312 - OKU 3
Record length, s	18
Record time after correlation, s	6
Sampling interval, ms	1
The number of vibrators in the group	3, total force 27 tons
Ground force	65÷70% of maximum
Sweep frequencies, Hz	OKU 1, 3 – 30-130 OKU 2: SP77.5÷217.5 – 130-20 SP219.5÷380.5 – 20-130
Sweep length, s	12
Number of vibroexcitations	8, on scheme 4+4
Noise suppression editor	Diversity
Noise editor sensitivity, dB	36
Noise editor length, ms	128
Preamplifier, dB	24
Filtering while recording, Hz	OFF
Tape format	SEG D, on cartridge 3490E

Table 2. Survey parameters of the HIRE Vibroseis lines V1, V2, V3, V7 & V8

	Vibroseis	Explosion
Recording	I/O-4	I/O-4
Number of active channels	402	402
Sampling interval, ms	1	1
Record length after correlation, s	6	6
Preliminary gain, dB	24÷36	24÷48
Notch filter, Hz	off	
Noise suppression editor (BURST+DIVERSITY)	on	on
High-pass filter, Hz	off	30
Tape format	SEG-Y	SEG-Y
Medium type	HARD DISC	HARD DISC
Acquisition geometry	Symmetrical split spread	Symmetrical split spread
Stacking fold	varying	Varying
Receiver group spacing, m	12.5	12.5
Spacing of source locations, m	25 or 50	50
Spread length, m	5012.5	5012.5
Linear geophone grouping	6 geophones on 12.5 m base	6 geoph. at a point or 3 swamp geoph. at a point
Linear SV-14/150 vibrator grouping	3 on 25 m base	
Sweep frequency limits, Hz	30÷165	
Sweep period, s	16	
Number of vibrations at a source point	6	
Shot hole number at a source point		1
Shot hole depth, m		2.5
Charge weight, g		125 or 250
Ground force	65%	
Control system and vibrator synchronization control	VIB PRO	Shot PRO

4. DATA PROCESSING

Data processing was done in three main steps. First, on-site processing was done by Vniigeofizika in the field base. The first results were used mainly for quality control. Second, basic processing was continued from the field results in the Moscow office of Vniigeofizika. Third, post stack processing was done by the Institute of Seismology of the University of Helsinki (HY-Seismo), working as a contractor and research partner for GTK.

The on-site and basic sequences of data processing is shown in Appendices 1 - 5 (Zamoshnyaya and Suleimanov, 2003; Zamoshnyaya, 2008).

Post-stack processing was made by HY-Seismo starting from the NMO stacked sections by Vniigeofizika. The post stack processing (Appendix 6) included four processing steps:

1) Whole trace amplitude equalization,
2) Stolt migration with depth dependent velocity function,
3) Spectral balancing,
4) Depth conversion.

The purpose of the first step was to eliminate the amplitude variations along the lines caused by changes in surface conditions and possible processing artifacts. The second step improves the migration results as the original migrations were done using the constant velocity of 5000 m/s. As a part of the basic processing, Vniigeofizika performed velocity analysis at every 100th CMP. From the measured values the average Vrms-velocity was estimated and this velocity function was used in Stolt migration. This takes into account the average increase of velocity as a function of traveltime, i.e. depth. The measured stacking velocities as well as the velocity function are shown in Figure 2.

In the spectra of the migrated traces the amplitudes decrease as a function of frequency, which results correspondingly in decreasing the resolution of the data. This can be improved by spectral balancing, i.e. by increasing the contribution of higher frequencies. Spectral balancing was done by multiplying the spectra with a linearly increasing function of frequency. The applied value of the multiplier was 1.0 at 40 Hz and 2.0 at 160 Hz.

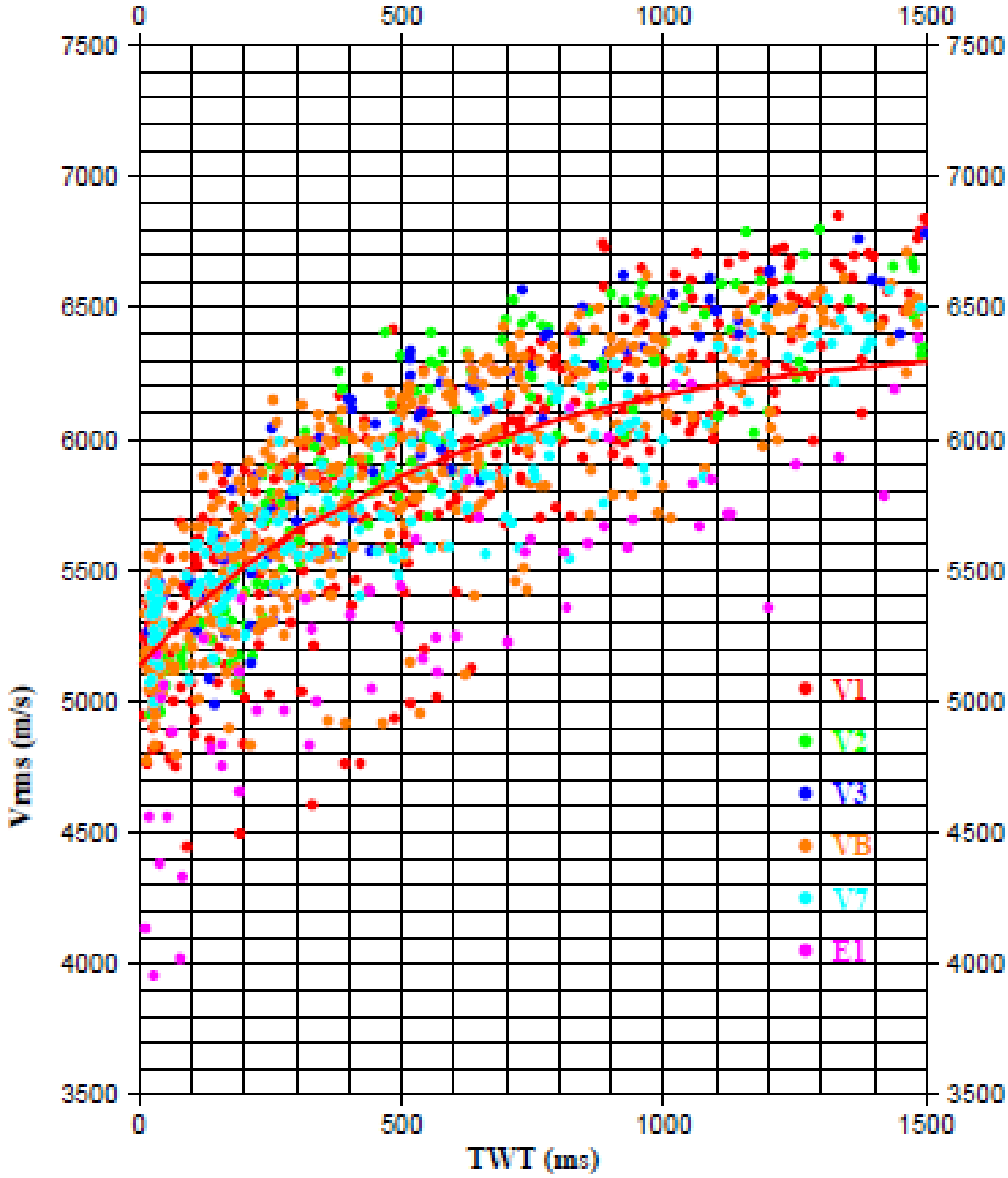


Figure 2. *The measured stacking velocitites (colored dots) and the velocity function used for post stack processing and time-to-depth conversion (red line). The color of the dot indicates the line (E1, V1-V3, V7, V8).*

5. RESULTS

The location of the survey lines is shown on a geological map in Figures 1 and 3 and on a magnetic map in Fig. 26. The map in Fig. 3 shows two lines for each section, first the receiver station line as it was located in the field, and second, the common mid point (CMP) line. The CMP line indicates the surface projection of average locations of reflection points. For a deep and long section these may differ noticeably if the survey line is curved or crooked. This issue must be taken into account, when locating reflectors in the field. Those very close to surface (less than ca. 200 m) are best located with the shooting line in the terrain, whereas deeper reflectors are best located with the CMP line.

When interpreting 2D seismic sections the effects of the cross dip of reflecting structures must be taken into account. The apparent dip of a planar reflector as seen in the seismic section depends on the true dip and strike of the reflector. If the strike is perpendicular to the line, the apparent dip is equal to the true dip, but the more the strike angle deviates from perpendicular, the smaller becomes the apparent dip angle. The relations between true and apparent dip are shown in a nomogram in Fig. 4. As can be seen in the figure, subvertical structures surveyed at small strike angles are imaged with apparent dip angles significantly smaller than the true dip.

Datum level of the reflection data is 100 m a.s.l. The uppermost layers (Quaternary sediments, weathered bedrock) have lower velocities than the intact crystalline rocks. Velocity and thickness variations of the surface layer generate spatially dependent delays in the arrival times of reflections, and the data must be corrected for these ‘static’ effects. This is done by shifting the signals to a common depth level, which is usually the highest level of topography in the survey area. The datum level is also the level to which the upper boundary of seismic sections (depth 0 m) should be referenced.

Frequency content of the data is very good. Examples of frequency spectra are shown in Figs. 5 and 6. In vibroseis data the applied frequency band of 30-165 Hz is well covered with received data. In the explosion data the achieved spectral content is even wider due to the detonation source and the data is at least 20 dB above noise level in the frequency band applied in data processing (30-260 Hz, App. 5). This predicts good resolution in the final images.

The processed sections show a wealth of reflectors. Reflectors as thin as 10 m vertically and 200-300 m wide horizontally can be distinguished in the sections.

The results of the survey are shown in migrated and depth converted NMO (normal-move-out) sections in Figs. 8-17 and in the appendices. The sections were converted from time sections to depth sections using the velocity function in Fig. 2 and in appendix 6. In the figures and appendices the reflectors are displayed as variable area plots of averaged instantaneous amplitude (traces). In addition, the amplitudes were averaged in moving windows (60 m in vertical and 90 m in horizontal directions, respectively) and displayed in dB scale in the background as a color-coded map. Lithological boundaries are given on the top of the 2D sections according to the data base on Precambrian geology (scale 1:200 000) of the GTK.

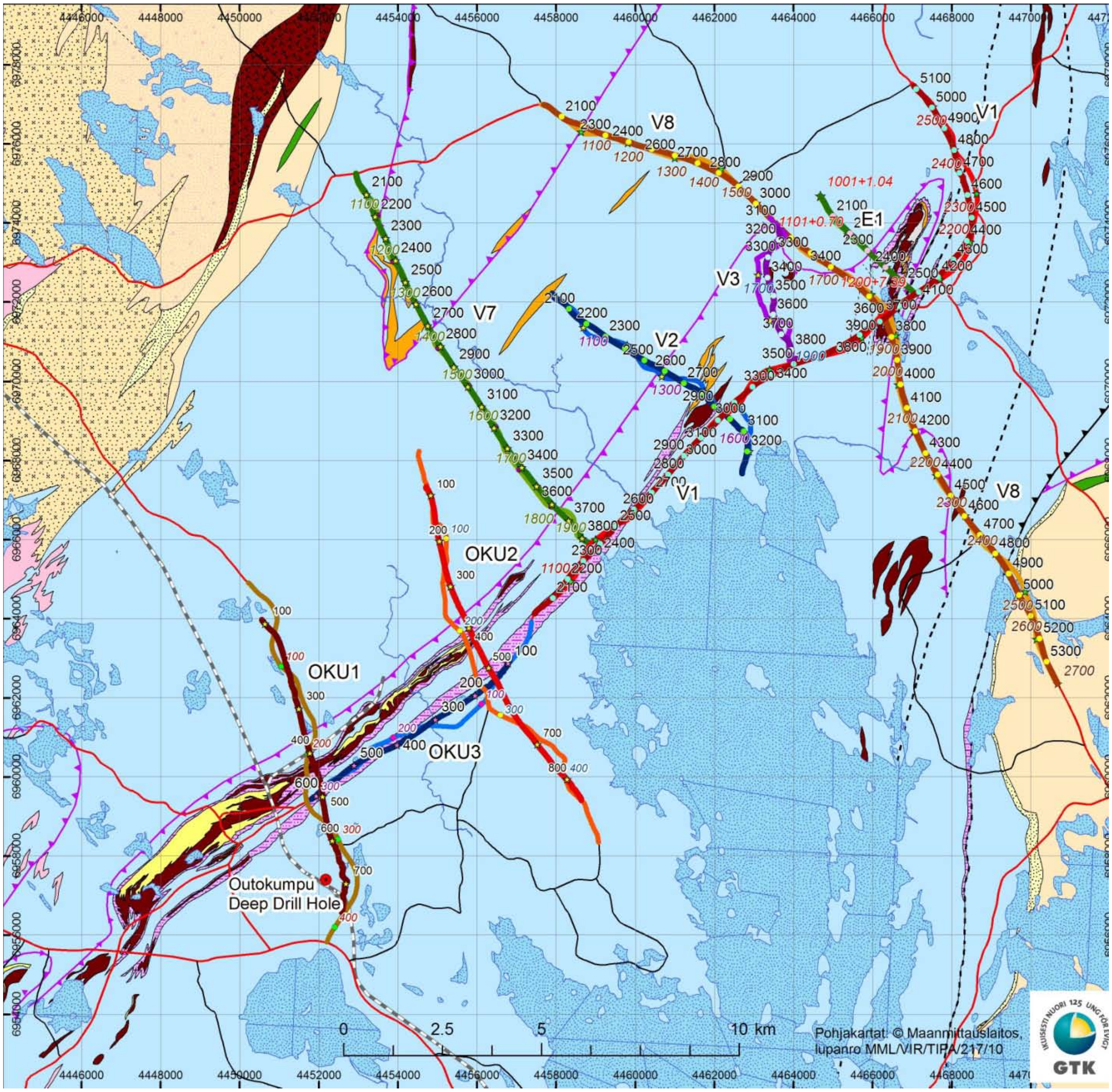


Figure 3. *High resolution survey lines in the Outokumpu-Polvijärvi area. Numbers along the lines indicate receiver station pole numbers (italics) and CMP coordinates (normal text). Base map derived from data in the digital bedrock map of Finland by GTK (DigiKP200).*

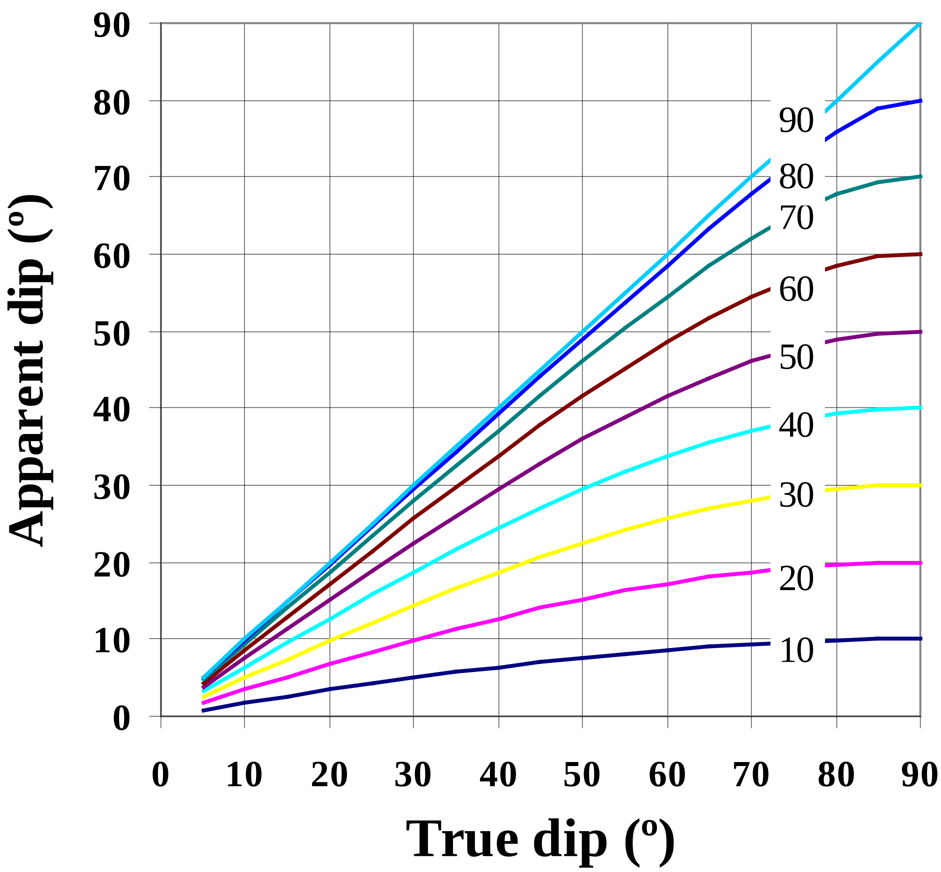


Figure 4. *Relations between true and apparent dip angles of planar reflectors. The curve parameter is the angle between the survey line and the strike of the reflector at surface.*

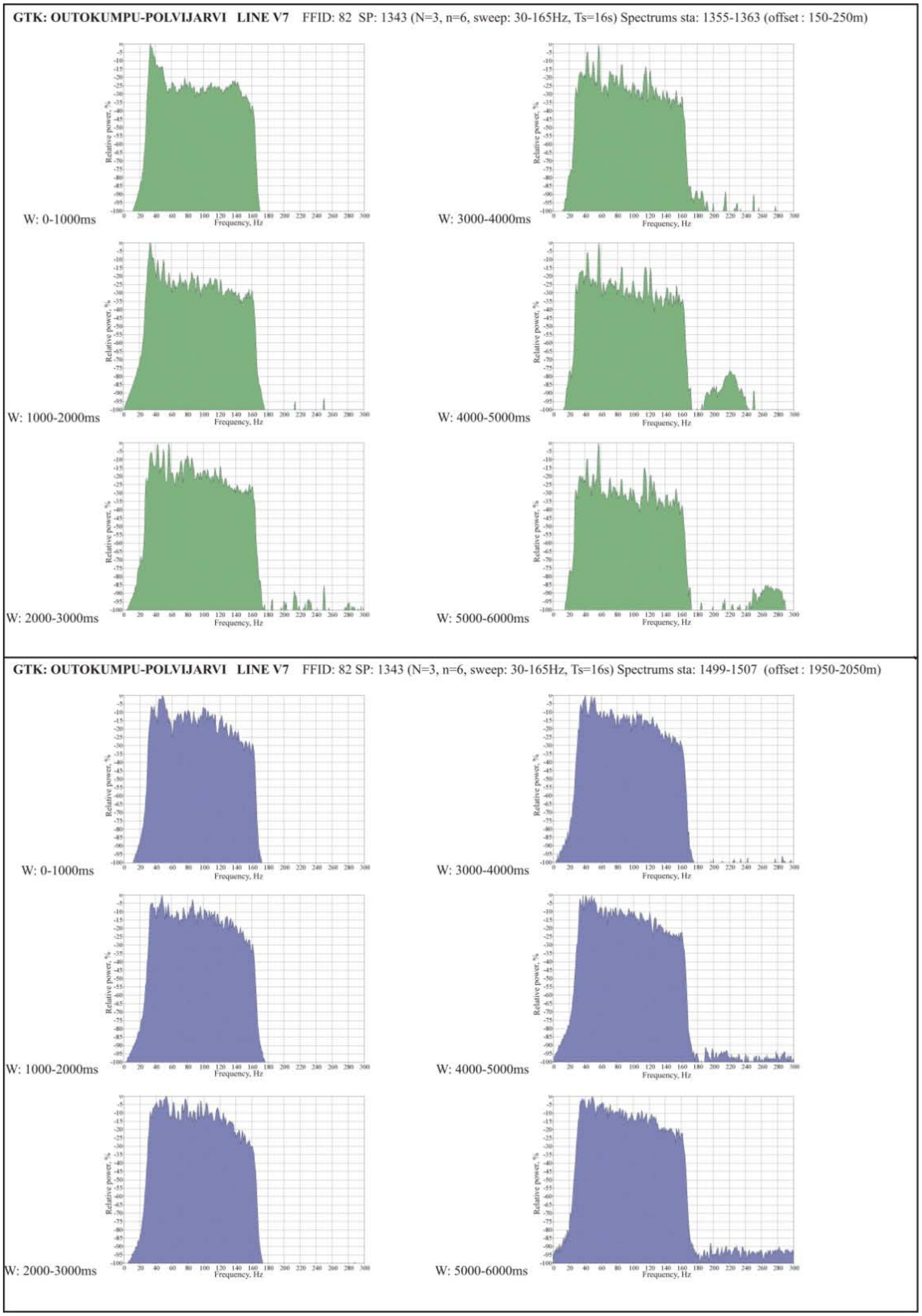


Figure 5. *Frequency spectra of the vibrator field data from V7 with two offsets from the shot point at CMP 2686 (Zamoshnyaya, 2008). Upper panels: offset 150-200 m, lower panels: offset 1950-2050. For location of the shot point, see Fig. 3.*

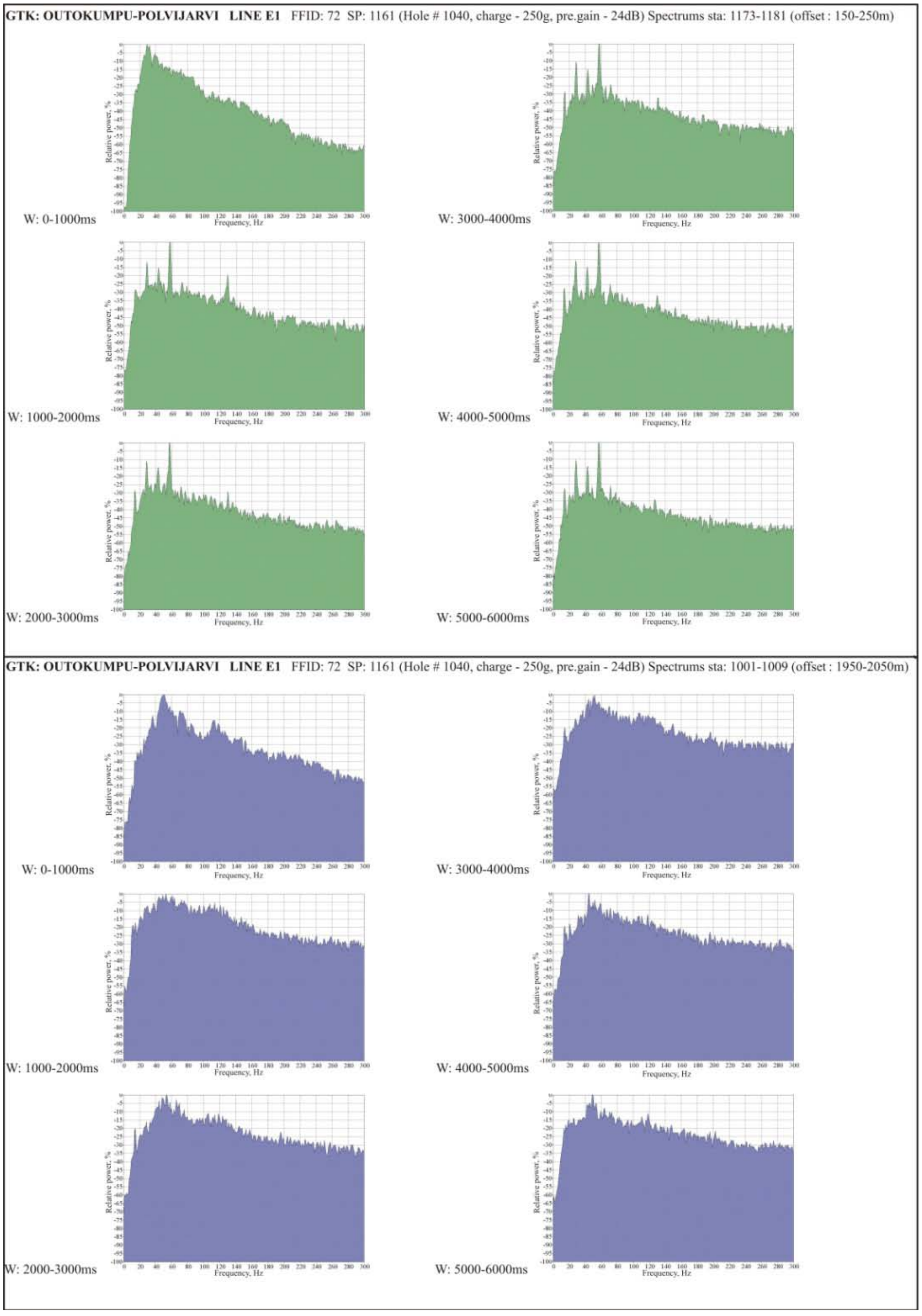


Figure 6. *Frequency spectra of the explosion seismic field data from E1 with two offsets from the shot point. Upper panels: offset 150-200 m, lower panels: offset 1950-2050 m. Shot point location (CMP 2322) is approximately in the middle of the line (see Fig. 3) (Zamoshnyaya, 2008).*

5.1. 2D and 3D presentation of the results

To obtain three-dimensional visualization of the reflector structures, the seismic sections were imported to *SURPAC* 3D visualization and modelling software. The sections were imported into *SURPAC* as images which were draped along vertical ‘curtains’ defined by the CMP coordinates of the lines. Relevant units were interpreted first from the sections in 2D, and the corresponding strings were digitized again in *SURPAC* on the drape surfaces of the sections. As a result, the 3D correlation of the strongly reflective units is presented with the 3D strings. From these strings and available geological and airborne magnetic maps, drilling sections and other data sets, reflective bodies (Surpac solids) were interpreted and constructed.

5.2. Reflecting structures of the Outokumpu belt

Strong seismic reflectivity is observed in association with the Outokumpu belt. It was noted already in the FIRE-3 reflection survey studying the crustal-scale structures. Some of the structures in the Outokumpu area are among the most reflective structures in the whole 2100 line-km of FIRE data (Kukkonen et al., 2006). This observation was further supported by the high resolution data of the present survey. An important factor from the point of view of mineral exploration is the presence of strong reflectivity associated with the ophiolite-derived rock type assemblages (the Outokumpu rock type assemblage). These highly deformed packages of serpentinite, skarn rock and quartz rock occurring in black schist ‘envelopes’ have distinct seismic properties as revealed by the Outokumpu deep drill hole studies (Kern et al., 2009; Kukkonen, 2011; Heinonen et al., 2011, Elbra et al., 2011; Schins et al., 2012). Due to layering of high and low-density and high and low-velocity rocks in the ophiolite-derived rock type assemblages, the seismic images are characterized by laminated (‘ringing’) reflectors with rapidly alternating reflections.

In the following we discuss the results of the crustal-scale and high resolution seismic surveys in Outokumpu and present 2D and 3D interpretations of the seismic results based on correlations with surface geology, drilling profiles, magnetic and gravity maps and other available data.

5.2.1. Crustal scale seismic results of the FIRE-3 transect

The FIRE-3 transect revealed strong reflectors in the upper crust of the Outokumpu area (Kukkonen et al., 2006; Figure 7). These reflectors, typically a few hundred metres thick and several kilometres long, show a laminated structure with layer thicknesses of about 20-50 m. In order to find out the geological character of these reflectors, the Outokumpu Deep Drill Hole was sited to pierce the uppermost of the strong reflectors in a place where the reflector forms a gentle antiform structure (Kukkonen et al., 2006; Kukkonen, 2011; Figure 7). The drilling results and additional seismic profiling on the drilling site confirmed that the reflector represents the Outokumpu assemblage of ophiolitic rocks (Kukkonen, 2011; Heinonen et al., 2011). All the strong reflectors present in the upper crust in the FIRE-3 transect are probably not due to Outokumpu assemblages of rocks, but the similarity of reflectors would suggest that the ophiolite-derived rock assemblages are more common than the surface expression suggests. The challenge is to find out which of the reflectors could represent host rocks environments of deposits.

Besides the strong reflectors an important fault structure can be identified in Figure 7. A very poorly reflective structure dipping about 60° southeast and reaching a depth of about 15 km can be identified on the western contact of the Outokumpu assemblage of rocks (the ore belt) (Figure 7). Reflectors on the southeast side of the dipping structure are truncated at this structure. On the ground level it concurs with a thrust surface interpreted by Koistinen (1981) to represent the western (folded) boundary of the Outokumpu nappe. The thrust line was defined by Koistinen with a thin layer of black schist and it is surrounded by 'Upper Kalevian' metasediments from both sides (Koistinen, 1981, Lahtinen et a., 2010). A detailed interpretation

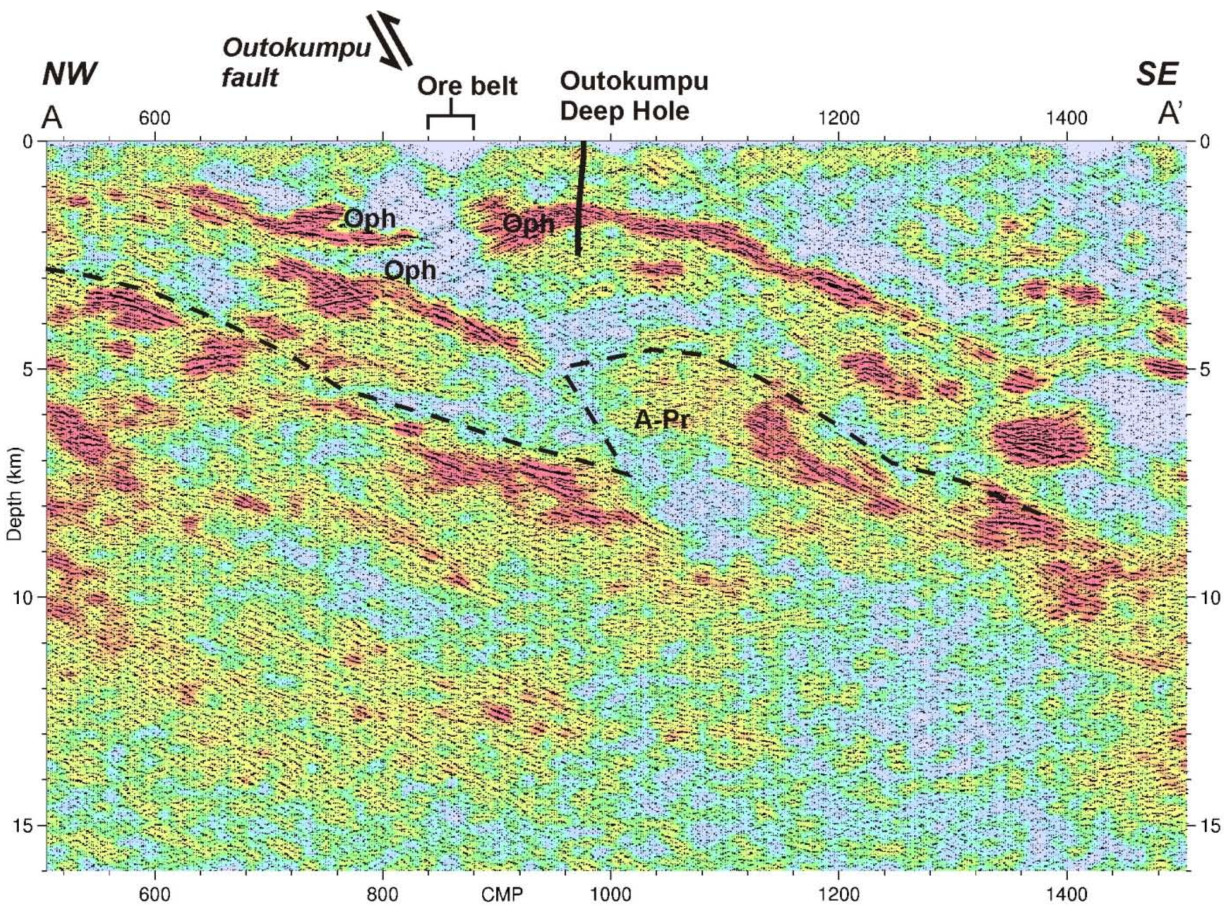


Figure 7. *Reflective structures in the uppermost 16 km of crust in the FIRE-3 transect (Kukkonen et al., 2006). Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. The interpreted Outokumpu fault is indicated with arrows. Oph: ophiolitic rocks; A-Pr: Archaean basement and Paleoproterozoic cover rocks. The broken line indicates the probable boundary between allochthononous rocks of the Outokumpu nappe and the Archaean basement and Proterozoic cover rocks. The location of the CMP line is shown in Figure 1 (A-A').*

of the course of the thrust on the surface has been given in the map by Korsman et al. (1997) and in the digital bedrock map of Finland by the Geological Survey of Finland. The seismically indicated planar structure does not represent the original thrust surface which is folded in a complicated manner; instead it can be attributed to reverse faulting along the axial plane of folds formed in the second major deformation phase which was finished at about 1.89 Ga (the D2-F2 phase of Koistinen, 1981). The seismic section allows a reconstruction of the reverse fault movement which may have been 1.5 – 2 km (cf. Sorjonen-Ward, 2006). In the following we use the term ***'Outokumpu fault'*** for this structure.

The poor reflectivity of the Outokumpu fault in the FIRE-3 section is attributed to shearing and breaking of the rock but also to presence of pegmatitic granite in the fault. In the Outokumpu deep drill hole, pegmatitic granite was the dominating rock type at depths beneath 2 km, and the acoustic rock properties suggest very weak reflectivity inside homogeneous sections of the granite (Heinonen et al., 2011). In contrast, the mica schist shows weak but consistent internal reflectivity due to its compositional and textural heterogeneity. The pegmatitic granite is of unknown age but it dissects the mica schist in the deep hole, and we tentatively correlate the pegmatitic granite with the Maarianvaara granite-granodiorite (1.86 Ga; Huhma, 1986) outcropping in a large area about 10 km to the northwest of the Outokumpu town (Figure 1). Similar rock is encountered in outcrops to the northwest of the main ore belt but practically not on the southeast side of the belt (Huhma, 1975). It is plausible that the pegmatitic granite intruded into an already existing zone of weakness at 1.86 Ga, about 30 Ma after the end of the D2 phase.

5.2.2. High resolution results from HIRE and FIRE

The high resolution seismic data provides a detailed view of the uppermost kilometres of crust. We have correlated the seismic data with available drilling profiles and the Outokumpu deep hole results (Kukkonen, 2011; Heinonen et al., 2011), and applied 3D modelling to visualise and connect the structures. In the following a discussion of main results is given proceeding from Keretti to Kylylahti. The migrated NMO sections and interpretations of the reflectors are shown in Figures 8-16.

Keretti-Vuonos area. In lines OKU1 and OKU2, the main ore belt is represented by southeast dipping subhorizontal reflectivity in a listric-like structure which gets thinner and becomes discontinuous at the depth of about 1 km (Figures 8 and 9). The main ore belt can be divided in two reflectors, which we call here the Keretti (K) and Horsmanaho (H) reflectors according to the related geology and the two main brances of the main ore belt at the ground surface level. In the Outokumpu deep hole only fracturing and a thin layer of black schist was encountered at this depth which implies in accordance with seismic data that the layer of ophiolitic rocks represented by the Keretti reflector ('K') thins out there. The same applies to the Horsmanaho reflector. At the deeper level, as shown by the Outokumpu deep hole results, the strong reflector at the depth of about 1.5 km is a laminated package of serpentinite, skarn rock and black schist of the Outokumpu assemblage (Kukkonen, 2011; Heinonen et al., 2011). To the northwest of the Outokumpu fault there are several strong reflectors in the uppermost 5 km in OKU1 (Figure 8).

The line OKU2 (Figure 9) shows structures similar in shape as the OKU1. It indicates that the reflectors have very good continuity along the geological strike. The formations are diving deeper towards northeast and the reflectors in OKU2 are located about 300 – 500 m deeper than in OKU1 (Figures 8 and 9). The Outokumpu fault is seen as a zone up to 1 km wide with only weak or no reflections.

The line OKU3 provides a direct correlation of reflectors in OKU1 and OKU2, and confirms the excellent continuity of the structures along strike. At the depth of the Outokumpu fault, where there is not at all or only very weak reflectivity in OKU1 and OKU2, the line OKU3 shows a subhorizontal package of reflectors about 200 - 300 m thick at about 2.0 - 2.3 km depth (Figure 10). The differences in reflection characteristics between lines running across and along strike can be attributed to anisotropy and acquisition geometry. We correlate the reflector in OKU3 beneath the ‘deep hole reflector’ as the Outokumpu fault structure. Such a fault may also contain black schist which is often met with in shear structures of the study area and also known to modify reflectivity (Figure 10). 3D correlation and visualization provides a view of the interpreted lithologies and the fault (Figures 21 and 22).

The geological nature of the strong reflectors on the northwest side of the Outokumpu fault is uncertain. The similarity of reflectors on both sides of the fault implies that they could both represent same lithologies. This is supported by the similar lithologies (mica schist) at surface on both sides of the Outokumpu thrust which belong to the ‘Upper Kaleva’ assemblage (Lahtinen et al., 2010). Assuming that the Outokumpu fault would show a reverse displacement of about 1.5-2.0 km (cf. Fig. 15 in Sorjonen-Ward, 2006) we can suggest that the reflectors on the foot wall (northwest) side could be correlated with those on the hanging wall (southeast) side (Figures 8 and 9). In this case the reflectors corresponding to the main ore belt at surface in OKU1 at CMP 450-500 are continued at about 1.0 - 1.5 km depth at CMP 200-300 (reflectors O4 – O5 in Figures 8 and 9). Correspondingly, the strong reflector drilled in the Outokumpu deep hole at 1.5 km depth at CMP 500-700 is interpreted to continue at 2.5 – 3.5 km depth at CMP 150 – 500 (Figure 8). This idea was followed in the 3D correlation and modelling of the reflectors, and the reflectors can be correlated practically over the length of the whole Outokumpu belt (see below).

Perttilahti-Horsmanaho area. Correlation of reflectors on the line V7 (Figure 14) with surface geology shows that the strong reflectors located at CMP 0 – 3300 and dipping to southeast at about 500 - 1500 m level mostly represent Proterozoic cover sediments and Archaean basement rocks outcropping about 2 km to northwest from the end of line in the Saarivaara area (see Figure 1 for localities). These rocks have both felsic and mafic lithologies and are expected to show good reflectivity. Recent shallow drilling (A. Kontinen, personal communication, 2011) has revealed rapidly alternating 5-50 m thick layers of Archaean granite gneiss, as well as Proterozoic quartzite, metadiabase, and calc-silicate rocks. The rocks are also strongly sheared. The reflections in V7 are of high amplitude.

Correlation of deep reflectors in OKU1 - OKU3 and V1 suggest that the Outokumpu assemblage rocks are present in V7 in the upper parts of the profile. However, here the Archaean and Proterozoic cover rocks are probably dominating in the northwest part, but the reflectors at CMP 2700 – 3300 at 1.5 – 3.5 km may represent ramp anticlines of ophiolitic rocks on top of the cover rocks (Figure 14).

In V2 (in Horsmanaho) the Keretti, Horsmanaho and Deep Hole reflector can be identified and correlated from the Keretti-Vuonos area (Fig. 12). To the NW of the interpreted Outokumpu fault, the reflectors O3 – O5 have been identified, but the imaging of particularly O3 and O4 suffer of the line being too short in NW direction. Under Horsmanaho, the Keretti reflector is seen as a thick (500 m) package of laminated reflections dipping about 40 SE. The shallowest part of the reflector is at about 800 m (CMP 2800, Figure 12).

3D comparison of reflectors and the drilling profile 200 in Perttilahti is shown in Figure 18. Reflectivity suggests that the Outokumpu assemblage of rocks drilled at the depth of about 1 km may actually extend to depths of about 1.5 – 2 km. This reflector is the Keretti reflector. It seems to be truncated by the Outokumpu fault in the NW direction.

Kylylahti area. When approaching the Kylylahti area from SW we observe a change in reflective structures in line V1 (Figure 11a,b). Due to tectonic structures reflector images are modified, and the Horsmanaho and Keretti reflectors, which are extremely continuous between Outokumpu and this area, come to an end. The Horsmanaho reflector finishes already close to Horsmanaho due to raising above the present erosion level, but the Keretti reflector continues to about 1 km SW of from Kylylahti, where it seems to be cut off by a SE-NW trending fault. Before reaching its end the reflector divides into two branches lying on top of each other (Figure 11a, b).

The Kylylahti area shows a different seismic image than the Outokumpu belt in general. Here the lines V8 and E1 show reflections with a mottled appearance, probably influenced by faulting in SE-NW direction (parallel to E1 and V8). The Kylylahti reflector (O7, Figures 15a,b and 16) hosting the Kylylahti ore deposit and mine extends to about 3 km depth with subvertical edges. In the Kylylahti area, three large faults have been interpreted (the Outokumpu fault, and the Kylylahti faults 1 and 2; Figure 19).

The ore deposit in Kylylahti is not directly imaged with seismic reflections (Figure 20). This is attributed to the small size of the deposit in comparison to seismic wavelengths as well as the subvertical vertical dip of the deposit. The vertical structures result in a difficult geometric situation and the reflections from the contact are guided out of the section. Furthermore, the explosion line E1 was too short in the eastern direction due to environmental and infrastructural reasons.

Hukkala-Kylylahti area. To the NW of Kylylahti area beyond the interpreted Outokumpu fault several reflectors dipping to SE at moderate angles were detected. They were correlated with similar structures on lines OKU1, OKU2, V7 and V2 as reflectors O3 – O5 and representing ophiolite-derived rock types (Figure 15a). At surface the reflectors (e.g. O4 and O5) coincide with black schist and skarn on the geological map. Strong shearing is very probably associated to these reflectors. In the deepest part of the section in the SE lower corner of the profile V8 the strong reflectors are interpreted as due to the Archaean basement and Proterozoic epicontinental rocks (Figure 15a). The about 1 km thick reflector package O6 is tentatively interpreted as ophiolitic rocks. Areas with very weak reflection amplitudes are probably representing granitoids of the Maarianvaara type (Figure 15a, b).

Sola and Sotkuma areas. To the SE of the Kylylahti and Polvijärvi areas the reflectivity suggests a synform structure related to the Sola occurrence of ophiolitic rocks and extending to the depth of about 1.5 km (V8, CMP 4400, Figure 15b). The outcrop of the Sola serpentinite is located 1-2 km to the SW of the synform (out of the line V8). Closer to Kylylahti the reflector O11 (at the depth of about 1.5 – 2.5 km) which can be followed on the eastern side of the Kylylahti formation as far as 2 km N of the Polvijärvi town (Figure 11b) is also interpreted as an occurrence of ophiolitic rocks.

Strong reflectivity is associated to the Sotkuma Archaean gneiss (Figure 15b). In line V8 strong, SE dipping (~20°) reflectivity is present immediately beneath the gneiss outcrop area (Figure 15b). This reflectivity relates to the mafic sill and black schist outcropping at the western contact of the Sotkuma gneiss and generating distinct magnetic anomalies. Reflectivity suggests that the structural orientation changes to NW dipping structures of the Sola synform about 1.5 km to NW from the gneiss contact. We have interpreted the Sotkuma gneiss as a slice of Archaean rocks (and some epicontinental sediments on its boundaries), thus not representing a true basement dome. The reflector attributed to mafic sill and black schist is interpreted to be underlain by a shear zone conforming with the reflector dip.

At deeper levels (1.5 – 2.5 km) there is a thick package of reflections partly under the mica schist and the Sotkuma gneiss (CMP 4600 – 5400, Figure 15b). We interpret this structure as tentatively representing ophiolite-derived rocks. In the old seismic reflection study by Penttilä (1968) the same structure was already imaged about 2 km km south of the line V8 (Penttilä's line A, section II), and we have used his data as supporting evidence in our 3D modelling.

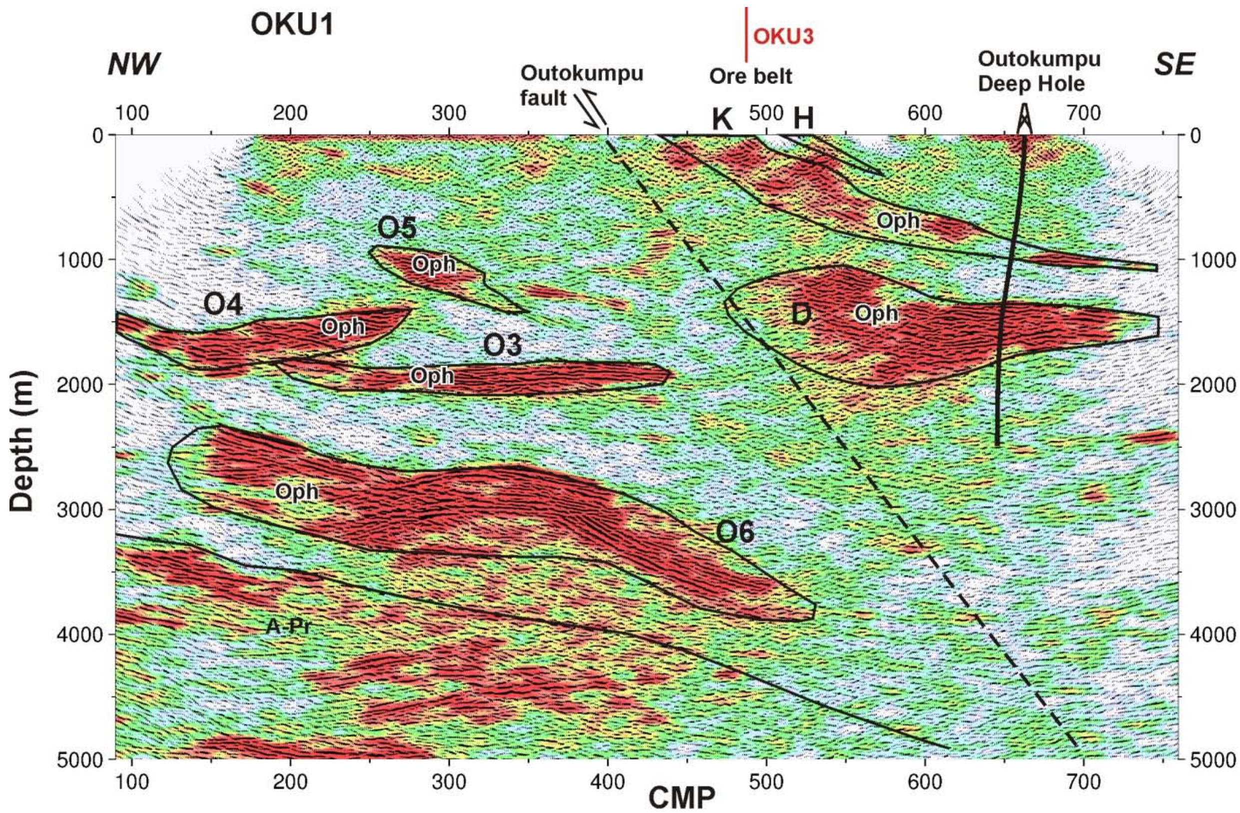


Figure 8. *Migrated NMO section of line OKU1. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and the Outokumpu fault with a broken line. A-Pr: Archaean basement and Proterozoic epicontinental rocks; K: Keretti reflector; H: Horsmanaho reflector; D: Outokumpu deep hole reflector.*

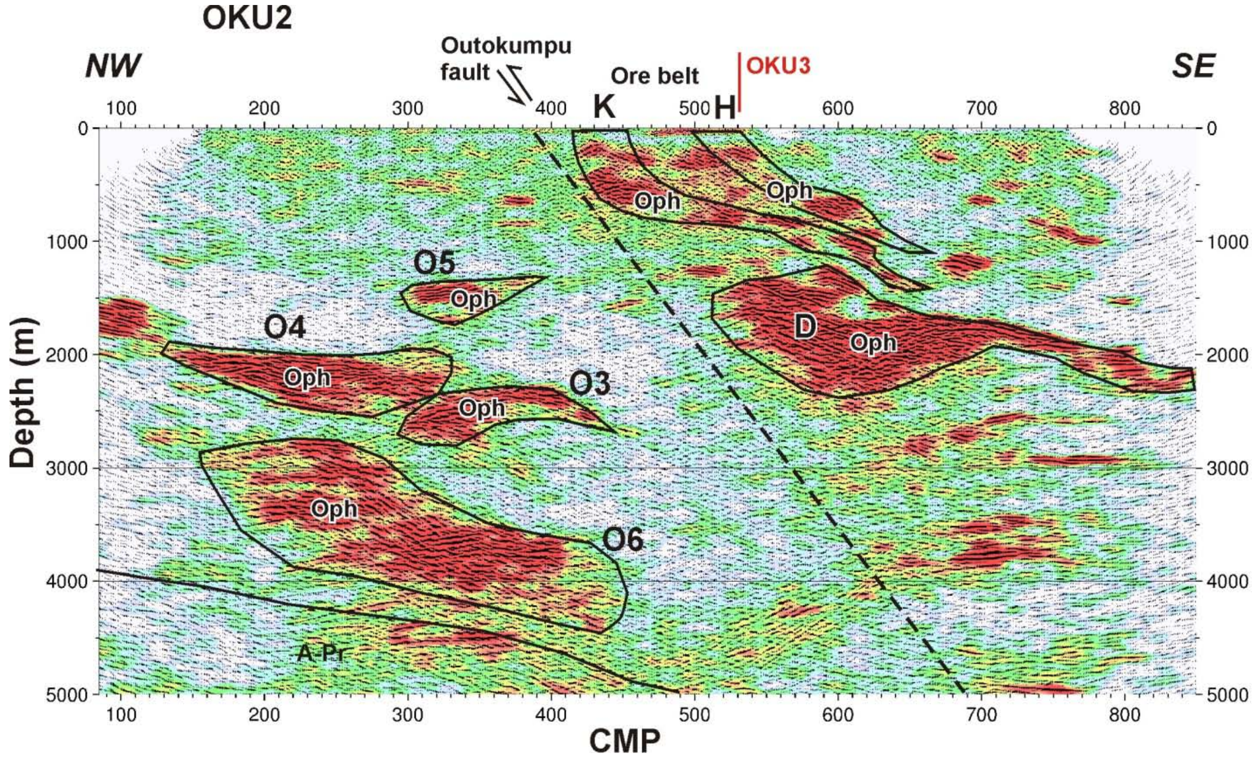


Figure 9. *Migrated NMO section of line OKU2. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and the Outokumpu fault with a broken line. A-Pr: Archaean basement and Proterozoic epicontinental rocks; K: Keretti reflector; H: Horsmanaho reflector; D: Outokumpu Deep Hole reflector; O3 – O6: reflectors interpreted to represent ophiolite-derived rock types (Oph).*

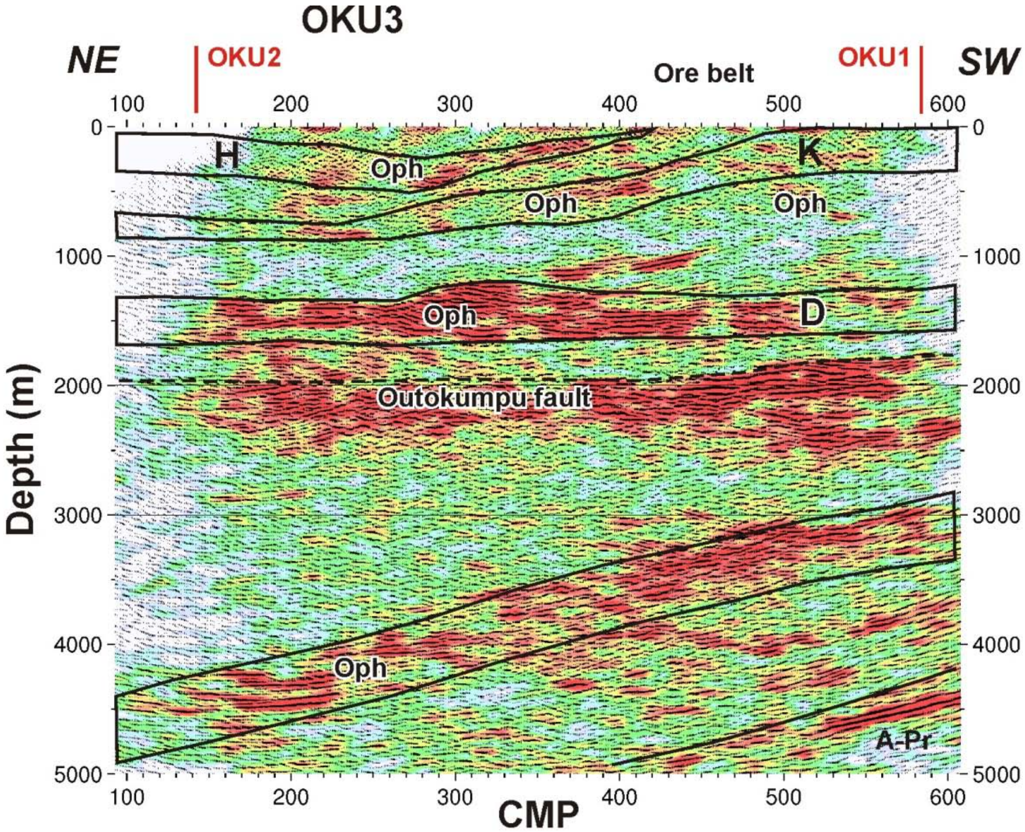


__Figure 10.__ Migrated NMO section of line OKU3. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and the Outokumpu fault with a broken line. A-Pr: Archaean basement and Proterozoic epicontinental rocks; K: Keretti reflector; H: Horsmanaho reflector; D: Outokumpu Deep Hole reflector; O3 – O6: reflectors interpreted to represent ophiolite-derived rock types (Oph).

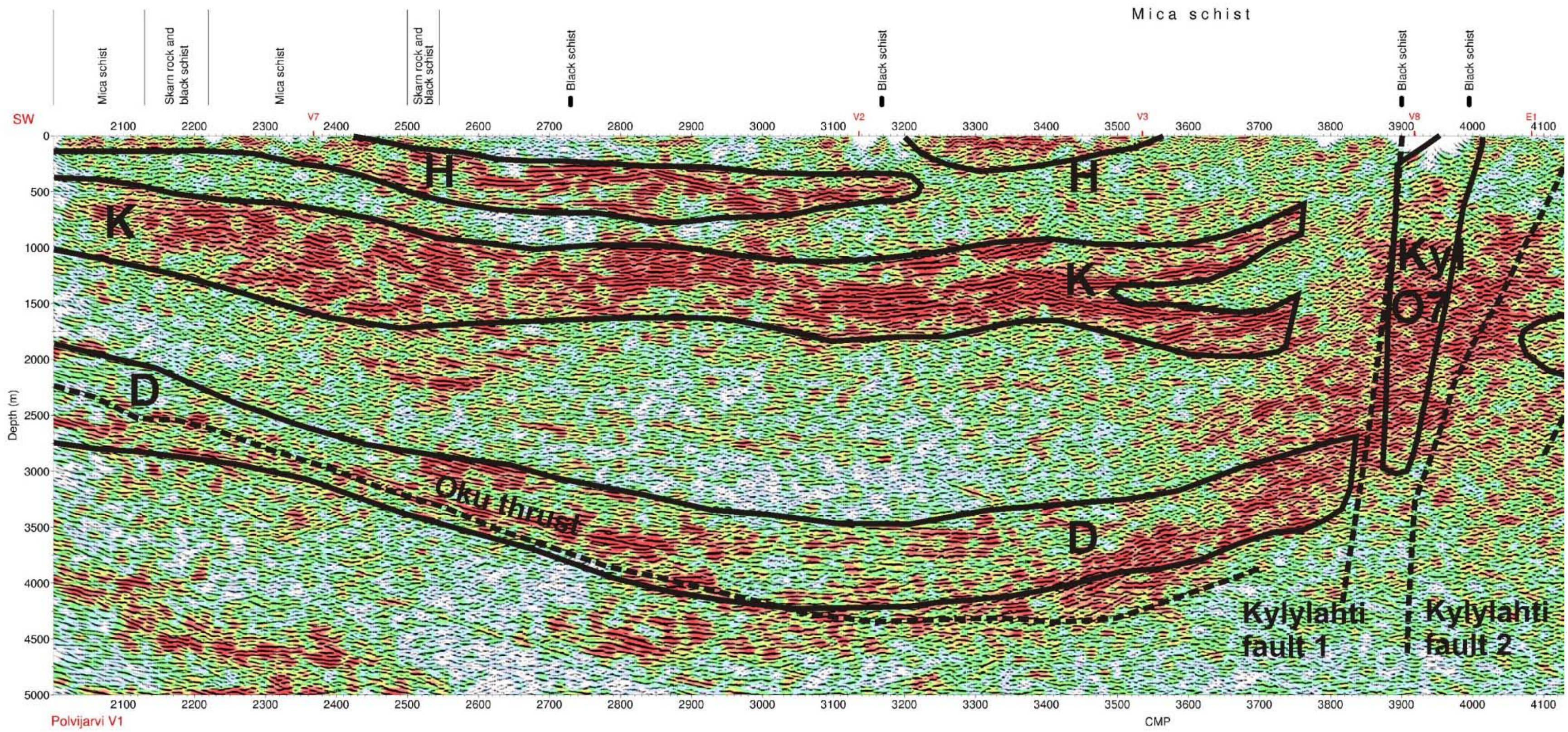


Figure 11a. *Migrated NMO section of line V1, SW part, CMP 2000-4100. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and the Outokumpu fault with a broken line. K: Keretti reflector; H: Horsmanaho reflector; D: Outokumpu Deep Hole reflector; Kyl: Kylylahti reflector.*

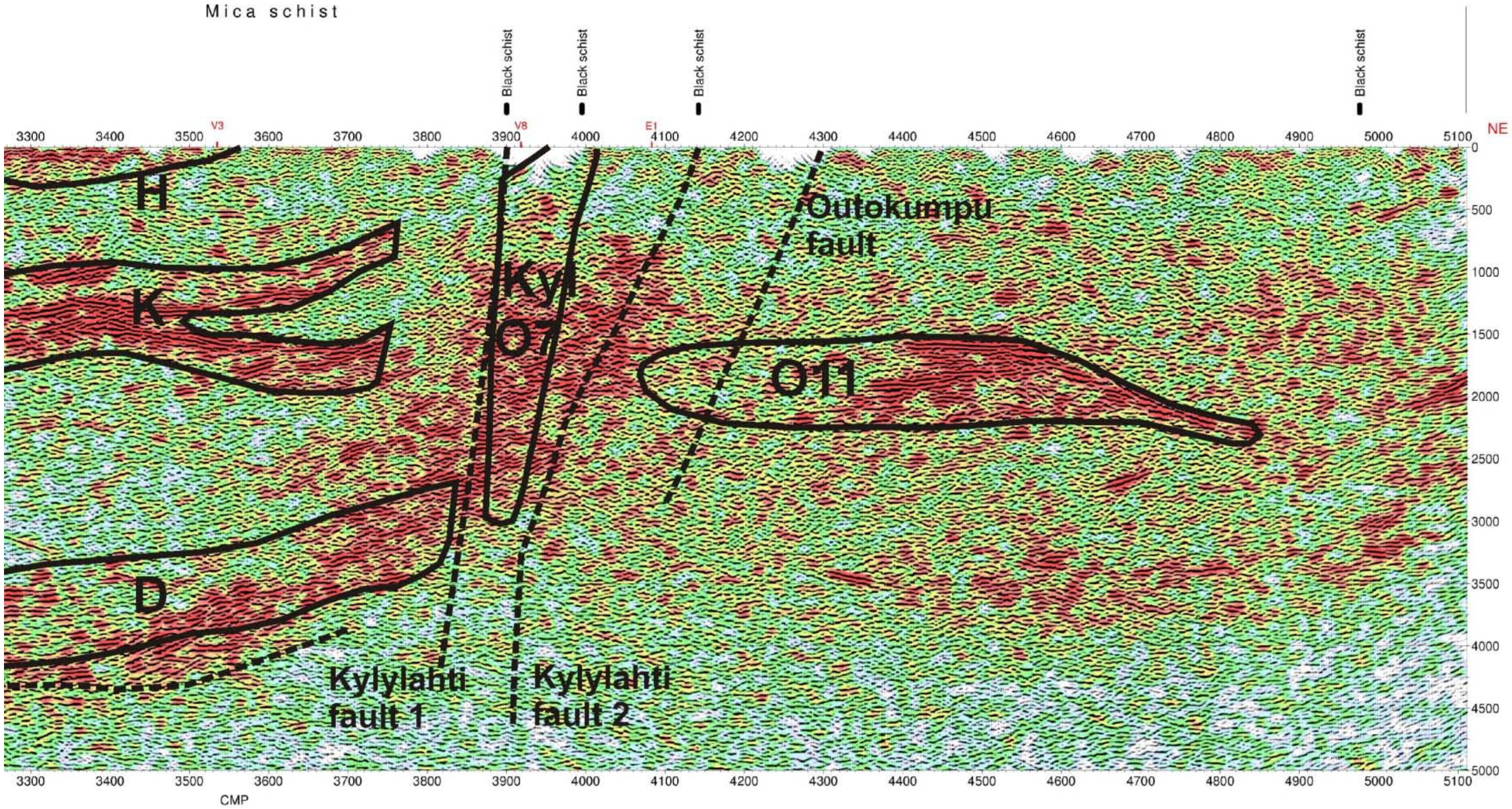


Figure 11b. V1. *Migrated NMO section of line V1, NE part, CMP 3300-5100. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and faults with a broken line. K: Keretti reflector; H: Horsmanaho reflector; D: Outokumpu Deep Hole reflector; Kyl: Kylylahti reflector, O11: reflector interpreted to possibly represent ophiolite-derived rocks.*

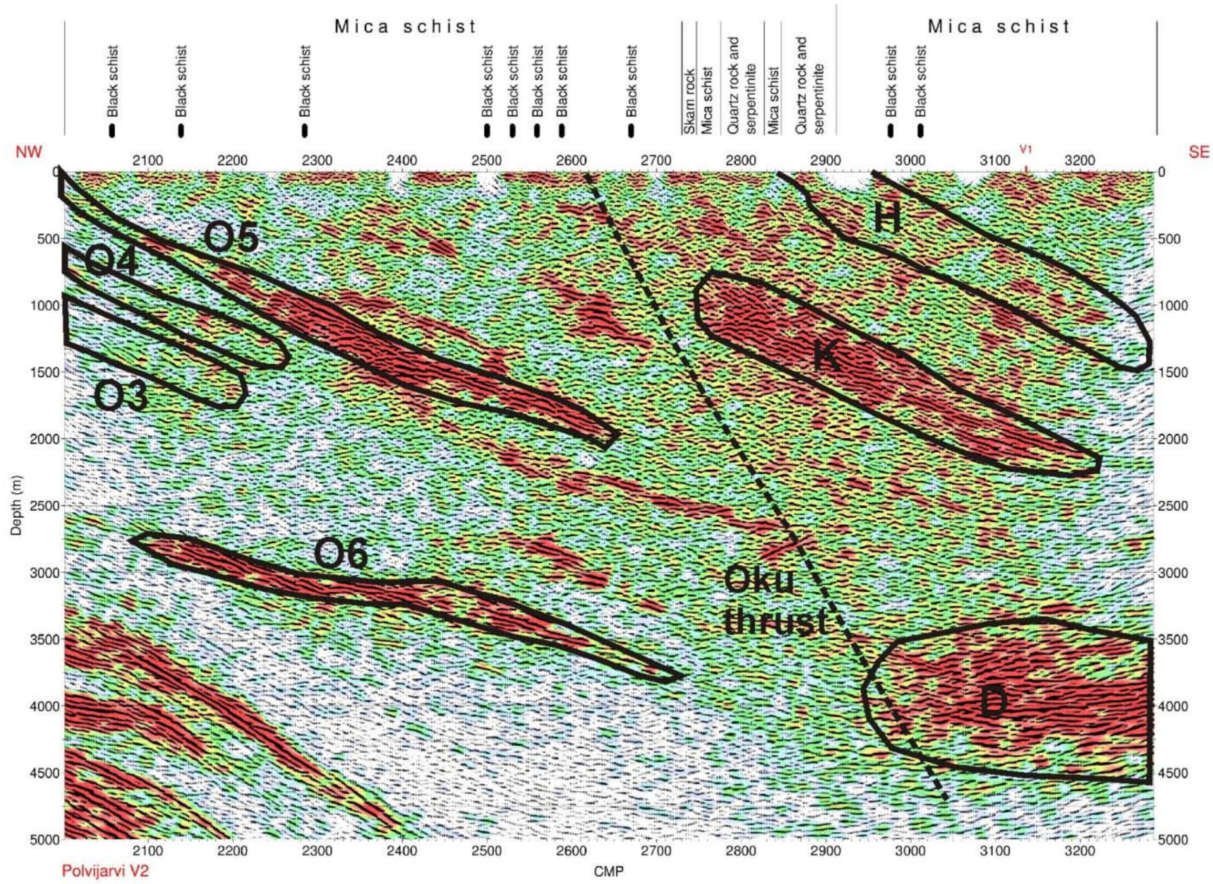


Figure 12. *Migrated NMO section of line V2. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and the Outokumpu fault with a broken line. K: Keretti reflector; H: Horsmanaho reflector; D: Outokumpu Deep Hole reflector; O3 – O6: reflectors interpreted to represent ophiolite-derived rock types.*

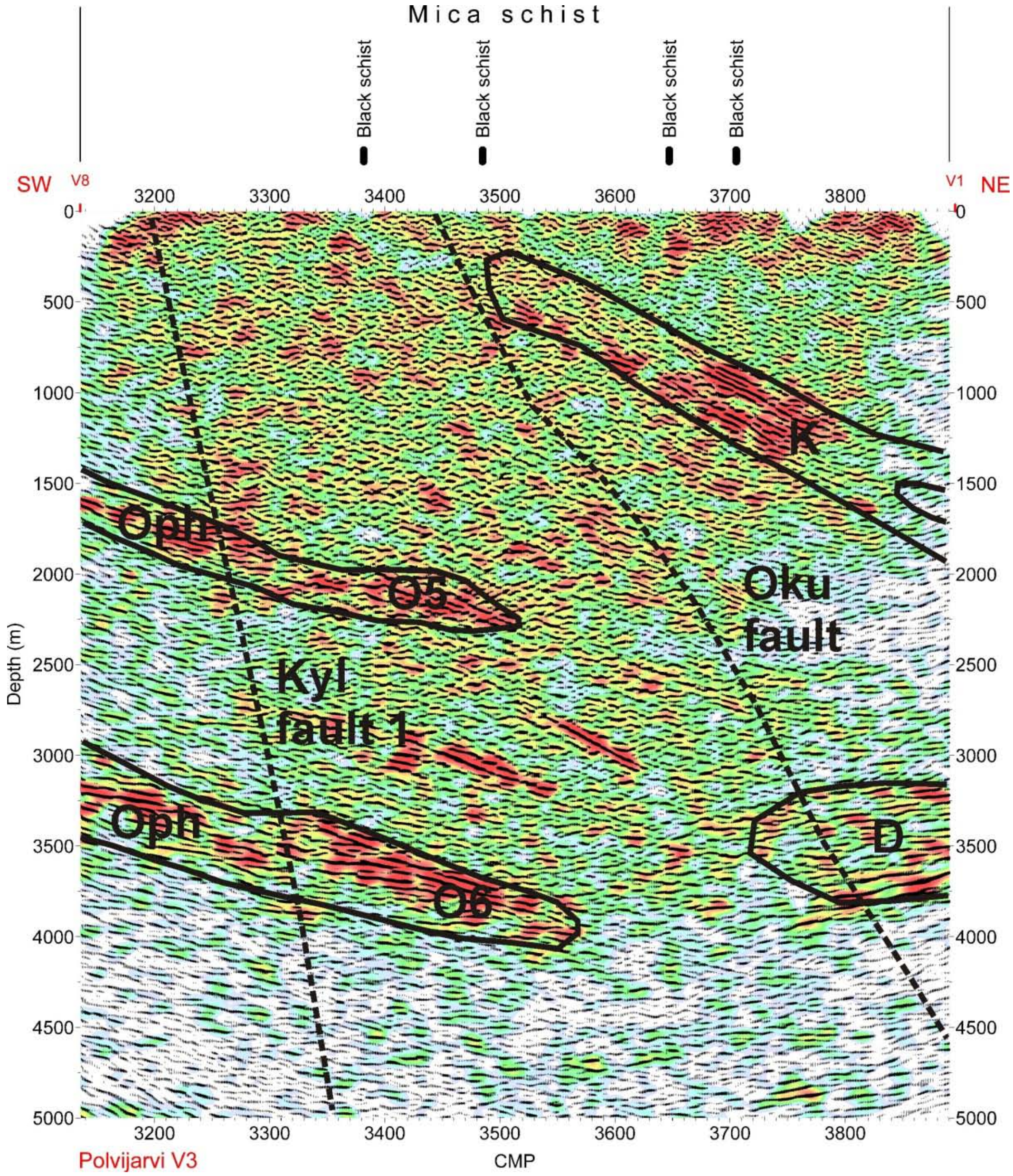


Figure 13. *Migrated NMO section of line V3. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and the faulst with broken lines. K: Keretti reflector; D: Outokumpu Deep Hole reflector; O5 and O6: reflectors interpreted to represent ophiolite-derived rock types (Oph).*

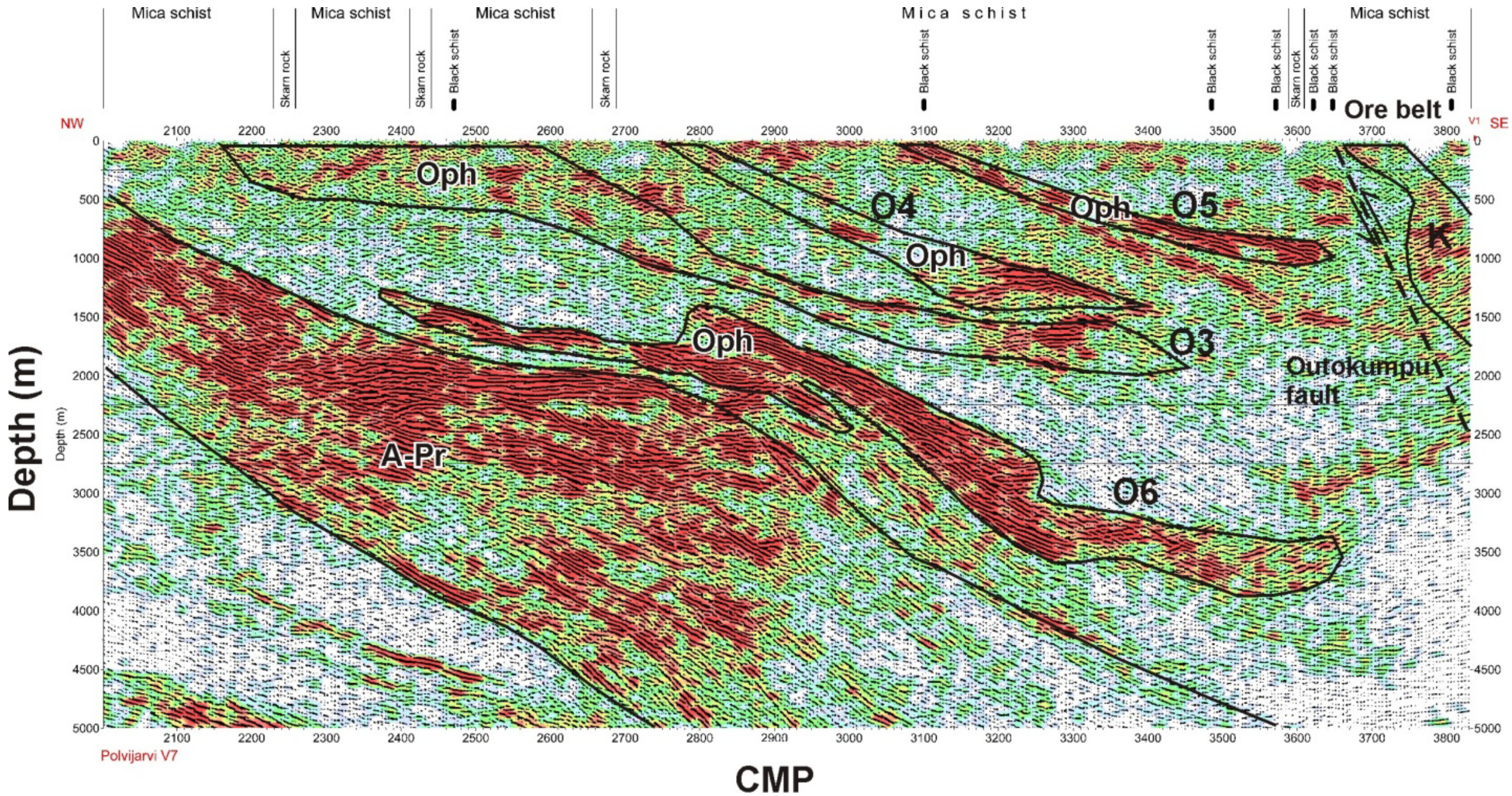


Figure 14. *Migrated NMO section of line V7. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and the Outokumpu fault with a broken line. A-Pr: Archaean basement and Proterozoic epicontinental rocks; K: Keretti reflector; O3 – O6: reflectors interpreted to represent ophiolite-derived rock types (Oph).*

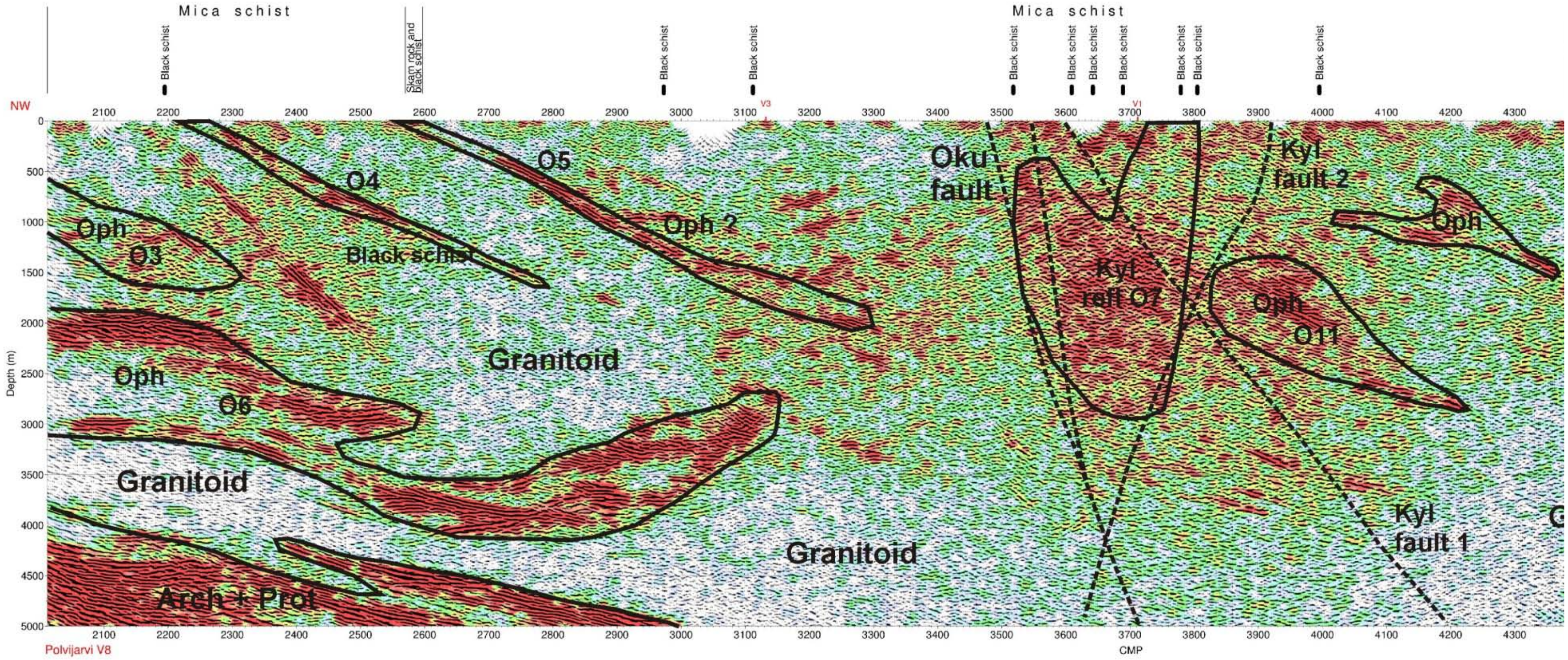


Figure 15a. *Migrated NMO section of line V8, NW part, CMP 2000 - 4400. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and the Outokumpu fault with a broken line. A-Pr: Archaean basement and Proterozoic epicontinental rocks; Kyl: Kylylahti reflector; O3 – O7 and O11: reflectors interpreted to represent ophiolite-derived rock types (Oph).*

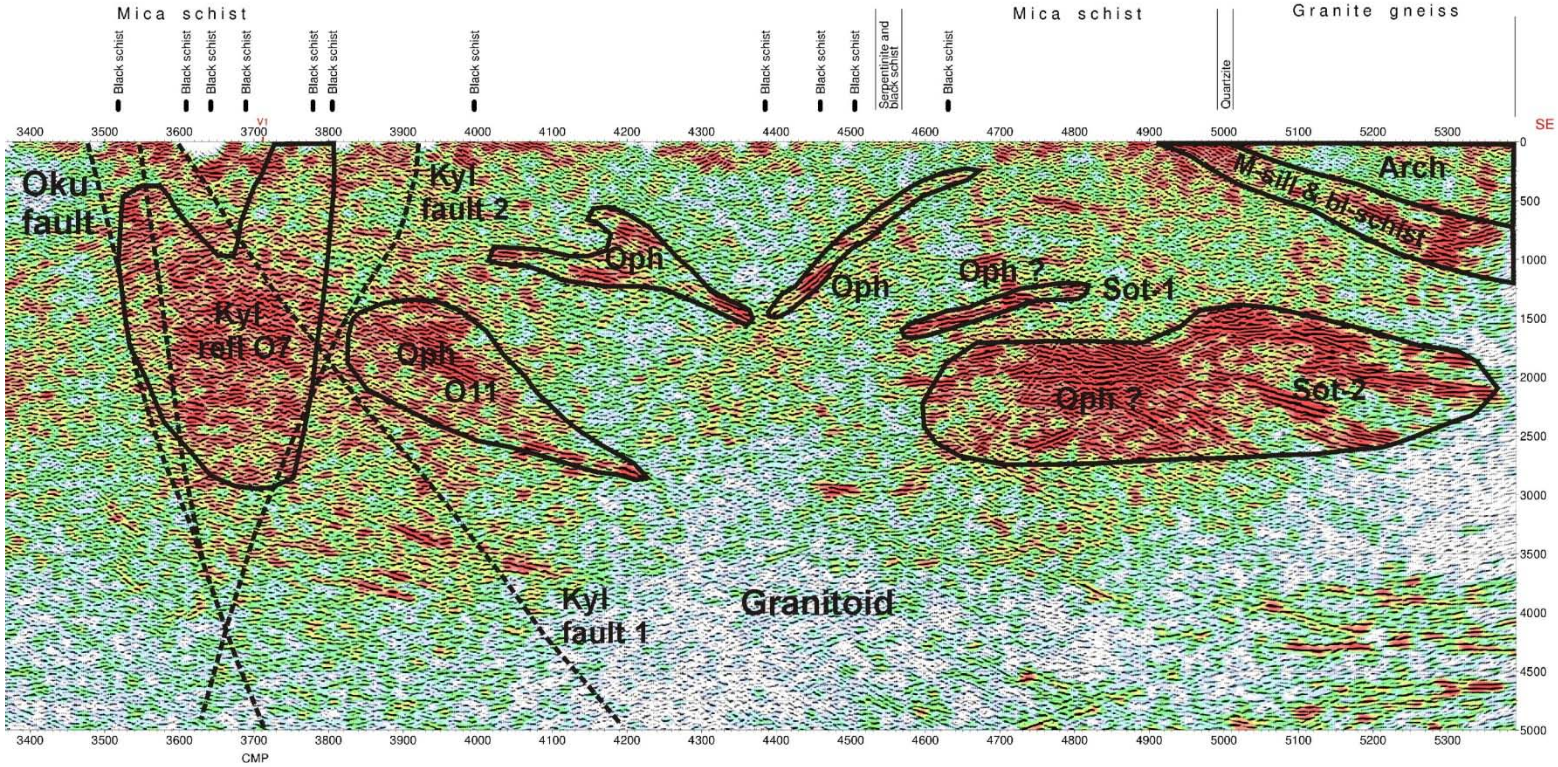


Figure 15b. *Migrated NMO section of line V8, SE part, CMP 3400 - 5400. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and faults with broken lines. Arch: Archaean granite gneiss of Sotkuma; M-sill and bl-schist: Mafic sills and black schist and other Proterozoic epicontinental rocks; Kyl: Kylylahti reflector; Oph: reflectors interpreted to represent ophiolite-derived rock types.*

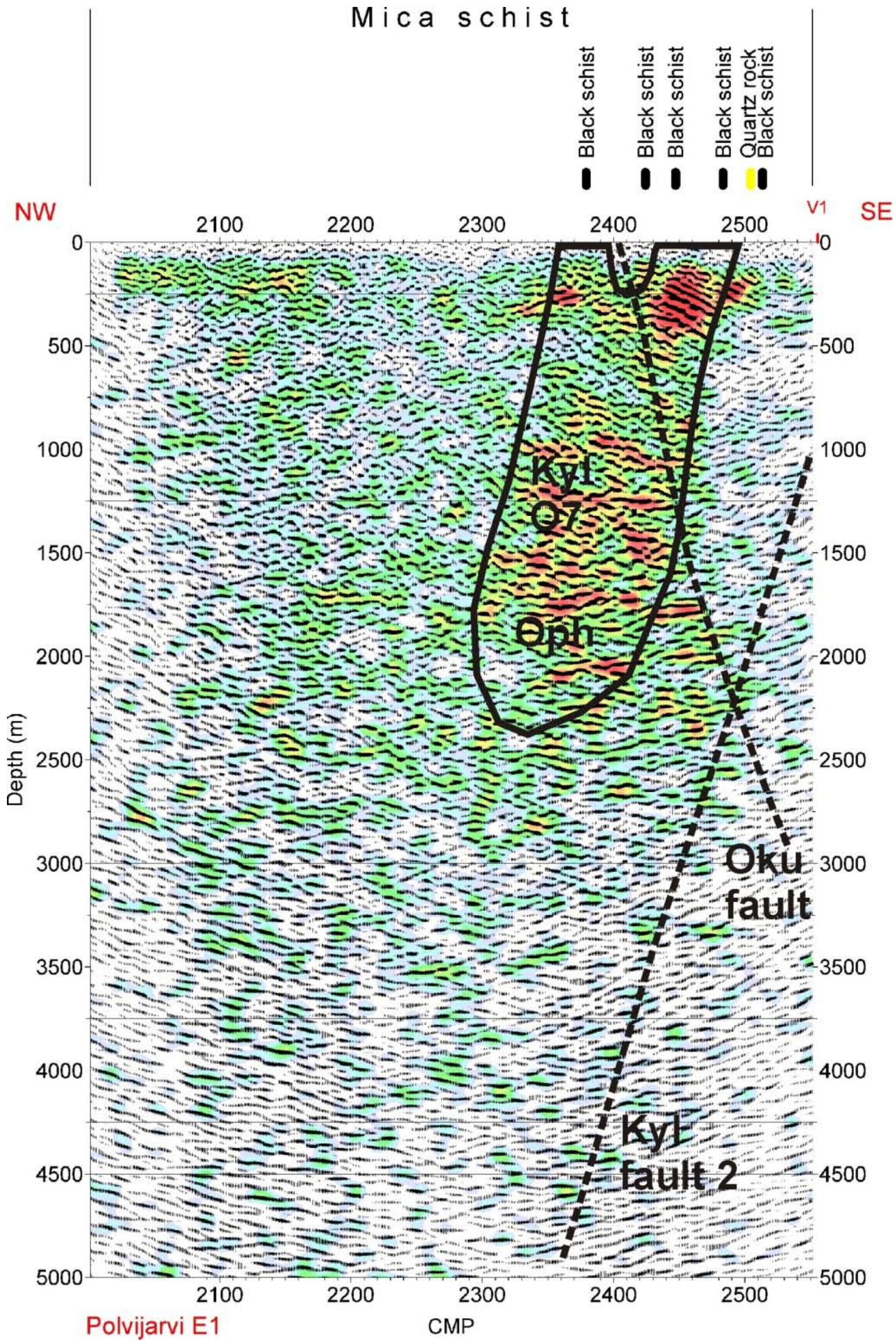


Figure 16. *Migrated NMO section of line E1. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of reflectors are indicated with solid lines and the Outokumpu fault with a broken line. A-Pr: Archaean basement and Proterozoic epicontinental rocks; Kyl O7: Kylylahti reflector; Oph: reflectors interpreted to represent ophiolite-derived rock types.*

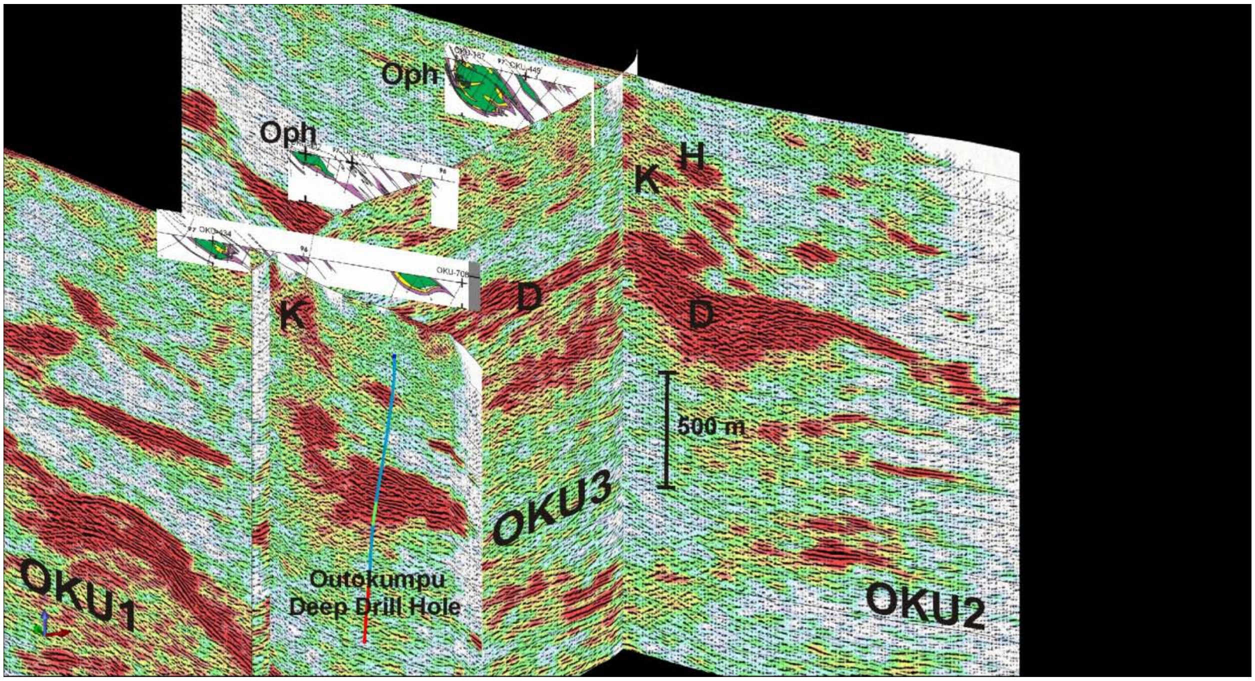


Figure 17. *Fence diagram looking from south and showing lines OKU1 – OKU3 and Outokumpu drilling profiles 189.0, 192.0 and 194.5 (adopted from Koistinen, 1981; green: serpentinite, yellow: quartz rock; lilac: black schist) and the Outokumpu deep drill hole main lithologies (blue: metasediments; pale green: ophiolitic rocks; red: pegmatitic granodiorite).*

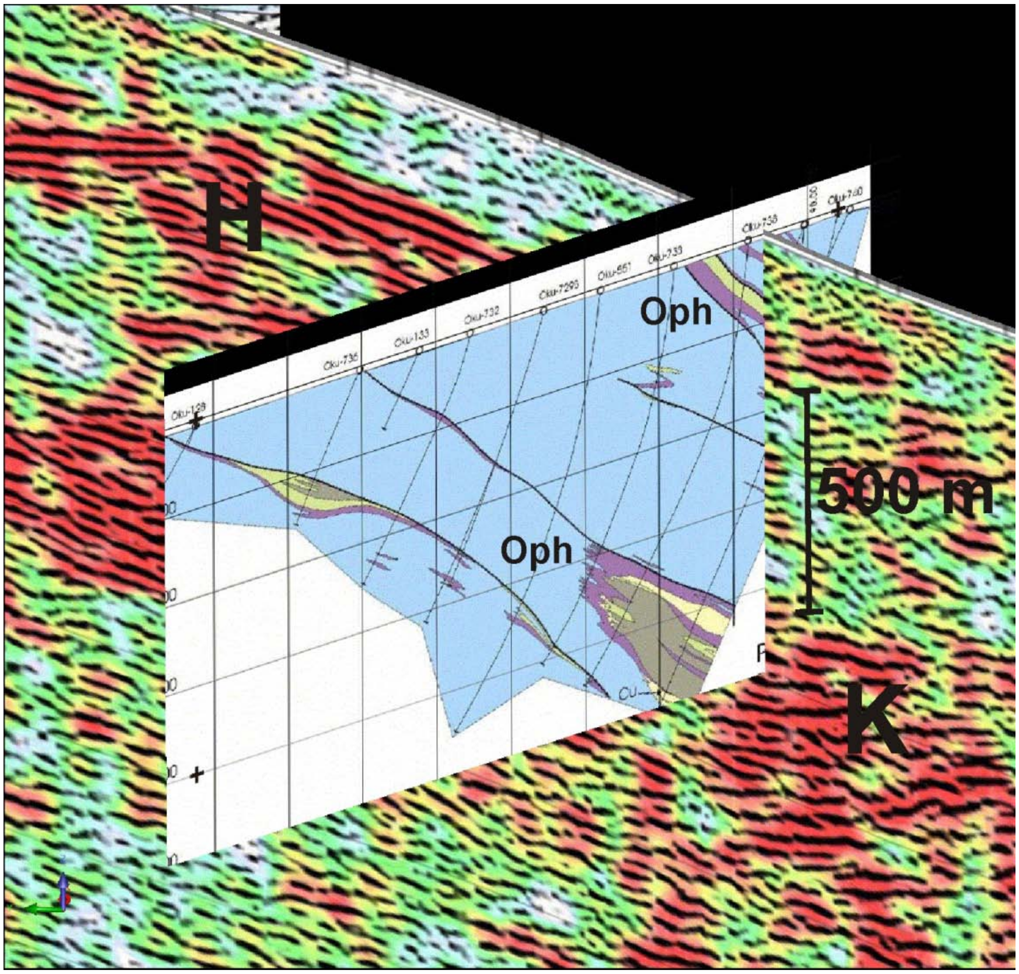


Figure 18. *Fence diagram looking from above in direction of east on seismic section V1 and the drilling profile Perttilahti-200 (adopted from Kontinen et al., 2006). Oph: ophiolite-derived rock types serpentinite (gray), quartz rock (yellow), skarn rock (green) and black schist (lilac); H: Horsmanaho reflector; K: Keretti reflector.*

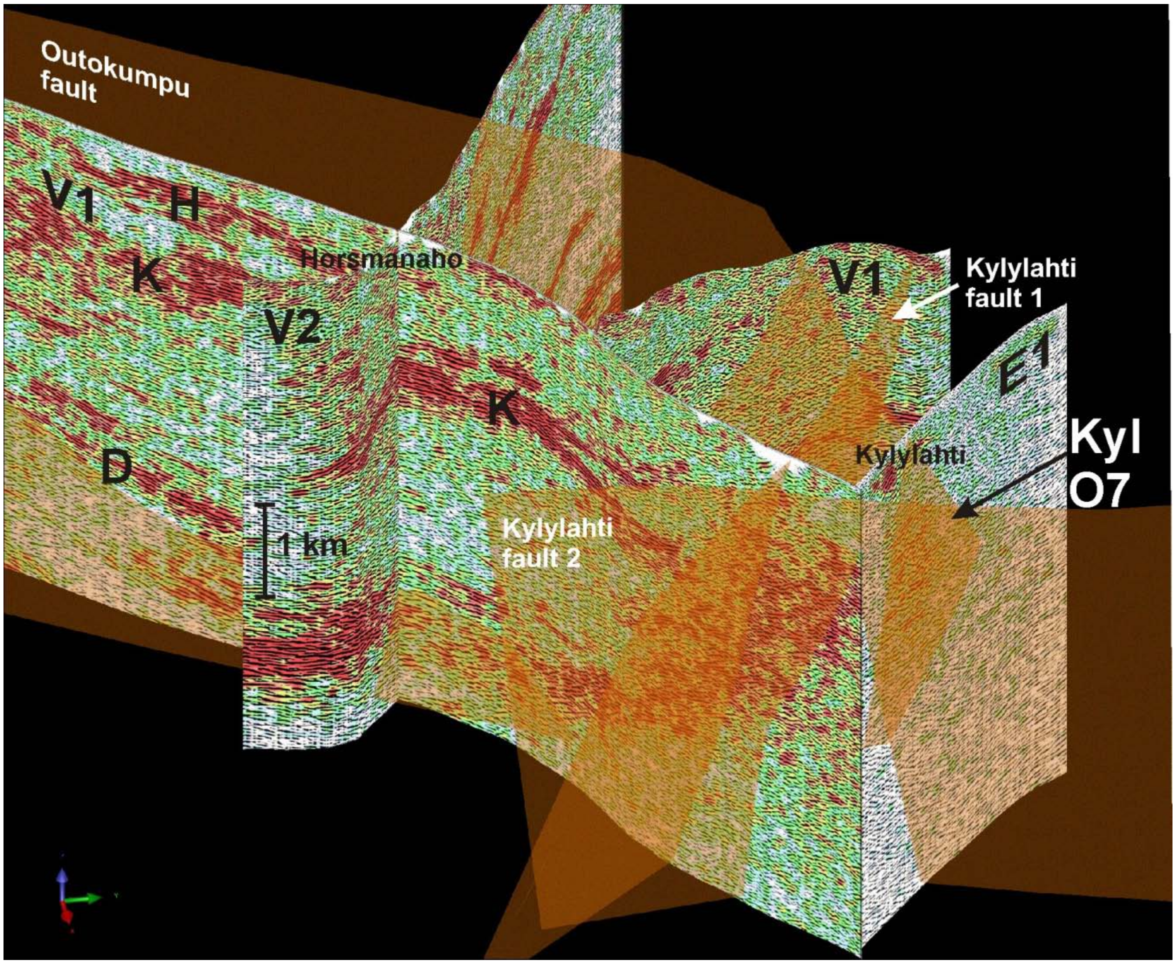


Figure 19. *Fence diagram of lines V1-V3 and E1 in the Horsmanaho-Kylylahti area. Interpreted fault planes are shown in transparent brown tone; K: Keretti reflector, H: Horsmanaho reflector; D: Deep hole reflector.*

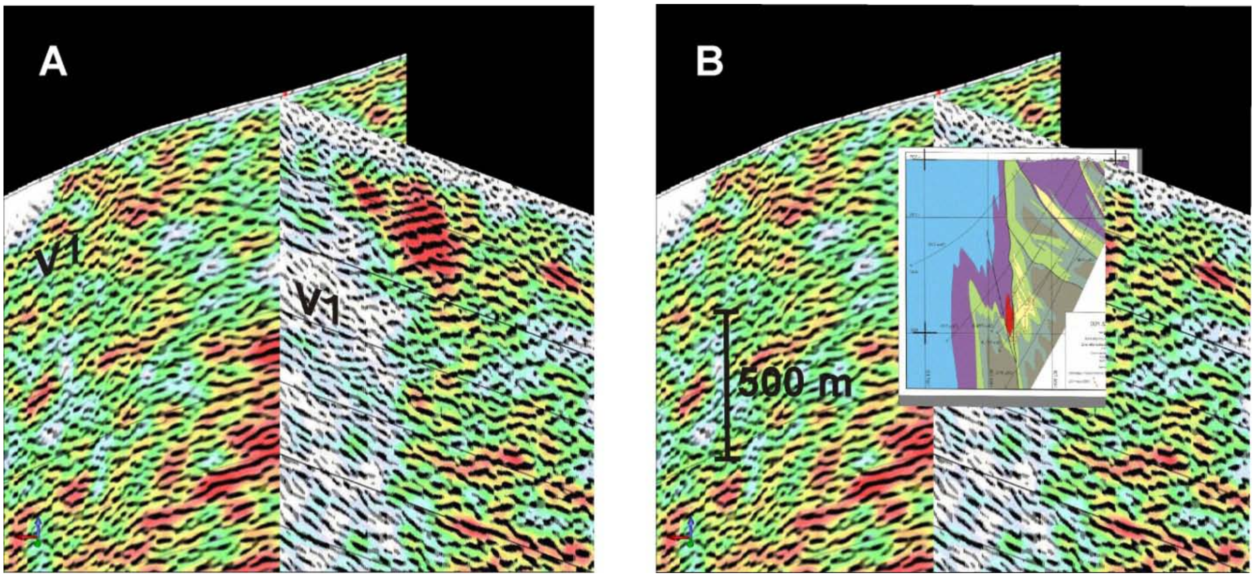


Figure 20. *Fence diagram looking the Kylylahti deposit from north. The seismic section E1 and part of V1 are shown in (a) and with the drilling profile Kylylahti 72700 in (b). Drilling profile color code: Blue: metasediments; green: skarn rock: gray: serpentinite; lilac: black schist; red: ore.*

5.3.3. 3D models of reflectors in the Outokumpu – Polvijärvi area

3D models of the reflective bodies were constructed in Surpac software environment. Using the seismic profiles, cross-sections between lines, surface geological and magnetic maps it is possible to compile comprehensive models of the ore belt structures. The reflector solids are given in the digital appendices of the report. An illustration of the solids is given in Figures 21 and 22.

In areas where the real 3D data is limited to only one seismic section, the presented solid was constructed with strings drawn on added additional planes. Details of these solids are of course quite speculative elsewhere than the seismic survey line. Such a situation applies, for instance, to the reflector solids in the Sotkuma and Sola areas where only line V8 is available as hard data in addition to surface geological and magnetic information. In this area the old reflection seismic data by Penttilä (1968) was applied as guiding information. The reflectors presented by Penttilä coincide reasonably well with the present data in the Horsmanaho area where both surveys cover more or less the same area, and we considered that the data is very probably reliable also in the Sotkuma area (see Surpac materials).

The outcropping part of the main ore belt is divided into two main layers comprising the northwest (‘Keretti reflector’) and southeast (‘Horsmanaho reflector’) components (Figures 21 and 22). The reflector intersected by the Outokumpu Deep Hole can be followed from OKU1 to OKU 2 and further about 10 km to the northeast where the reflector is at the depth of about 4.5 km (in V2). The reflector joins the tectonically disturbed structures in the Kylylahti area.

In the opposite direction to southwest from OKU1 we have no seismic data, but good continuity of reflectivity suggests the Deep hole reflector may extend as far as to the northeast side of the closed Keretti mine (see below, chapter 6.2).

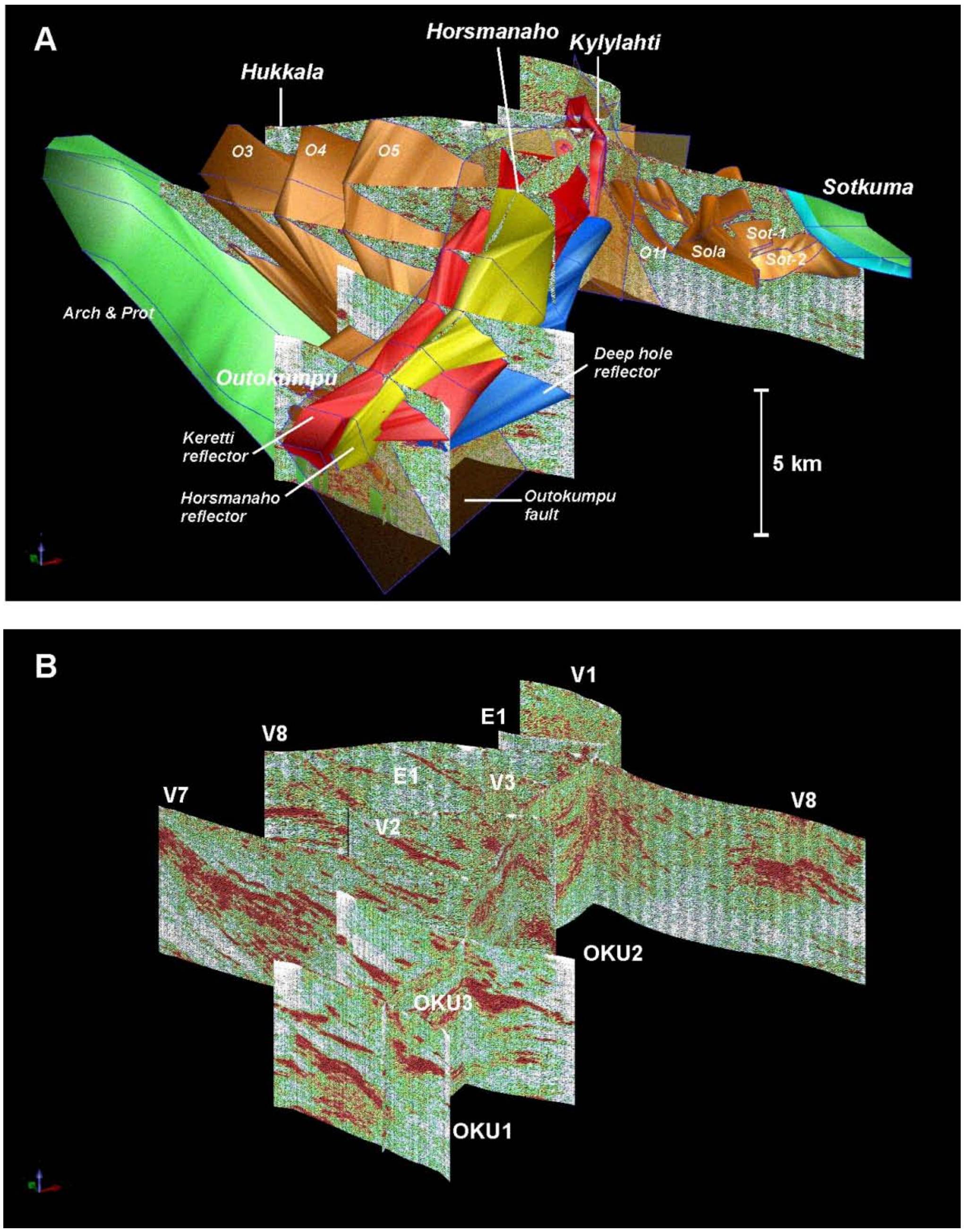


Figure 21. *(A) Fence diagram of seismic survey lines in the Outokumpu-Polvijärvi area together with the interpreted reflector bodies. View is from south. (B) The seismic survey lines are shown only.*

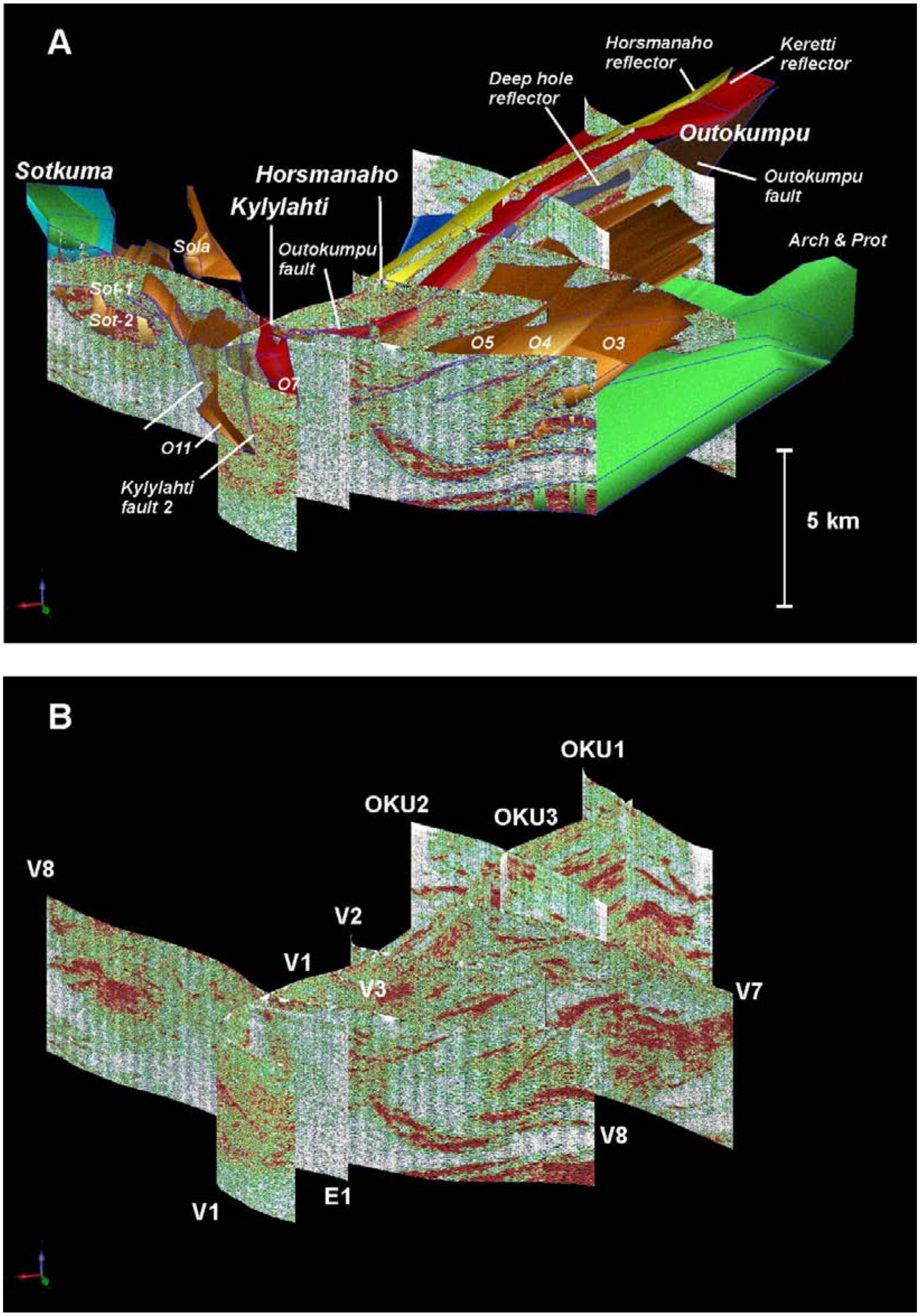


Figure 22. *(A) Fence diagram of seismic survey lines in the Outokumpu-Polvijärvi area together with the interpreted reflector bodies. View is from north. (B) The seismic survey lines are shown only.*

6. DISCUSSION

6.1 Reflective structures and their correlation over the study area

The general observation of the present results is that very strong reflectivity is present in the upper 5 km of crust in the Outokumpu-Polvijärvi area. Surface geology, available drilling profiles (Koistinen, 1981; Kontinen et al., 2006) and the Outokumpu deep hole results (Kukkonen, 2011; Heinonen et al., 2011) imply that the strong reflectivity is very often associated with the ophiolite-derived rocks of the Outokumpu assemblage. The close association of black schist with the ophiolite-derived altered ultramafic rocks makes it sometimes difficult to distinguish these two rock types in the seismic sections, because both are reflective against the metasedimentary rocks. Furthermore, serpentinite bodies are often present as boudin-like structures, whereas the black schist tends to be more continuous in cross-sections.

There is also strong reflectivity related to the Archaean basement and Proterozoic cover rocks outcropping for instance in the Saarivaara area to the NW of the survey, and it is not always possible to give firm statements of the geological character of some of the deep-seated reflectors.

The high resolution seismic reflection survey revealed the deep structure of the Outokumpu ore belt. The ophiolite-derived rock types seem to be much more common in the upper crust of the Outokumpu – Polvijärvi area than previously anticipated. The depth extent of the overthrusted ophiolitic rocks in the Outokumpu belt is probably of the order of 5-8 km in the northern part of the belt as revealed by the deep section of line V8 (Figure 23).

The high resolution data is limited in area and does not allow an interpretation of the continuation of the Keretti, Horsmanaho and Deep hole reflectors to the depths of the Viinijärvi basin, but the FIRE-3 section clearly shows that at least the Deep hole reflector (Figure 7) continues further to SE from the Outokumpu area to depths of several kilometers. We also compared the audiomagnetotelluric (AMT) soundings by Lehtonen (1980) with the seismic data and observed that the conductive structures correlate with seismic reflectors (Figure 24). The FIRE-3 transect also shows (see sections in Kukkonen et al., 2006) that the reflectors diving deep into the Viinijärvi basin return close to the surface in the southern contact area of the Sotkuma Archaean gneiss block (in the area of Viinijärvi and Kontkala).

The Sotkuma area is interpreted here as a slice of Archaean basement rocks and Proterozoic cover rocks, and not as a basement window (Figure 15b). The geological evidence shows that many of the outcrops of Archaean rocks in the Outokumpu-Maarianvaara-Heinävesi area have quite complicated structures derived from the overthrust tectonics and even overturned stratigraphic sequences implying non-trivial structural situations (e.g., Koistinen, 1993).

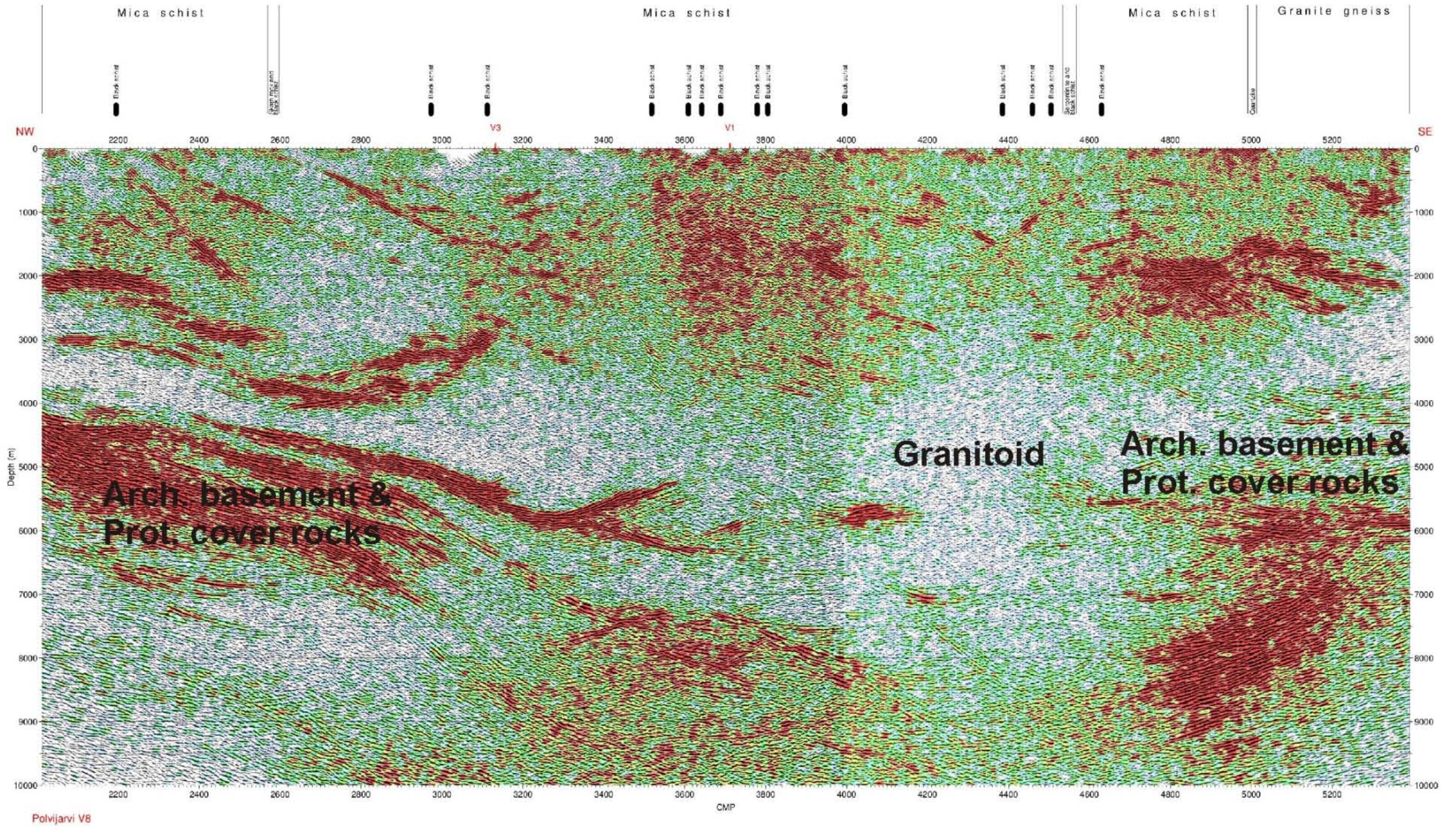


Figure 23. *Migrated NMO section of line V8 showing data up to the depth of 10 km. The strong reflectors at 5 – 9 km are interpreted as Archaean basement and Proterozoic cover rocks, whereas the poorly reflective areas are most probably due to granitoids of the Maarianvaara type. For the interpretation of the uppermost 5 km, see Figures 15a and 15b.*

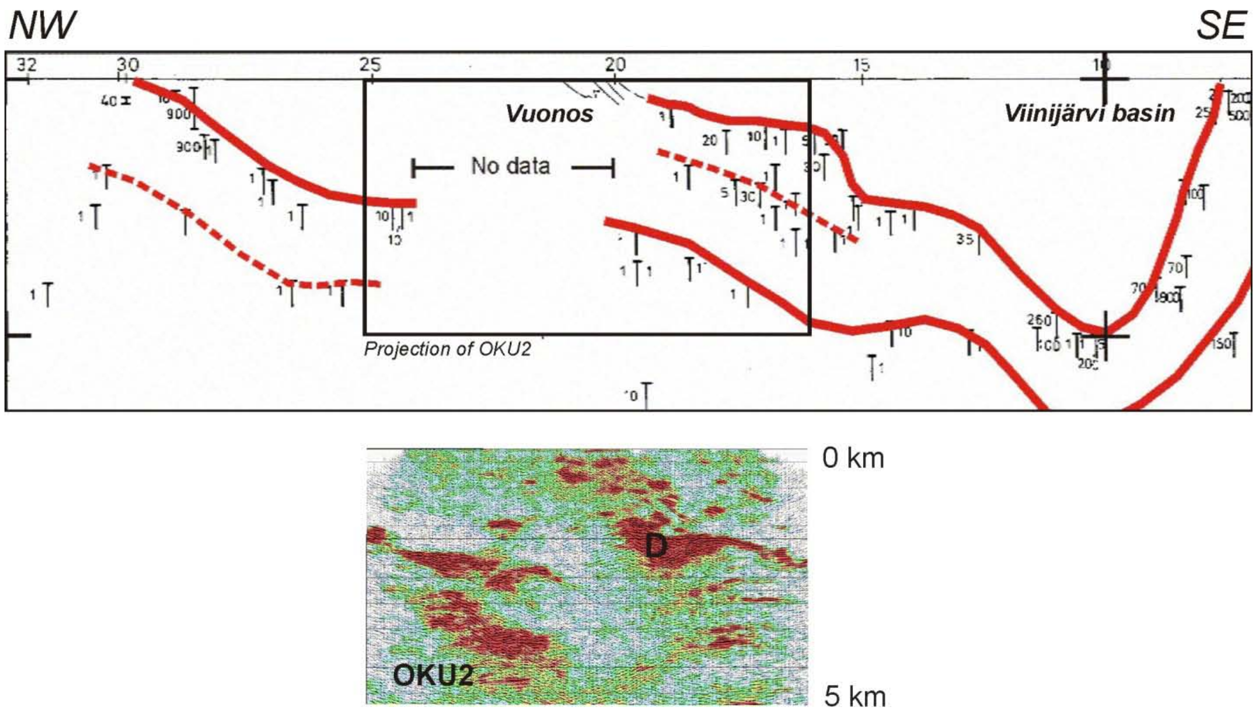


__Figure 24.__ Comparison of the NW-SW oriented AMT profile running through the Vuonos area (adapted from Lehtonen, 1980) and the seismic section OKU2. The seismic section is projected on the AMT profile in the direction of the geological strike. The red solid and broken lines show the upper boundaries of the conductors. Small numbers indicate the modeled resistivity in ohm-m.

6.2. Suggestions for further exploration

The Outokumpu ore belt has been quite thoroughly explored for sulphide deposits in the past one hundred years. The ubiquitous association of the Outokumpu type massive-semimassive deposits and mantle-derived serpentinitic ultramafic rocks implies that the exploration task is straightforward in principle. First, sufficiently big ‘frames’ of ophiolitic rocks of the Outokumpu assemblage need to be localized and then the possible deposits within them. However, all serpentinite bodies do not host deposits, and moreover, the volume of sulfide ore bodies is of the order of 1 % of the host rock formation volume. Therefore detailed targeting with geophysics and drilling is required.

The latest extensive exploration campaign in the Outokumpu area was the project GEOMEX 1999-2003 (Kuronen et al., 2003; Kontinen et al., 2006). GEOMEX checked probably all indications of ophiolitic rocks known from geological mapping, diamond drilling and geophysics and the probability of discovering new interesting serpentinites at depths of less than about 500 m was considered to be small by Kontinen et al. (2006). Therefore, future exploration probably needs to be focused at greater depths. In order to be economic, any discovered deposits would need to be bigger and preferably of a higher grade than at shallower depths. However, at this stage we ignore economic considerations and set the task as one of locating serpentinitic ophiolite-derived rock bodies which could potentially host sulfide mineralizations.

The big deposits in the Outokumpu belt are associated with big and thick occurrences of the ophiolitic rock type assemblage. This was the case with the Keretti and Vuonos deposits, which were both located in the Outokumpu belt at places where the assemblage is 500 -1500 m thick in cross section. In Kylylahti, the ophiolitic assemblage is about 500 m thick. In Horsmanaho (where no sulfide deposit exists, but talc is mined) the assemblage is about 500 m thick.

The present seismic data is well suited for detecting ophiolite-derived rock type assemblages of such thickness. We have many such reflectors in the sections, namely those in OKU1 – OKU3 at depths of 1.5 – 2 km, which were confirmed to represent Outokumpu assemblage rocks by the Outokumpu Deep Drill Hole. However, in the deep hole, no indication of mineralization was observed. The Outokumpu type deposits do not show extensive geochemical halos, and lithogeochemistry was considered to be of little value in exploring OKU type deposits (Kontinen et al., 2006).

We have used the present seismic data and the modelings for indicating a number of potentially interesting targets in the Outokumpu belt. The targets are shown on the airborne magnetic map with seismic survey lines in Figure 25. A short discussion of suggested targets follows.

The reflector structures in lines OKU1 and OKU2 are surprisingly similar indicating a very good continuity of reflectors along the geological strike. Although we have no seismic sections in the thickest part of the Outokumpu belt in the Keretti area, we consider it quite plausible that the Deep hole reflector extends also to the SW. The continuity is supported by the magnetic map which does not suggest any serious disruptions of the serpentinite and black schist related anomalies.

The target no. 1 is the modeled ***SW extension of the deep hole reflector*** is shown in Figure 26. We also pay attention to the fact that the ophiolite-derived rock type assemblage is at its thickest in the Keretti area. This may be due to the influence of the Outokumpu fault. Thrusting and deformation of the ophiolitic rocks in the fault movements may have contributed to the thickening. We postulate that a structure similar to that in Keretti is possibly present at the depth of 1 – 2 km on the hanging wall side of the Outokumpu fault. Such a thick ‘frame’ of ophiolitic rocks could be an interesting target for deep exploration.

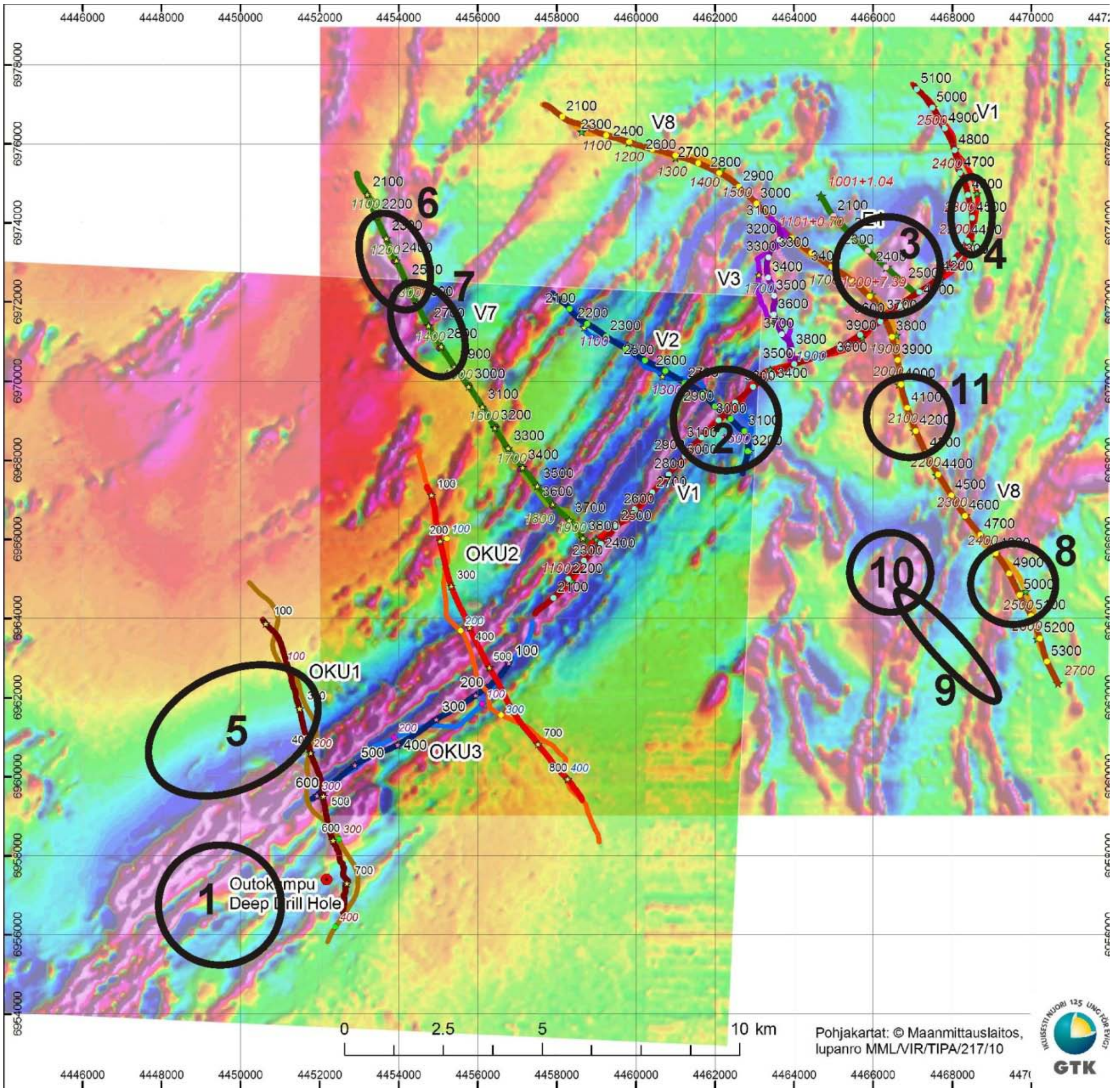


Figure 25. *Suggested targets for further exploration in the Outokumpu ore belt. See text for details.*

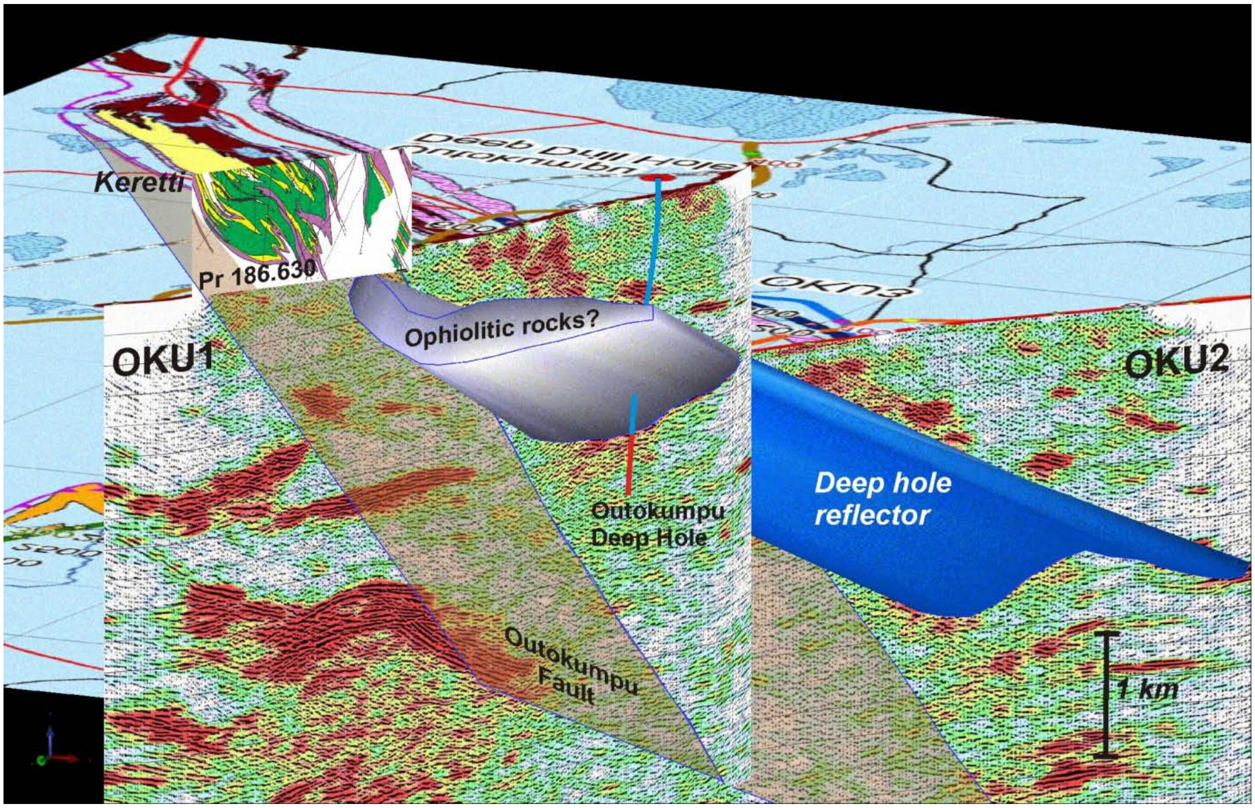


Figure 26. The deep hole reflector is interpreted to continue to SW from line OKU1 and the Outokumpu deep drill hole. This fence diagramis looking form below to the direction NNW and shows the deep hole reflector extrapolated about 2 km to the SW as far as the drilling profile 186.630 in the Keretti area (adapted from Koistinen, 1981).

The Keretti and Horsmanaho reflectors are also interesting targets in general. The Keretti reflector is thicker and can be more easily identified from the seismic data, whereas the Horsmanaho reflector is thinner and shows more often discontinuities. One potential spot of the Keretti reflector is seen in the Horsmanaho area in line V2 where the reflector is about 500 m thick and about 2.5 km wide in cross section (***Target no. 2***) (Figure 12 and 25). The uppermost parts of the reflector are at the depth of about 800 m. In the Horsmanaho area, the reflector shows high reflection amplitudes (Figure 11a).

The Kylylahti reflector (O7) is the target no. 3, which extends to the depth of 3 km. The overall image arising from the seismic data shows the Kylylahti area as a result of strong deformation and faulting. The reflectors of the main ore belt running from SW seem to converge in the Kylylahti area into a dense cloud of reflections. Tectonically it may implicate favourable environments for deformation-related thickening of sulphide-bearing layers. The Kylylahti reflector (O7) would be a good target for a 3D reflection seismic survey.

Target no. 4 is the reflector located to the north of Kylylahti and Polvijärvi town in V1 (***reflector O11***, Figure 11b) possibly representing ophiolitic rocks. It could be speculated that it could be the northernmost end of the deep hole reflector, although cut by the faulting in the Kylylahti area. This reflector is unfortunately quite deep (1.5 – 2 km).

Target no. 5 comprises reflectors located to the NW of the Outokumpu ore belt and the Outokumpu fault. In lines OKU1 and OKU2 the ***reflectors O3 – O5*** (Figures 8-9) are interpreted to represent ophiolitic rocks. In line OKU1 the uppermost of them (O5) is at the depth of about 1 km, but in OKU2 at about 1.3 km. If we extrapolate also these structures to the SW they are expected to be met with at somewhat shallower depths and located about 3 km to the north of Keretti.

Target no. 6 is also related to the ***reflectors O3 – O5*** which were interpreted to continue to the NE from OKU1 and OKU2 according to the geological strike of the ore belt. According to the present interpretation they reach the surface on line V7 (Figure 14) where the discontinuous reflector O3 is correlated with the black schist and skarn rocks of the southernmost tip of the Miihkali fold structure (Figure 1). These reflectors also reach the surface in line V8 (Figure 15).

Target no. 7 is the strong ***reflector O6*** showing very strong amplitudes in line V7 (Figure 14). We suggest that the reflector would represent ophiolitic rocks, although it may also be a part of the Proterozoic epicontinental cover rocks or sills in association of the Archaean basement rocks. The reflector is at a considerable depth for exploration (> 1.3 km in V7; Figure 14).

Although the seismic data is limited in the Sotkuma area we consider the strong reflectors beneath the Archaean gneiss relevant for checking. ***Target no. 8*** is the interpreted ***mafic sill and black schist under the Sotkuma Archaean gneiss*** (Figure 15b) which would deserve testing.

Target no. 9 is the pair of strong reflectors located partly under the Sotkuma Archaean gneiss (line V8, ***Sot-1 and Sot-2***, Figure 15b, 22 a) which are interpreted here as possible ophiolitic rocks. Under line V8 they are at the depth of more than 1.5 km. If we assume that the reflectors reported by Penttilä (1968) in his reflection survey line (located about 2 km to SW of our line V8; see Surpac materials) would represent the same structures as Sot-1 and Sot-2 they would be at much shallower depths there and located between the Sola serpentinite and the western contact of the Sotkuma Archaean gneiss.

Target no. 10 is the Sola serpentinite which is considered interesting simply due to its surface area suggesting a considerable volume of ophiolitic rocks. Our seismic line V8 does not run over the Sola serpentinite, but we observe a synform structure extending to the depth of about 1.5 km in the section at a location on the strike of the Sola serpentinite continued to NE. ***Target no. 11*** is the NW part of the synform reflector with its upper boundary at about 750 – 1000 m (CMP 4200; Figure 15b).

7. CONCLUSIONS

The seismic surveys in the Outokumpu-Polvijärvi area revealed that the upper crust has very strong reflectors. Reflectivity can often be attributed to ophiolite-derived rocks of the Outokumpu nappe, namely serpentinite, skarn rock and quartz rock, as well as black schist. In addition to the ophiolitic rock type assemblage, strong reflectivity is associated with Proterozoic epicontinental rocks and mafic sills covering the Archaean basement and probably with Archaean mafic rocks. Shearing may also be an important factor contributing to the reflectivity of these rocks.

Correlating the reflectors between survey lines, and using surface geology, airborne magnetic maps and drilling data, 3D models of the deep structures of the Outokumpu ore belt were constructed. In the Outokumpu belt, three major reflective packages representing ophiolitic rock types can be identified between Keretti and Kylylahti, namely, the Keretti, Horsmanaho and Deep hole reflectors.

A major fault structure, the Outokumpu fault, was interpreted from the seismic results. The fault is running immediately along the NW contact of ore belt contact and dips about 60° SE. The fault truncates the structures of the main ore belt. On the NW side of the ore belt, strong reflectivity is also present in the uppermost five km. A group of reflectors is interpreted to represent ophiolitic rock types and correlated to those in the main ore belt, although located 1-2 km deeper. Towards the NE along the belt, these reflectors also seem to become thinner but they also meet the surface at locations where black schist and skarn rock occur.

In the Kylylahti area, the reflectors of the main ore belt converge into a tectonically disturbed volume which extends to the depth of about 3 km, and the Kylylahti reflector shows subvertical contacts and disturbances by deep faults. The Kylylahti ore deposit is not directly imaged with seismic reflections. This is attributed to the small size of the deposit in comparison to seismic wavelengths as well as the subvertical vertical dip of the deposit.

About 10 km to the NW of the Outokumpu ore belt Archaean rocks and Proterozoic sills and cover rocks outcrop, for instance, in the Saarivaara area and they can be followed along reflector dips to the depth of about 4-6 km under the Outokumpu belt. This also gives the thickness of the allochthonous rocks of the Outokumpu nappe beneath the ore belt. The Sotkuma Archaean gneiss is interpreted as a slice of Archaean rocks and it does not represent a true basement window.

The seismic data indicates several potentially interesting structures for further deep exploration of Outokumpu type sulphide deposits. Such structures can be found, for instance, (1) beneath and to the SE of the Keretti area at the depth of 1-2 km, (2) in the thick parts of the Keretti reflector along the main ore belt (one of the them at Horsmanaho, at depths >800 m), (3) the Kylylahti reflector extending to about 3 km depth, and (4) the reflectors on the NW side of the Outokumpu fault.

REFERENCES

Altona Mining Ltd (AOH.ASX), 2011. Initiation. Emerging Copper Producer. Foster Stockbroking report 18 April 2011. 31 p. http://www.altonamining.com/static/uploads/documents/Foster_Report_-_19-4-11.pdf

Elbra, T., R. Karlqvist, I. Lassila, E. Hæggström & L. J. Pesonen, 2011, Laboratory measurements of the seismic velocities and other petrophysical properties of the Outokumpu deep drill core samples, eastern Finland: Geophys. J. Int. (2011) 184, 405–415.

Gaál, G., T. Koistinen, and E. Mattila, 1975, Tectonic and stratigraphy of the vicinity of Outokumpu, North Karelia, Finland, including a structural analysis of the Outokumpu deposit: Geological Survey of Finland, Bulletin 271, 67p.

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

Huhma, H., 1986, Sm-Nd, U-Pb and Pb-Pb isotopic evidence for the origin of the Early Proterozoic Svecokarelian crust in Finland: Geological Survey of Finland, Bulletin 337.

Iljina, M. & Salmirinne, H. 2011. Suhanko seismic reflection profile and integrated geological-geophysical model of the Portimo area. Geological Survey of Finland, Report of Investigation 189, 20 p.

Kern, H., K. Mengel, K.W. Strauss, T.I. Ivankina, A.N. Nikitin, I.T. Kukkonen, 2009, Elastic wave velocities, chemistry and modal mineralogy of crustal rocks sampled by the Outokumpu scientific drill hole: Evidence from lab measurements and modeling: Physics of the Earth and Planetary Interiors, 175, 151–166.

Koistinen, T., 1981, Structural evolution of an early Proterozoic strata-bound Cu-Co-Zn deposit, Outokumpu, Finland: Transactions of the Royal Society of Edinburgh-Earth Sciences, 72, 115-158.

Koistinen, T., 1993. Heinäveden kartta-alueen kallioperä. Summary: Pre-Quaternary rocks of the Heinavesi map-sheet area. Geological Survey of Finland, Espoo, 64 p.

Kontinen, A., P. Peltonen, and H. Huhma, 2006, Description and genetic modelling of the Outokumpu-type rock assemblage and associated sulfide deposits. Final technical report for GEOMEX J.V., Workspace Geology: Geological Survey of Finland, Report M10.4/2006/1.

Korsman, K., T. Koistinen, J. Kohonen, M. Wennerstöm, E. Ekdahl, M. Honkamo, H. Idman, and Y. Pekkala, 1997, Bedrock map of Finland, 1: 1 000 000. Geological Survey of Finland, Espoo.

Kukkonen, I.T., 2011, ed., Outokumpu Deep Drilling Project 2003-2010: Geological Survey of Finland, Special Paper 51, 252 p.

Kukkonen, I.T. and Lahtinen, R. (eds.), 2006. Finnish Reflection Experiment FIRE 2001-2005. Geological Survey of Finland, Special Paper 43, 247 p.

Kukkonen, I.T., P. Heikkinen, E. Ekdahl, S -E.Hjelt, J. Yliniemi, E. Jalkanen, and FIRE Working Group, 2006, Acquisition and geophysical characteristics of reflection seismic data on FIRE transects, Fennoscandian Shield in Kukkonen, I.T. and R. Lahtinen, eds., Finnish Reflection Experiment 2001-2005: Geological Survey of Finland, Special Paper 43.

Kuronen, U., Kontinen, A., Kokkonen, J., 2003. GEOMEX project report 1999-2003. Geological Survey of Finland, 38 p. (http://geomaps2.gtk.fi/Geomex-tiedostot/DocumentData/FinalReport2003/Geomex)

Lahtinen, R., H. Huhma, A. Kontinen, J. Kohonen, and P. Sorjonen-Ward, 2010, New constraints for the source characteristics, deposition and age of the 2.1–1.9 Ga metasedimentary cover at the western margin of the Karelian Province: Precambrian Research, 176, 77–93.

Lehtonen, T., 1980. AMT-luotaus: Käsämä (Liperi) – Maarianvaara (Kaavi). Outokumpu Oy, malminetsintä, raportti 24.11.1980, 3 s.

Park, A.F, D.R. Bowes, N.M. Halden, and T.J. Kolstmen, 1984, Tectonic evolution at an early Proterozoic continental margin the Svecokarelides of eastern Finland: Journal of Geodynamics, 1, 359-386.

Parkkinen, J., 1997, An outline of the history of exploration and mining in the Outokumpu district, in Loukola-Ruskeeniemi, K. and Sorjonen-Ward, P., eds., Research and exploration-where do they meet? 4th Biennial SGA Meeting, August 11-13, 1997, Turku, Finland. Excursion guidebook A4, Ore deposits in eastern Finland. Geologian tutkimuskeskus. Opas 42, 27-28.

Papunen, H., 1987, Outokumpu-type ores, in Häkli, T. A., ed., Otto Trüstedt symposium in Finland on June 3-5, 1985: Geological Survey of Finland, Special Paper, 1, 41-50.

Peltola, E., 1978, Origin of Precambrian copper sulfides of the Outokumpu district, Finland: Economic Geology, 73, 461-477

Peltonen, P., A. Kontinen, H. Huhma, and U. Kuronen, 2008, Outokumpu revisited: New mineral deposit model for the mantle peridotite-associated Cu–Co–Zn–Ni–Ag–Au sulphide deposits: Ore Geology Reviews, 33, 559–617.

Säntti, J., A. Kontinen, P. Sorjonen-Ward, B. Johanson, and L. Pakkanen, 2006, Metamorphism and chromite in serpentinized and carbonate-silica–altered peridotites of the Paleoproterozoic

Outokumpu-Jormua ophiolite belt, eastern Finland: International Geology Review, 48, 494–546.

Schijns,H. Schmitt, D.R., Heikkinen, P.J. and Kukkonen, I.T., 2012. Seismic anisotropy in the crystalline upper crust: observations and modelling from the Outokumpu scientific borehole, Finland. Geophys. J. Int. (2012). doi: 10.1111/j.1365-246X.2012.05358.x

Sorjonen-Ward, P. 2006, Geological and structural framework and preliminary interpretation of the FIRE 3 and FIRE 3A reflection seismic profiles, central Finland in Kukkonen, I.T. and R. Lahtinen, eds., Finnish Reflection Experiment 2001-2005: Geological Survey of Finland, Special Paper, 43, 105-159.

Zamoshnyaya, N., 2008. Report on the HRSS 2D reflection survey carried out in Finland during 2008 – Outokumpu-Polvijärvi (Volume 1). Federal State Unitary Geological Research-and-Production Enterprise for Geophysical Works of the Russian ministry of Natural Resources, GFUP Vniigeofizika, AE Spetsgeofizika. Contract No. 50-0701/042362, Povarovka, Russia, 61 p.

Zamoshnyaya, N. & Suleimanov, A.S., 2003. Final Report on FIRE deep reflection survey carried out in Finland during 2001-2003 (Volume 1). Federal State Unitary Geological Research-and-Production Enterprise for Geophysical Works of the Russian Ministry of Natural Resources “Spetsgeofizika”. Contract N 51/02-13007, Povarovka, Russia, 134 p.

APPENDICES

1. On-site processing of FIRE OKU1 – OKU3 data.
2. Basic data processing sequence FIRE OKU1-OKU3
3. On-site processing of data HIRE V1, V2, V7 & V8
4. Basic data processing sequence HIRE V1, V2, V7 &V8
5. Data processing sequence HIRE E1
6. Post-stack processing of HIRE data
7. Seismic survey lines plotted on the geological map
8. Seismic survey lines plotted on the airborne magnetic map
9. Migrated NMO section of line OKU1
10. Migrated NMO section of line OKU2
11. Migrated NMO section of line OKU3
12. Migrated NMO section of line V1
13. Migrated NMO section of line V2
14. Migrated NMO section of line V3
15. Migrated NMO section of line V7
16. Migrated NMO section of line V8
17. Migrated NMO section of line E1

(appendices 7-17 in a separate folder)

DIGITAL APPENDICES

1. Report text file (pdf)
2. Survey line maps (pdf and jpg)
3. NMO migrated sections (pdf)
4. NMO migrated sections (SEG-Y)
5. CMP coordinate files (xls)
6. Field coordinates (recording stations and shooting stations) (xls)
7. *SURPAC* files
    - 7.1 NMO migrated sections draped on CMP profiles
    - 7.2 Loops and strings digitized from the sections
    - 7.3. Reflector solids
    - 7.4 Lithological map with survey lines
    - 7.4 Airborne magnetic map with survey lines
    - 7.5. Seismic reflectors (Penttilä, 1968)
    - 7.6. AMT conductors (Lehtonen, 1980)
    - 7.8. Ground bouguer gravity maps (isolines, surface, grid)
    - 7.9. Drilling profiles
    - 7.10. Outokumpu Deep Drill Hole string
    - 7.11. Exploration targets (on airborne magnetic map with seismic survey lines)
    - 7.12. SURPAC style (ssi) files

Appendix 1. On-site processing of FIRE OKU1 – OKU3 data.

Transformation of data from SEG-D to SEG-Y format → Writing raw data onto CD-ROM

↓

2D geometry application

↓

Trace editing

↓

Gain recovery → Plotting of each 20^{th} SGM

↓

Spectral analysis → Plotting of each 40^{th} SGM

↓

↓

Deconvolution
OL – 120 ms, Noise 0.1,
w=400-2000 ms

↓

Frequency band-pass filter
OKU 1, 2, 3

Hz	ms
27, 33 – 124, 130	0 – 6000

↓

Amplitude Equalization
w (0-2000) ms

↓

Calculation and input of the static corrections

↓

1 st velocity analysis (Constant Velosity Stacks) → Velocity scanning plotting

↓

Muting

↓

Automatic static corrections
OKU 1, 2, 3
picking start time, ms – 600
picking window length, ms – 1700
maximum allowable static, ms – 10

↓

Final STACKING → Plotting

CD-ROM

↓

Deconvolution
OL – 120 ms, Noise 0.1
w (400-2000) ms

↓

Frequency band-pass filter

	Hz	***ms***
OKU 2	27, 33÷124, 130	0-6000
OKU 1,3	(27, 33÷90, 96)	0-6000

↓

Automatic Gain Control
0, 500, 1000, 3000, 4000 ms

↓

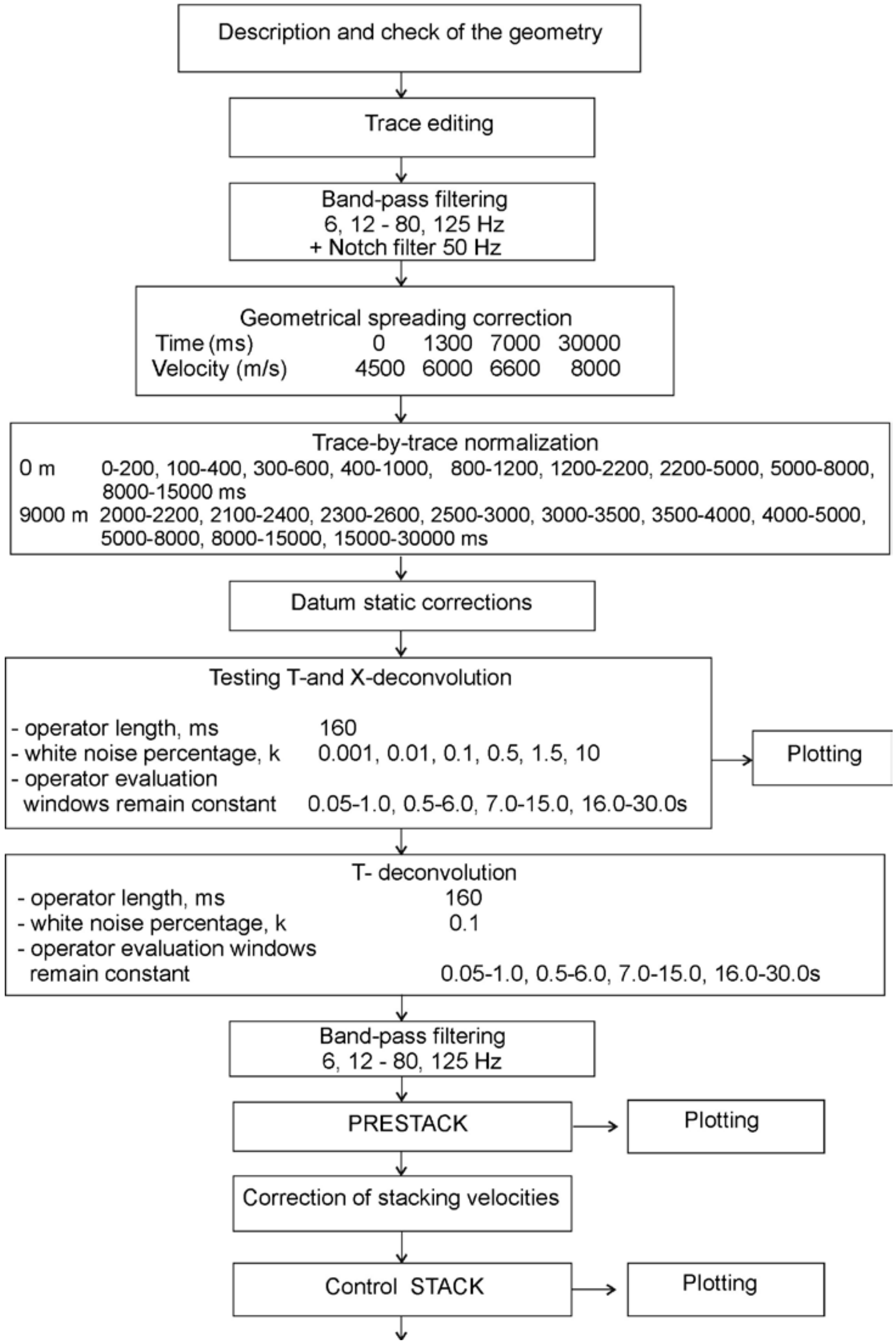
SPATIAL NOISE FILTER

↓

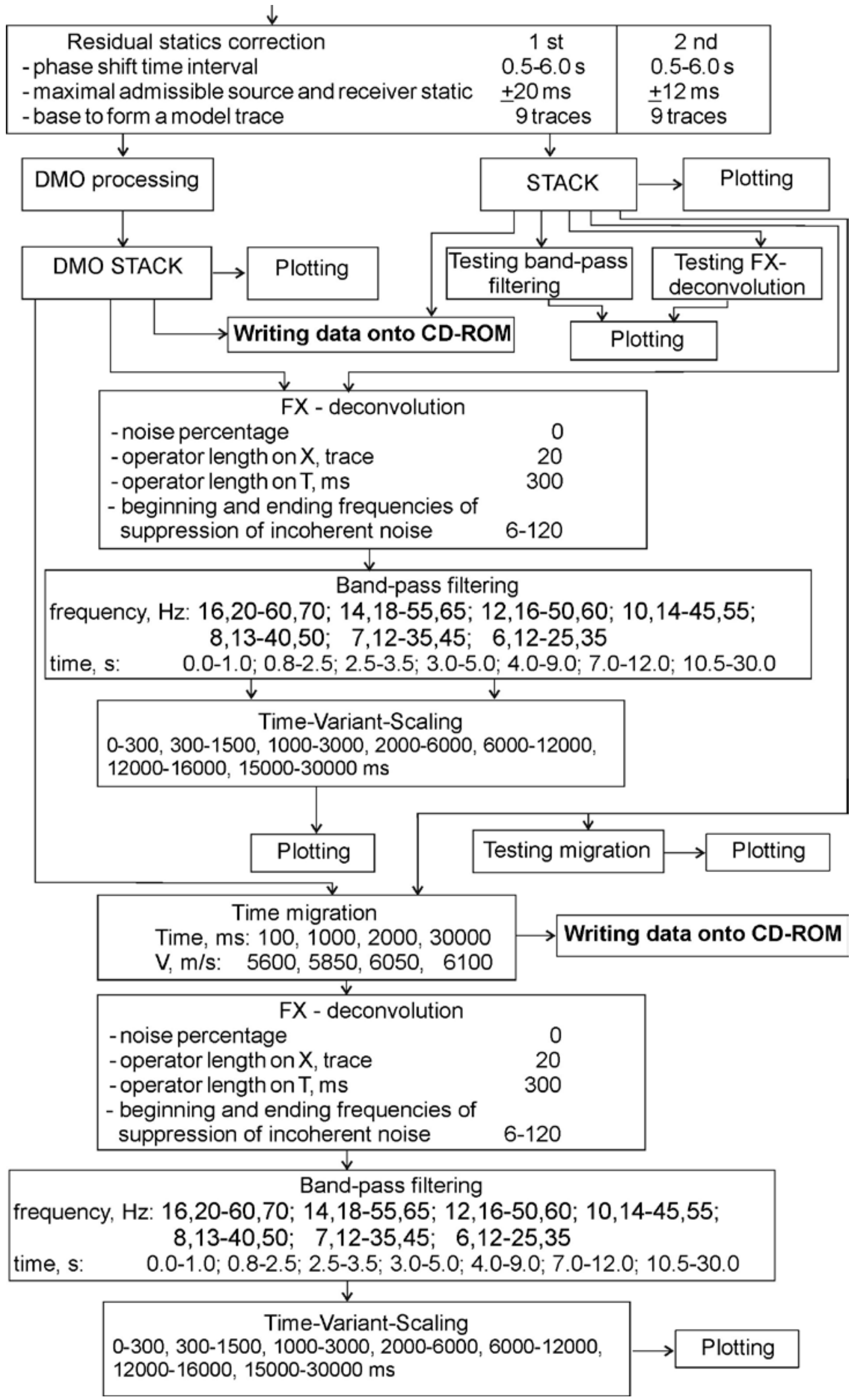
COHERENCE FILTER → Plotting

Appendix 2. Basic data processing sequence FIRE OKU1-OKU3

Generalized procedures and parameters of final processing



Appendix 2. Data processing sequence FIRE OKU1-OKU3 (cont.)

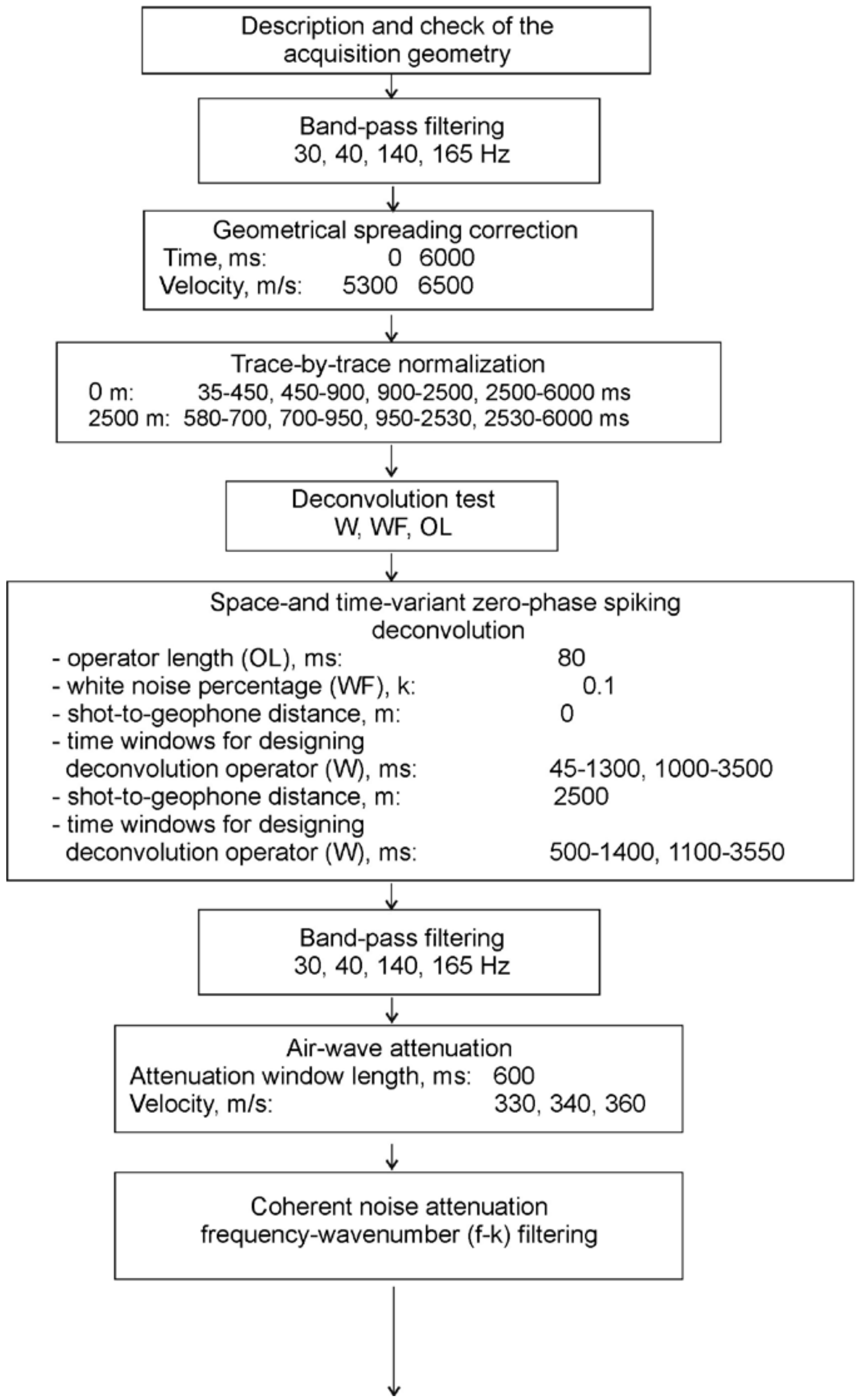


Appendix 3. On-site processing of data HIRE V1, V2, V7 & V8.

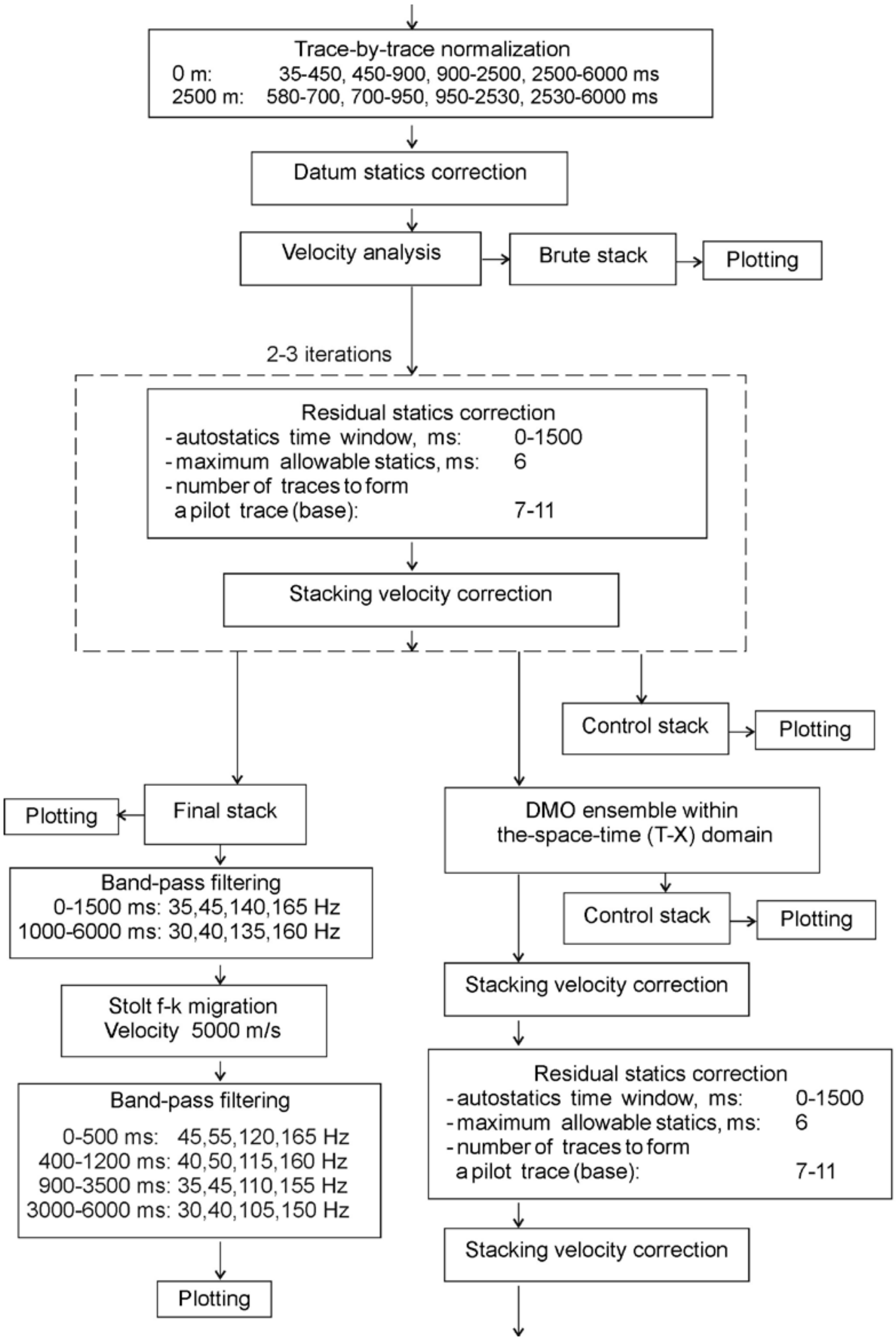
1.	2D geometry application
2.	Band-pass filtering 30-40-140-165 Hz
3.	Spherical divergence compensation
4.	Amplitude equalization, window 300-5000 ms
5.	Spiking deconvolution: noise 0.1 %, OL 80 ms, w 200-2500 ms
6.	Band-pass filtering 30-40-140-165 Hz
7.	Amplitude equalization, window 0-5000 ms
8.	Trace editing
9.	Datum statics correction
10.	1st moveout correction, surgical mute
11.	FK-filtering on seismograms with moveout corrections
12.	Automatic statics correction: calculation window 200-2500 ms, maximum allowable shift 6 ms
13.	2nd moveout correction, surgical mute
14.	Stacking
15.	Amplitude equalization, window 0-6000 ms
16.	Time-variant band-pass filtering: 35-45-140-165 Hz and 30-40-130-160 Hz in windows 0-1500 ms and 1000-6000 ms correspondingly
17.	Noise space filter
18.	Coherence filter
19.	Automatic gain control: 0-800, 600-2500, 2200-4500, 4000-5500, 5000-6000 ms

Appendix 4. Basic data processing sequence HIRE V1, V2, V7 &V8

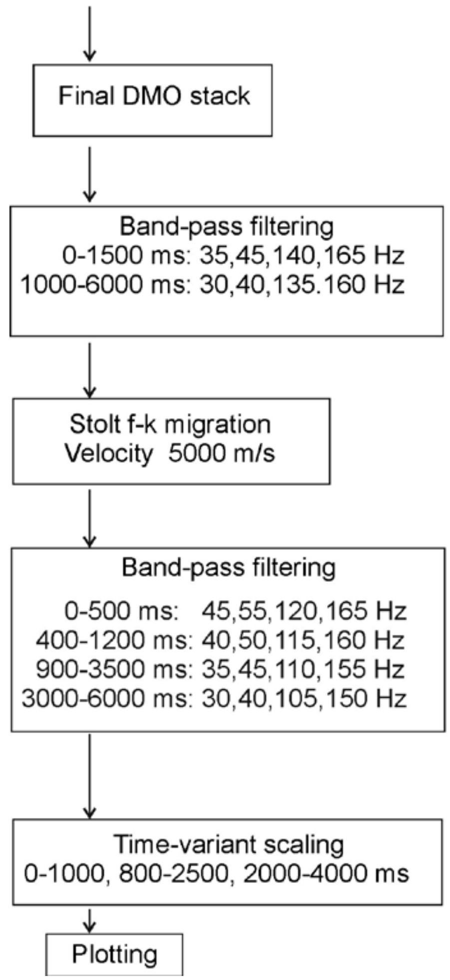
Processing flow of vibroseis data



Appendix 4. Basic data processing sequence HIRE V1, V2, V7 &V8 (cont.)

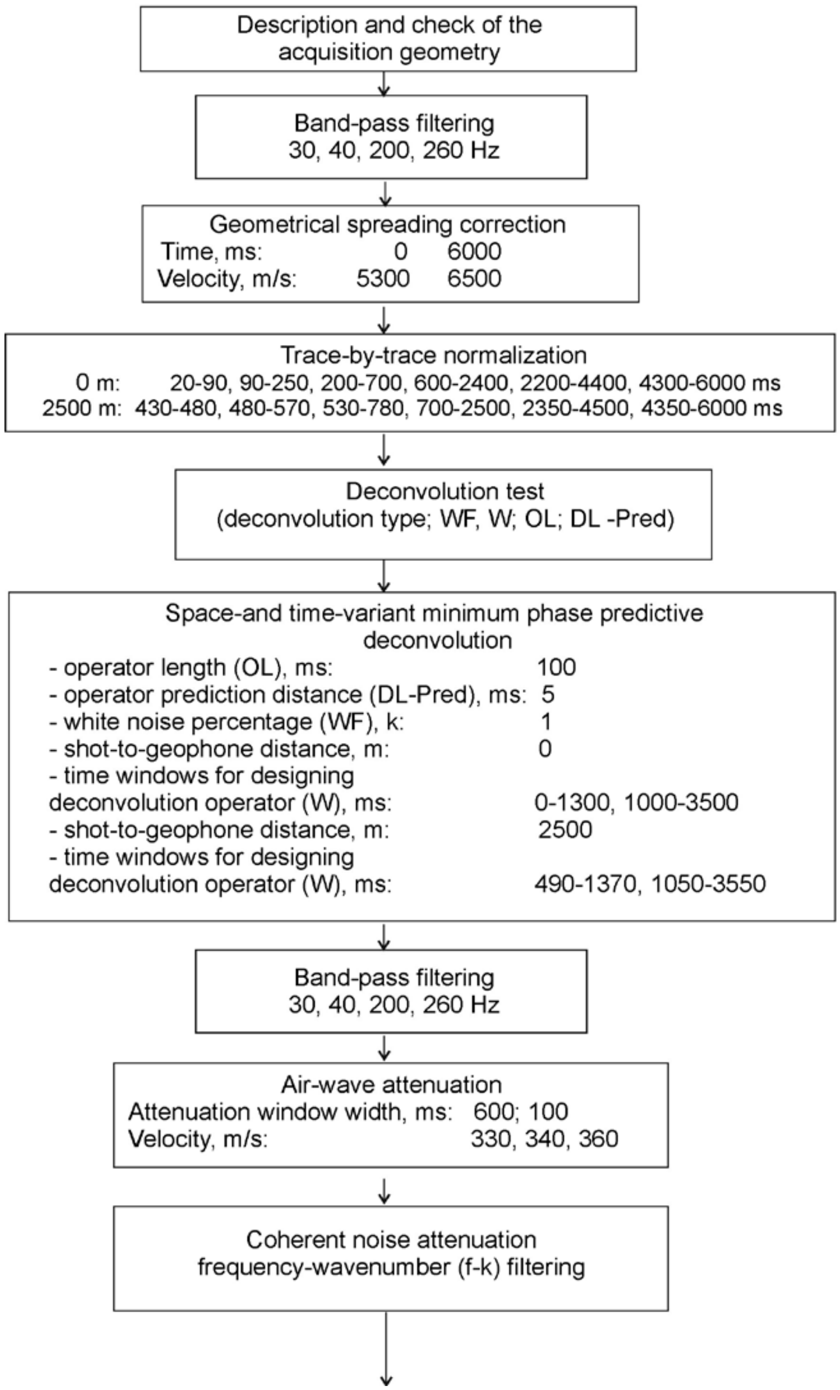


Appendix 4. Basic data processing sequence HIRE V1, V2, V7 &V8 (cont.)

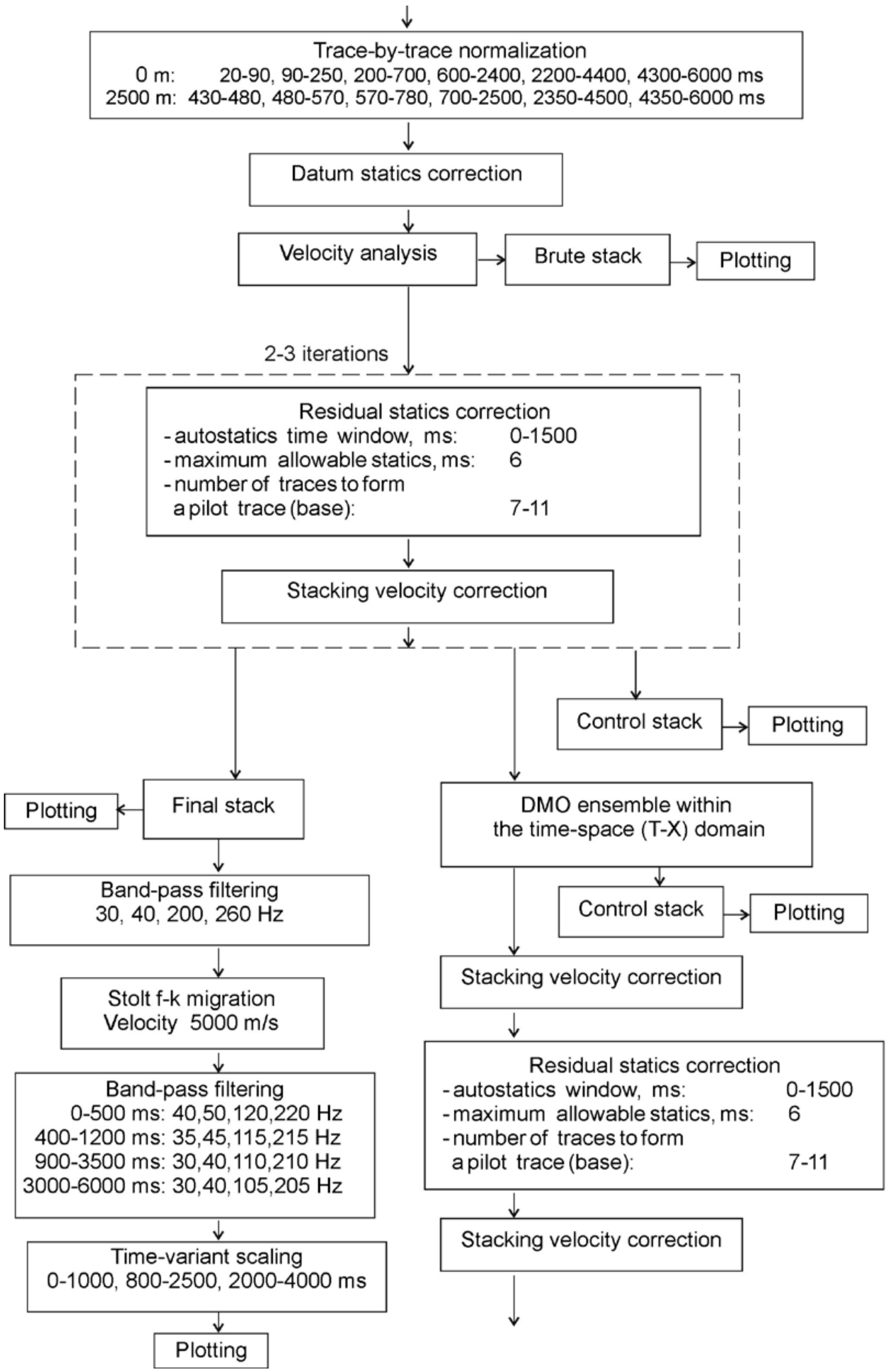


Appendix 5. Basic data processing sequence HIRE E1

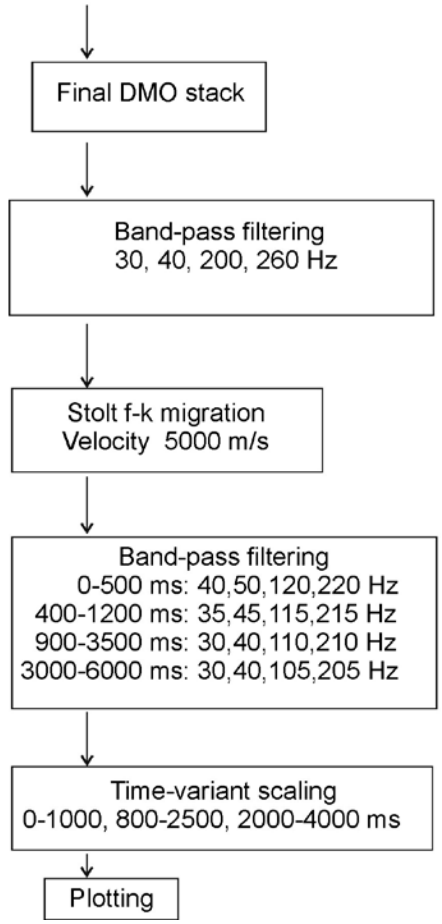
Processing flow of dynamite data



Appendix 5. Basic data processing sequence HIRE E1 (cont.)



Appendix 5. Data processing sequence HIRE E1 (cont.)



Appendix 6. Post-stack processing of HIRE data.

Final DMO stack →

Migration (Stolt)

TWT (ms)	V_{rms} (m/s)	TWT (ms)	V_{rms} (m/s)
0	5110	1100	6831
100	5700	1200	6862
200	6035	1300	6906
300	6265	1400	6920
400	6381	1500	6920
500	6472	1600	6931
600	6567	1700	6948
700	6634	1800	6956
800	6699	1900	6961
900	6735	2000	6963
1000	6782		

→

Spectral balancing
Band pass filter

Frequency	Filter amplitude
20.0	0.0
40.0	1.0
160.0	2.0
200.0	2.0
240.0	0.0

→

Depth conversion

Depth (m)	Conversion velocity (m/s)
0.0	5228
271.40	5428
560.15	5602
862.55	5750
1170.15	5851
1488.00	5952
1809.10	6030
2142.65	6122
2479.70	6199
2816.15	6258
3159.00	6318
4784.00	6379
6427.75	6428
20000.00	6533

→

Plotting