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Title of report

HIRE Seismic Reflection Survey in the Talvivaara Ni mining area, Eastern Finland

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The Talvivaara deposit is a Paleoproterozoic mineralized black schist deposit containing 890 Mt of low-grade ore @ 0.22% Ni, 0.49% Zn, 0.13% Cu, 0.02% Co, and 17 ppm U (at 0.07% nickel cut-off).

The HIRE survey revealed numerous previously unknown structures in the uppermost 5 km of crust of the Talvivaara area. A dominant feature in the Talvivaara seismic results are the subhorizontal and gently folded strong reflectors. The reflectors are continuous and range in thickness from about 100 m to 1 km. They are most probably due to 2.1-2.3 Ga Proterozoic mafic sills and dykes cutting the Archaean basement and the Jatulian strata.

Down-hole density and seismic P-wave velocity data and synthetic seismograms from two diamond drill holes in Talvivaara suggest that reflections can be expected from the black schist-quartzite contacts, shears and major fracture zones. The logged drill holes do not intersect any mafic dykes, but the mafic rocks (or their amphibolitic metamorphic equivalents) can be expected to be also strongly reflective within the intermediate-felsic Archaean basement rocks and the Jatulian metasedimentary rocks.

The strong reflectors reveal a gently folded synform-antiform structure which shows dip angles ranging from subhorizontal to about 30°. Assuming that the reflectors represent mafic sills and dykes, the seismic data suggest that there are considerable amounts of mafic material in the upper crust of the Talvivaara area. As the sills have intruded originally in horizontal positions parallel to the ground surface and sediment layering, the present subhorizontal structure would imply only relatively modest deformation in the Archaean basement. In the Proterozoic layers the deformation has been more efficient as indicated by geological data. The Talvivaara deposit has been preserved in a synform structure of the basement. The depth extent of the Lower Kaleva rocks hosting the ore deposit extend to about 500 m depth in line V3 between the Kolmisoppi and Kuusilampi deposits.

The present seismic results and other geophysical maps were applied for suggesting targets for further structural studies of the Talvivaara black schist and exploration in the area.

Keywords

Seismic reflection surveys, black schist, Ni-Zn-Cu-Co-U deposits, Talvivaara, Fennoscandian Shield

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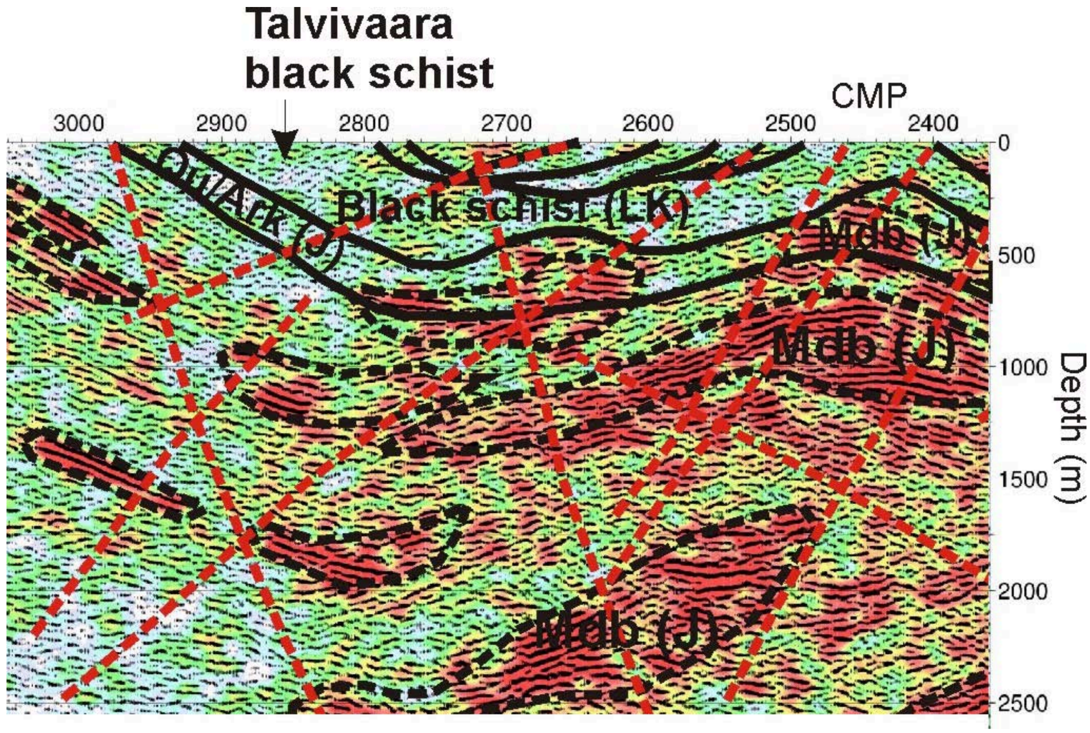

HIRE Seismic Reflection Survey in the Talvivaara Ni mining area, Eastern Finland

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The present seismic results and other geophysical maps were applied for suggesting targets for further structural studies of the Talvivaara black schist and exploration in the area.

1. INTRODUCTION

A seismic reflection survey comprising two Vibroseis lines (total length of 30.8 km) was carried out in the Talvivaara Ni mining area, eastern Finland, in August, 2008. The survey is a part of the project HIRE (*High Resolution Reflection Seismics for Ore Exploration 2007-2011*) of the Geological Survey of Finland (GTK). The Talvivaara survey was done in co-operation with Talvivaara Oy.

The aims of the HIRE project in general 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 Talvivaara were to delineate the upper crustal structures of the mining camp, and to correlate reflectors with surface and mine geology data as well as with other surface and airborne 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 Talvivaara Oy based on the offers by GTK dated Feb 5, 2008.

The surveys comprised Vibroseis soundings along roads in the neighbourhood of and within the Talvivaara mining area. The data was acquired in August, 2008 along the two lines, V1 and V3. The original survey plan included also a line V2, but it was not possible to be surveyed due to ongoing mine construction works during the time of seismic field work.

2. BRIEF GEOLOGICAL AND GEOPHYSICAL DESCRIPTION OF THE TALVIVAARA AREA AND THE ORE DEPOSIT

Talvivaara is located in the southern part of the Lower Proterozoic Kainuu (schist) Belt which consists mostly of metasediments ranging in age from 2.5 to 1.9 Ga. The Kainuu Belt is located between two Archaean blocks, the Iisalmi-Pudasjärvi complex in the west and the Kuhmo-Ilomantsi complex in the east. According to gravity modelling the Kainuu Belt is only about 2 km thick (Elo, 1997). The main stratigraphic units in the Kainuu Belt are (1) Sumi-Sariola and Jatuli, 2.5-2.1 Ga, (2) Lower Kaleva, 2.1-1.95 Ga, and (3) Upper Kaleva, 1.95-1.90 Ga (Laajoki 2005, Kontinen 2012). Sumi-Sariola and Jatuli represent mainly cratonic and epicratonic sediments. Lower Kaleva consist of wackes and pelitic sediments and Upper Kaleva deep-water turbiditic sediments, respectively (Kontinen, 2012). Graphite and sulphide-bearing black schists are common in the Kainuu Belt.

In addition to metasediments the Kainuu schist belt contains thin allochthonous slices of ophiolite-derived rocks representing 1.95-1.96 Ga oceanic lithosphere (Kontinen 1987a). The ophiolitic rocks occur in association with the Upper Kaleva metasediments. The largest occurrence of ophiolitic rocks in the Kainuu Belt is the Jormua ophiolite located about 30 km to the north of Talvivaara.

Palaeoproterozoic mafic dykes and sills are common in the Kainuu Belt and the surrounding Archaean basement. They range in age from 2.5 to 1.95 Ga. Thus, they dissect rocks ranging from Archaean to Lower Kaleva (Havola, 1981; Kontinen 1987b, 2005, 2012).

The Kainuu Belt can be seen as a sequence of thrust sheets piled against the eastern Archaean basement and metamorphosed during the 1.91 – 1.78 Ga Svecofennian orogeny (Laajoki and Tuisku, 1990; Tuisku and Laajoki, 1990; Laajoki, 2005). The belt is divided by N-S running thrusts into eastern and western parts. The eastern part of the belt represents mainly autochthonous-parautochtonous rocks in greenschist facies, whereas the western part is more allochthonous and characterized by polyphase deformation in the amphibolites facies. In the central part of the Kainuu Belt the metamorphic peak was reached at about 1.87 Ga with 5 kb and 550-600°C. Structural deformation of the Kainuu Belt is a result of both thrust and strike-slip tectonics and comprises six major deformation phases (Laajoki and Tuisku, 1990; Tuisku and Laajoki, 1990). In the first deformation phase (D1) thrusting took place from southwest direction, and in the second phase (D2) the F1 folds were folded into NNW-SSE orientated upright positions. In D3-D5 the principal stress orientation rotated clockwise and the deformation was characterized by dextral strike-slip movements in a medium becoming gradually more rigid with decreasing temperature and pressure after the metamorphic peak.

In the Talvivaara area black schist horizons can be followed for tens of kilometers on magnetic and electromagnetic maps (Figure 1). Already the normal (unmineralized) black schist in Talvivaara has very low electric resistivity, in the range of 0.01-0.1 ohm-m due to its graphite and sulfide content, but the mineralized black schist has even lower resistivity below 0.01 ohm-m (Tervo, 1980). The magnetic properties are controlled by pyrrhotite. Magnetic susceptibility varies from practically paramagnetic levels to about $700 \cdot 10^{-5}$ SI in normal black schist and up to

$1700 \cdot 10^{-5}$ SI in mineralized black schist. Magnetic modeling of the Kolmisoppi area by Tervo (1980) suggests depth extents of about 250-800 m for the magnetized bodies.

In Talvivaara black schist is present in both Upper and Lower Kaleva horizons. In Lower Kaleva the black schist is mineralized and contains anomalous concentrations of Ni, Cu, Zn and Mn. The main minerals of the black schist ore are quartz, micas, graphite and sulfides. Pyrite and pyrrhotite are the principal sulfides, but also chalcopyrite, sphalerite, alabandite, and pentlandite occur. The original sediment was a carbon and sulfur rich mud intercalated with carbonate rocks. The present metamorphosed black schist has interlayers of carbonate-diopside-tremolite-bearing calc-silicate rocks (Loukola-Ruskeeniemi and Heino, 1996; Kontinen, 2012).

The mineralized Talvivaara black schist is 100 – 500 m thick and the (economic) ore comprises two deposits, the Kolmisoppi and Kuusilampi deposits (Figure 2). According to drilling data the Kuusilampi deposit extends to about 500 m and the Kolmisoppi deposit to about 300 m below ground surface. The exposed strike length of the ore is about 12 km (Figure 2).

The metal-bearing black schist in Talvivaara has been known already in the 1930's, but the ore deposit was delineated with extensive exploration by the Geological Survey of Finland in the 1970-80's (Ervamaa, 1978; Ervamaa and Heino, 1980; Tervo, 1980; Loukola-Ruskeeniemi and Heino, 1996). The deposit is mined by Talvivaara Oy since 2008. The Talvivaara Ni deposit is huge containing 890 Mt of low-grade ore @ 0.22% Ni, 0.49% Zn, 0.13% Cu, 0.02% Co, and 17 ppm U (at 0.07% nickel cut-off) (Talvivaara Mining Company, 2010).

The deposit is stratigraphically controlled and located in the Lower Kaleva tectofacies. Svecofennian thrusting and deformation have modified the strata, and the deposit was also thickened in the Svecofennian tectonic movements. Thrusting has taken place from southwest (Laajoki and Tuisku, 1990), but the thrust faults in the Kainuu Belt are oriented north - south (e.g. Kontinen, 1987a).

Loukola-Ruskeeniemi and Heino (1996) considered that the precursors of the Talvivaara metalliferous black schist were organic-rich muds deposited in anoxic conditions. Influx of metals was related to upwelling of hydrothermal fluids in a rifted environment. Hydrothermal alteration is supported by Na depletion, sulphur isotope data and depletion in light REE of the mineralized black schist. Recently, Kontinen (2012) has suggested that the genesis of the ore deposit would not be hydrothermal. Instead, the metal enrichment is attributed to synsedimentary processes in an environment with sea water enriched in Ni, Co, Cu and Zn. The elevated Mn concentrations would, however, require a hydrothermal source according to the interpretation by Kontinen (2012).

Black schist and ophiolite-derived rocks occur in close association both in the Talvivaara and Outokumpu areas. Ophiolitic rocks and associated black schist are present in eastern Finland in an over 200 km long discontinuous chain thrusted onto the eastern Finland Archaean complex margin. In Outokumpu, located about 160 km to the southwest of Talvivaara, ophiolite-derived slices of altered ultrabasic rocks host massive Cu-Co-Zn deposits (Peltonen et al., 2008). Due to the overall similarities between Talvivaara and Outokumpu, the black schists have been often compared (Loukola-Ruskeeniemi and Heino, 1996, Loukola-Ruskeeniemi, 1999, 2011;

Kontinen, 2012). There are, however, significant geochemical differences, e.g. the elevated concentrations of Mn in the Talvivaara black schist but not in Outokumpu, potentially reflecting differences in the oxygen content and basin properties in the depositional environment (Loukola-Ruskeeniemi, 2012). Further, lead isotopes are highly different suggesting different sources of the metals (Kontinen, 2012). Loukola-Ruskeeniemi (2011) concludes that the existence of Outokumpu type sulfide deposits in the Talvivaara area, and the existence of Talvivaara type metalliferous black schist in the Outokumpu area are both unlikely.

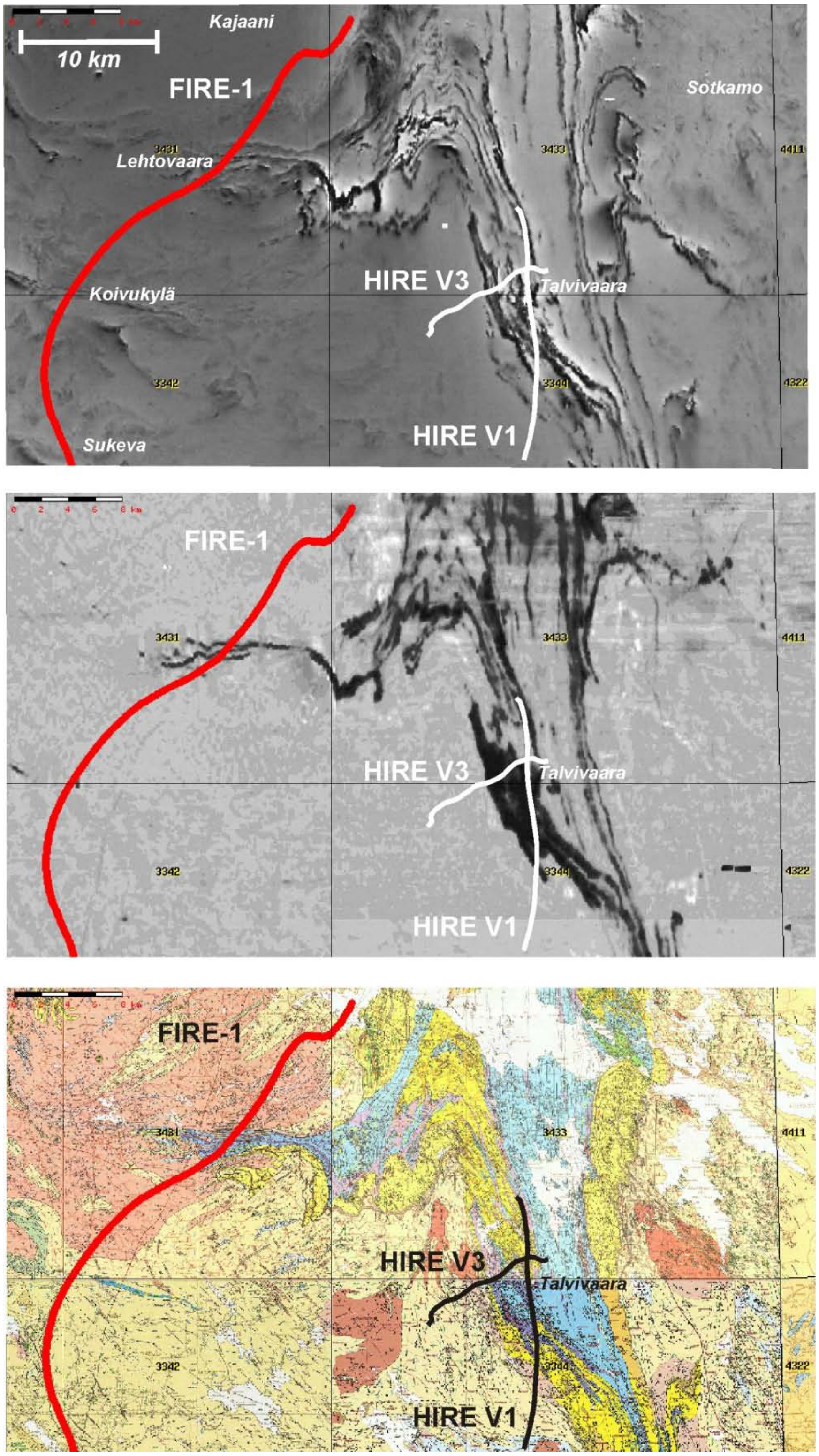

Figure 1. *Regional map showing airborne magnetic total field map (top), EM in-phase map (middle) and bedrock map (bottom) of the southern part of the Kainuu Belt together with the HIRE and FIRE seismic lines. Data by the Geological Survey of Finland.*

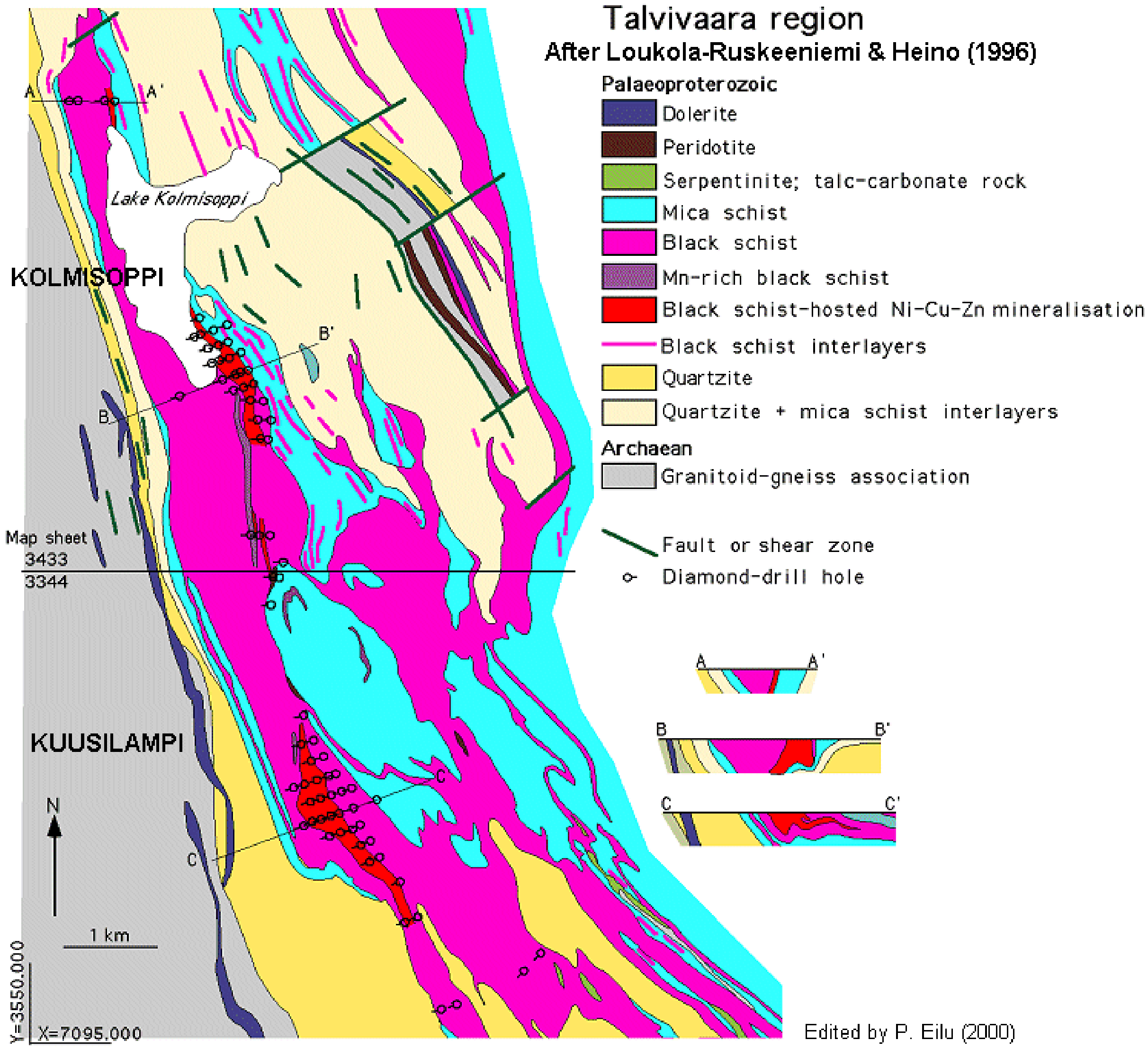

Figure 2. *Geological map of the Talvivaara area. Figure adopted from* *http://en.gtk.fi/informationservices/commodities/Zinc/kuusilampi.html. Original map by Loukola-Ruskeeniemi and Heino (1996).*

3. SURVEY METHOD

The Talvivaara CMP reflection surveys consisted of 2D lines placed according to the geology and road conditions. The applied method is the CMP (Common Mid Point) method with symmetrical split-spread geometry, with asymmetric shooting at the end of lines. The number of active channels was 402, and the channel interval was 12.5 m. 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 source point interval was 50 m, and locally, for instance in the vicinity of the structures considered interesting, it was reduced to 25 m. Vibroseis type sources were applied. In Vibroseis surveys, three (minimum two) 15.4 ton Geosvip vibrators were used as a group. The applied force was about 10 ton/vibrator. The sweep was a 16 s linear upsweep with a frequency band of 30-165 Hz, and the total listening time was 22 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.

Geodetic positioning of the lines was done 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 Table 1 (Zamoshnyaya, 2008).

Table 1. Survey parameters.

	Vibroseis
Recording	I/O-4
Number of active channels	402
Sampling interval, ms	1
Record length after correlation, s	6
Preliminary gain, dB	24÷36
Notch filter, Hz	off
Noise suppression editor (BURST+DIVERSITY)	on
High-pass filter, Hz	off
Tape format	SEG-Y
Medium type	HARD-DISC
Acquisition geometry	Symmetrical split spread
Stacking fold	varying
Receiver group spacing, m	12.5
Spacing of source locations, m	25 or 50
Spread length, m	5012.5
Linear geophone grouping	6 geophones on 12.5 m base
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
Ground force	65%
Control system and vibrator synchronization control	VIB 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 processing sequence of data processing is shown in Tables 2-3 (Zamoshnyaya, 2008).

Post stack processing was made by HY-Seismo starting from the NMO stacked sections by Vniigeofizika. The post stack processing 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 applied in depth conversion are shown in Fig. 3 and Table 4.

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 multiplying the spectra with a linearly increasing function of the frequency. The applied value of the multiplier was 1.0 at 40 Hz and 2.0 at 160 Hz.

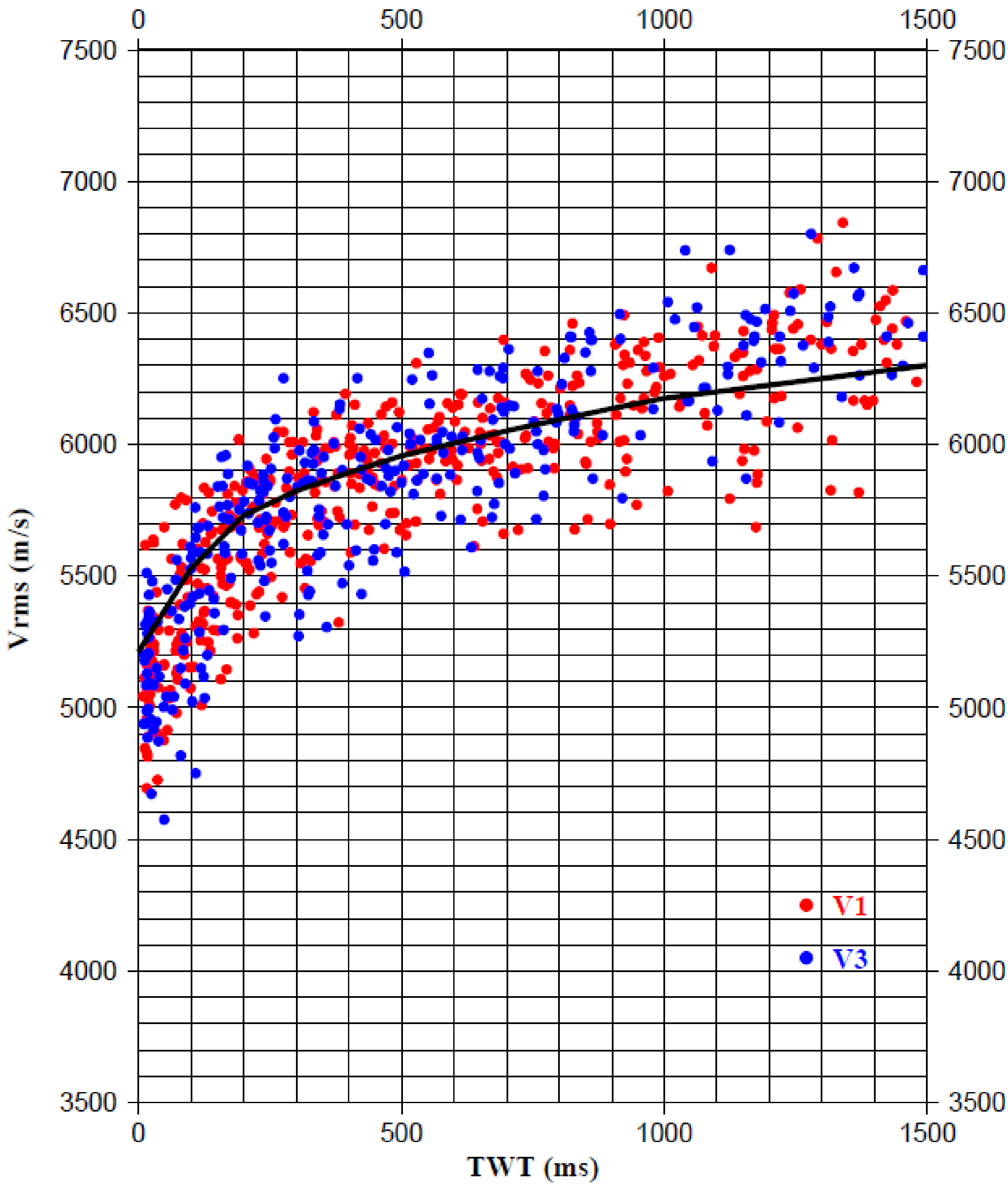

Figure 3. *The measured stacking velocitites (colored dots) and the velocity function used for post stack processing (black line). The color of the dot indicates the line (V1 or V3).*

Table 2. On-site processing of vibroseis data.

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

Table 3a. Basic processing of vibroseis data.

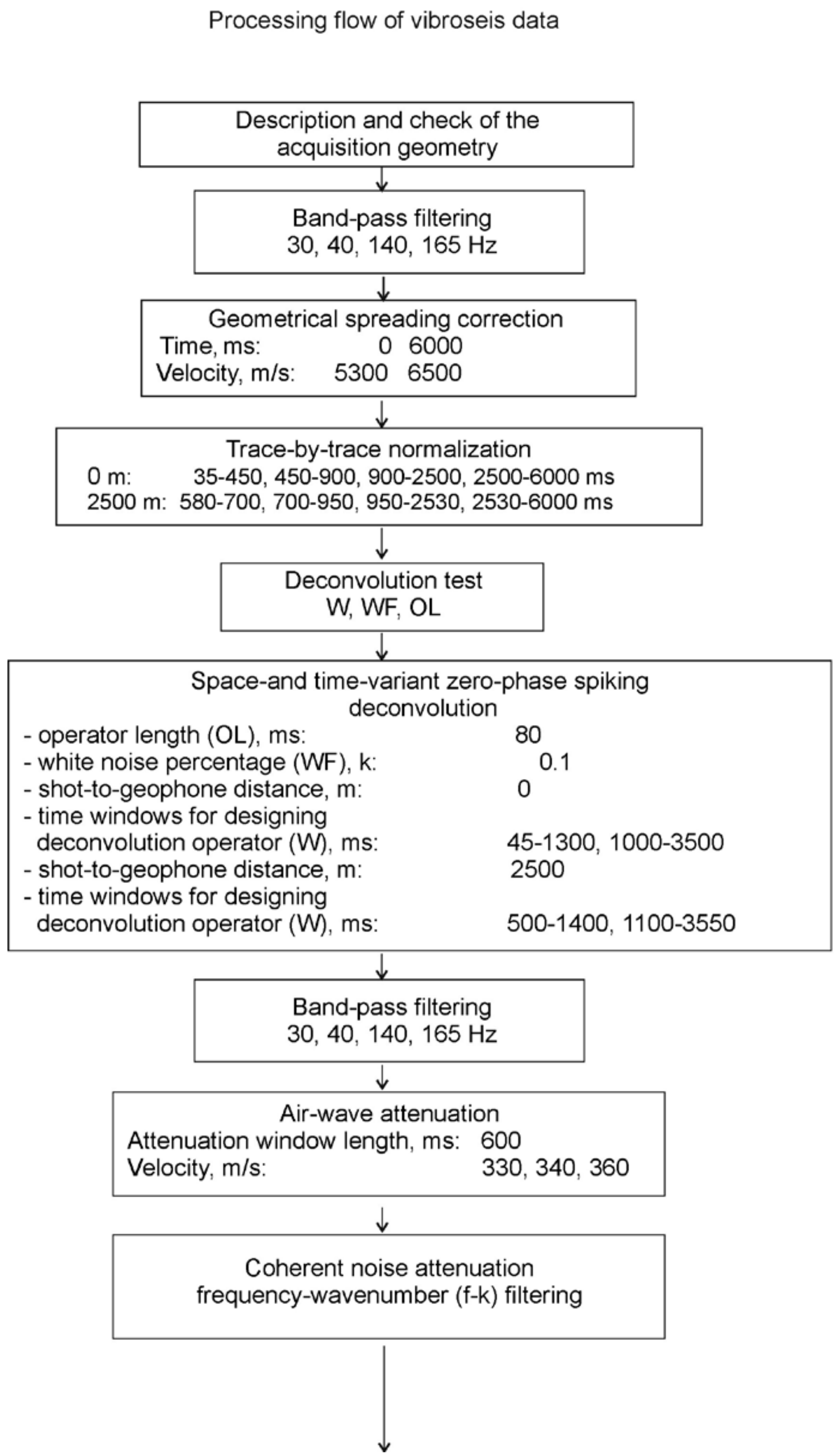

Table 3b. Basic processing of vibroseis data (cont.).

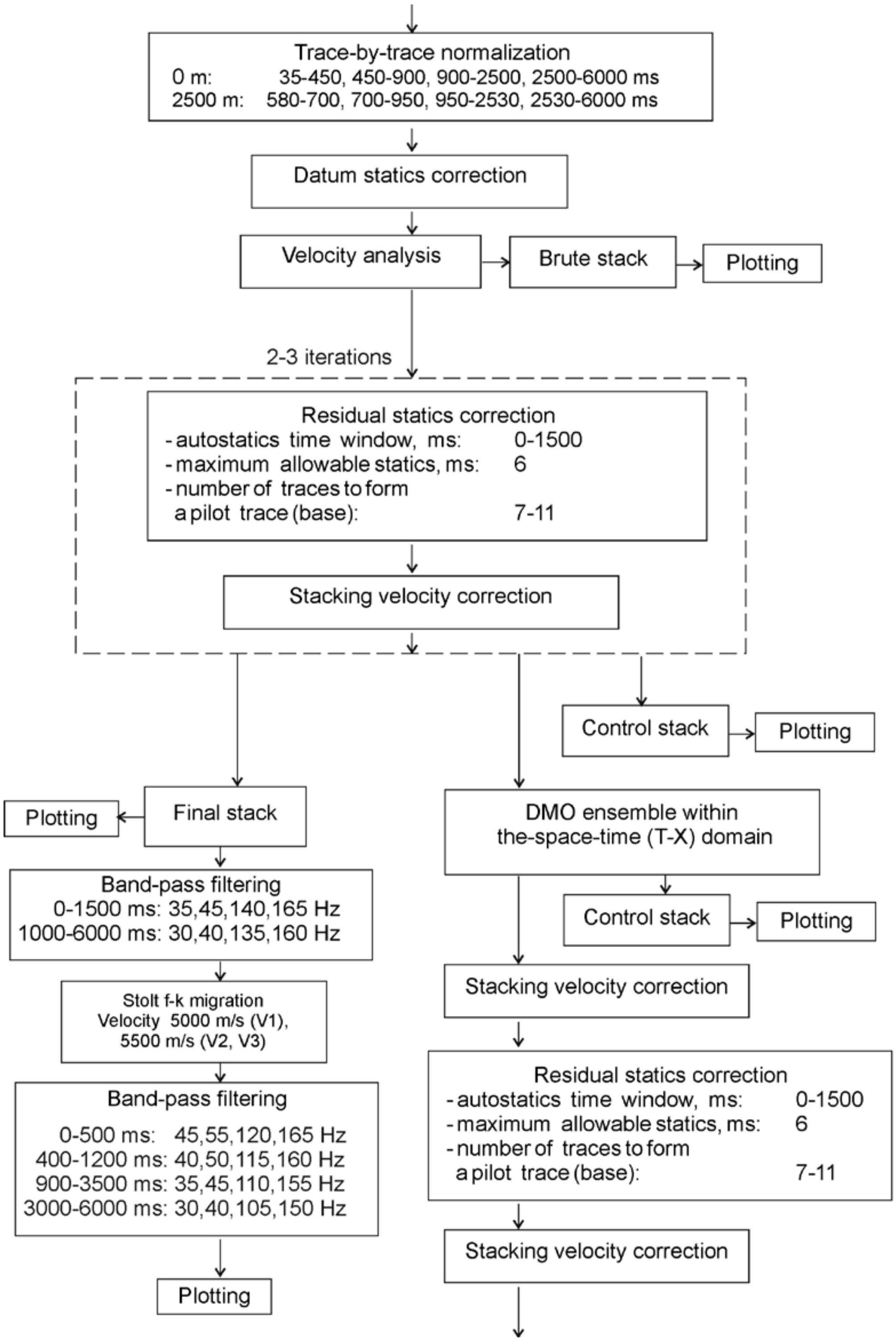

Table 3c. Basic processing of vibroseis data (cont).

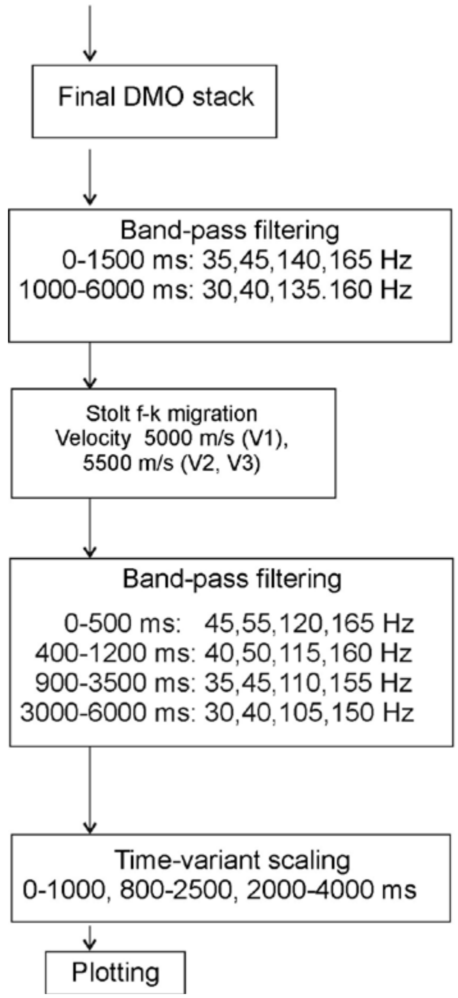

***Table 4. Steps of post-stack processing*.**

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	5212
276.40	5528
572.65	5727
873.05	5820
1177.80	5889
1488.10	5952
1800.05	6000
2116.40	6047
2435.40	6089
2758.95	6131
3084.30	6169
4720.05	6293
6357.05	6357
20000.00	6368

→

Plotting

5. RESULTS

The location of the survey lines is shown on a geological map in Fig. 5 and on a magnetic map in Fig. 12 and appendix 2. The map in Fig. 4 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. 6. 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.

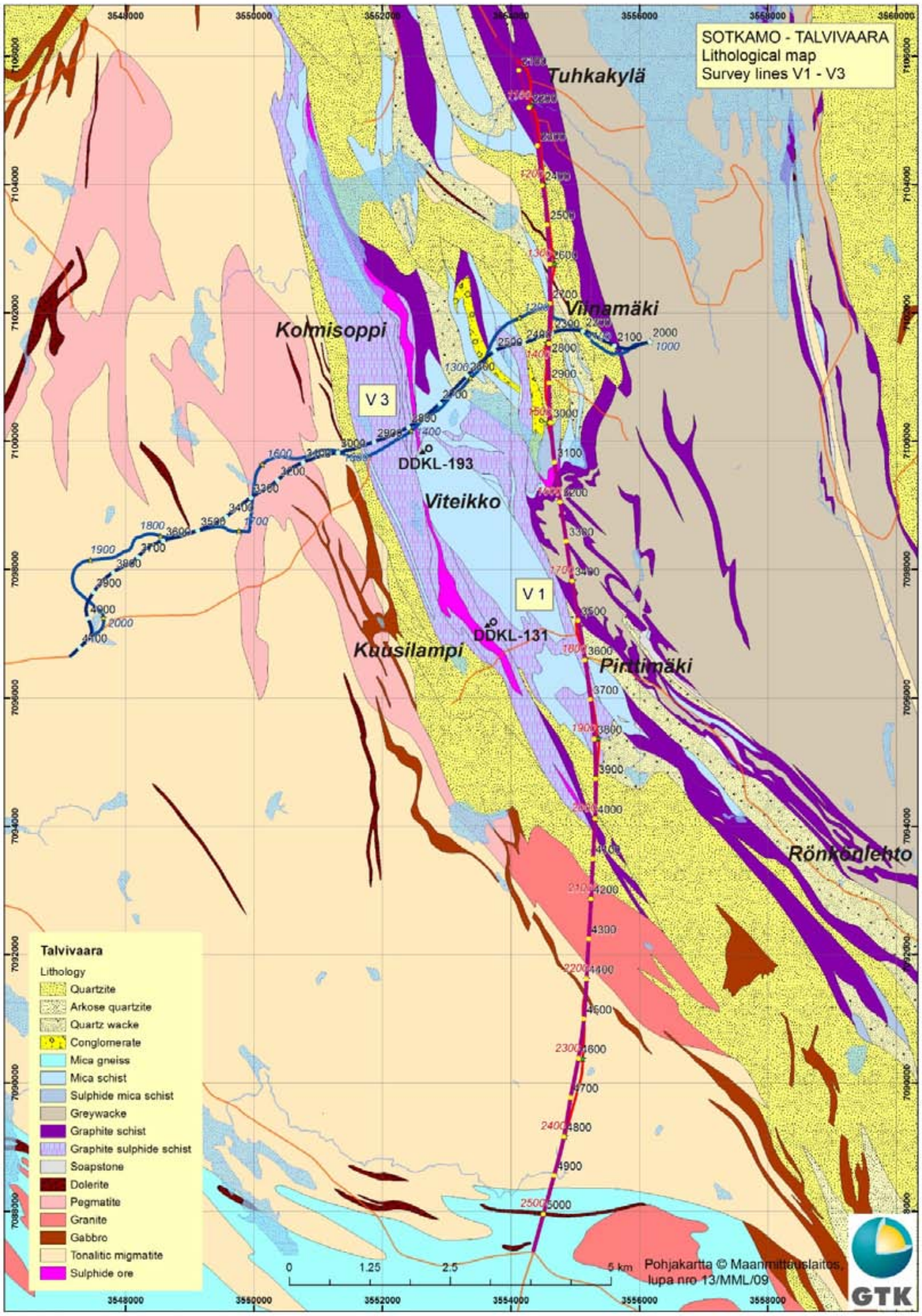

Figure 5. *Survey lines in Talvivaara. Numbers along the lines indicate receiver station pole numbers (italics) and CMP coordinates (normal text). Locations of drill holes logged for their seismic reflection properties are also shown. Base map derived from data in the digital bedrock map of Finland by GTK (DigiKP200).*

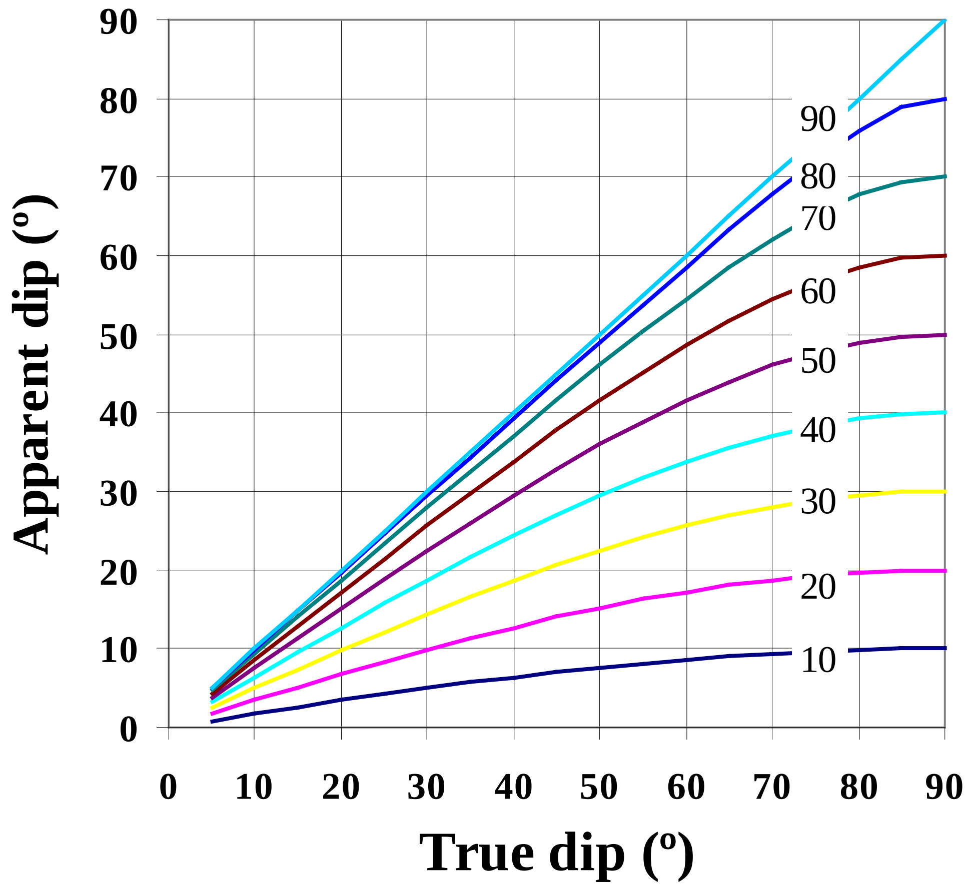

Figure 6. *Relations between true and apparent dip angles of planar reflectors. The curve parameter is the angle between the survey line and the strike of the reflector at surface.*

Datum level of the seismic reflection data is 200 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 Figure 7. The applied frequency band of 30-165 Hz is well covered with received data. This predicts good resolution in the final images. The processed sections show a wealth of reflectors. Reflectors as thin as 10 -20 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 Figures 8 – 9 and in the appendices. The sections were converted from time sections to depth sections using the velocity function in Table 4. 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.

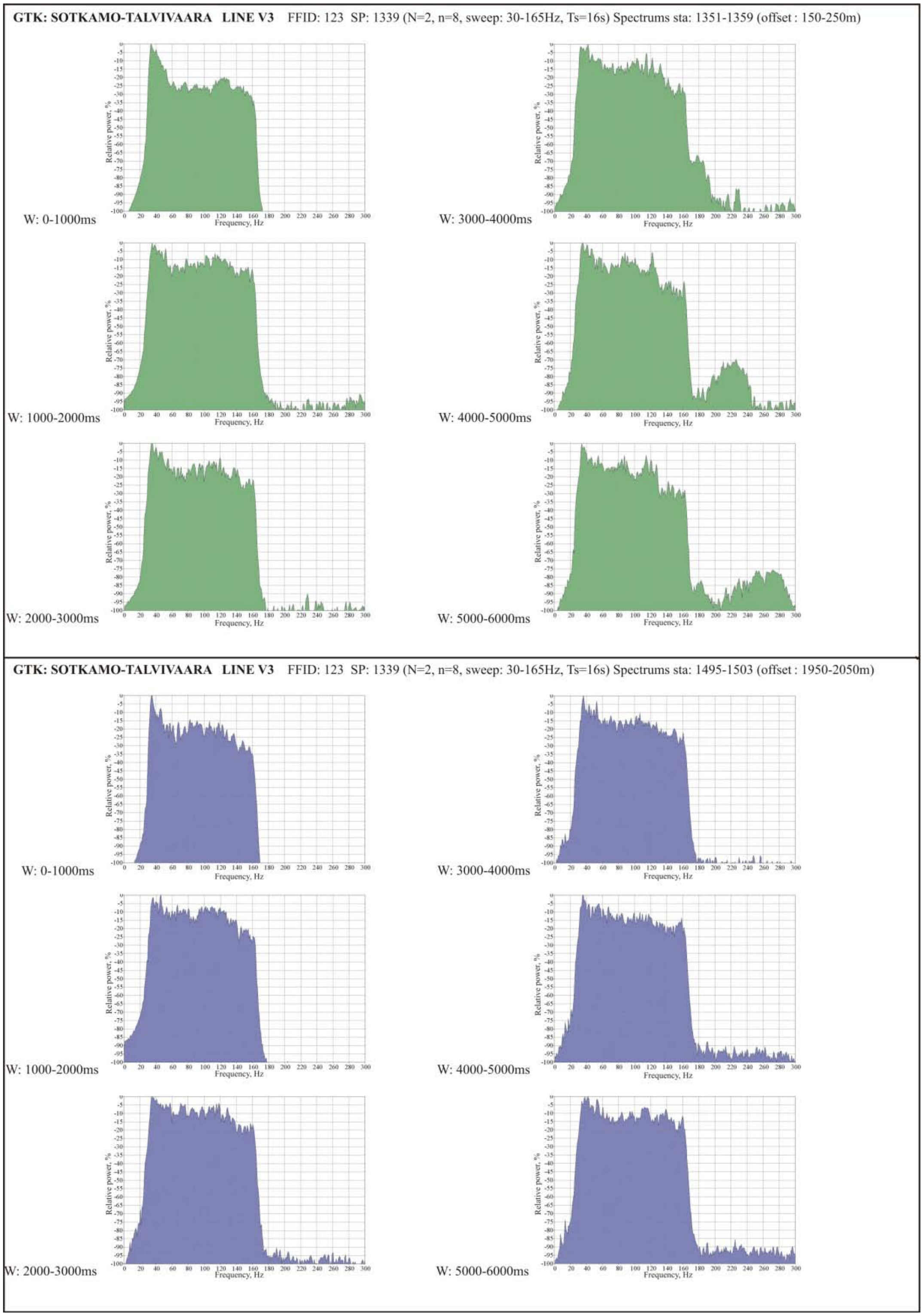

Figure 6. *Frequency spectra of the vibrator field data from line V3 with two offsets from the shot point. Upper panels: offset 150-200 m, lower panels: offset 1950-2050 m (Zamoshnyaya, 2008). The shot point is at CMP 2678 (see Figure 5 for location on the survey map).*

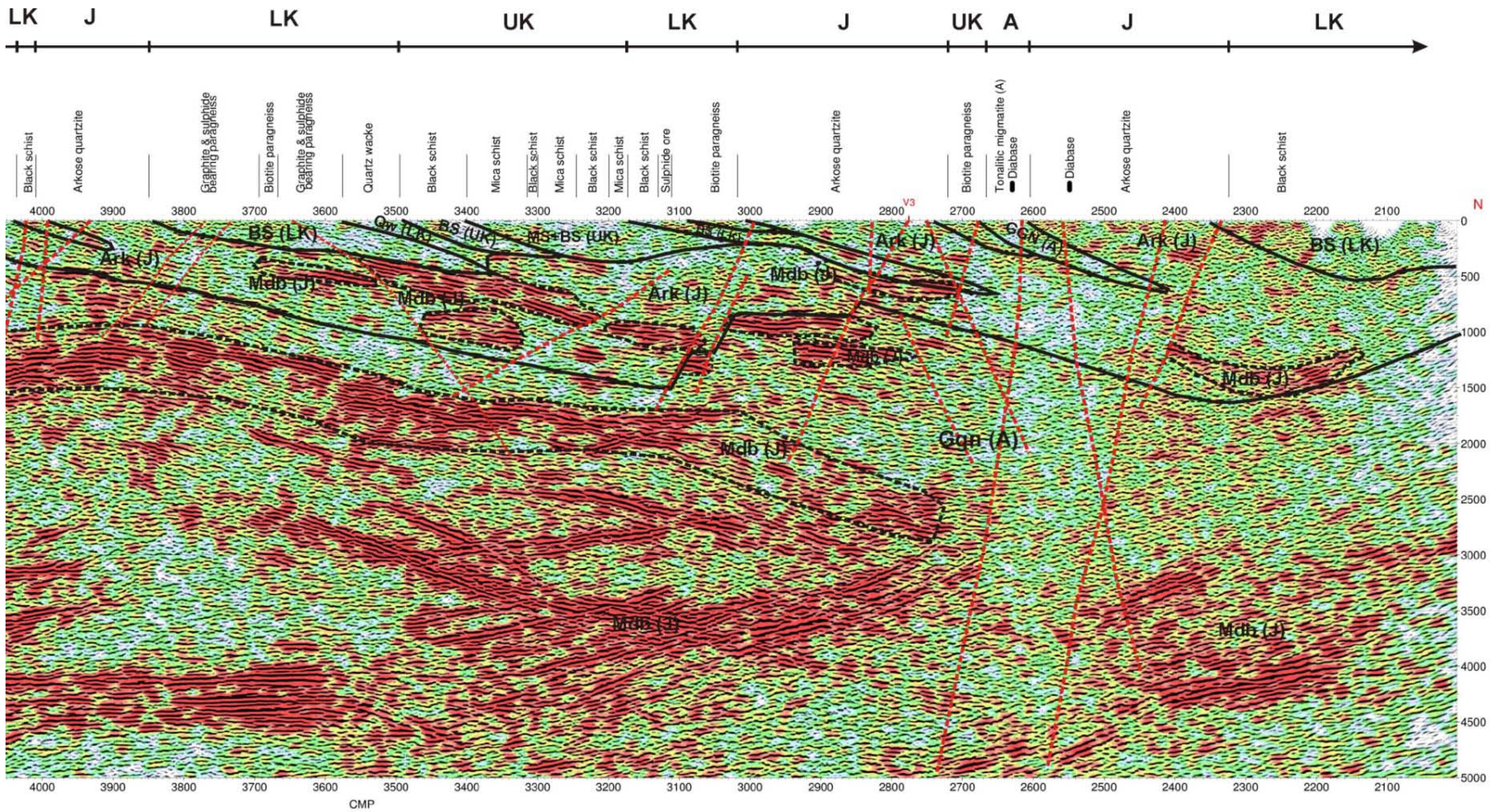

Figure 8a. *Migrated NMO section of line V1, northern part, CMP 2000-3800. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. The horizontal coordinate is the common mid point (CMP) number. Vertical and horizontal scale ratio is 1:1. Boundaries of the interpreted boundaries of lihological units are shown with solid lines except the metadiabases which are shown with broken lines. Broken red lines indicate faults and shear zones. Abbreviations: GGN, granite gneiss and Archaean rocks in general; BS, black schist; MS, mica schis; Qu, quartzite; Ark, arkose quartzite; Mdb, metadiabase and mafic dyke rocks. Age groups: A, Archaean; J, Jatulian; LK, Lower Kaleva; UK, Upper Kaleva. The boundaries of main surface tectofacies units A, J, LK and UK have been adopted from the map by Kontinen (2012).*

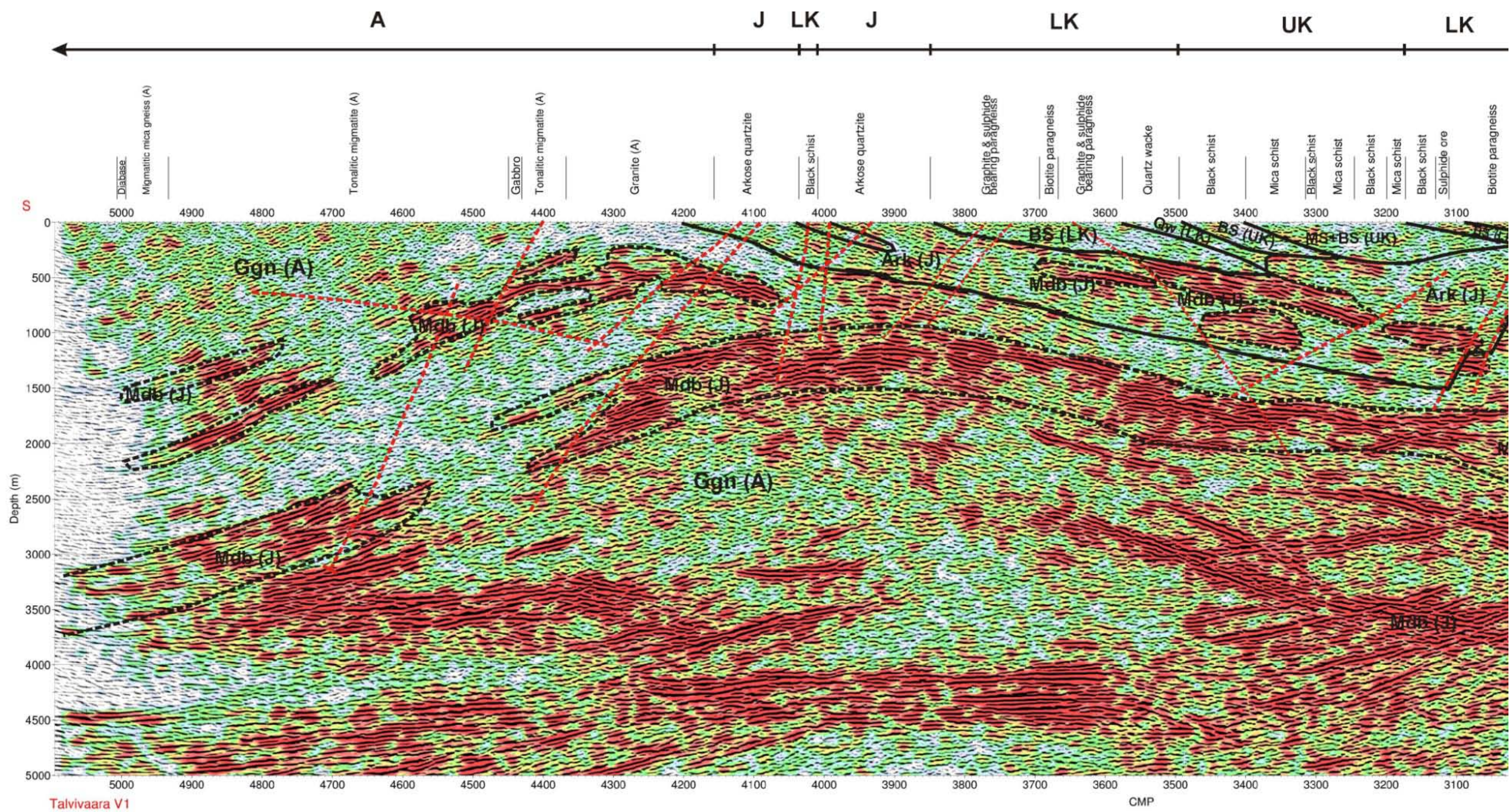

Figure 8b. *Migrated NMO section of line V1, southern part, CMP 3100-5100. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. The horizontal coordinate is the common mid point (CMP) number. Vertical and horizontal scale ratio is 1:1. Boundaries of the interpreted boundaries of lihological units are shown with solid lines except the metadiabases which are shown with broken lines. Broken red lines indicate faults and shear zones. Abbreviations: GGN, granite gneiss and Archaean rocks in general; BS, black schist; MS, mica schis; Qu, quartzite; Ark, arkose quartzite; Mdb, metadiabase and mafic dyke rocks. Age groups: A, Archaean; J, Jatulian; LK, Lower Kaleva; UK, Upper Kaleva. The boundaries of main surface tectofacies units A, J, LK and UK have been adopted from the map by Kontinen (2012).*

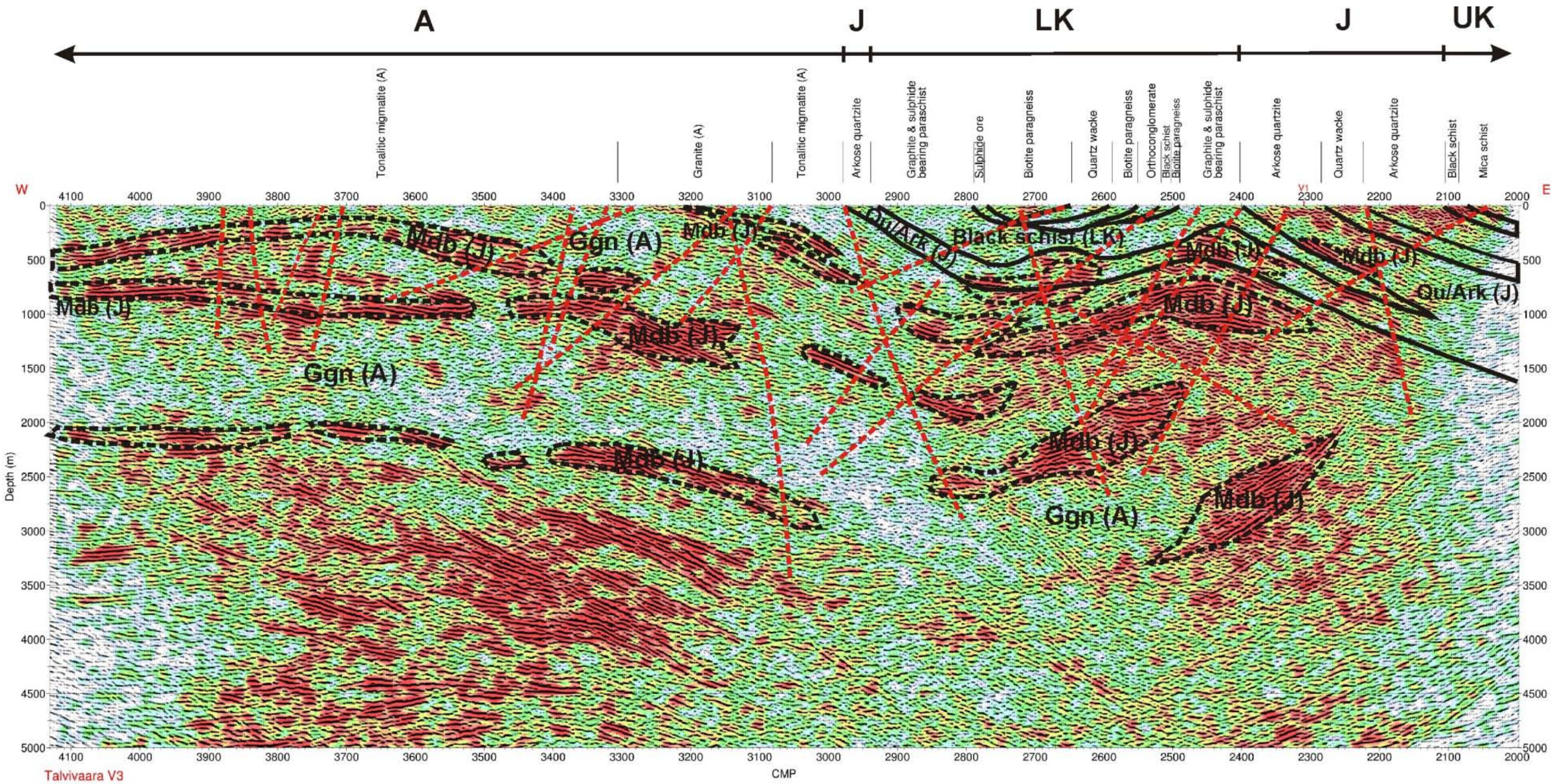

Figure 9. *Migrated NMO section of line V3. Reflectors with high amplitude are automatically enhanced with red background colour behind the wiggle plot. Boundaries of the interpreted boundaries of lihological units are shown with solid lines except the metadiabases which are shown with broken lines. Broken red lines indicate faults and shear zones. Abbreviations: GGN, granite gneiss; BS, black schist; MS, mica schis; Qu, quartzite; Ark, arkose quartzite; Mdb, metadiabase and mafic dyke rocks. Age groups: A: Archaean; J, Jatulian; LK, Lower Kaleva; UK, Upper Kaleva. The boundaries of main surface tectofacies units A, J, LK and UK have been adopted from the map by Kontinen (2012).*

5.1. 2D and 3D presentation of the results

To obtain three-dimensional visualization of the reflector structures, the seismic sections and line location maps were imported to *SURPAC* 3D visualization and modelling software. The sections were imported 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.

In addition to the basic seismic results, selected ground and airborne geophysical maps compiled from the data bases of GTK were included in the 3D data compilation. The applied airborne map is the total magnetic field anomaly and its hill-shaded version. The applied ground geophysical map is a hill-shaded version of the ground bouguer gravity anomalies.

In addition to seismic reflection images, the available geological and geophysical maps were applied for correlating reflectors and bedrock structures. Furthermore, drilling and mining data was incorporated from materials obtained from Talvivaara Oy. The mine data includes 3-D models of the Kuusilampi and Kolmisoppi ore bodies. In addition it was possible to use acoustic and density downhole logs of two boreholes in the mining area (DDKL-131 and DDKL-193).

The original survey plan included also a line V2 which was planned to cross the Kuusilampi deposit. However, this line could not be measured due to simultaneous construction of the mine in 2008. The line V3 crosses the Talvivaara deposit between the two Kolmisoppi and Kuusijärvi ore bodies where the black schist mineralization is not economic.

5.2. Reflectivity of the upper crust in the Talvivaara survey area

The reflectors in the seismic sections were correlated with surface geological and magnetic maps, and the interpreted depth continuation and extent of lithological and tectonic structures have been presented in Figures 8 and 9 and in the 3D data in the digital appendices. Good continuity of the reflections allows correlating them over considerable distances.

A dominant feature in the Talvivaara seismic results are the low-angle subhorizontal strong reflections in the uppermost 5 kilometers. The reflectors are continuous and range in thickness from about 100 m to 1 km (Figures 8 and 9). They are most probably due to Proterozoic mafic sills and dykes. In the bedrock maps of map sheets 3344 Laakajärvi (Kontinen, 2005) and 3433 Sotkamo (Havola, 1981), Lower Proterozoic mafic sills and dykes cutting the Archaean basement and metasediments of the Jatulian period are common. In contrast, mafic dykes are not met with in the Kalevian strata in the Talvivaara area.

The present HIRE data set is located only about 20 km from the crustal seismic reflection transect FIRE-1 (Kukkonen et al., 2006; Korja et al., 2006) in the Lehtovaara-Koivukylä-Sukeva area to the SW of Kajaani (Figure 1). The structures revealed by FIFE-1 in this area are mostly subhorizontal or south dipping at low angles. According to the magnetic anomaly map (Figure 1) the subhorizontal structures continue to the east to the immediate vicinity of the Talvivaara area.

It supports the interpretation that the subhorizontal reflectors in the western part of line V3 can be attributed to subhorizontal mafic sills within the Archaean basement. Reflectivity of mafic (or amphibolitic) rocks in an intermediate or felsic environment is good and therefore the mafic sills and dykes are expected to generate strong reflections.

Due to small reflection contrast between the Archaean basement and the Proterozoic Jatulian metasediments, and the presence of mafic rocks cutting both rock groups, it is not always straightforward to draw the Archaean - Proterozoic boundary according to seismic data.

Between Kajaani and Sonkajärvi, the FIRE-1 results suggested (Korja et al., 2006, Kukkonen et al., 2006) that the Archaean basement in the south and Proterozoic rocks in the north have a tectonically controlled or at least affected contact relations. The Archaean basement is apparently trhusted on the Proterozoic rocks from southern or southwestern direction.

The Kainuu Belt shows a folded structure with open synforms and antiforms in the Talvivaara area, and it extends to a depth of about 700-800 m in the mining area, but in the eastern part of the line V3 at Viinamäki it reaches a depth of about 1.5 km. Further east beyond the end of the line V3 the maximum thickness of the Proterozoic rocks may extend to about 2 km (Figure 9). The Kainuu belt rocks and the Talvivaara deposit have been preserved in the synform depressions.

To the south of the crossing of lines V1 and V3 in Viinamäki (Figure 5) the Archaean basement nears the surface and the contact with Proterozoic rocks is met with at about CMP 4150 in line V1 (Figure 8b). In the same area the strong reflectors show a broad antiform structure. The ridge of the antiform seems to follow the Archaean-Proterozoic contact (and the related Archaean granite, see Figure 5) to the NW to line V1 at about CMP 3300.

5.3. Seismic impedance and synthetic seismograms of metasedimentary rocks in Talvivaara

In situ information of seismic reflection properties measured in drill holes provides direct information of the geological factors behind observed reflectivity. This is obtained by measuring the rock density and seismic P-wave velocity in drill holes. Synthetic seismograms can then be calculated corresponding to the frequency band of the applied Vibroseis signal. The synthetic seismograms can be compared with measured seismograms and conclusions can be drawn of the geological factors affecting reflectivity.

Geophysical down hole logging of rock density and seismic P-wave velocity *in situ* was carried out in two drill holes in Talvivaara, holes DDKL131 (depth 520 m, dip 59°, azimuth 250°) and DDKL193 (depth 454 m, dip 51°, azimuth 250°, drill hole locations shown in Figure 5). The measurements were done by the logging company Astrock Oy in 2009. Talvivaara Oy kindly provided these data for use in the present project.

Drill hole data and calculated seismic impedance (product of density and P-velocity), reflection coefficients and synthetic seismograms are shown in Figures 10 and 11. The holes are not located exactly on the seismic profiles. Hole DDKL193 is about 330 m to the SE of line V3, and if projected to the line the hole collar corresponds to about CMP 2770. The hole DDKL131 is located about 1.3 km to the west of line V1 in the Kuusilampi deposit (Figure 5).

Due to borehole instability and blocking, the holes could not be completely logged. In DDKL131 the density-velocity data extends to 485 m and in DDKL193 to 185 m, respectively (Figures 10 and 11).

The synthetic seismograms suggest that there is an impedance contrast between black schist and quartzite. Inside quartzite (DDKL131) there is continuous high frequency variation in P-velocity perhaps due to fractures, but it does not generate significant synthetic reflections. This can be attributed to the low-pass filtering effect of the applied Vibroseis frequency band. In addition, at depths of shear zones characterized by talc schist and core loss (i.e., fractured and sheared rock) very strong synthetic reflections are generated.

It can be concluded that reflections can be expected from the black schist-quartzite contacts, shears and major fracture zones. The logged drill holes do not intersect any mafic dykes, but it can be expected that the mafic rocks (or their amphibolitic metamorphic equivalents) are also strongly reflective within the intermediate-felsic Archaean basement rocks and the metasedimentary rocks. The present drill hole data does not tell anything about the contrasts between the basement and the metasediments, but experience from elsewhere in Finland suggests that they would not show a significant reflection coefficient. Only mineralized black schist would be reflective against the basement rocks, but such contact relations are not met with in the Talvivaara area.

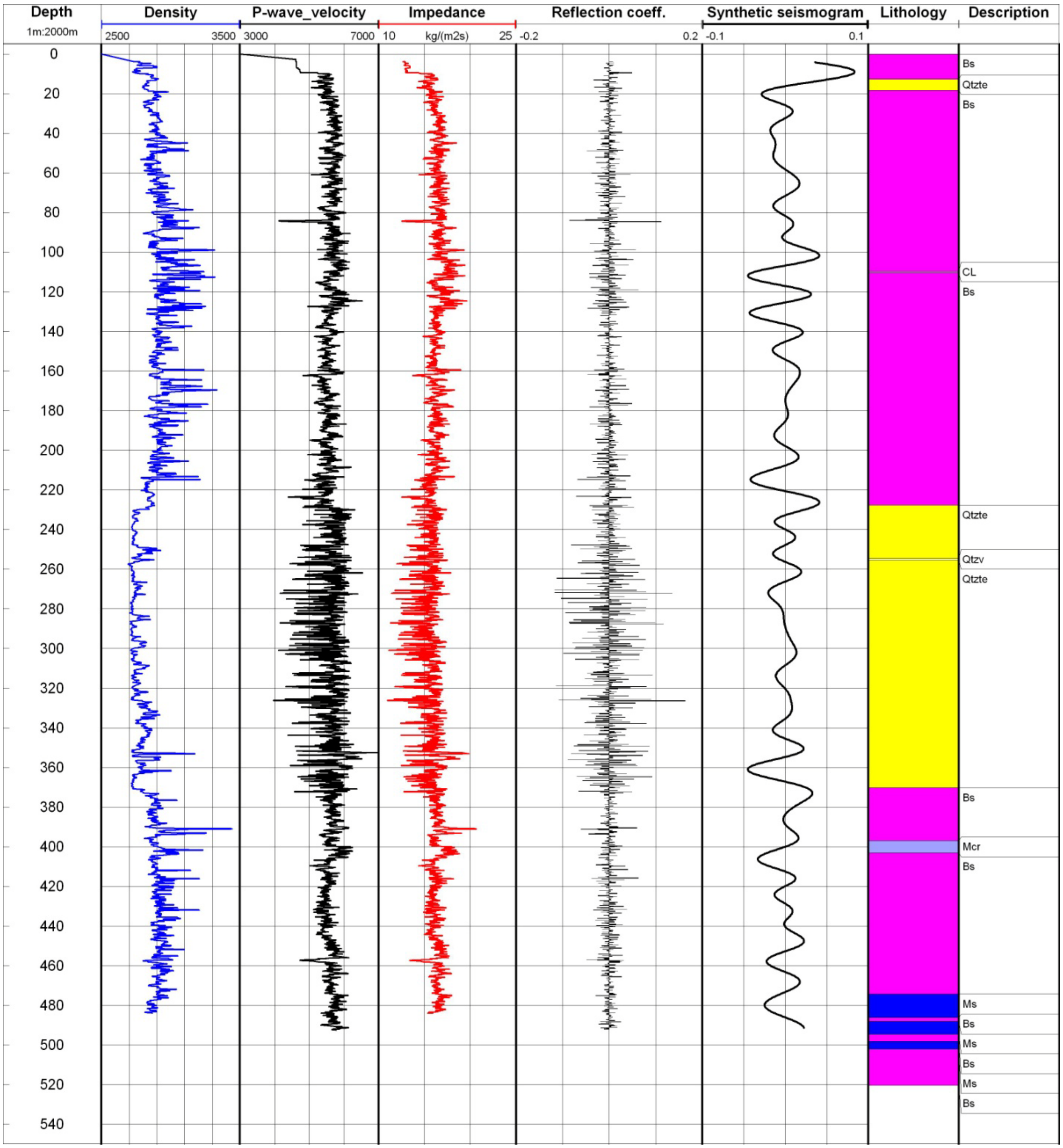

Figure 10. *From left: Density and P-wave velocity logged in situ in the drill hole DDKL-131, calculated seismic impedance, reflection coefficients and a synthetic seismogram. The seismogram was calculated using an Ormsby wavelet 20-40-100-150 Hz. On the right, lithological column. Abbreviations: Bs, black schist; Qtzte, quartzite; Qtzv, quartz wacke; Mcr, meta-carbonate rock; Ms, mica schist; CL, core loss. Location of drill hole, see Figure 5.*

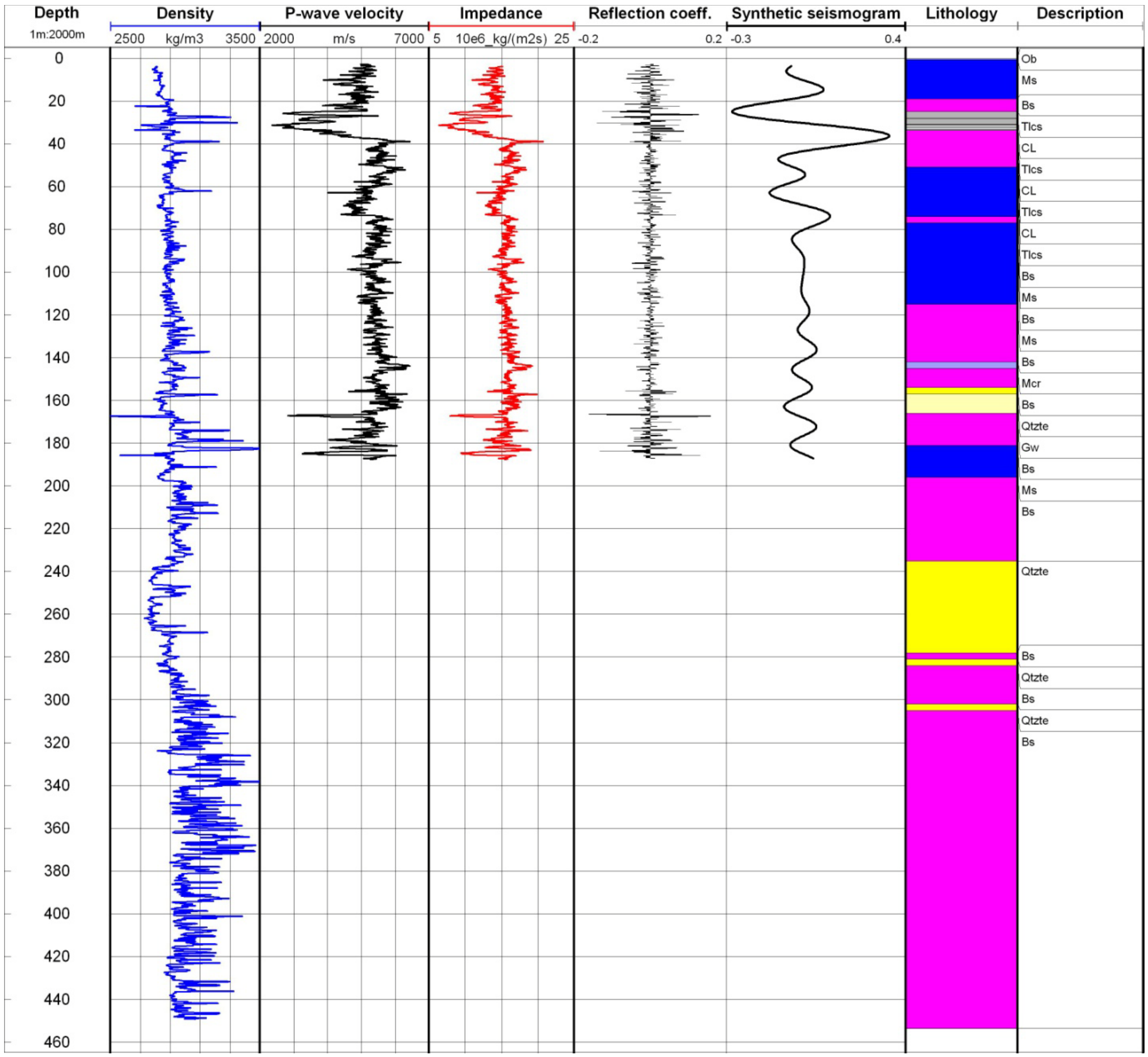

Figure 11. *From left: Density and P-wave velocity logged in situ in the drill hole DDKL-193, calculated seismic impedance, reflection coefficients and synthetic seismogram. The seismogram was calculated using an Ormsby wavelet 20-40-100-150 Hz. On the right, the lithological column. Abbreviations: Bs, black schist; Qtzte, quartzite; Qtzv, quartz wacke; Mcr, meta-carbonate rock; Ms, mica schist; Tlcs, talc schist; CL, core loss. Location of drill hole, see Figure 5.*

5.4. Reflectivity related to the mineralized black schist

Line V3 suggests that the thickness of the mineralized graphite and sulphide bearing black schist is about 500 m thick at maximum under the line V3 at CMP 2750 (Figure 9) where the reflectors form an open synform structure. This is also the area where the strongest bouguer gravity anomalies occur (Tervo, 1980; see also Figure 12). The highest density rocks among the Talvivaara metasediments are the mineralized black schists which range from 2930 to 3000 kg m^{-3} whereas the normal (non-mineralized black schist and mica schist have densities of 2860 and 2720 kg m^{-3} (Tervo, 1980). Diabase and amphibolite (not analysed in Talvivaara) have typically densities of 2850 - 3000 kg m^{-3} (Schön, 1983) and they may also be contributing to the gravity anomalies. The strong reflectors beneath the interpreted Lower Kaleva black schist synform (line V1, CMP 2500-3000, Figure 8b) probably represent such high density mafic rocks.

The black schist does not show very strong internal reflectivity, but it seems to be more reflective than the quartzites and quartz wackes in contact with the black schist. In the eastern part of V3, there is relatively strong reflectivity in areas under quartzite and black schist on the geological map. This may be due to tectonization and/or sulphide content, but may also be due to mafic dyke rocks.

6. DISCUSSION

6.1 Reflective structures and their correlation over the study area

The strong reflectors in the Talvivaara data set are attributed to Lower Proterozoic 2.1-2.3 Ga mafic sills and dykes cutting the Archaean basement and the Jatulian metasediments. The sills have deformed into gentle open folds below the Proterozoic metasediments. Some of the metadiabses outcrop in the Archaean basement to the west of Talvivaara area (Kontinen, 2005). The metadiabases can be either magnetic or non-magnetic (Korhonen, 1987; Kontinen, 1987b) which complicates their representation on geological and magnetic maps. Although the strong reflections most probably reflect mafic sills, there may be also other rocks or shearing related to them. They could be tested with shallow drill holes, e.g., at V3 CMP 2450 where their upper contact occurs at a depth of about 250 m.

The good continuity of reflectors is disturbed in the northern part of line V1 in the Viinamäki-Tuhkakylä area where the strong reflectors terminate at about CMP 2700 into a relatively transparent section at CMP 2500 – 2700 (Figure 8a). This is interpreted as due to faulting with a vertical displacement of about 1 km. It is best seen at the depth of 2.5 – 3.5 km where the continuity of the strong reflectors is disturbed.

Several seismically highly transparent non-reflective domains but apparently conforming to the surrounding layers can be attributed mostly to Archaean granitoids. Such a case is well documented under V1 at CMP 4200 - 4400 (Figure 8b). It is plausible that similar transparent parts of the sections at greater depths also represent Archaean granitoids.

The seismic data may give clues on ophiolite-derived serpentinites. In Talvivaara, such rocks are present in the Upper Kaleva tectofacies about 2 km to the SE of the Viteikko klippe in the Rönkönlehto-Pirttivaara area (Figure 5). When projected along strike to line V1 the serpentinite would correspond approximately to CMP 3300 (Fig. 8b). The reflectors in this part of the section have been interpreted as metasediments of the Upper Kaleva and metadiabases. The presence of serpentinite cannot be proven or disproven. It should be noted, that the seismic reflection coefficient between metasediments and granitoids against serpentinite is relatively small due to the low density and low P-wave velocity of serpentine.

6.2. Suggestions for further studies and exploration

The present seismic results are in a good agreement with drilling-based models of the Talvivaara deposit and suggest that the Lower Kaleva black schist extends to a depth of about 500 m under the line V3 between the Kolmisoppi and Kuusilampi deposits. The seismic data brought also forward new questions on the Talvivaara rocks and reflectors. In the following targets are suggested for further structural studies and mineral exploration in the area (Table 5 and Figure 12).

Targets 1-2. It would be useful to know more about the deep geology of the synform on line V3 by drilling the strong reflectors at CMP 2600 – 2800 at the depth of about 500 – 1000 m (**target**

1, Figures 9 and 12). These reflectors very probably represent mafic sills, but the possibility of unknown mineralized black schist or other mineralizations could be excluded with a 1 km deep drill hole. Further east, the strong reflectors in the same reflective layer could also be checked on the top of the antiform structure at CMP 2450 at the depth of 250 - 500 m (**target 2**, Figures 9 and 12). In addition to the direct geological information, such drill holes would provide excellent opportunities for logging the holes for the density and acoustic properties *in situ* in order to obtain a more detailed understanding of the geological factors behind seismic reflectivity.

Apart from the seismic structures, the **gravity anomalies** in Talvivaara (Figure 12) would deserve more detailed analysis and quantitative modelling. Gravity highs are related to the thick parts of the Kuusilampi deposit, but the biggest anomalies in the gravity map are located in the NW part of the Viteikko klippe and continue to about 1 km to the northeast of it. The bouguer gravity high coincides with the seismically interpreted synform of Lower Kaleva black schist in V3 at CMP 2400 – 2900. In the SE part of the Viteikko klippe the anomaly changes into a large minimum area. The positive anomaly may be due to mineralized black schist under the relatively thin (about 100 m) klippe (A. Kontinen, Geological Survey of Finland, pers. comm., 2012).

Target 3. The Lower Kaleva black schist is interpreted to continue dipping about 30°E under the Jatulian metasediments at CMP 2100 – 2400 in V3 on the eastern flank of the antiform with its rigde at CMP 2450 (Fig. 9). This potential extension of the mineralized black schist could be checked with shallow (<500 m) holes at CMP 2300-2400.

Target 4. The gravity high in Rönkönlehto is probably associated with a serpentinite body outcropping about 2 km to the NW of the anomaly high and located on the local strike of rocks on the geological map. There is also a related magnetic anomaly but it is not exactly overlapping with the gravity anomaly and it is most probably due to pyrrhotite-bearing black schist.

Table 5. Targets for exploration and further structural studies of the Talvivaara area.

Target no.	Line	CMP	Northing	Easting	Notes
1	V3	2650	7100800	3553120	Synform geology and strong reflectors
2	V3	2450	7101500	3554000	Antiform structure and strong reflectors
3	V3	2350	7101700	3554410	Deep continuation of Lower Kaleva black schist
4	n.a.	n.a.	7093600	3559360	Gravity high, possible serpentinite

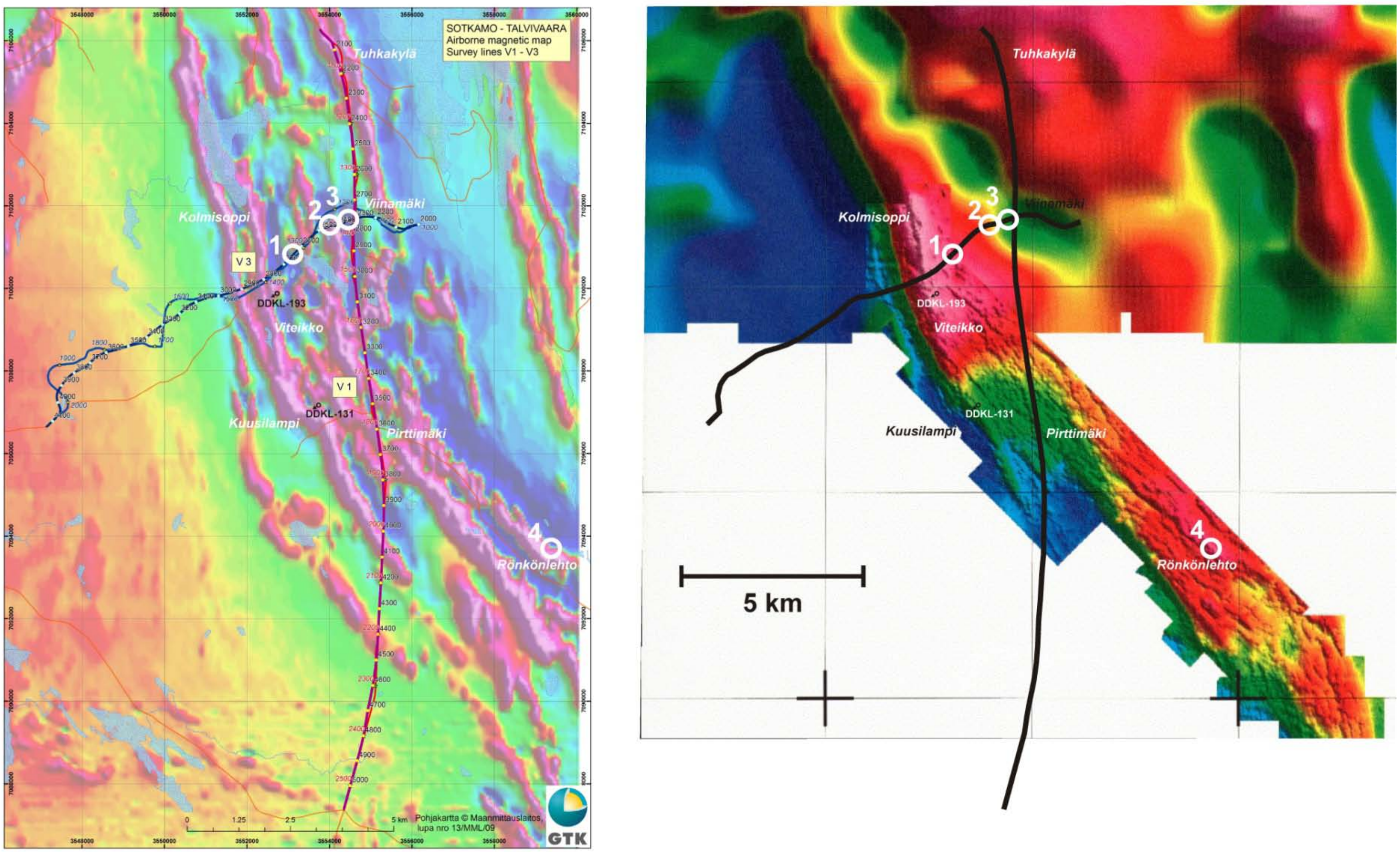

Figure 12. *Suggested targets for further exploration and structural studies in the Talvivaara area. Left: Low-altitude airborne magnetic total field map. Right: Ground Bouguer gravity anomaly map. Southern part of the gravity map is based on systematic ground surveys at 20 m station and line interval, and the northern part on a regional survey with stations at about 1 km intervals. Data from digital data bases of the Geological Survey of Finland. Numbers of targets refer to text and Table 5.*

7. CONCLUSIONS

The HIRE seismic survey comprising 30.8 line-km of Vibroseis reflection data in the Talvivaara area revealed numerous previously unknown structures in the uppermost 5 km of crust. A dominant feature in the Talvivaara seismic results are the low-angle subhorizontal and gently folded strong reflectors. The reflectors are continuous and range in thickness from about 100 m to 1 km (Figures 8-9). They are most probably due to 2.1-2.2 Ga Proterozoic mafic sills and dykes intersecting the Archaean basement and the Jatulian strata.

Down-hole logging data and synthetic seismograms suggest that reflections can be expected from the black schist-quartzite contacts, shears and major fracture zones. The logged drill holes do not cut any mafic dykes, but it can be expected that the mafic rocks (or their amphibolitic metamorphic equivalents) are also strongly reflective in the intermediate-felsic Archaean basement rocks and the Jatulian metasedimentary rocks.

The strong reflectors reveal a gently folded synform-antiform structure which shows dip angles ranging from subhorizontal to about 30°. Assuming that the reflectors represent mafic sills and dykes, the seismic data suggest that there are considerable amounts of mafic material in the upper crust of the Talvivaara area. As the sills have intruded originally in horizontal positions parallel to the ground surface and sediment layering, the present subhorizontal structure would imply only relatively modest deformation in the Archaean basement. In the Proterozoic layers the deformation has been more efficient as indicated by geological data. The Talvivaara deposit has been preserved in a synform structure of the basement. The depth extent of the Lower Kaleva rocks hosting the ore deposit extend to about 500 m depth in line V3.

The present seismic results and other geophysical maps were applied for suggesting targets for further exploration and structural studies of the Talvivaara black schist.

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APPENDICES

1. Seismic survey lines plotted on the geological map
2. Seismic survey lines plotted on the airborne magnetic map
3. NMO migrated section of line V1
4. NMO migrated section of line V3

DIGITAL APPENDICES

1. Report text and figures (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 Lithological map with survey lines
    - 7.4 Airborne magnetic map with survey lines
    - 7.5. Hill-shaded ground bouguer gravity map
    - 7.6. Mine data (Kuusilampi and Kolmisoppi deposits)