**Type of report**
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GTK & Agnico-Eagle Finland

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**Title of report**
HIRE Seismic Reflection Survey in the Suurikuusikko gold mining and exploration area, North Finland

**Abstract**
A seismic reflection survey comprising five vibroseis lines (total length of 79.3 km) and one explosion seismic line (length 6.8 km) was carried out in the Suurikuusikko gold mining and exploration area, in Kittilä, northern Finland, in February-March, 2008. The survey is a part of the project HIRE (High Resolution Reflection Seismics for Ore Exploration 2007-2010) of the Geological Survey of Finland (GTK). The Suurikuusikko survey was done in co-operation with Agnico-Eagle Finland.

The results reveal a detailed structure of the uppermost 5 km of crust. The upper crustal reflectors are generally moderately dipping or subhorizontal, and correlation with surface geology and geophysics indicates that the strongest reflectivity is due to mafic tuffs and tuffitic rocks (volcanoclastic and sedimentary material), whereas tholeites (mafic lavas) and granitoids are less reflective. The mafic tuffitic rocks can be followed and correlated over the complete area of study.

The subvertical Kiistala Shear Zone, which is the main structure bearing gold deposits in the Suurikuusikko area, was imaged as discontinuities in horizontally oriented reflectors. Trend lines of reflectors suggest that there are open antiform folds under the KSZ, which is located approximately on the axial plane of these folds. Furthermore, the seismic data indicate that the antiform folds and KSZ are on the hanging wall side of an east dipping reflector (30-40º) which is interpreted to represent a contact zone between mafic graphitic tuffitic rocks (lower unit) and mafic lavas (upper unit). The KSZ may have developed as a part of thrusting along the east-dipping reflector and folding on the hanging wall side of it.

Drill hole data on density and acoustic properties of two deep drill holes in the KSZ (SUU08001B and ROU08001) and synthetic seismograms calculated from these suggest that strong reflectivity is due to layers of volcanoclastic rocks and iron sulphide-rich banded iron formation rocks within more homogeneous lava units. Reflectivity is also produced by fracturing and other zones of weakness.

Gold prospects hosted in quartz-carbonate veins in the Iso-Kuotko area in the northern part of the study area seem to correlate with reflectivity when projected on the corresponding seismic sections. Furthermore, the postglacial Suasselkä fault is also imaged as a weak reflector on top of a SE dipping reflective contact between mafic graphitic tuffs and mafic lavas. The postglacial fault follows the NE oriented section of the KSZ in its northern part and coincides with the strike of one of the gold lodes in the Iso-Kuotko area (the Tiira lode).

The data is applied for indicating potential sites for further exploration and for locating analogue sites of the Suurikuusikko deposits.

**Keywords**
Seismic reflection surveys, mafic volcanic rocks, orogenic gold deposits, Fennoscandian Shield

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Finland, Lapland, Kittilä, Suurikuusikko

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HIRE Seismic Reflection Survey in the Suurikuusikko gold mining and exploration area, North Finland

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Abstract

A seismic reflection survey comprising five vibroseis lines (total length of 79.3 km) and one explosion seismic line (length 6.8 km) was carried out in the Suurikuusikko gold mining and exploration area, in Kittilä, northern Finland, in February-March, 2008. The survey is a part of the project HIRE (High Resolution Reflection Seismics for Ore Exploration 2007-2010) of the Geological Survey of Finland (GTK). The Suurikuusikko survey was done in co-operation with Agnico-Eagle Finland.

The results reveal a detailed structure of the uppermost 5 km of crust. The upper crustal reflectors are generally moderately dipping or subhorizontal, and correlation with surface geology and geophysics indicates that the strongest reflectivity is due to mafic tuffs and tuffitic rocks (volcanoclastic and sedimentary material), whereas tholeites (mafic lavas) and granitoids are less reflective. The mafic tuffitic rocks can be followed and correlated over the complete area of study.

The subvertical Kiistala Shear Zone, which is the main structure bearing gold deposits in the Suurikuusikko area, was imaged as discontinuities in horizontally oriented reflectors on a line (V4) running through the active mining area of the Kittilä mine. On another line about 3 km to the north (E1), also crossing the KSZ, subvertical structures are less evident but present. Trend lines of reflectors suggest that there are open antiform folds under the KSZ, which is located approximately on the axial plane of these folds. Furthermore, the seismic data indicate that the antiform folds and KSZ are on the hanging wall side of an east dipping reflector (30-40º) which is interpreted to represent a contact zone between mafic graphitic tuffitic rocks (lower unit) and mafic lavas (upper unit). The KSZ may have developed as a part of thrusting along the east-dipping reflector and folding on the hanging wall side of it.

Drill hole data on density and acoustic properties of two deep drill holes in the KSZ (SUU08001B and ROU08001) and synthetic seismograms calculated from these suggest that strong reflectivity is due to layers of volcanoclastic rocks and iron sulphide-rich banded iron formation rocks within more homogeneous lava units. Reflectivity is also produced by fracturing and other zones of weakness.

Gold prospects hosted in quartz-carbonate veins in the Iso-Kuotko area in the northern part of the study area seem to correlate with reflectivity when projected on the corresponding seismic sections. Furthermore, the postglacial Suasselkä fault is also imaged as a weak reflector on top of a SE dipping reflective contact between mafic graphitic tuffs and mafic lavas. The postglacial fault follows the NE oriented section of the KSZ in its northern part and coincides with the strike of one the gold lodes in the Iso-Kuotko area (the Tiira lode).

The data is applied for indicating potential sites for further exploration and for locating analog sites of the Suurikuusikko deposits.
1. Introduction

A seismic reflection survey was carried out in February-March 2008 in the Suurikuusikko gold mining and exploration area in Kittilä as a part of the project HIRE (High Resolution Reflection Seismics for Ore Exploration 2007-2010) of the Geological Survey of Finland (GTK).

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 were to delineate the upper crustal structures of the Suurikuusikko area in the Central Lapland Greenstone Belt, and to study the seismic response of the mineralized subvertical Kiistala Shear Zone and its relations to larger scale structures.

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 Suurikuusikko survey was agreed between GTK and Agnico-Eagle Finland based on the offer by GTK dated May 3, 2007.

The survey comprised mainly vibroseismic soundings along roads and one off-road explosion seismic line. The preparatory works on the explosion line and drilling of the shooting holes was done in February 2008. The topographic survey and data acquisition were carried out during February 15 – March 14, 2008.

2. Short geological description of the survey area

The study area is located in the eastern part of the Central Lapland Greenstone Belt (CLGB) characterized by mostly Paleoproterozoic volcanogenic rocks. The area experienced an extended period of rifting at 2.5-2.0 Ga, followed by an orogenic stage beginning at 2.0-1.9 Ga and ending probably at about 1.88 Ga or possible as late as 1.77 Ga (Hölttä et al., 2007; Patison, 2006; 2007). The metamorphic grade of the rocks in the study area is low, representing typically greenschist facies, and in larger scale there is a general trend of increasing metamorphic grade from SW to NE in central and northeastern Lapland. The high grade units overlie the low grade ones suggesting thrusting from NE direction (Hölttä et al., 2007).
To the S and SW of the CLGB and the Central Lapland Area, the main neighbouring formation is the Central Lapland Granitoid Complex characterized mostly by migmatites. To the NE of CLGB, the main crustal units are the high grade Tanaelv Belt and the Lapland Granulite Belt.

The structural evolution consisted of early N and NE directed thrusting in the southern and western parts of the Central Lapland area, but W and SW vergent folding in areas close to the Lapland Granulite Belt (Hölttä et al., 2007). These deformations ($D_1+D_2$) have been interpreted as about 1.88-1.87 Ga in the west. The age of peak metamorphism, and probably also the thrusting time of the Lapland Granulite belt is 1.9 Ga (Patison, 2006). The present shape of the Central Lapland Area was reached in the late $D_3$ deformation which took place either at 1.90-1.88 Ga or 1.84-1.80 Ga. The last deformation $D_4$ at about 1.77 Ga or slightly later was already completely brittle (Eilu et al., 2007).

Au mineralizations in the CLGB are controlled by structure, and the dominant structural elements are thrust and shear zones of the $D_3$ deformation (Patison, 2007). The most prominent ones are the Sirkka Shear Zone and particularly the Kiistala Shear Zone (KSZ) which is hosting the Suurikuusikko deposit (Härkönen et al., 1997; Patison, 2007; Patison et al., 2007). The regional direction of the main stress component was rotated dextrally during $D_3$ from NW-SE to NE-SW (Ward et al., 1989; Patison, 2007). As a result, the $D_3$ shear zones generally strike NW-SE, N-S and NE-SW, but they are locally strongly influenced by pre-existing structures.

The 25 km long Kiistala Shear Zone (KSZ) is cutting through volcanic and volcanoclastic rocks of the Kittilä Group of the Central Lapland Greenstone belt. The KSZ probably represents a wrench fault of the NE-SW thrusting. The rocks range from ultramafic to felsic, but are mainly mafic-ultramafic. In the Suurikuusikko area of the KSZ several mineralized zones are known over a length of about 1.5 km of the shear zone. Au is hosted by arsenopyrite, As-bearing pyrite and free gold in a strongly altered rocks of the KSZ. The alteration is characterized by albitization, carbonate alteration as well as graphitic alteration, which has produced non-crystalline carbon. The degree of shearing in the KSZ correlates positively with Au concentrations (Patison et al., 2007).

The Suurikuusikko deposit was opened for production in 2008 as the Kittilä mine. There are probable reserves (2008) of about 18.2 Mt of ore with 5.1 g/ton Au with a total of 3 million ounces Au (Agnico Eagle Mines, 2008). In general, the ore potential of the Central Lapland Greenstone belt is considered to be much larger, and the region is an area of active exploration interest.

Other known Au mineralisations in the present study area are the prospects in the Iso-Kuotko area (Härkönen et al. 2000; Salmirinne and Turunen, 2007). They are located about 12 km to the north from the Kittilä mine. Gold is related to structurally controlled sulphide-bearing quartz-carbonate vein systems. In contrast to Suurikuusikko, gold is present in free gold minerals to a major part. There are four prospects with different strikes of the vein swarms but with steep or moderate dip angles.
3. Survey method

The Suurikuusikko reflection survey consisted of 2D lines located according to the geology, road and terrain conditions. The applied method is the CMP (Common Mid Point) method with symmetrical split-spread geometry. At end of lines asymmetric shooting was applied. 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 KSZ, it was reduced to 25 m. Two source types were applied, i.e., Vibroseis and explosion seismic. 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 6 s linear upsweep with a frequency band of 30-165 Hz, and the listening time was 12 s. The final correlated signal length was 18 s. The number of sweeps/source point was six. The sweeps were stacked and the stacked data were saved.

In the explosion line dynamite was used as a detonation source, with a typical shot size of 125 or 250 g of dynamite. Shot holes were drilled in the Quaternary soil to a depth of 2.5 m, and cased with a plastic tube. Before shooting the holes were filled with water to maximize the transmission of seismic energy to the ground.

Geodetic positioning of the lines was done during the drilling stage 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 Table 1 (Zamoshnyaya, 2008).
### Table 1. Survey parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Vibroseis</th>
<th>Explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording</td>
<td>I/O-4</td>
<td>I/O-4</td>
</tr>
<tr>
<td>Number of active channels</td>
<td>402</td>
<td>402</td>
</tr>
<tr>
<td>Sampling interval, ms</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Record length after correlation, s</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Preliminary gain, dB</td>
<td>24±36</td>
<td>24±48</td>
</tr>
<tr>
<td>Notch filter, Hz</td>
<td>off</td>
<td>on</td>
</tr>
<tr>
<td>Noise suppression editor (BURST+DIVERSITY)</td>
<td>on</td>
<td>on</td>
</tr>
<tr>
<td>High-pass filter, Hz</td>
<td>off</td>
<td>30</td>
</tr>
<tr>
<td>Tape format</td>
<td>SEG-Y</td>
<td>SEG-Y</td>
</tr>
<tr>
<td>Medium type</td>
<td>HARD</td>
<td>HARD</td>
</tr>
<tr>
<td>Acquisition geometry</td>
<td>Symmetrical split spread</td>
<td>Symmetrical split spread</td>
</tr>
<tr>
<td>Stacking fold</td>
<td>varying</td>
<td>varying</td>
</tr>
<tr>
<td>Receiver group spacing, m</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Spacing of source locations, m</td>
<td>25 or 50</td>
<td>50</td>
</tr>
<tr>
<td>Spread length, m</td>
<td>50</td>
<td>5012.5</td>
</tr>
<tr>
<td>Linear geophone grouping</td>
<td>6 geophones on 12.5 m base</td>
<td>6 geoph. at a point or 3 swamp geoph. at a point</td>
</tr>
<tr>
<td>Linear SV-14-150 vibrator grouping</td>
<td>3 on 25 m base</td>
<td></td>
</tr>
<tr>
<td>Sweep frequency limits, Hz</td>
<td>30±165</td>
<td></td>
</tr>
<tr>
<td>Sweep period, s</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Number of vibrations at a source point</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Shot hole number at a source point</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Shot hole depth, m</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Charge weight, g</td>
<td></td>
<td>125 or 250</td>
</tr>
<tr>
<td>Ground force</td>
<td></td>
<td>65%</td>
</tr>
<tr>
<td>Control system and vibrator synchronization control</td>
<td>VIB PRO</td>
<td>Shot PRO</td>
</tr>
</tbody>
</table>
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 2-5 (Zamoshnyaya, 2008).

Post stack processing was made by HY-Seismo starting from the DMO 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 are shown in Fig. 1.

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.

The migrated traces are functions of traveltime and before plotting they have to be converted to functions of depth. The conversion velocity was calculated from the average interval velocities estimated from the average stacking velocity function. The values of the depth conversion velocity are listed in Table 6. Between the listed values linear interpolation was used. The difference between the stacking velocity of Fig. 1 and the depth conversion function is very small, less than 10 m/s. As one can see in Fig. 1, the variation of the velocities is of the order of 4-5 % and similar error can be expected in depth conversion.
Figure 1. The average velocity (black line) and measured stacking velocities (colored dots). The color of the dot indicates the lines E1 and V3-V5. The vertical axis is the velocity in m/s and the horizontal axis is the two-way traveltime in milliseconds.
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>2D geometry application</td>
</tr>
<tr>
<td>2.</td>
<td>Band-pass filtering 30-40-140-165 Hz</td>
</tr>
<tr>
<td>3.</td>
<td>Spherical divergence compensation</td>
</tr>
<tr>
<td>4.</td>
<td>Amplitude equalization, window 300-5000 ms</td>
</tr>
<tr>
<td>5.</td>
<td>Spiking deconvolution: noise 0.1 %, OL 80 ms, w 200-2500 ms</td>
</tr>
<tr>
<td>6.</td>
<td>Band-pass filtering 30-40-140-165 Hz</td>
</tr>
<tr>
<td>7.</td>
<td>Amplitude equalization, window 0-5000 ms</td>
</tr>
<tr>
<td>8.</td>
<td>Trace editing</td>
</tr>
<tr>
<td>9.</td>
<td>Datum statics correction</td>
</tr>
<tr>
<td>10.</td>
<td>1st moveout correction, surgical mute</td>
</tr>
<tr>
<td>11.</td>
<td>FK-filtering on seismograms with moveout corrections</td>
</tr>
<tr>
<td>12.</td>
<td>Automatic statics correction: calculation window 200-2900 ms, maximum allowable shift 6 ms</td>
</tr>
<tr>
<td>13.</td>
<td>2nd moveout correction, surgical mute</td>
</tr>
<tr>
<td>14.</td>
<td>Stacking</td>
</tr>
<tr>
<td>15.</td>
<td>Amplitude equalization, window 0-6000 ms</td>
</tr>
<tr>
<td>16.</td>
<td>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</td>
</tr>
<tr>
<td>17.</td>
<td>Noise space filter</td>
</tr>
<tr>
<td>18.</td>
<td>Coherence filter</td>
</tr>
<tr>
<td>19.</td>
<td>Automatic gain control: 0-800, 600-2500, 2200-4500, 4000-5500, 5000-6000 ms</td>
</tr>
</tbody>
</table>
Table 3. On-site processing of explosion data.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2D geometry application</td>
</tr>
<tr>
<td>2</td>
<td>Band-pass filtering 30-40-200-260 Hz</td>
</tr>
<tr>
<td>3</td>
<td>Spherical divergence compensation</td>
</tr>
<tr>
<td>4</td>
<td>Amplitude equalization, window 300-5000 ms</td>
</tr>
<tr>
<td>5</td>
<td>Predictive deconvolution: noise 0.1 %, OL 100 ms, prediction distance 10 ms, windows 0-2000, 1800-4000 ms</td>
</tr>
<tr>
<td>6</td>
<td>Band-pass filtering 30-40-200-260 Hz</td>
</tr>
<tr>
<td>7</td>
<td>Amplitude equalization, window 0-5000 ms</td>
</tr>
<tr>
<td>8</td>
<td>Trace editing</td>
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<td>2nd moveout correction, surgical mute</td>
</tr>
<tr>
<td>14</td>
<td>Stacking</td>
</tr>
<tr>
<td>15</td>
<td>Amplitude equalization, window 0-6000 ms</td>
</tr>
<tr>
<td>16</td>
<td>Time-variant band-pass filtering: 40-50-120-220 Hz, 35-45-115-215 Hz, 30-40-110-210 Hz in windows 0-700 ms, 500-2400 ms, 2200-6000 ms correspondingly</td>
</tr>
<tr>
<td>17</td>
<td>Noise space filter</td>
</tr>
<tr>
<td>18</td>
<td>Coherence filter</td>
</tr>
<tr>
<td>19</td>
<td>Automatic gain control: 0-800, 600-2500, 2200-4500, 4000-5500, 5000-6000 ms</td>
</tr>
</tbody>
</table>
Table 4a. Basic processing of vibroseis data.

Processing flow of vibroseis data

Description and check of the acquisition geometry

<table>
<thead>
<tr>
<th>Band-pass filtering</th>
</tr>
</thead>
<tbody>
<tr>
<td>30, 40, 140, 165 Hz</td>
</tr>
</tbody>
</table>

Geometrical spreading correction

<table>
<thead>
<tr>
<th>Time, ms:</th>
<th>0 6000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity, m/s:</td>
<td>5300 6500</td>
</tr>
</tbody>
</table>

Trace-by-trace normalization

| 0 m: | 35-450, 450-900, 900-2500, 2500-6000 ms |
| 2500 m: | 580-700, 700-950, 950-2530, 2530-6000 ms |

Deconvolution test

| W, WF, OL |

Space-and time-variant zero-phase spiking deconvolution

| operator length (OL), ms: | 80 |
| white noise percentage (WF), k: | 0.1 |
| shot-to-geophone distance, m: | 0 |
| time windows for designing deconvolution operator (W), ms: | 45-1300, 1000-3500 |
| shot-to-geophone distance, m: | 2500 |
| time windows for designing deconvolution operator (W), ms: | 500-1400, 1100-3550 |

Band-pass filtering

| 30, 40, 140, 165 Hz |

Air-wave attenuation

| Attenuation window length, ms: | 600 |
| Velocity, m/s: | 330, 340, 360 |

Coherent noise attenuation

frequency-wavenumber (f-k) filtering
Table 4b. Basic processing of vibroseis data (cont.).

Trace-by-trace normalization
0 m: 35-450, 450-900, 900-2500, 2500-6000 ms
2500 m: 580-700, 700-950, 950-2530, 2530-6000 ms

Datum statics correction

Velocity analysis → Brute stack → Plotting

2-3 iterations

Residual statics correction
- autostatic time window, ms: 0-1500
- maximum allowable statics, ms: 6
- number of traces to form a pilot trace (base): 7-11

Stacking velocity correction

Final stack

Band-pass filtering
0-1500 ms: 35,45,140,165 Hz
1000-6000 ms: 30,40,135,160 Hz

Stolt f-k migration
Velocity 5000 m/s

Band-pass filtering
0-500 ms: 45,55,120,165 Hz
400-1200 ms: 40,50,115,160 Hz
900-3500 ms: 35,45,110,155 Hz
3000-6000 ms: 30,40,105,150 Hz

Plotting

DMO ensemble within the-space-time (T-X) domain

Control stack → Plotting

Stacking velocity correction

Residual statics correction
- autostatic time window, ms: 0-1500
- maximum allowable statics, ms: 6
- number of traces to form a pilot trace (base): 7-11

Stacking velocity correction

Plotting
Table 4c. Basic processing of vibroseis data (cont).

Final DMO stack

Band-pass filtering
- 0-1500 ms: 35,45,140,165 Hz
- 1000-6000 ms: 30,40,135,160 Hz

Stolt f-k migration
- Velocity 5000 m/s

Band-pass filtering
- 0-500 ms: 45,55,120,165 Hz
- 400-1200 ms: 40,50,115,160 Hz
- 900-3500 ms: 35,45,110,155 Hz
- 3000-6000 ms: 30,40,105,150 Hz

Time-variant scaling
- 0-1000, 800-2500, 2000-4000 ms

Plotting
Table 5a. Basic processing of explosion data.

Processing flow of dynamite data

Description and check of the acquisition geometry

Band-pass filtering
30, 40, 200, 260 Hz

Geometrical spreading correction
Time, ms: 0   6000
Velocity, m/s: 5300   8500

Trace-by-trace normalization
0 m: 20-90, 90-250, 200-700, 600-2400, 2200-4400, 4300-6000 ms
2500 m: 430-460, 460-570, 530-780, 700-2500, 2350-4500, 4350-6000 ms

Deconvolution test
(deconvolution type; WF, W; OL; DL-Pred)

Space-and time-variant minimum phase predictive deconvolution
- operator length (OL), ms: 100
- operator prediction distance (DL-Pred), ms: 5
- white noise percentage (WF), k: 1
- shot-to-geophone distance, m: 0
- time windows for designing deconvolution operator (W), ms: 0-1300, 1000-3500
- shot-to-geophone distance, m: 2500
- time windows for designing deconvolution operator (W), ms: 490-1370, 1050-3550

Band-pass filtering
30, 40, 200, 260 Hz

Air-wave attenuation
Attenuation window width, ms: 600; 100
Velocity, m/s: 315, 320, 340, 360; 2035

Coherent noise attenuation
frequency-wavenumber (f-k) filtering
Table 5b. Basic processing of explosion data (cont.).

- Trace-by-trace normalization
  - 0 m: 20-90, 90-250, 200-700, 600-2400, 2200-4400, 4300-6000 ms
  - 2500 m: 430-480, 480-570, 570-780, 700-2500, 2350-4500, 4350-6000 ms

- Datum statics correction

- Velocity analysis → Brute stack → Plotting

- 2-3 iterations

- Residual statics correction
  - Autostatics time window, ms: 0-1500
  - Maximum allowable statics, ms: 6
  - Number of traces to form a pilot trace (base): 7-11

- Stacking velocity correction

- Control stack → Plotting

- Final stack

- Band-pass filtering
  - 30, 40, 200, 260 Hz

- Stolt f-k migration
  - Velocity 5000 m/s

- Band-pass filtering
  - 0-500 ms: 40, 50, 120, 220 Hz
  - 400-1200 ms: 35, 45, 115, 215 Hz
  - 900-3500 ms: 30, 40, 110, 210 Hz
  - 3000-6000 ms: 30, 40, 105, 205 Hz

- Time-variant scaling
  - 0-1000, 800-2500, 2000-4000 ms

- Plotting

- DMO ensemble within the time-space (T-X) domain

- Control stack → Plotting

- Stacking velocity correction

- Residual statics correction
  - Autostatics window, ms: 0-1500
  - Maximum allowable statics, ms: 6
  - Number of traces to form a pilot trace (base): 7-11

- Stacking velocity correction

- Plotting
Table 5c. Basic processing of explosion data (cont.).

1. Final DMO stack
2. Band-pass filtering
   30, 40, 200, 260 Hz
3. Stolt f-k migration
   Velocity 5000 m/s
4. Band-pass filtering
   0-500 ms: 40,50,120,220 Hz
   400-1200 ms: 35,45,115,215 Hz
   900-3500 ms: 30,40,110,210 Hz
   3000-6000 ms: 30,40,105,205 Hz
5. Time-variant scaling
   0-1000, 800-2500, 2000-4000 ms
6. Plotting
### Table 6. Steps of post-stack processing.

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<td>Plotting</td>
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5. Results

5.1. 2D and 3D presentation of the results

The location of the survey lines is shown in Fig. 3 and Appendices 1-4. The map 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.

![Figure 2](image_url)

*Figure 2.* relations between true and apparent dip angles of planar reflectors. The curve parameter is angle between the survey line and the strike of the reflector at surface.
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. 2. As can be seen in the figure, subvertical structures surveyed at small strike angles are represented by apparent dip angles significantly smaller than the true dip.

Datum level of the reflection data is 250 m a.s.l. (for the additional FIRE 4A data 120 m). 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. 4 and 5. In vibrator 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 up to 350 Hz. This predicts high resolution in the final images.

The processed sections show a wealth of reflectors. Reflectors as thin as 10 m vertically and 100-200 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. 6-11 and in the appendices. The sections were converted from time sections to depth sections using the velocity function in Table 3. 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.

To obtain three-dimensional visualization of the reflector structures, the seismic sections were input 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. The lithological 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 lithological units is presented with the 3D strings.
Only selected examples of the 3D images can be shown here (e.g. Figs. 16, 18-19). In addition to seismic reflection images, the available maps on bedrock geology and geophysics were also applied to provide a means to correlate reflectors with other bedrock properties. These correlations were used in the interpretations below.

5.2. Reflective properties of the uppermost crust in the Suurikuusikko area

The general characteristic feature of the Suurikuusikko seismic sections are the strong semi-continuous reflectors with relatively modest dip angles. The thicknesses of the reflectors and dense groupings of reflectors range from a few tens of metres to 2 km.

The geological map of the study area is characterized by (1) mafic tholeiitic lavas, (2) mafic graphitic tuff and tuffite and (3) intermediate granodioritic igneous rocks (Fig. 3). When correlated with surface geology, the strong reflectors coincide with areas of mafic graphitic tuff and tuffite. On the other hand, mafic lavas (tholeites on the geological map) and granitoids show much less reflectivity. Here we must keep in mind, that the study area is very poorly exposed, and the geological map is based mostly on airborne geophysics and drilling, and may inevitably include some uncertainty in the rock types and their boundaries. It should be noted that under the lithological group name ‘mafic graphitic tuffs and tuffitic rocks’ also iron formations of the Porkonen type, i.e., Fe-sulphide and graphite rich metasediments, are present too. Therefore, this lithological group is actually a relatively heterogeneous compilation of rocks.

Further supportive information was obtained using the reflection seismic data of the FIRE project (Kukkonen et al., 2006; Patison et al.; 2006). The crustal scale reflection line FIRE 4A runs on the Sirkka-Pokka road connecting with the Suurikuusikko HIRE lines V1 and V2 at their northern ends. The strong subhorizontal reflectors correlated with mafic graphitic tuffitic rocks on V1 and V2 are well-seen also on FIRE 4A at 1.5-5 km depth (Fig. 12). These reflectors were interpreted as belonging to the CLGB rocks by Patison et al. (2006) and they should outcrop in the Pokka area. Granitoids of the Hetta Suite are seen as transparent, non-reflective layers both on FIRE 4A and on the northern part of V2.

Since the HIRE survey lines are connected and form together a continuous network, a preliminary 3D correlation of the reflectors was possible. This was done with the aid of the SURPAC images. In the southern part of the survey area on line V5, the main reflective layers, i.e., the mafic graphitic tuff and tuffite seem to form a synform structure (CMP 3000-3900; Fig. 10). The seismic data allows connecting these rocks from the Kiistala area to Lintula. They outcrop on the western end of V5 and run parallel to V1 as far as the Sirkka-Pokka road and FIRE 4A. On V1 the upper contact of the mafic graphitic tuffs and tuffitic rocks is seen undulating at the depths of about 1-2 km, and locally reaching the surface (Fig. 6a,b). This boundary is dipping to the east at about 30-40°.
On the eastern side of the study area, on line V2, the mafic graphitic tuffitic rocks are partly on the surface, and partly under a thin layer of tholeite (between V3 and E1; Figs. 7a,b). In the northern part of V2, upper contact of the graphitic tuffitic rocks is about 500 m depth.
Figure 3. Survey lines in Suurikuusikko. Numbers along the lines indicate receiver station pole numbers (italics) and CMP coordinates (normal text).
Figure 4. Frequency spectra of the vibrator field data from V4 with two offsets from the shot point. Upper panels: offset 150-200 m, lower panels: offset 1950-2050 m. Shot point location (CMP 3086) is on the eastern side of the KSZ (Zamoshnyaya, 2008).
Figure 5. 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 2648) is on the eastern side of the KSZ (Zamoshnyaya, 2008).
Figure 6a. Migrated NMO section of line V1 (northern part). Reflectors with high amplitude are automatically enhanced with red colour. Geological boundaries at the surface are from the geological database of GTK (1:200 000 scale bedrock geology). Interpreted lithological boundaries are shown with black lines.
Figure 6b. Migrated NMO section of line V1 (southern part). Data representation and geological boundaries as in Fig. 6a.
Figure 7a. Migrated NMO section of line V2 (northern part). Data representation and geological boundaries as in Fig. 6a.
**Figure 7b.** Migrated NMO section of line V2 (southern part). Data representation and geological boundaries as in Fig. 6a.
Figure 8. Migrated NMO section of line V3. Data representation and geological boundaries as in Fig. 6a.
Figure 9. Migrated NMO section of line V4. Data representation and geological boundaries as in Fig. 6a. For details on Kiistala Shear Zone, see Figs. 15-18 and text.
Figure 10. Migrated NMO section of line V5. Data representation and geological boundaries as in Fig. 6a.
Figure 11. Migrated NMO section of line E1. Data representation and geological boundaries as in Fig. 6a. For details on Kiistala Shear Zone, see Figs. 15-18 and text.
Figure. 12. Migrated NMO section of the uppermost 5 km of crust on the FIRE 4A transect connecting with the HIRE lines V1 and V2 (Kukkonen et al., 2006). Datum of the section is 120 m a.s.l. Data representation and geological boundaries as in Fig. 6a.
5.3. Reflection properties of the Kiistala Shear Zone

The Kiistala Shear Zone was crossed in the mining area on line V4 and about 3 km to the N from the mining area on the explosion line E1. According to drilling, the KSZ is either vertical or subvertical shear zone and at the surface the zone of most intense shearing is not thicker than 60 m. Due to properties of the seismic reflection method, such steep structures are not easy targets. However, subvertical faults and shear zones often reveal themselves as discontinuities disturbing otherwise more horizontally or subhorizontally oriented reflectors. Sometimes, the oblique angle between strike and survey line may make the subvertical reflectors detectable due to decrease of the apparent dip angle (Fig. 1). Lines V4 and E1, however, cross the KSZ more or less perpendicularly.

On line V4, steeply dipping fault-like structures are seen at the location of the KSZ. It is plausible that these seismic structures actually represent the KSZ (Figs. 9 and 15). The horizontal reflectivity at KSZ in the uppermost 300 may be due to fracturing, which would explain the apparent disagreement with subvertical structures encountered in drilling.

On line E1, the steeply dipping structures are less obvious than on V4 at the location of the KSZ, but such ‘lineaments’ can be interpreted. On the other hand, the E1 data suggest that the contact between mafic lavas and mafic graphitic tuffites is dipping to the east at an angle of about 40º (Fig. 10). The structure on V4 is somewhat similar to E1 with relatively strong reflectors dipping at an intermediate angle to the east at about 1000 m depth beneath the KSZ. The correlation of the KSZ with drilling data and surface geophysics is discussed in more detail below.

Where the seismic profiles run across the KSZ structures (V4, E1, V3), the general observation is that there is a low-angle (30-40º) east dipping reflector located beneath the subvertical KSZ structures. On V4 this structure is met with at about 1 km depth level beneath the KSZ (Fig. 9), whereas on E1 the reflector is practically on the surface at KSZ (Fig. 11). On V3, the upper contact of the same reflector system is at about 700-1000 m at the location of the KSZ (Fig. 8). The reflector is interpreted as the uppermost part of the mafic graphitic tuffs and tuffitic rocks below mafic lavas. It may have had a role in controlling the gold mineralisation along KSZ.

5.4. Drill hole logs and synthetic seismograms on the Kiistala Shear Zone

Down-hole density (gamma-gamma) and P-velocity (full wave sonic) logs measured by Astrock Oy were provided for our use by the Client. The data is from two deep drill holes, SUU08001B and ROU08001, located on the Kiistala Shear Zone. The holes are located on southern and northern sides of the profile V4 at the distance of 300 and 100 m from the line, respectively. Hole SUU08001B has been drilled from the eastern side of the KSZ. Judging from the sections and SURPAC images (Figs. 15 and 16), the hole should
cross the KSZ structure in its deeper parts. The hole ROU08001 has been drilled from the western side, and it also seems to cross the KSZ. Both holes have dip angles of about 65-70°. In hole ROU08001 the data is affected by a steel casing at 430-500 m. The applied geological core logs of the holes as well as magnetic susceptibilities of core samples from SUU08001B measured at 1 m intervals were provided by the Client.

The seismic impedance (i.e., product of velocity and density) was calculated from the depth matched density and velocity logs. The impedance curve was convolved into a synthetic seismogram, which can be directly compared with the traces of the measured seismic section. Results are shown in Figs. 13 and 14 and in the appendices. The projections of holes on the seismic section V4 are shown in Figs. 15 and 16.

The two holes have remarkably different appearances in the log data. ROU08001 represents mafic massive and pillow lavas. Density and velocity values increase downward in the uppermost 300 m. Locally there are sharp density and velocity minima (e.g. at 245, 580, 764, and 808 m; Fig. 13). We attribute them to fracturing and shear zones at 245, and 808 m, where core losses of 25 and 15 % have been reported, and at 580 m pyrite veining is present (N. Patison, written comm., 2009). The velocity and density minima may also be related to volcanoclastic layers within the massive and pillow lava layers.

The main lithologies of the SUU08001B hole are mafic lavas, but there are frequent layers of volcanoclastic rocks and banded iron formations (BIF) within the lava units (Fig. 14). The acoustic properties of these layers, and particularly, the BIF differ from the hosting mafic lavas. The BIF layers are about 2-10 m thick. They generate strong and sharp density maxima and velocity minima. The mineral composition of the BIF is dominated by iron sulphides (~90%) with minor graphite (<10%). Normal pyrite is not able to generate the density highs and velocity lows. Pyrrhotite, on the other hand, has high density but relatively low P-velocity in comparison to other sulphide minerals (Salisbury et al., 2003), and thus, massive or semi-massive pyrrhotite would be able to generate these anomalies. The core susceptibility data indicates that the BIF layers are not magnetic. Since the presence of pyrrhotite in the BIF is confirmed (N. Patison, written communication, 2009), pyrrhotite must represent the antiferromagnetic hexagonal variety of the mineral.

Although the density highs and velocity lows tend to cancel out each other in the calculated impedance (e.g., at 595 or 800 m; Fig. 14), the BIF layers seem to cast reflections in the synthetic seismogram. These reflections seem to be stronger where the BIF is together with much thicker volcanoclastic rocks (e.g. at 803-827 m) whose densities and velocities are lower than mafic lavas.

Outside BIF layers, there are also sharp velocity and density minima in the mafic lavas, which we attribute to fracturing and shearing as in the hole ROU08001.

The hole data in this study is quite limited and its relevance should therefore not be overemphasized. However, the results indicate that the mafic lavas are probably
relatively poor in reflectivity, whereas layers of volcanoclastic materials and BIF may generate strong reflections. The volcanic-sedimentary suite can be expected to be heterogeneous and the layering is not necessarily very continuous due to the original conditions of geological deposition and later deformation-induced changes. These results are in agreement with the general regional correlation of reflectors and surface geology discussed above.

The hole ROU08001 is only at the distance of about 100 m to the N from V4, whereas SUU80001B is as far as about 300 m to the S. When the borehole data is compared with the seismic section of line V4, the ROU08001 should be given more weight. The synthetic seismogram of ROU08001 is in a good agreement with the V4 seismic section, and strong reflectivity at about 150-300 m as well as at about 670-820 m below surface in both data sets (Fig. 15 and 16).

Figure 13. Drill hole logs of susceptibility, density and P-velocity, together with calculated seismic impedance and synthetic seismogram of drill hole ROU08001.
5.5. Correlation of seismic data, ground geophysics and geological profile data along the Kiistala Shear Zone

To provide a more detailed correlation of the KSZ, seismic data and other geophysical data we added the ground geophysical magnetic and horizontal loop EM (slingram) maps of Salmirinne and Turunen (2006) to the SURPAC materials. The ground geophysical data (measured at the station interval of 20 m and line spacing of 50 m) provides a more detailed view on the geophysical properties of the KSZ than the common low-altitude airborne maps. In addition the drilling profile by Patison et al. (2007) imaging the KSZ at about X = 7536.3 was also included.

Geophysically the KSZ is observed as a negative anomaly in magnetic maps, and due to pyrite and graphite as a low in resistivity maps (Salmirinne and Turunen, 2007; Patison et al., 2007). Shearing and low-temperature alteration have destroyed the original magnetic minerals (magnetite and/or pyrrhotite).

Figure 14. Drill hole logs of density and P-velocity together with drill core magnetic susceptibility, and calculated seismic impedance and synthetic seismogram of drill hole SUU08001B.
The lithologies in the KSZ are mafic lava dominated on the western side of the zone but grade towards intermediate and felsic compositions close to the KSZ and in the ore zone. On the eastern side of KSZ lithologies are more sediment-rich, and contain BIF, argillitic material and gradually become more mafic and ultramafic away from the zone. The KSZ is vertical at the surface but dips steeply to the west at 200 m level. The zone of intense shearing is about 60 m wide. The zone of altered rocks is wider than the intensely sheared zone and it seems to become a little wider at depth (Fig. 19; Patison et al., 2007).

Figure 15. Detail of the NMO migrated section of line V4 at the Kiistala Shear Zone. Interpreted shear and fault zones are shown in red solid lines, reflector trends in white dashed lines, and projections of drill holes SUU08001B and ROU08001 with black lines. The hole ROU08001 is located about 100 m behind the section and SUU08001B about 300 m in front of the section.
Figure 16. Perspective view of the section V4 crossing the Kiistala Shear Zone. On top the ground magnetic map of Salmirinne and Turunen (2007). Compare with fig 15.

Figure 17. Detail of the NMO migrated section of line E1 at the Kiistala Shear Zone. Interpreted shear and fault zones are shown in red solid lines and reflector trends in white dashed lines.
The contacts of the magnetic minimum of the KSZ correlate with subvertical fault-like discontinuities in the seismic section to a depth of about 900 m. Several subvertical lineaments can be identified in relation to KSZ (Fig. 15). In the uppermost 300 m, the structures seem to form blocks and bodies displaced in relation to the area under the magnetic minimum of the KSZ. The areas to the west and east of the magnetic minimum are more reflective in the uppermost 250 m. This may be due to the strong shearing in the KSZ which has destroyed the subhorizontal reflectivity (presumably due to fracturing) in the neighbouring areas which are also more magnetic.

Trend lines of reflectors suggest that the KSZ is be located on an antiform structure (Figs. 15 and 17). The folds we can distinguish in the reflection sections are gentle open folds, but it does not exclude steepening of the structures in the immediate neighbourhood of the KSZ. Thus the subvertical KSZ structure could represent the axial shear plane of this folding. In a larger scale, this folding could be related to thrusting along the east dipping reflector discussed above in chapter 4.3.

The drilling section (from Patison et al., 2007) included in the SURPAC data is located at a distance of about 1 km to the S from the line V4, and cannot be directly compared with any seismic data. However, the ground magnetic data covers also the area of the drilling profile. Intermediate volcanic rocks and the area of most intense shearing are correlated

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**Figure 18.** Perspective view of the section E1 crossing the Kiistala Shear Zone. On top the airborne magnetic map of GTK. Red dashed line on top indicates the general trend of the Kiistala Shear Zone. Compare with fig 17.
with the magnetic minimum (Fig. 19), whereas the mafic lavas on the western side as well as the more volcanoclastic and sedimentary rich rocks on the eastern side of the sheared zone correlate with magnetic highs. This is in agreement with Patison et al. (2007) and Salmirinne and Turunen (2007).

Figure 19. Correlation of ground magnetic map (Salmirinne and Turunen, 2007) and drilling profile at $x = 7536.3$ (Patison et al., 2007). In the geological section the blue colour indicates altered rocks, whereas the zone of intense shearing mostly follows the pink and brown colours.
6. Discussion

6.1. Regional structures

The general observation on the HIRE Suurikuusikko data is that in the upper crustal scale the reflectors seem to form moderately dipping structures. Three main rock types can be distinguished by correlating seismic data and surface geology, namely, the mafic graphitic tufts and tuffitic rocks (volcanoclastic and sedimentary rocks), tholeites (mafic lavas) and granitoids. The mafic graphitic tuffitic rocks are the best reflectors, whereas mafic lavas and granitoids tend to be more transparent in terms of reflectivity. The geological nature of the reflectors within tuffitic rocks were revealed by the down-hole logs of two deep holes in the mining area. Reflectivity is produced on one hand by layers of volcanoclastic rocks and BIF rocks within mafic lava units, and on the other hand, by fracturing and zones of weakness in the rock. The layers themselves can be relatively thin and located at several tens of metres from each other, but in the seismic imaging, which acts as an efficient low-pass filtering, such formations are seen as thick reflective packages. However, the individual reflective elements can be very thin within broad zones of high reflection amplitude.

6.2. Kiistala Shear Zone

Deposits where Au is related to sulphide dissemination and free gold, such as the deposits mined in the Kittilä mine cannot be directly imaged with reflection seismics. However, seismic reflection sounding can be used a structural tool in revealing the large-scale structural elements related to deposits. In Suurikuusikko, the vertical attitude of the main gold-bearing structure, the Kiistala Shear Zone, further complicates the seismic imaging. Anyhow, the HIRE results did indicate vertical and subvertical discontinuities which correlate with the known KSZ structures.

The KSZ is characterized by considerable mineral alteration which was related to the ore forming processes. The most important alteration processes are albitisation, carbonate alteration and graphitic alteration. The latter includes non-crystalline graphite. Main sulphides in the ore zone are pyrite and arsenopyrite, whereas outside the intense shearing zone pyrrhotite is present. This suggests alteration due to shearing and reactions with the ore-forming fluid in the ore zone, and formation of pyrite at the cost of pyrrhotite destruction. In the less altered lavas outside the KSZ, magnetite is very probably present as a magnetic mineral contributing to the magnetic anomalies.

The reflection image of the profile V4 showed a good correlation with the magnetic and EM anomalies recorded in the ground geophysics (Turunen and Salmirinne, 2007). The accurate location of the known KSZ in ground and airborne geophysics, together with drilling data, made it possible to interpret the seismic response on V4 and correlate it with the KSZ. Seismically, the KSZ seems to consist of vertical and subvertical shears...
and faults which extend to a depth of about 1000 m, possibly deeper. At surface the zone of intense shearing correlates with a poorly reflective area and a magnetic minimum.

The apparent discrepancy between the mostly horizontal reflectors at the KSZ and its immediate vicinity, and the subvertical lithologies revealed by drilling, can be understood by the properties of the seismic method. Due to the applied source-receiver geometry, the method always prefers subhorizontal and low-angle structures to vertical structures. In a sheared zone, such as the KSZ, the intense fracturing and shearing generate vertical velocity gradients which are able to generate reflections. As a result, the image is dominated by the structurally controlled subhorizontal reflectivity, and true vertical structures can be observed only as discontinuities of the other reflectors.

6.3. Seismic responses of the Au mineralisations in the Iso-Kuotko area

We compared the available data on the gold prospects in the Iso-Kuotko area with the HIRE sections. Härkönen et al. (2000) and Salmirinne and Turunen (2007) provide some basic information on the different gold ore lodes in Iso-Kuotko. The known prospects are related to steeply-moderately dipping quartz-carbonate vein systems.

We note the following possible correlations with the seismic data. The Kati lode, which is located to the N from V3 at about X=7550, Y=2559, has a NW-SE strike and the veins dip of about 40-50º NE. If projected along strike to V3, any corresponding structures should be met with at about CMP 2350. On the V3 section there are weak reflectors which reach the surface at about CMP 2370 and have an apparent dip angle of about 30 degrees to E. The angle between the lode strike and V3 is about 45º. Assuming a true dip of 40-50º would require an apparent dip of 28-32º, which agrees with the V3 section (Figs. 2 and 8).

The Tiira lode is located at about x=7549.3, Y=2650. It has a NE-SW strike and subvertical dip, and it is located immediately to the SW of line V2. Its approximate projection on line V2 is at about CMP 5800, and on V3 at about CMP 2420. Since the dip direction is not known, the correlation with seismic data remains open. However, on V2 at the lode projection place there is reflectivity dipping apparently to SE with a dip of about 20º, but also subvertical discontinuities can be interpreted. On V3 there is relatively prominent reflectivity dipping to E with an apparent dip of about 30º, which is also a potential seismic expression of the lode. These results are of course speculative, but they suggest that we may actually have recorded projections of the mineralised veins of the Kati and Tiira lodes.

6.4. Seismic reflection response of the Suasselkä postglacial fault

We pay attention to a very young tectonic structure in the Iso-Kuotko area. There is a well-known postglacial fault running about 50 km from the Rautuskylä village area to the Iso-Kuotko area and finally ending a few kilometres SW from the Pokka village (Kujansuu 1964, Kuivamäki et al., 1998). The fault is a thrust with a surface step of about
4-5 m. The dip is about 40-50° SE. The age of the fault is younger than the last deglaciation (~9500-9000 years). The fault is located in the northern part of the HIRE Suurikuusikko area and it was crossed by lines V1, V2 and V3. The CMP addresses of the Suasselkä fault are CMP 4630 on V1, CMP 5840 on V2 and CMP 2555 on V3. For comparison, we included also the surface projection of the Suasselkä fault in the SURPAC materials. The postglacial fault seems to be running very close to the surface projection of the Tiira lode. In the upper crustal scale, the fault is located on the hanging wall side of the contact between mafic lavas and graphitic tuffitic rocks. Although the postglacial fault has probably nothing to do with gold deposits, it is an indication of an active tectonic zone. Indirectly, it may indicate zones which probably have been reactivated several times during geological history, and which have been active fluid flow pathways in the past.

6.5. Suggestions for further exploration

The sub-vertical Kiistala Shear Zone hosts several economic deposits and prospects, and will surely remain as the most promising exploration target of the area in the future. The present data allows suggesting new areas for exploration as well. The most straightforward principle is to look for analogues for the KSZ. The present HIRE seismic data indicates that the KSZ is located above an east dipping reflector system, interpreted to represent mafic graphitic tuffs and tuffitic rocks beneath mafic lavas. The shear zone itself seems to be on the axial plane of open antiform folds. This folding may have resulted from thrusting along the east-dipping reflector system. It is difficult to judge from the seismic data how deep the KSZ actually extends. In some cases it may end within the east-dipping reflector, in other cases it may penetrate it.

We pay attention to the apparent relation between the volcanoclastic rocks present in strong reflector systems and the gold bearing structures present in the KSZ sub-vertical structure. The combination of such structures may be potential for new discoveries, and may reflect the change of chemical and physical conditions which deposited the gold from upward migrating metamorphic fluids, perhaps in an interaction between deep fluid and meteoric fluids. The graphite bearing volcanoclastic and sedimentary rocks may have provided the change in conditions required for deposition of gold from fluids migrating by. Alternatively, they may represent the fluid pathways, although they are commonly considered not as a gold-bearing environment.

Combining the seismic data with airborne magnetic and EM maps, three potential structures and types of structures can be suggested. The surface locations of the suggested structures are included as SURPAC string files in the digital data files of the report.

1) Kapsajoki magnetic minimum. This 25 km long structure is running approximately parallel to the line V1 about 1-3 km to the W of the line with a general N-S strike. The minimum is also following an electrically conductive zone along its eastern margin. Extrapolating the seismic data to this area would suggest that the structure may be analogous to the KSZ. The strong reflectors interpreted
Figure 20. Suggested structures which may be potential for further gold exploration in the Suurikuusikko area. KSZ: Kiistala Shear Zone; Suasselkä PGF: Suaselkä postglacial fault, Kapsajoki magmin: Kapsajoki magnetic minimum. Base map: Airborne magnetic map of GTK. See text for details.

as mafic graphitic tuffs and tuffitic rocks on line V1, whose upper contact is about 0.5-1.5 km depth, are very probably outcropping in the area of the conductive zone. This supported by the geological map. The magnetic minimum possibly represents the steeply dipping zone of sheared and altered rocks. The southern end of the magnetic minimum is imaged on line V5 at CMP 3700-3800 in Lintula, where subvertical fault-like structures seem to cross the low-angle reflector at 250-500 m depth.
2) **Possible eastern branch of the KSZ.** There is a magnetic minimum which deviates from the KSZ at about $x = 7540$ with a SSE-S strike. The magnetic minimum runs about 12 km and ends at about $x = 7529$. EM maps show that the structure is partly running at the western margin of a conductive zone. At the place of the magnetic minimum, there is a fault-like structure on V2 (CMP 3260), which extends to about 500 m depth. The apparent dip is about 35º. Taking into account the strike angle of the magnetic anomaly with line V2, we obtain the true dip of about 55 º E for the structure. (This structure is so close to the mining area, that it is probably well studied already).

3) **Possible western branch of the KSZ.** This is a magnetic low, and not conductive either. The structure deviates from the KSZ at about $x = 7545$ with a SSW-NNE strike and joins the Kapsajoki magnetic minimum at about $x = 7540$. The structure is crossed by the line V1, where the structure is located at about CMP 3400. The angle between strike of the magnetic low and the survey line is only about 20 º. In the seismic data there are candidates dipping apparently 30 - 40º in both directions. The corresponding true dip angles would be very steep.

4) **Suasselkä postglacial fault.** This structure and its seismic responses were discussed already above. Since the fault indicates structures which were tectonically active in the past (and probably presently too), and the structure is spatially related to the northern part of the KSZ and the gold lodes known in the Iso-Kuotko area, it is considered here worth of consideration. The fault seems to be related on the same moderately east dipping reflector system interpreted as volcanoclastic and BIF rocks, and which is encountered below the subvertical KSZ. Therefore, the fault may be an indirect hint of gold bearing areas. In the W and SW the Suasselkä fault continues well beyond the limit of the present study area. Similarly in the NE the fault can be followed almost to the Pokka village.

### 7. Conclusions

The HIRE seismic reflection survey provided a very detailed image of seismic reflectivity of the Suurikuusikko gold mining area and its surroundings, and distinct new data on the deep structure were obtained. Numerous previously unknown structures were discovered.

The results show a detailed structure of the uppermost 5 km of crust. The upper crustal reflectors are generally moderately dipping or subhorizontal, and correlation with surface geology and geophysics indicates that the strongest reflectivity is due to mafic tuffs and tuffitic rocks (volcanoclastic and sedimentary material), whereas tholeites (mafic lavas) and granitoids are less reflective. The mafic tuffitic rocks can be followed and correlated over the complete area of study.

The subvertical Kiistala Shear Zone, which is the main structure bearing gold deposits in the Suurikuusikko area, was imaged as discontinuities of more horizontally oriented
reflectors on a line (V4) which is running through the active mining area of the Kittilä mine. On another line about 3 km to the north (E1), also crossing the KSZ, subvertical structures are less evident but present. Trend lines of reflectors suggest that there are open antiform folds under the KSZ, which is located on approximately on the axial plane of these folds. Furthermore, the seismic data indicate that the antiform folds and KSZ are on the hanging wall side of an east dipping reflector (30-40⁰) which is interpreted to represent a contact zone between mafic graphitic tuffitic rocks (lower unit) and mafic lavas (upper unit). The KSZ may have developed as a part of thrusting along the east-dipping reflector and folding on the hanging wall side of it.

Drill hole data on density and acoustic properties of two deep drill holes in the KSZ (SUU08001b and ROU08001) and synthetic seismograms calculated from these suggest that strong reflectivity is due to layers of volcanoclastic rocks and iron sulphide-rich banded iron formations within more homogeneous lava units. Reflectivity is also produced by fracturing and other zones of weakness.

Gold prospects hosted in quartz-carbonate veins in the Iso-Kuotko area in the northern part of the study area seem to correlate with reflectivity when projected on the corresponding seismic sections. Furthermore, the postglacial Suasselkä fault is also imaged as a weak reflector on top of a SE dipping reflective contact between mafic graphitic tuffs and mafic lavas. The postglacial fault seems to follow the NE oriented section of the KSZ in its northern part as well as the strike of one the gold lodes in the Iso-Kuotko area (the Tiira lode).

The data was applied for indicating potential sites for further exploration and for locating analogue sites of the Suurikuusikko deposits.
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