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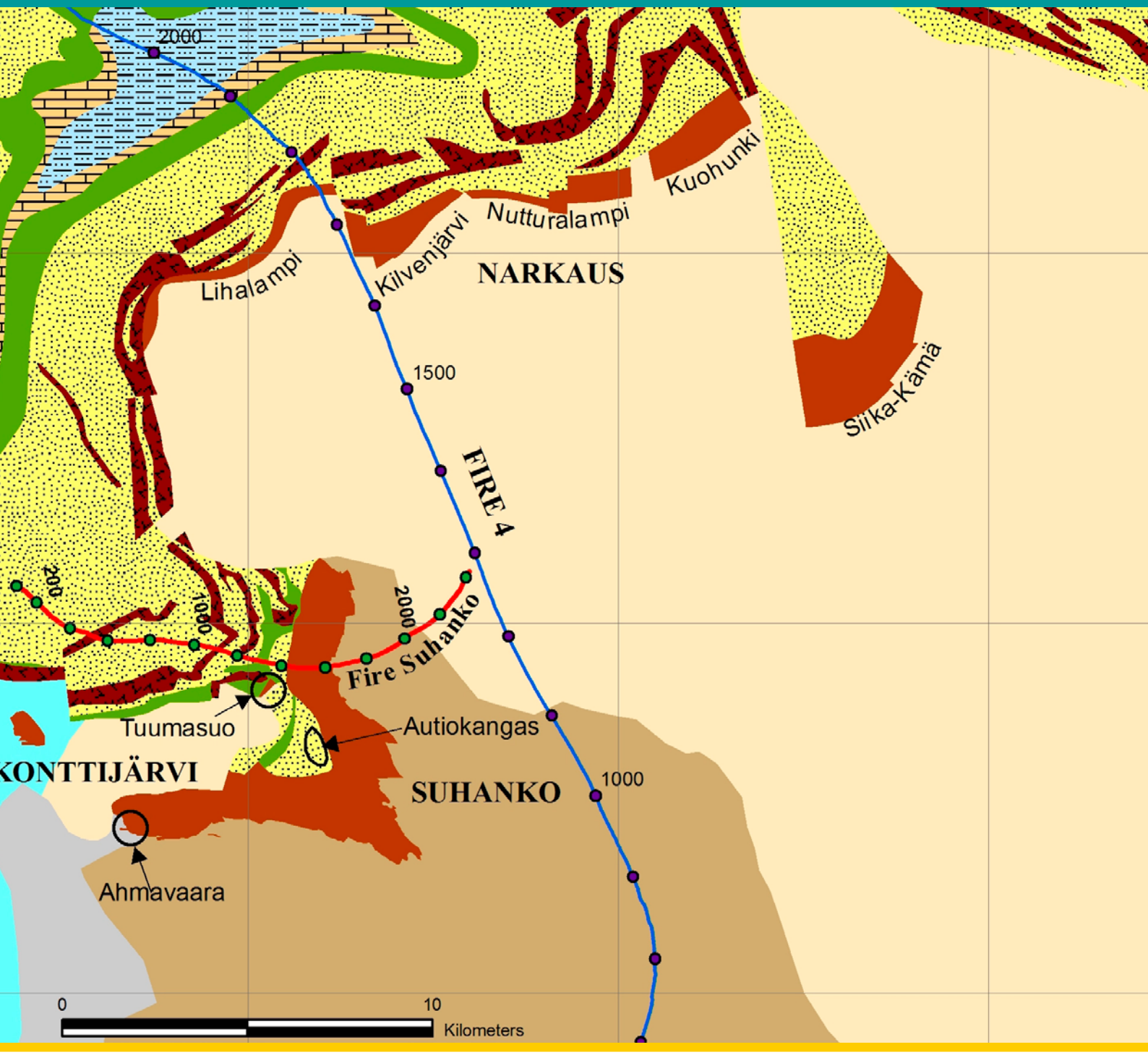

Suhanko seismic reflection profile and integrated geological-geophysical model of the Portimo area

Markku Iljina and Heikki Salmirinne

GEOLOGIAN TUTKIMUSKESKUS **GEOLOGICAL SURVEY OF FINLAND**

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In 2003, about 14 km of common midpoint (CMP) seismic reflection data were recorded on the Suhanko high resolution test line in northern Finland. The line cross-cuts the Archaean basement complex, the Palaeoproterozoic Suhanko Layered Intrusion and the overlying Peräpohja Schist Belt, including mafic sills intruding the Belt. The main aim of the seismic measurements was to investigate the structure of the economic minerals enriched in the Suhanko Intrusion and also to indicate new potential targets for exploration. Another aim was to study the general suitability of seismic reflection imaging for mineral exploration in Precambrian crystalline bedrock.

The first interpretation of the Suhanko seismic measurement line is presented in this paper. The principal observation was the conspicuously clear separation of the Archaean basement complex and the Proterozoic lithologies due to their differing acoustic properties. Within the Proterozoic, sills intruding the Peräpohja Schist Belt were identifiable. The 2.7 Ga Ranua diorite intruding the older gneiss showed up less prominently.

Interpretations of seismic measurements are in agreement with earlier gravimetric and geological studies. The seismic measurement results also suggest new targets for further exploration of the contact type Cu-Ni-PGE mineralization at the basal contact of the Suhanko Intrusion, which can be followed 2.7 km down-dip underneath the Peräpohja Schist Belt but still remaining within a viable drillable/mineable depth of 620 m.

Keywords (GeoRef Thesaurus, AGI): layered intrusions, seismic methods, deep seismic sounding, reflection methods, FIRE, gravity methods, three-dimensional models, mineral exploration, platinum ores, Proterozoic, Suhanko, Portimo, Narkaus, Konttijärvi, Lapland, Finland

Markku Iljina
Geofirma
Harjukatu 5
FI-96100 Rovaniemi
Finland

E-mail: markku.iljina@pp.inet.fi

Heikki Salmirinne
Geological Survey of Finland
P.O. Box 77
FI-96101 Rovaniemi
Finland

E-mail: heikki.salmirinne@gtk.fi

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Keväällä 2003 mitattiin noin 14 km pitkä heijastusseisminen linja Pohjois-Suomessa Ranualla sijaitsevan Suhangon kerrosintruusion ylitse. Mittauslinja alkaa idästä päin arkeeiselta Pudasjärven pohjakompleksilta, ylittää paleoproterotsooisen Suhangon kerrosintruusion ja jatkaa yläpuoliselle Peräpohjan liuskealueelle ylittäen mm. sen sisältämiä mafisia kerrosjuonia. Seismisen mittausten tarkoituksena oli tutkia malminetsinnällisesti kiinnostavan Suhangon intruusion ja sen ympäristön rakenteita uusien potentiaalisten malminetsintäkohteiden löytämiseksi sekä selvittää heijastusseismisen menetelmän soveltuvuutta malminetsintään kiteisessä kallioperässä yleisesti.

Tässä raportissa on esitetty Suhangon heijastusseismisen mittauksen tulkinta pohjautuen alueen tunnettuun geologiaan sekä painovoimamittausten tulkintoihin. Tulokset sopivat hyvin yhteen aikaisempien tutkimusten kanssa tarkentaen niitä. Arkeeisten ja proterotsooisten kivilajien erilaisista akustisista ominaisuuksista johtuen, ne erottuvat mittaustuloksissa hyvin toisistaan. Tuloksista voidaan selkeästi havaita myös proterotsooisten kivilajien sisällä olevat mafiset kerrosjuonet. 2.7 Ga ikäinen Ranuan dioriitti erottuu heikosti sitä ympäröivistä vanhemmista gneisseistä. Kerrosintruusion alaosan reunasarja ja siihen liittyvä kontaktityyppin Cu-Ni-PGE mineraalisaatio tulkittiin jatkuvan loivalla kaateella 2.7 km Peräpohjan liuskejakson alle 620 metrin vertikaaliseen syvyyteen. Tulokset osoittavat menetelmän soveltuvan kiteisen kallioperän litologian ja rakenteiden selvittämiseen silloin kun eri yksiköiden akustiset impedanssierot ovat riittävät ja heijastavat rajapinnat riittävän vaaka-asentoisia. Tätä kautta menetelmää voidaan soveltaa myös malmipotentiaalisuuden selvittämiseen.

Asiasanat (Geosanasto, GTK): kerrosintruusiot, seismiset menetelmät, seisminen syväluotaus, heijastusmenetelmät, FIRE, painovoimamenetelmät, kolmiulotteiset mallit, malminetsintä, platinamalmit, proterotsooinen, Suhanko, Portimo, Narkaus, Konttijärvi, Lappi, Suomi

Markku Iljina
Geofirma
Harjukatu 5
96100 Rovaniemi

Sähköposti: markku.iljina@pp.inet.fi

Heikki Salmirinne
Geologian tutkimuskeskus
PL 77
96101 Rovaniemi

Sähköposti: heikki.salmirinne@gtk.fi

CONTENTS

1 INTRODUCTION

The project FIRE (Finnish Reflection Experiment) was carried out during the years 2001–2005 by a consortium between the Geological Survey of Finland, the Institute of Seismology of the University of Helsinki, the Department of the Geosciences of the University of Oulu and the Sodankylä Geophysical Observatory of the University of Oulu. More than 2,000 km of 2-dimensional seismic reflection lines were surveyed throughout Finland along four transects giving information to depths of up to about 60–80 km. A description of the FIRE acquisition and the first interpretations of these crustal-scale results has been presented by Kukkonen and Lahtinen (eds. 2006). In addition to these crustal-scale transects, two highly potential mineral exploration areas were selected for high resolution measurements. These areas were the ophiolitic Outokumpu Cu-Co-Zn belt in eastern Finland and the Suhanko layered intrusion in northern Finland hosting Cu-Ni-PGE enrichments.

In the spring of 2003, about 14 km of common midpoint (CMP) data were measured along the Suhanko high resolution test line using Vibroseis sources by a contractor (the Russian state-owned companies Spetsgeofizika S.E and Machinoexport S.E). The first interpretation of the data from this experiment in Suhanko is presented in this paper. The locations of the high-resolution Suhanko transect and crustal-scale FIRE 4 transect are presented in Figure 1.

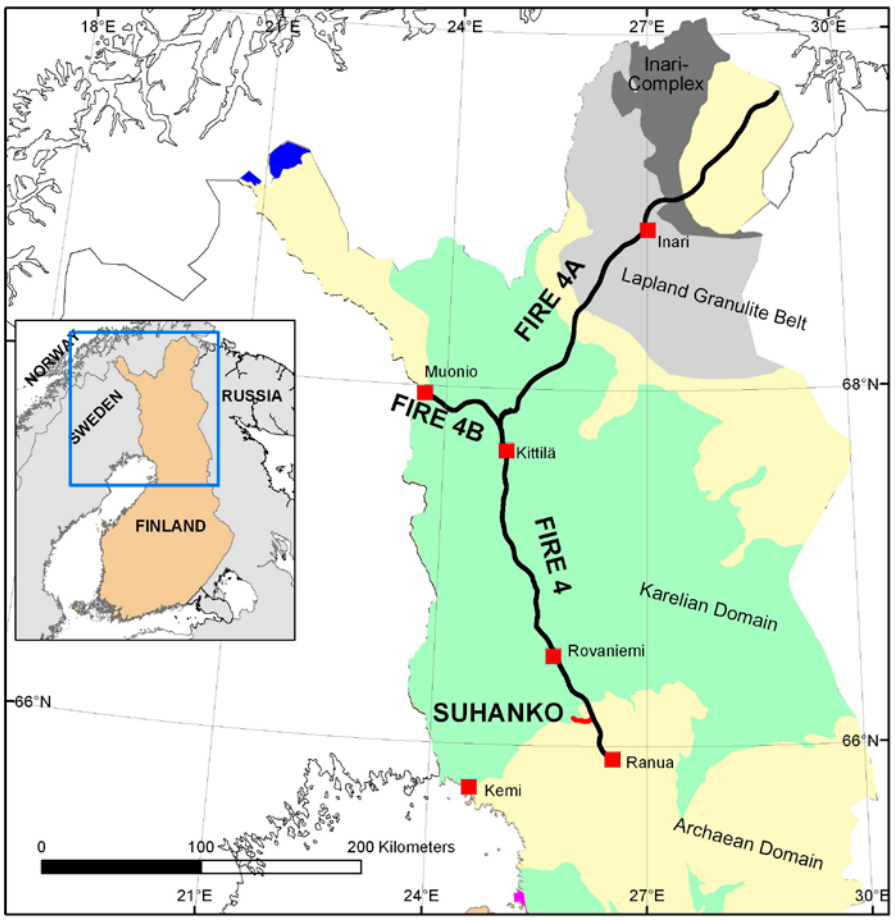

Figure 1. Location of FIRE 4 (black) and Suhanko (red) transects in northern Finland. The main geological domains after Korsman et al. (1997).

2 GENERAL GEOLOGY

The study area consists of three main geological units. These are the Archean Pudasjärvi Complex, the Palaeoproterozoic Portimo Layered Igneous Complex (Portimo Complex) and the younger Peräpohja Schist Belt (Figure 2).

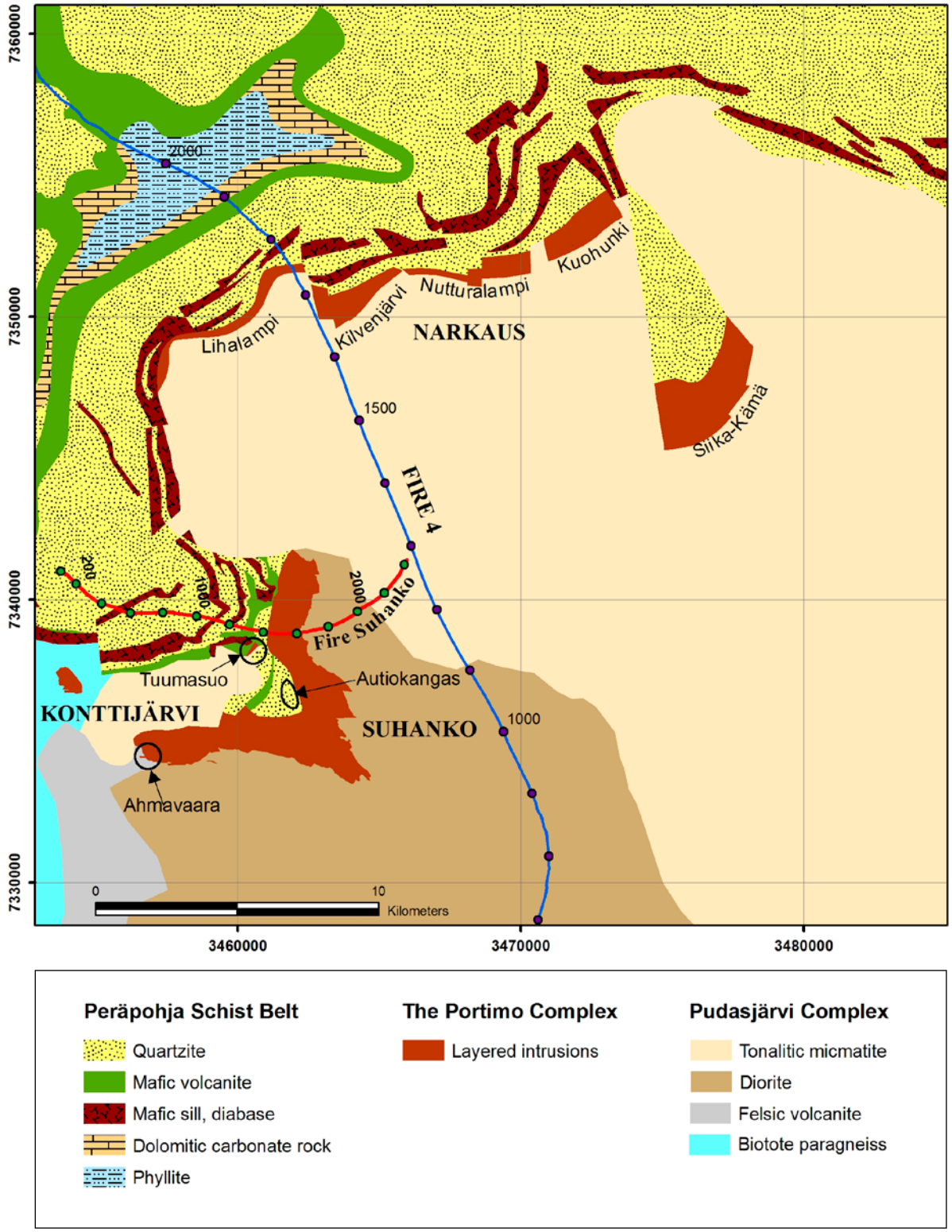

Figure 2. Geological map of the Portimo Complex area (Bedrock Map Database DigiKP Finland, GTK. Version 1.0, 04.08.2009). The Suhanko high resolution seismic line is plotted as a red line and the FIRE 4 seismic profile as a blue line. Numbers on these lines refer to CMP coordinates.

2.1 The Pudasjärvi Complex

The Pudasjärvi Complex is mainly composed of tonalite-trondhjemite gneisses, subordinate granites and remnants of greenstone belts, of which the Oijärvi Greenstone Belt forms a 1–4 km wide N–S trending zone in the south-western corner of the study area (Perttunen & Vaasjoki 2001). Outcrop evidence indicates the Suhanko intrusion to cut the Oijärvi greenstone belt. The Pudasjärvi Granulite Belt is also a prominent component of the Pudasjärvi Complex locating to the south of the study area, while the Ranua diorite covers a significant proportion of the southeastern part of study area. Isotope ages for the Pudasjärvi Complex vary from 3.5 Ga, the oldest known value for the Fennoscandian Shield, to 2.65 Ga for a mafic granulite (Mutanen & Huhma 2003). The Ranua diorite (2.7 Ga, Mutanen & Huhma 2003) varies from diorite to quartz diorite in mineral composition and is characterized by elevated magnetic intensity and a gravimetric anomaly.

2.2 The Portimo Layered Igneous Complex

The Portimo Layered Igneous Complex (Portimo Complex, Figure 2) belongs to the Tornio-Näränkävaara Belt of c. 2.44 Ga old layered intrusions and is composed of three principal structural units (Alapieti et al. 1989, Iljina 1994, Iljina 2005): the Narkaus, Suhanko, and Konttijärvi intrusions.

2.2.1 Premetamorphic cumulate and other types

Each intrusion contains *a marginal series and an overlaying layered series* (Figure 3). The marginal series of the Suhanko and Konttijärvi intrusions differ from that of the Narkaus intrusions in thickness and prevailing rock types. The Narkaus marginal series generally varies from 10 to 20 m in thickness, while the Suhanko and Konttijärvi marginal series may reach several tens of metres. The Narkaus marginal series is mainly composed of pyroxenite with some plagioclase-bearing rocks in its lower parts, whereas olivine cumulates commonly constitute the upper half of the Suhanko and Konttijärvi marginal series.

A striking difference between the layered series of the intrusions is the presence of marked reversals in the Narkaus intrusion, as shown by the thick ultramafic olivine-rich cumulate layers, whereas crystallization in the Suhanko and Konttijärvi intrusions continued without notable reversals. The Suhanko layered series commences with plagioclase-bronzite orthocumulates (with poikilitic augite) that also contain some bronzite cumulate interlayers. This poikilitic rock is separated from the overlying, rather monotonous plagioclase-bronzite-augite adcumulates by a pyroxenite layer few metres thick. Approximately midway through the stratigraphy, bronzite disappears as a cumulus mineral, but returns higher up in the Suhanko sequence. Four poikilitic anorthosite layers also occur in the upper Suhanko layered series. Granophyric material is limited to discontinuous patches and cross-cutting dykes in the upper Suhanko and Konttijärvi layered series.

The major reversals in the Narkaus layered series resemble those of the Penikat intrusion and enable its layered series to be divided into three megacyclic units, MCU I-III (Figure 3). The lowermost (MCU I) commences with a thick (~80 m) bronzite cumulate layer with a massive chromitite layer close to its top. The rest of MCU I as well as the gabbroic parts of MCU II and MCU III are mainly composed of plagioclase-bronzite-augite adcumulates, with the exception of a poikilitic plagioclase cumulate layer above the ultramafic basal part of MCU III. Well developed MCU II, however, is found only in the Kilvenjärvi Block and fades away eastwards.

Mafic and ultramafic dykes, known as the Portimo Dykes, are found in the basement below the Konttijärvi intrusion and in the Ahmavaara area of the Suhanko intrusion. They have also been found as fragments in the marginal series of the Konttijärvi intrusion. The dykes have not been dated and their association with the main intrusions is based on geochemical observations. The dykes are subparallel to the basal contact of the intrusion and merge with it locally.

The cumulus sequences in the layered series of the small Konttijärvi intrusion and the Ahmavaara area of the Suhanko Intrusion resemble each other. Pyroxenite, which separates the lowermost poikilitic orthocumulate from the overlying gabbroic adcumulate, attains a thickness of some tens of metres in both sections. The present-day Konttijärvi stratigraphy is rather ultramafic when cumulus terminology is applied. The lower contact of the Konttijärvi intrusion is also rather unique. Below the lowermost, more homogenous cumulate there is a thick mixing zone of *varitextured gabbro*, which in some places is up to c. 150 m wide. The combined thickness of the homogeneous Konttijärvi marginal and layered

series is only slightly greater (c. 160 m) than this varitextured gabbro zone.

The varitextured gabbro zone (also called the transition or mixing zone) comprises a rock type termed 'hybrid gabbro' and of banded gabbro. The 'hybrid gabbro' is characterised by grain-size variations from fine to medium and also contains an almost assimilated felsic contaminant. Further away from the intrusion, the hybrid gabbro turns into banded gabbro, which in its outcrop appearance looks like recrystallised banded Archaean quartz dioritic gneiss that still has a primary folded texture but gabbroic mineralogy. Some of the banding is due to the turbulent flow of an unhomogenised mixture of the mafic and felsic (melted basement) melts. Contacts between homogenous gabbro, hybrid gabbro and banded gabbro are arbitrary, but the hybrid and banded gabbros are mapped to form a domain of their own. This division is due to a pattern in which many drill holes contain several sections of hybrid and banded gabbros (1–20 m in length) immediately next to each other, so that the two gabbro types together form a distinctive, mappable unit. This unit also contains basement gneiss blocks up to several tens of metres in size. The varitextured gabbro zone appears to be a result of the mechanical and metasomatic mixing of melted Archaean gneiss and mafic magma, indicating dynamic intrusion of the mafic magma.

Fine-grained, non-cumulate-textured gabbroic bodies up to a few tens of metres thick and several hundreds of metres long occur in many places in the Suhanko marginal series. The chemical composition of these bodies seems to vary along the strike as the Ahmavaara bodies turned out to have a distinctly higher Cr content than bodies in the SE tip of the Suhanko intrusion. The chemical composition of the bodies of the SE tip is similar to the mean composition of the Suhanko intrusion, while the Ahmavaara one differs from it by a having a higher chromium content. On the other hand, the Ahmavaara autoliths bear chemical resemblances to the magma that gave rise to MCU I and II of the Narkaus intrusion of the Portimo Complex. The chemical features and the mode of occurrence of these plagioclase-two pyroxene rocks have led to the interpretation that the bodies are autoliths and representatives of chilled margin rocks that were disrupted and entrained by subsequent magma pulses (Iljina 1994).

Konttijärvi, Suhanko and Narkaus intrusions were uplifted and eroded soon after emplacement. The overlying supracrustal sequences of the Peräpohja Schist Belt lie unconformably over the cumulates. For example, the missing stratigraphic interval not intersected by the FIRE 4 profile crossing the Narkaus intrusion (Figure 3) is due to this erosion.

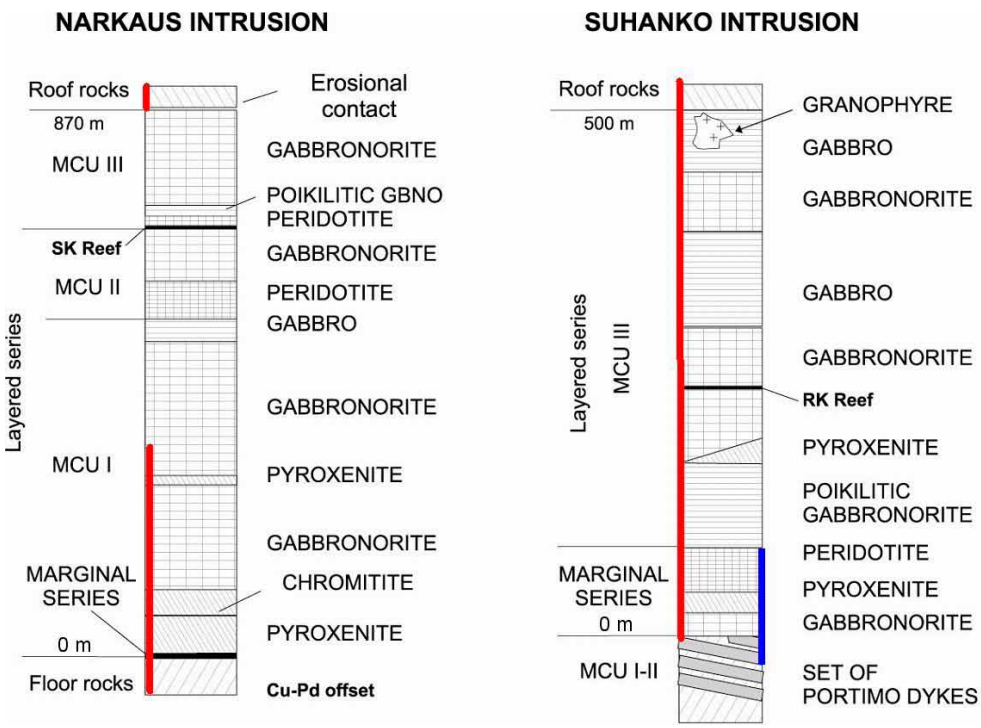

Figure 3. Primary, premetamorphic cumulus stratigraphies of the Narkaus and Suhanko intrusions. MCU, megacyclic unit. Red bars show the stratigraphic sections on the seismic lines. Blue lines indicate the host rocks of the contact type Ni-Cu-PGE mineralisation. In metamorphism the gabbroic cumulates have recrystallized to plagioclase-amphibole rocks, pyroxenites to amphibole-chlorite rocks and peridotites to serpentinites. Modified after Iljina (1994).

2.2.2 Metamorphic alteration of primary cumulates

After crystallization, the Portimo Complex underwent deformation and metamorphism, which was largely isochemical. However, the mineral composition of the cumulates changed in the metamorphic recrystallization. The degree of alteration has mainly depended on primary mineralogy, so that the gabbroic cumulates have undergone less mineralogical change. Metamorphic recrystallization also varies from place to place, the central parts of the intrusions being less affected by the metamorphism. Magmatic pyroxenes have altered to amphiboles and decomposition of olivine has produced serpentine, chlorite, carbonate and magnetite in varying mutual proportions. Original gabbroic cumulates are now plagioclase-amphibole rocks in which the plagioclase has often granulated and saussuritized. Pyroxenites are amphibole-chlorite rocks and often schistose. Olivine rich rocks, peridotites, have larger variation among their metamorphic counterparts. The most common metaperidotite is a serpentine rock with smaller amounts of chlorite, amphibole and magnetite. In places, metaperidotites can be highly carbonaceous, and the proportions of amphibole, chlorite and magnetite also vary substantially.

2.2.3 Ni-Cu-PGE mineralization

Among the layered intrusions, the Portimo Complex is exceptional in hosting a variety of styles of PGE mineralisation (Figure 4). The principal mineralisation types are (Iljina 1994):

Contact type deposits:
- PGE-bearing Cu-Ni-Fe sulphide dissemination in the marginal series and varitextured gabbro of the Suhanko and Konttijärvi intrusions (circles 2 and 3, Figure 4).
- Predominantly massive pyrrhotite deposits located close to the basal contact of the Suhanko intrusion (circles 2 and 3, Figure 4).

Reef type deposits:
- Siika-Kämä PGE Reef in the Narkaus layered series (circle 1, Figure 4).
- Rytikangas PGE Reef in the layered series of the Suhanko intrusion (circle 5, Figure 4).

Other types:
- Offset Cu-PGE mineralisation below the Narkaus intrusion (circle 4, Figure 4)

Five other PGE enrichment types are depicted in Figure 4. These are 1) the PGE enrichment in the Portimo Dykes below the Konttijärvi and Ahmavaara marginal series, 2) the PGE concentrations near the roof of the Suhanko intrusion, mostly associated with pegmatites, 3) a Pt-anomalous pyroxenitic pegmatite pipe in the western limb of the Suhanko Intrusion, and 4) chromite and silicate-associated PGE enrichments in the lower parts of the Narkaus intrusion and MCU II.

Figure 4 shows the structural model for the Portimo Complex and the positions of the mineralisations described above, as interpreted by Iljina (1994). Taking the boundary of the two parental magmas as a reference level, it can be seen that the Siika-Kämä Reef and the highly mineralised Ahmavaara and Konttijärvi marginal series are located in the same positions in terms of magmatic stratigraphy.

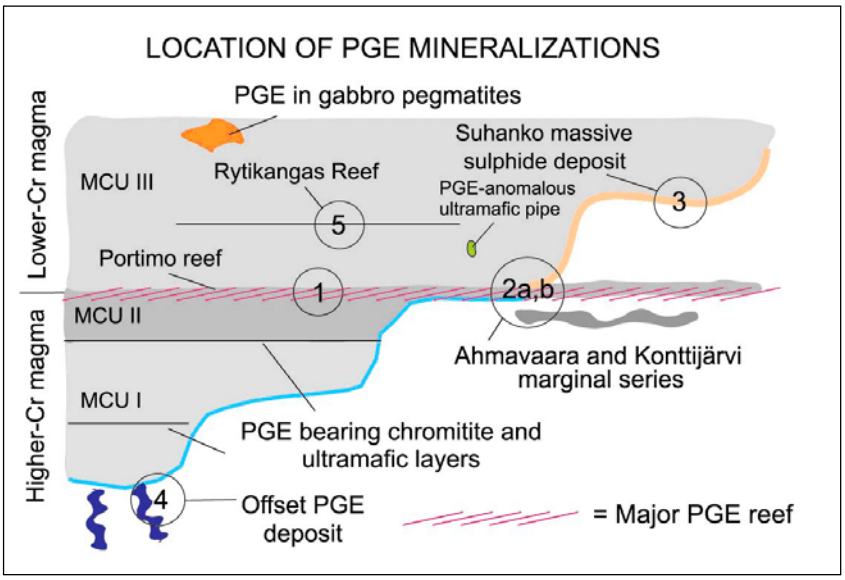

Figure 4. Schematic presentation of the locations of the various PGE enrichments encountered in the Portimo Layered Igneous Complex. Circled numbers are referred to in the text. Modified after Iljina (1994).

2.3 The Peräpohja Schist Belt

The rocks of the Palaeoproterozoic Peräpohja Schist Belt (PSB) lie unconformably on the Archaean Pudasjärvi Complex as well as on the Portimo Complex layered intrusions. The stratigraphic sequence present in the study area belongs to the lower Kivalo Group, constituting sedimentary rocks of the orthoquartzite-dolomite association as well as intercalated mafic volcanic rocks (Perttunen & Hanski 2003).

The lowermost unit, a polymictic Sompujärvi conglomerate at the base, is detected in the Autiokangas area (Figure 2), and at the top of the Kilvenjärvi block of the Narkaus Intrusion, where gabbroic fragments derived from the layered intrusion are also identified in the conglomerate. The Sompujärvi Formation is overlain by amygdaloidal lavas of the Runkaus Formation and sedimentary Palokivalo Formation. Mapped sedimentary structures refer to both subaerial and shallow subaqueous deposition environments in the study area.

The rocks of the Palokivalo Formation have been penetrated by mafic sills. These sills bracket the study area PSB sequence between 2.44 Ga and 2.21 Ga, the older age referring to the Penikat intrusion with which the Portimo Complex has been interpreted to be coeval, and the younger age to the isotope age of the Konttikivalo albite diabase located in the study area (Perttunen & Vaasjoki 2001).

3 THREE-DIMENSIONAL STRUCTURE OF THE PORTIMO COMPLEX BASED ON GEOLOGICAL AND GRAVITY INTERPRETATION

3.1 Gravity model of the Suhanko layered intrusion

The gravimetric measurements above and in the immediate vicinity of the Suhanko intrusion were carried out during 1984–1985 in a joint project between the Oulu University and Lapin Malmi (Outokumpu Oy) entitled "*Geophysical investigations of Suhanko layered intrusion*" (Lerssi et al. 1991, Pernu et al. 1986, Pernu et al. 1987). The data gathered in this joint project has since been merged with the regional gravity database of Geological Survey of Finland surrounding the intrusion. The combined dataset discussed in this paper includes regional gravity data with a data density of 2–4 points/km^2 and 8 profiles crossing the Suhanko intrusion block. A regional Bouguer anomaly map with the geological boundaries is presented in Figure 5.

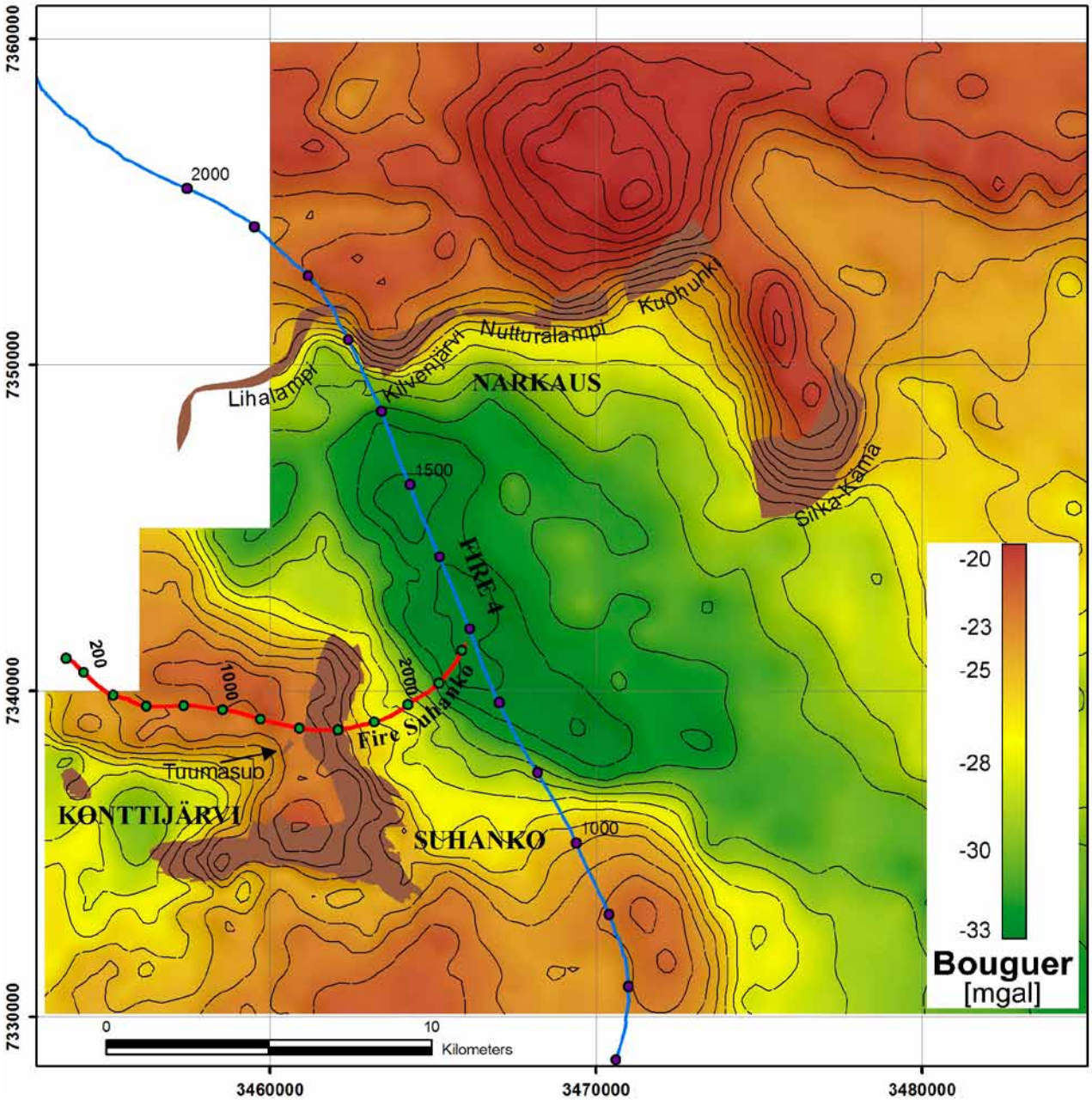

Figure 5. Regional Bouguer anomaly map with the geological boundaries of the Portimo layered igneous complex. The interval of the Bouguer anomaly contours is 1 mgal. The seismic profile FIRE 4 is plotted as a blue line and the Suhanko profile as a red line. Figure: Iljina and Salmirinne, GTK.

The gravity interpretations based on profile data revealed the mass distributions of the intrusion (Figure 6). The 3D model was created using 3D plunging prisms, and a density difference of 200 kg/m^3 between the intrusion and Archean complex was used. The resulting interpretation turned out to be quite compatible with the older ones of Pernu et al. 1986 (Figures 7 and 8).

The calculated surface area of intrusion is about 17 km^2 and the volume is about 13.9 km^3. The intrusion is thickest in its central part, where it continues to a depth of about 1000 m. The central part and N-S wing of the intrusion have been interpreted to plunge underneath the roof rocks, while at least the western half of the E-W wing has an almost vertical roof contact. The thickness of the E-W wing and SE tip of the intrusion varies between 100 and 500 m. The N-S wing has been interpreted to be only 150–200 m thick, but possibly plunging deeper under the rocks of the Peräpohja Schist Belt reaching the depth of 600 m. The insignificant density difference between the intrusion and overlying PSB lithologies makes the separation of these two difficult, and the interpretation is chiefly based on the anticipated geological structure, which also is supported by seismic results presented below.

The lower contact of the intrusion is 'transgressive', with the base of the SE tip much higher than that of the western and northern limbs if the intrusion is rotated to its original position (Figure 9). The western wing of the Suhanko intrusion, the Ahmavaara block, can be divided into southern and northern embayments, separated from each other by an east-west-trending 'anticline' (Figure 8A). The southeastern tip of the Suhanko body is shallow, and only marginal series cumulates are preserved, the overlying cumulates having been eroded away.

In view of their cumulus stratigraphy and chemistry, the Ahmavaara section is interpreted as representing the deepest section of the original Suhanko intrusion.

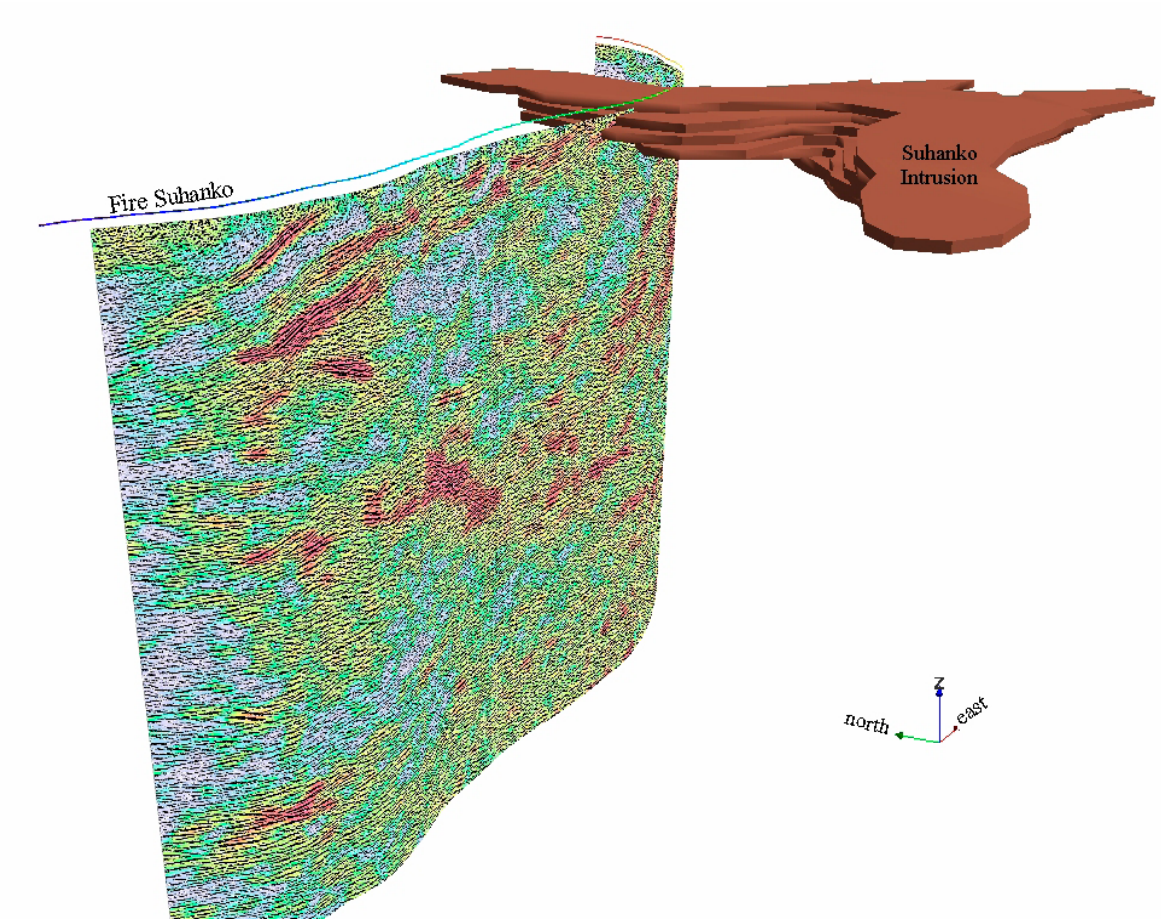

Figure 6. 3D gravity model of the Suhanko intrusion and location of the seismic section crossing the intrusion. View from the southwest. Figure: Salmirinne, GTK.

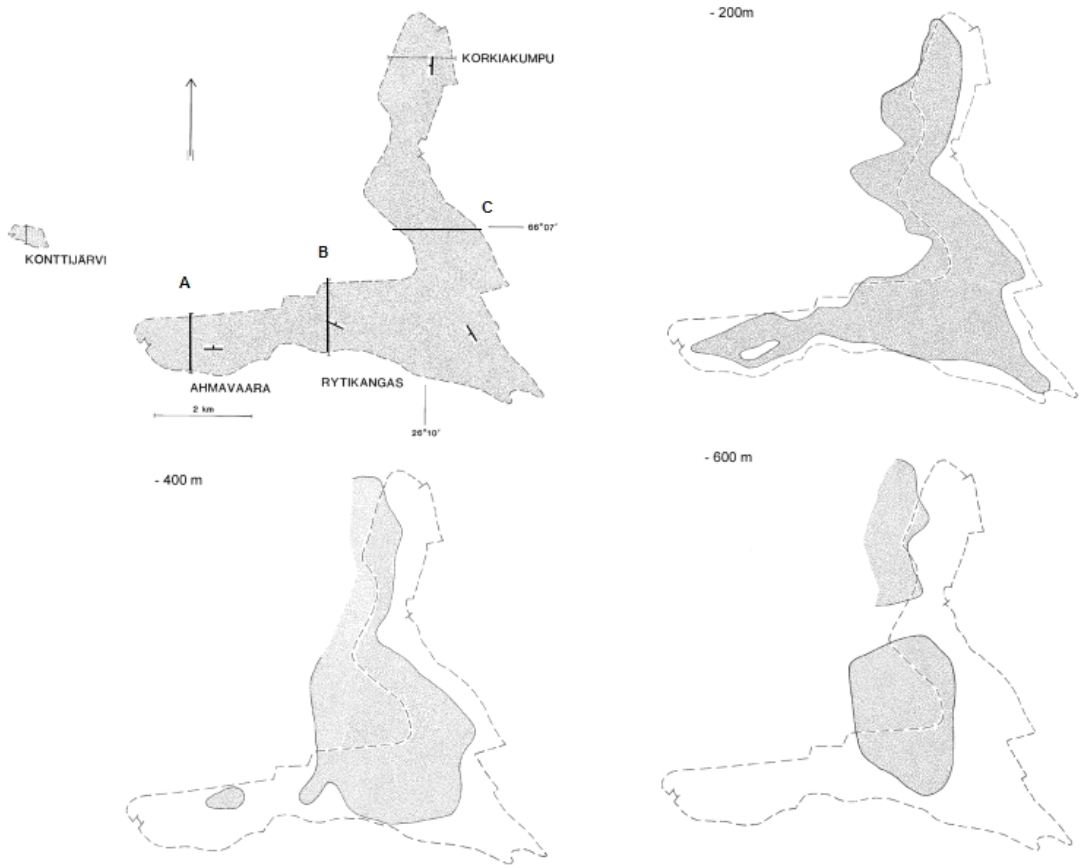

Figure 7. Suhanko intrusion: plan view and horizontal cross-sections at depths of 200, 400 and 600 metres. Sites of the vertical cross-sections A–C depicted in Figure 8 are also shown. Modified after Pernu et al. (1986).

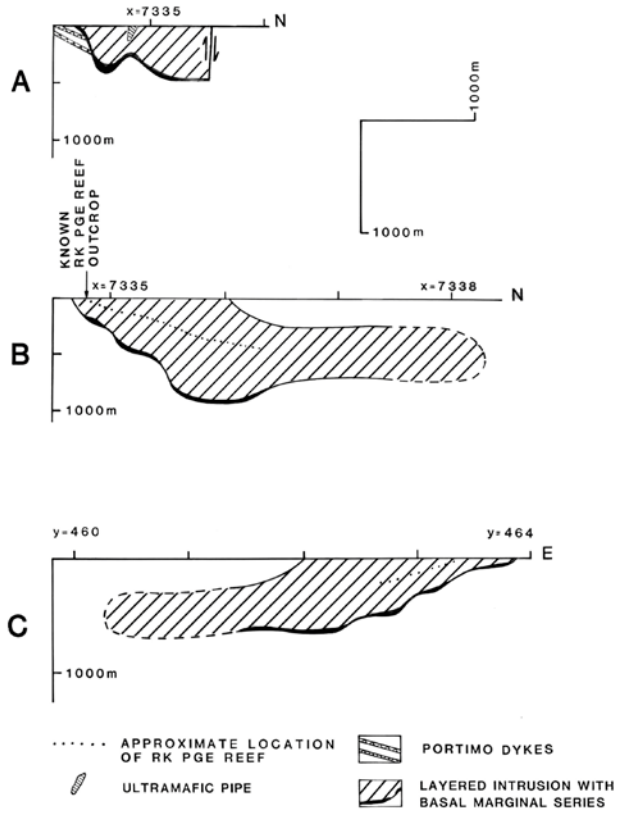

Figure 8. Three vertical cross-sections through the Suhanko intrusion. Sites marked on Figure 7. Modified after Pernu et al. (1986).

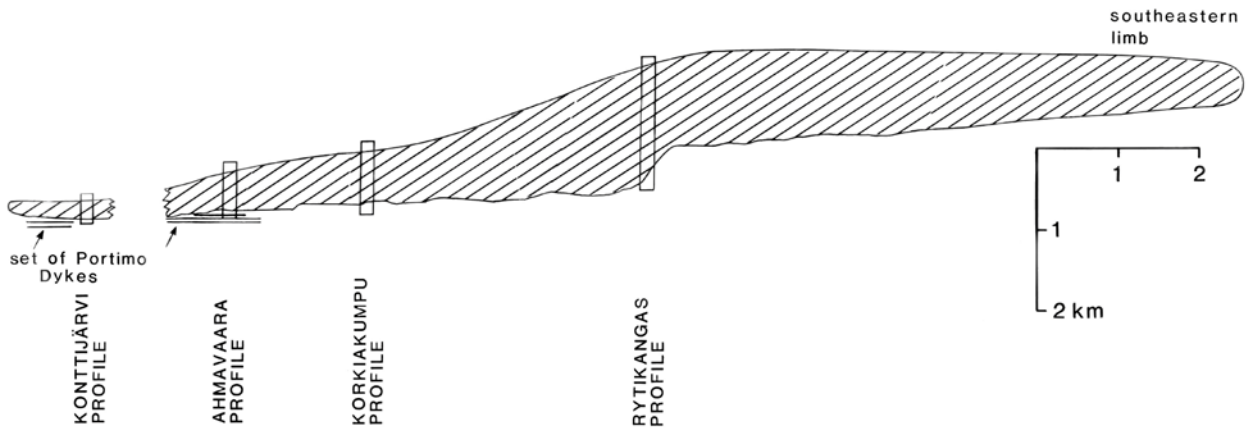

Figure 9. Schematic cross-section of the initial Suhanko intrusion. Modified after Iljina (1994).

3.2 Geological model of the Narkaus layered intrusion

Geophysical and geological modelling of the Narkaus intrusion indicate the numerous intrusion blocks to plunge beneath the roof rocks at a medium or steep angle (corresponding to the dip of the layering), reaching a depth of one kilometre from the present erosion surface at maximum. The cumulate layers are at their thickest in the Kilvenjärvi block, which seems to be a structural embayment in the Narkaus intrusion, otherwise interpreted as sheet-like in form. The present cross-section of the Narkaus intrusion resembles that of the Penikat intrusion. Moreover, the feeder channel for the Narkaus intrusion can be hypothesized beneath the Kilvenjärvi block. (Iljina 1994)

4 SEISMIC DATA, REFLECTIVE UNITS AND THEIR INTERPRETATION

4.1 Data acquisition and processing

In the spring of 2003, about 14 km of common midpoint (CMP) data were measured on the Suhanko high resolution test line using Vibroseis sources by a contractor (Russian state-owned companies Spetsgeofizika S.E and Machinoexport S.E). Data acquisition was performed along the local gravel road from west to east. At the eastern end the Suhanko line meets the FIRE 4 transect (Figure 2).

At Suhanko, three 15.4-ton vibrators were used to generate the signal, which was a linearly increasing sweep from 30 to 150 Hz. The sweep length was 16 s, the total recording time 22 s and the final correlated record length 6 s. The source point interval was 25 m. The acquisition was carried out with symmetrical split-spread geometry using 12 geophone groups at 12.5 m intervals with a maximum offset of 5012.5 m, recording 402 channels in one spread. (Zamozhnyaya & Suleimanov 2003)

Data processing in the first stage was carried out by the contractor, who produced final stacks and first migrated results after fieldwork. The migrated sections presented in this paper were subsequently prepared at the Institute of Seismology, University of Helsinki starting from the final stacks produced by the contractor (Appendices 1 and 2).

Table 1 presents the major geological units that are cross-cut by the seismic profiles. The FIRE 4 seismic line and the high resolution Suhanko line cross-cut tonalitic gneisses and the Ranua diorite as well as the Proterozoic Peräpohja Schist Belt. The Suhanko line also cross-cuts (from east to west) a 100 m wide (horizontal width) Suhanko marginal series with associated disseminated Ni-Cu-PGE enrichments followed by poikilitic gabbroic orthocumulates and then by gabbroic adcumulates further up in the stratigraphy (i.e. going westwards). Glacial boulders c. 1.5 km to the north of the profile suggest that practically the entire Suhanko stratigraphy (Figure 3) is present in the measurement line. However, no boulder or drillhole evidence is available to indicate whether the Rytikangas Reef (Figure 4) is present in the seismic profile.

Table 1. Seismic measurement lines and geological units they cross-cut in the study area.

Seismic measurement line	**Geological unit and lithologies**
Suhanko high resolution line	Archaean basement gneisses.
	Ranua diorite.
	Suhanko layered intrusion covering the whole sequence from basal Cu-Ni-PGE mineralized marginal series to evolved gabbros and anorthosites close to the original roof of the intrusion.
	Quarzites and mafic lavas of the PSB.
	Mafic sills cross-cutting PSB.
FIRE 4	Archaean basement gneisses.
	Ranua diorite.
	Narkaus layered intrusion covering only the lowermost pyroxenite cumulate of MCU I and about 100 m of overlying gabbroic cumulates. Also the offset Cu-Pd enrichment right underneath the intrusion.
	Quarzites and mafic lavas of the PSB.
	Mafic sills cross-cutting PSB.

4.2 Seismically identifiable blocks and planar structures

Seismically identifiable blocks are discussed separately for the Suhanko and FIRE 4 lines. The discussed seismic units and planar features are outlined in Figures 10 and 11, and Appendix 3. Identifiable blocks (high or low reflectivity 'areas') are labelled as B1, B2, …, while the planar features have the labels P1, P2, … . These identifiable blocks and planar features appear 'uniform and continuous' in the processed seismic sections. These features can be either real geological units and structures or just seismic echoes (false anomalies) due to cross-dip effects and 3D structures in the vicinity of the measurement line. Identified blocks and planar features with geological interpretations are listed in Table 2.

4.2.1 Suhanko high resolution line

Results from the 14-km-long high resolution Suhanko seismic line are depicted in Figure 10. The interpretation of the results extends to the depth of 7.5 km.

The seismic line crosses the Suhanko intrusion at a location which is tectonically complex. The complexity is evidenced by the small Autiokangas body of PSB, and by even smaller block of layered intrusion and Archaean gneiss at Tuumasuo (Figure 2).

In the seismic measurement results the conspicuous observation is the prominent change in reflection across the plane (P1), which has the surface intersection at the CMP 1620 and dips at low angle to the lower CMP numbers i.e. to the west. Rocks to the east of that plane exhibits clearly lower reflectivity than rocks on the western side. Another distinct set of planes (P2) is observable on the western end of the measurement line. These structures look not to cut the PSB referring therefore pre- or syn-rifting age. Planar structure P3 coincides to the contact of the Ranua diorite and older Archaean gneisses and the interpretation is supported by the magnetic and gravity results.

A c. 500 m wide zone immediately on the western side of the plane P1 has higher reflectivity and is also dividable into internal smaller blocks (B1a and B1b). The block B2 locating further to the west from B1 has lower reflectivity and is lying conformable with B1. An interesting, but smaller reflective unit (B3) is located close the surface, but not outcropping in the site of the profile, below the CMP 920-1030. This body B3 fits with smooth and low magnetic and gravimetric anomalies, both positive. A domain of elevated reflectivity (B4) is also noticeable below the CMP ca 1900 at depths between ca 0.5 -3.2 km. One interpretation of the B4 could be the Ranua diorite and its internal compositional and structural variations. Here we have to take to account that the reflector B4 may also represent cross-dip effects and 3D structures not properly understood in a single 2D line.

Two planar structures (P4 and P5) are also indicated in the Figures 10c and 10d, and Table 2. P4 structures can possibly represent deep shear zone relating the west contact zone of the Ranua diorite against Archean gneisses. No geological interpretation is discussed for P5.

4.3 FIRE 4

The overall description and interpretation of the FIRE 4 line is given by Patison et al. 2006 and is not discussed in further details in this paper. Two items are picked up, one being a plane (P6), which has the surface intersection at CMP 1120 (Figure 11) and low-mediun angle dip to left i.e. to the south. The other area of interest is the Proterozoic-Archaean contact close the CMP 1800, where a body (B5) and a plane (P7) are indentified.

4.4 Comparison with geological and gravity modelling

The plane P1 has a surface intersection exactly at the point where the N-S wing of the Suhanko intrusion is known to have its basal contact with the Archaean Pudasjärvi Complex. The gravity interpretation (Figure 7) as well as the geological interpretation refers to a gentle dip of this basal contact to the west, while a westwards dip has also been verified by close-surface drilling along the eastern margin of the intrusion. The identified block B1a has been interpreted to be the Suhanko intrusion. The extent of the intrusion to depth is questionable, but referring to the sill-like nature of the Penikat and Narkaus intrusions, the assumable subsurface extent to the west is merely a few kilometres rather than hundreds of metres only. Using this geological argumentation and the results of the seismic measurements, the basal contact of the Suhanko intrusion has been interpreted to extend 2.7 km to the west and to reach a vertical depth of 620 m (Figure 10d).

Tornio-Näränkävaara Belt layered intrusions most commonly have a younger Proterozoic subracrustal cover quite often lying immediately above the mafic intrusions (Iljina & Hanski 2005). Based on this common geological setting, the body B1b has been interpreted to represent the PSB sequences, perhaps a mafic volcanite dominated sequence. This is also supported by the outcropped surface geology.

Table 2. Seismically identifiable blocks and planar structures with interpretation. Codes refer to Figures 10 and 11, and Appendix 3.

Indentified blocks	**Description**	**Interpretation**
B1a and B1b	Well definable 0.5–1 km thick zone of higher reflectivity.	Has been interpreted to be composed of Suhanko intrusion (B1a) and mafic volcanic rocks of PSB (B1b) with intercalated clastic sediment layers and mafic sills.
B2	A zone of lower reflectivity unit above the B1.	Has been interpreted to be mainly composed of quartzites of PSB with intercalated mafic sills.
B3	Small 'body' of lower reflectivity	No obvious geological interpretation. The 'body' does not outcrop, but does coincide with positive gravity and magnetic anomalies.
B4	Large irregular block of elevated reflectivity	No obvious geological interpretation. The eastern contact of the block may coincide with that of Archaean gneiss and Ranua diorite.
B5 (FIRE 4)	Body of distinctly high reflectivity.	Narkaus intrusion and PSB. Supported by surface exposures.

Indentified planar feature		
P1	Separates a clearly more reflective unit above from the less reflective unit below.	Boundary of the Archaean Pudasjärvi Complex below and overlying Proterozoic lithologies.
P2a and P2b	Cut horizontal structures in the depth interval of c. 1–4 km.	Interpreted to be real faults. May represent a pre- or syn-rifting structure.
P3	Almost vertical structure. Surface intersection of the plane coincides to the contact of Archaean gneiss in the east and Ranua diorite.	East contact zone between Archaean gneiss and Ranua diorite.
P4a and P4b	Cut horizontal structures to the depth of c. 5 km.	West contact zone between Archaean gneiss and Ranua diorite.
P51 and P52	Clearly identifiable low angle features, which cut horizontal structures. Little or no shifting of horizontal structures across the features	
P6 (FIRE 4)	Clearly identifiable feature. Surface intersection of the plane coincides with the contact of Archaean gneiss and Ranua diorite.	Contact between Archaean gneiss and Ranua diorite.
P7 (FIRE 4)	Clearly identifiable feature.	Contact between the Archaean basement in the south and overlying package of Narkaus intrusion and PSB.

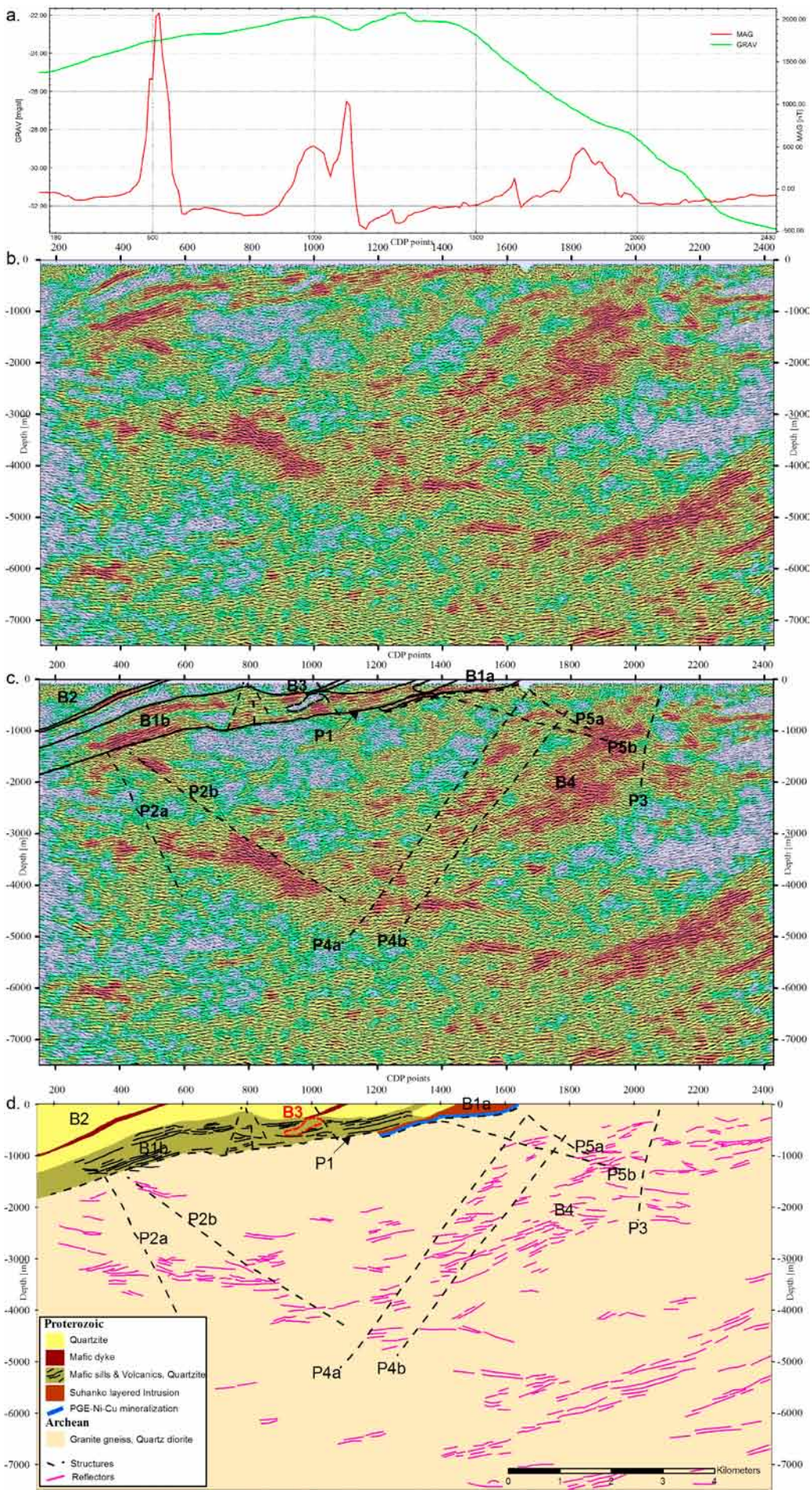

Figure 10. Colour-coded seismic envelope overlaid by a biased variable plot (b) with interpreted blocks (B) and planar (P) structures (c) and geological interpretation (d). A magnetic anomaly interpolated from aeromagnetic data as a red curve and gravimetric Bouguer anomaly interpolated from regional gravity data as a green curve are also plotted (a). Figure: Iljina and Salmirinne, GTK.

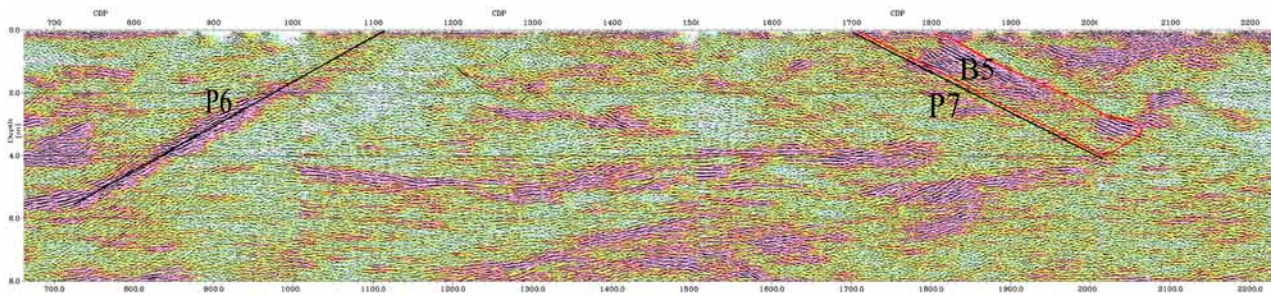

Figure 11. Colour-coded seismic envelope overlaid by a biased variable plot for the FIRE 4 seismic profile between CDP-points 700–2200. Figure: Iljina and Salmirinne, GTK.

5 IMPLICATIONS FOR EXPLORATION

One aim in executing the Suhanko higher resolution seismic measurements was to investigate the seismic response of the economic mineral-enriched Suhanko intrusion, and also to reveal new targets for exploration. The results indicate two seismically identifiable blocks (B3 and B4), for which there is currently no geological explanation. These blocks do not outcrop on the present erosion surface, at least not on the measurement profile. Although no definite proof of their economically critical geological nature can be given, they represent seismic targets that warrant further investigation.

The principal positive implication for exploration is the considerably long extension of the Suhanko intrusion westwards down to a shallow, economically drillable/mineable depth. The seismic results, in line with the gravimetric interpretation, suggest that the basal contact of the Suhanko intrusion (and associated contact type Cu-Ni-PGE mineralization) extends 2.7 km along the down-dip strike underneath the PSB. The possible deeper continuation of the intrusion along the reflector P1 would also provide an interesting target for further studies in the area.

6 CONCLUSIONS

The Suhanko high resolution seismic line has provided detailed structural information in an important mineral prospecting area in Finland. The line crosscuts the Archaean basement complex, the Palaeoproterozoic Suhanko layered intrusion and the overlying Peräpohja Schist Belt, including sills intruding the Belt. The Suhanko intrusion, which was the main target in this line, has been distinctly imaged seismically, and the consistency of the results with the known surface geology is very good.

The results, together with the identified structures, correspond to results of earlier gravity and geological studies (Pernu et al. 1986, Iljina 1994). The seismic measurement results also suggest new targets for further exploration of the contact type Ni-Cu-PGE mineralization, as they indicate the basal contact of the Suhanko intrusion to extend 2.7 km along the down-dip strike underneath the Peräpohja Schist Belt and still remain within a viable drillable/mineable depth of 620 m.

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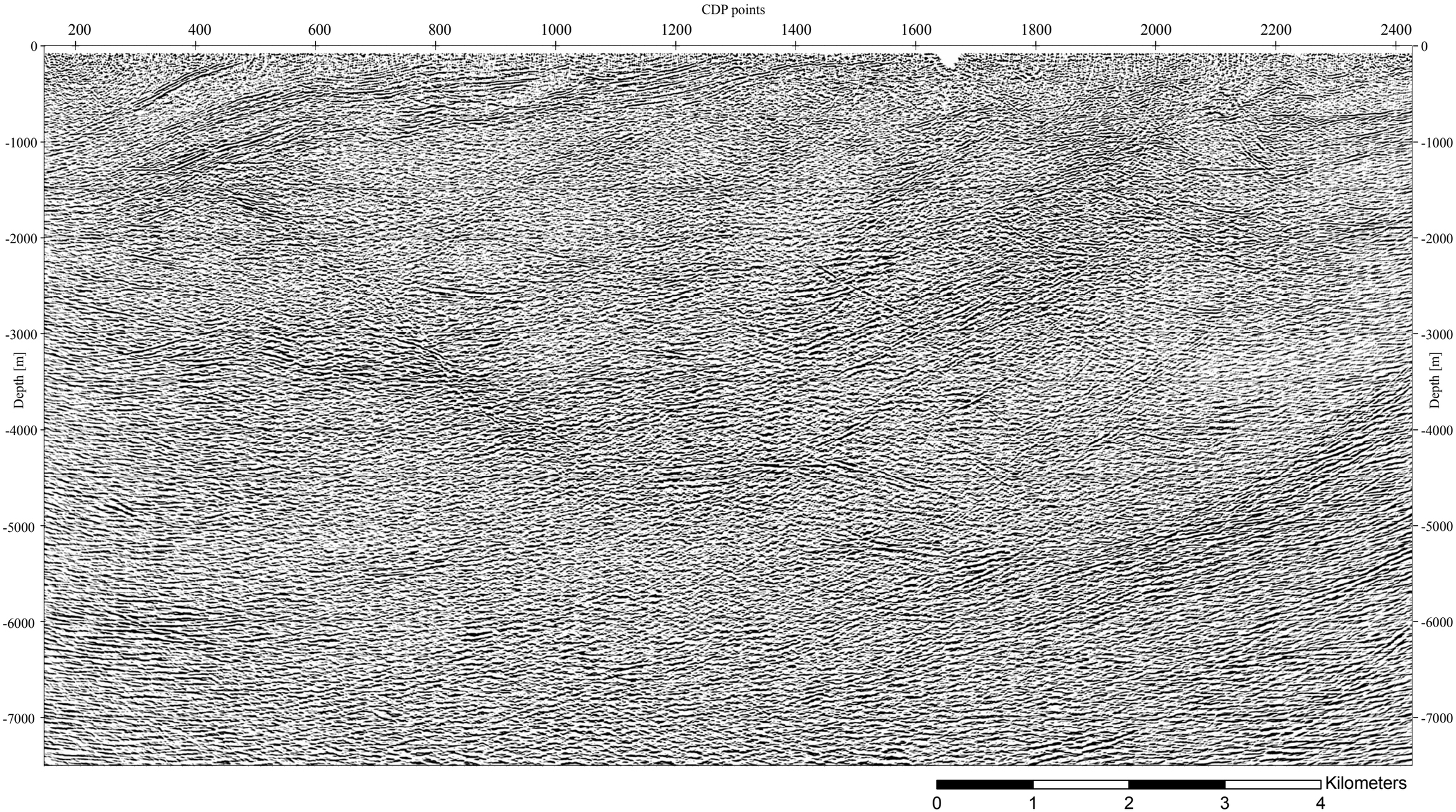
APPENDICES

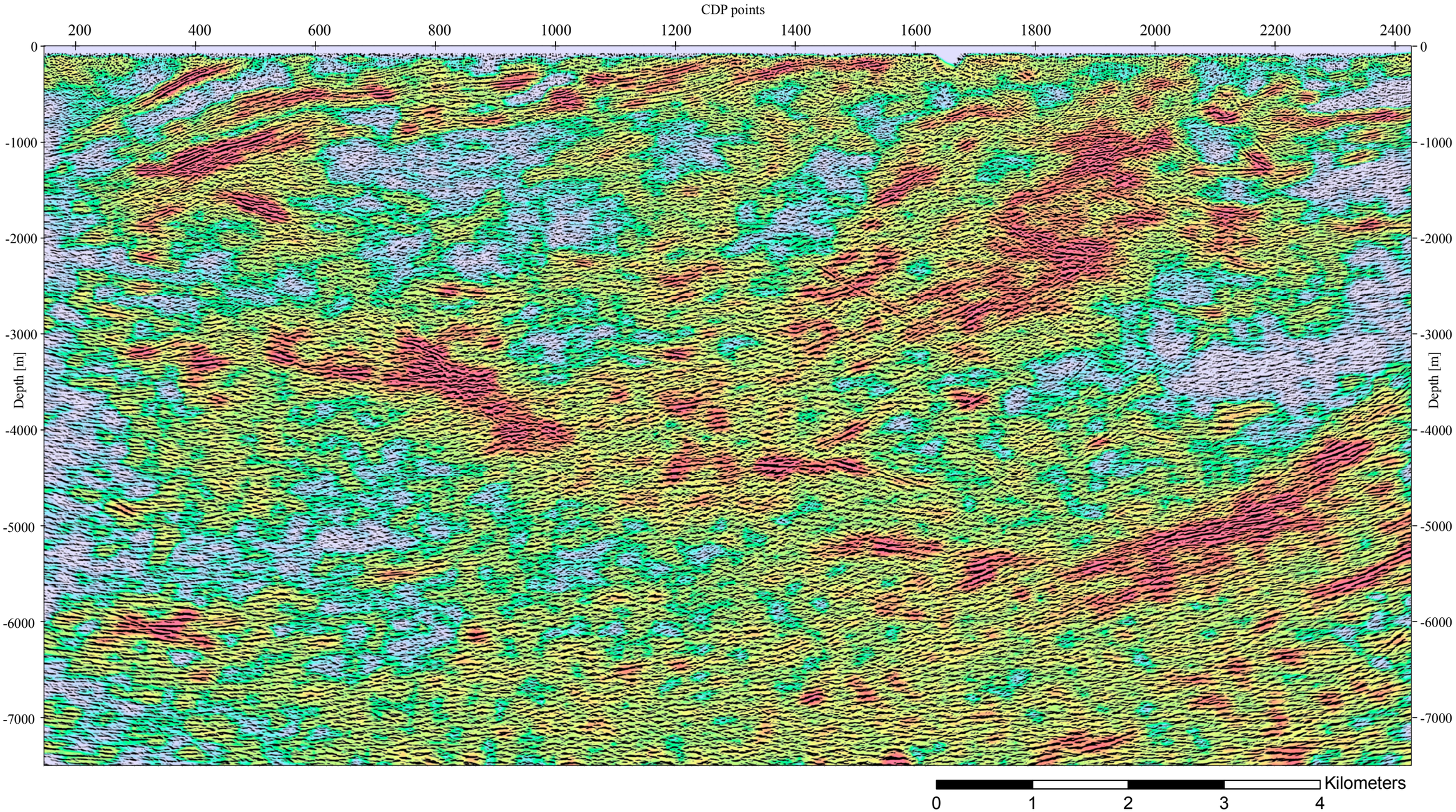
Appendix 1. Seismic gray scale section.

FIRE - Suhanko high resolution reflection seismic - Seismic gray scale section



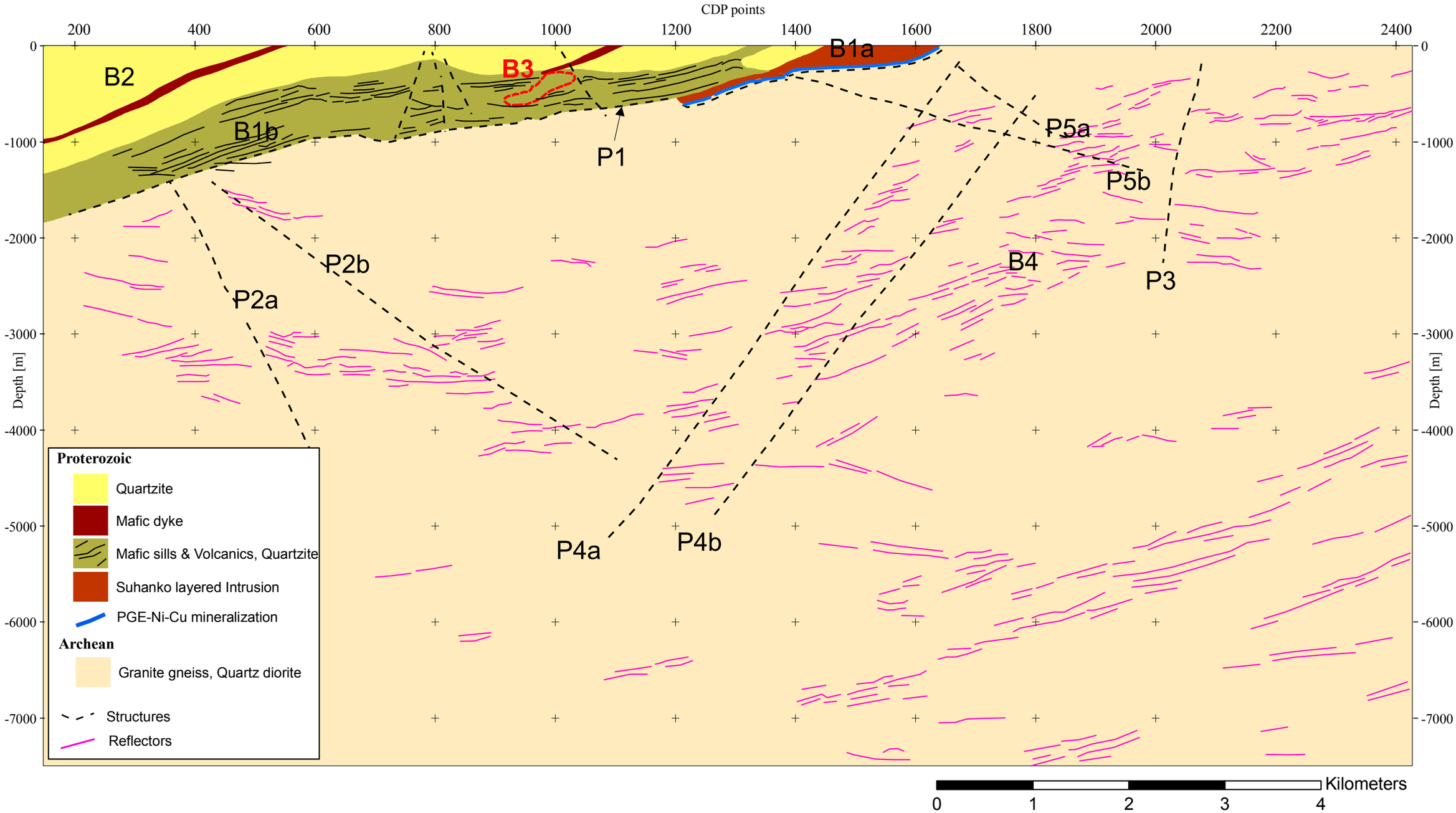
Appendix 2. Colour-coded seismic envelope overlaid by biased variable plot.

FIRE - Suhanko high resolution reflection seismic - Color-coded seismic envelope overlaid by biased variable plot



Appendix 3. Geological interpretation of Suhanko FIRE –profile.

FIRE - Suhanko high resolution reflection seismic - Geological interpretation - Markings B1, ... and P1, ... refer to identified blocks (B) and planar structures (P) discussed in the text



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The high resolution reflection seismic line crossing the Suhanko layered intrusion in northern Finland was measured in 2003 during the crustal scale Finnish Reflection Experiment (FIRE). The aims of the measurements were to investigate the structure of the economic minerals enriched in the Suhanko intrusion, to indicate new potential targets for exploration and to study the general suitability of seismic reflection imaging for mineral exploration in Precambrian crystalline bedrock. Through the integrated geological-geophysical approach described in this paper, we show that surface seismic reflection profiling can be used for mineral exploration in Precambrian crystalline bedrock to detect and delineate deep structures in a complex geologic setting characterized by moderate dips.

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