Novel technologies for greenfield exploration
Edited by Pertti Sarala
Geological Survey of Finland, Special Paper 57, 121–134, 2015

3D/4D GEOLOGICAL MODELLING OF THE HIETAKERO AND VÄHÄKURKKIO AREAS IN THE LÄTÄSENO SCHIST BELT, ENONTEKIÖ, NORTHERN FINLAND

by
Tuomo Karinen, Ilkka Lahti and Jukka Konnunaho

Karinen, T., Lahti, I. & Konnunaho, J. 2015. 3D/4D geological modelling of the Hietakero and Vähäkurkkio areas in the Lätäseno Schist Belt, Enontekiö, northern Finland. *Geological Survey of Finland, Special Paper 57*, 121–134, 11 figures.

In this article, we present 3D geological models of the Hietakero and Vähäkurkkio areas in northern Finland and discuss their geological evolution. The models were reconstructed using 3D potential field inversion. It is generally required that a model is in harmony with existing data, but we recognize that during model reconstruction it is also important to consider the geological evolution of the study area. This type of modelling, which considers the 3D history of a certain area, is referred to as 4D modelling. It is likely that the geological evolution of Hietakero began with the sedimentation of quartzites and eruption of volcanic rocks. This was followed by a tilting episode during which a gabbroic intrusion comagmatic with volcanic rocks was emplaced. Subsequent folding episodes resulted in the fold interference pattern of the area. The geological evolution of the Vähäkurkkio area is envisaged as folding of a volcano-sedimentary sequence that deposited during transgression. The vergence of folding is due to later thrusting from the east.

Keywords (GeoRef Thesaurus, AGI): three-dimensional models, geophysical methods, Palaeozoic, Proterozoic, Archean, Enontekiö, Hietakero, Vähäkurkkio, Finland

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

E-mail: tuomo.karinen@gtk.fi

INTRODUCTION

Since 2008, the Enontekiö district in north-western Finland has been under geological mapping in various projects of the Geological Survey of Finland (GTK). The principal focus of these projects has been on unravelling the geotectonic history, tectonostratigraphy, age and mineral potential of the area. Both Hietakero and Vähäkurkkio represent key areas for these questions, since they provide a cross-section of the stratigraphy and show folding patterns. Therefore, these areas were chosen for detail airborne surveys to obtain geophysical data on the conductive and magnetic zones of the bedrock. GTK has recently implemented 3D potential field inversion as a tool in geophysical modelling (Ruotsalainen et al. 2013). Electromagnetic SkyTEM data and one-dimensional inversion results were used to image the conductive horizons of the areas, and gravity and magnetic data were utilized in the geophysical 3D inversion.

GENERAL GEOLOGY OF THE ENONTEKIÖ AREA

The Enontekiö area in the NW part of Finland includes Archaean, Proterozoic and Palaeozoic rocks (Fig. 1). The youngest, i.e. Palaeozoic rocks of the Caledonian belt have been relatively well mapped and described in the publications of Lehtovaara (1994a, b, 1995). In contrast, the Archaean and Proterozoic areas are regarded as poorly mapped; only some relatively small areas have been covered by exploration surveys or M.Sc. projects (for these past studies in the area, the reader is referred to the report of Konnunaho et al. 2013). To date, the conception of the general geology of the Archaean and Proterozoic areas has largely been based on mappings already performed over 25 years ago (Matisto 1959, 1969, Idman 1988). In Sweden, the geological continuation of the areas has been investigated by the Geological Survey of Sweden (Bergman et al. 2001), and this work has provided valuable information for the projects of GTK. More recently, Sorjonen-Ward & Luukkonen (2005) provided a synthesis of the evolution of the Archaean bedrock in Finland, but this publication is a review based on earlier studies.

Recent fieldwork and research performed by GTK has revealed lithological differences between separate areas of the Archaean basement complex. Rocks of the Rommaeno Complex cover large areas in the NW of the study areas and are mainly composed of leucocratic granites and orthogneisses. In contrast, the Muonio Complex, which occurs as domes in the younger supracrustal rocks, is also composed of gneisses, but they can often be characterized as paragneisses. The Lätäseno Schist Belt (LSB) includes the Archaean Ropi Suite and the Proterozoic Lätäseno Group. The metasedimentary and metavolcanic rocks of the Ropi Suite occur as a ragged belt in the eastern side of the Rommaeno Complex. The Ropi Suite is unconformably overlain by the Proterozoic metasedimentary and metavolcanic rocks that comprise the Lätäseno Group. Age data (Huhma, pers. com.) indicate that the Archaean magmatism producing both granitic intrusions and acid volcanites (the volcanites belong to the Ropi Suite) occurred in two phases, ca. 2930 and 2760 Ma. The Archaean part of the LSB hosts 2450-Ma-old intrusions and the LSB is intersected by ca. 2200-Ma-old diabase dykes, which gives the minimum age for the schist belt (Fig. 1).

The LSB and adjacent areas are characterized by N–S structural trends, generated by folds with N–S-striking axial surfaces. Such folds are evident, for instance, from the dome-like pattern of the Archaean rocks of the Muonio Complex inside the LSB. However, there is another generation of folds with an E–W-striking axial surface interpreted from distinct fold interference patterns in the area. There is one prominent shear zone in the area, the Lätäseno Shear Zone (LSZ). A topographic change with the eastern side up in this shear zone accompanied by vergence of folding towards the west in the LSB area indicates overthrusting from the east. Age data (Huhma, pers. com.) from the pegmatite that cross-cuts the LSZ indicate that the overthrusting took place before 1760 Ma. Furthermore, the occurrence of 2450 Ma layered intrusions indicates the presence of a zone of rift-related faults that could have been reactivated in later deformation phases as shear zones (Fig. 1).

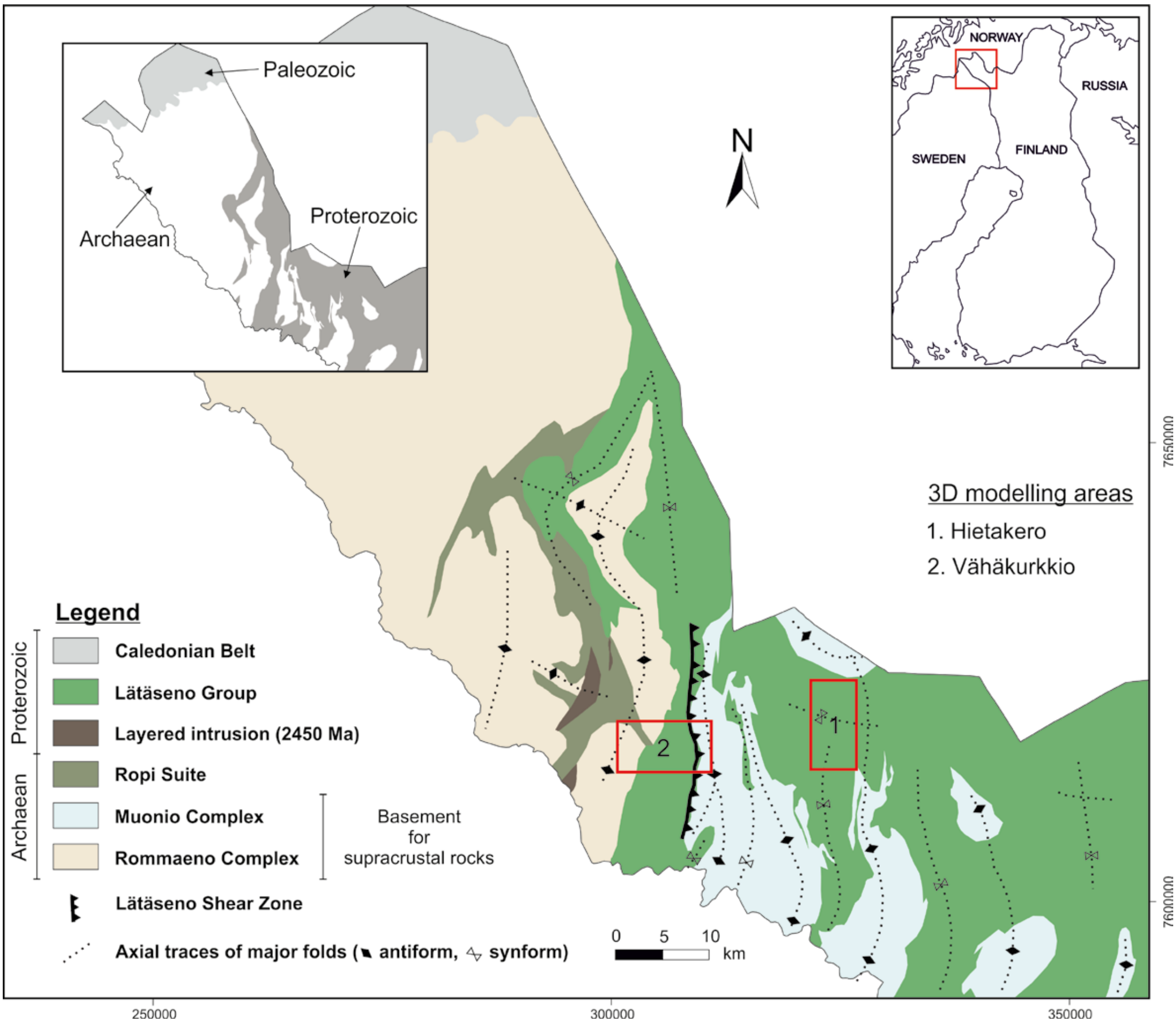

Fig. 1. Simplified geological map of the NW part of Finland showing the areas that have been modelled in 3D: 1 = Hietakero, 2 = Vähäkurkkio.

Hietakero area

The Hietakero area (Fig. 2) is characterized by a large scapolite-bearing gabbro sill, metamorphosed mafic volcanic rock, quartzite and sulphide-bearing schist. This metavolcanic rock is amphibolite, which was originally amydaloidal lava of thoileiitic composition. In chemical composition, it is comparable to the gabbros in the area, suggesting a comagmatic source for these igneous rocks. The sulphide-bearing schist is unexposed, but it has been intersected in one drill profile, where the rock is probably of orthomagmatic origin. The rocks of the Hietakero area have been multiply folded, as indicated by the complex interference pattern. The fold axes are orthogonally located, indicating N–S- and E–W-trending shortening.

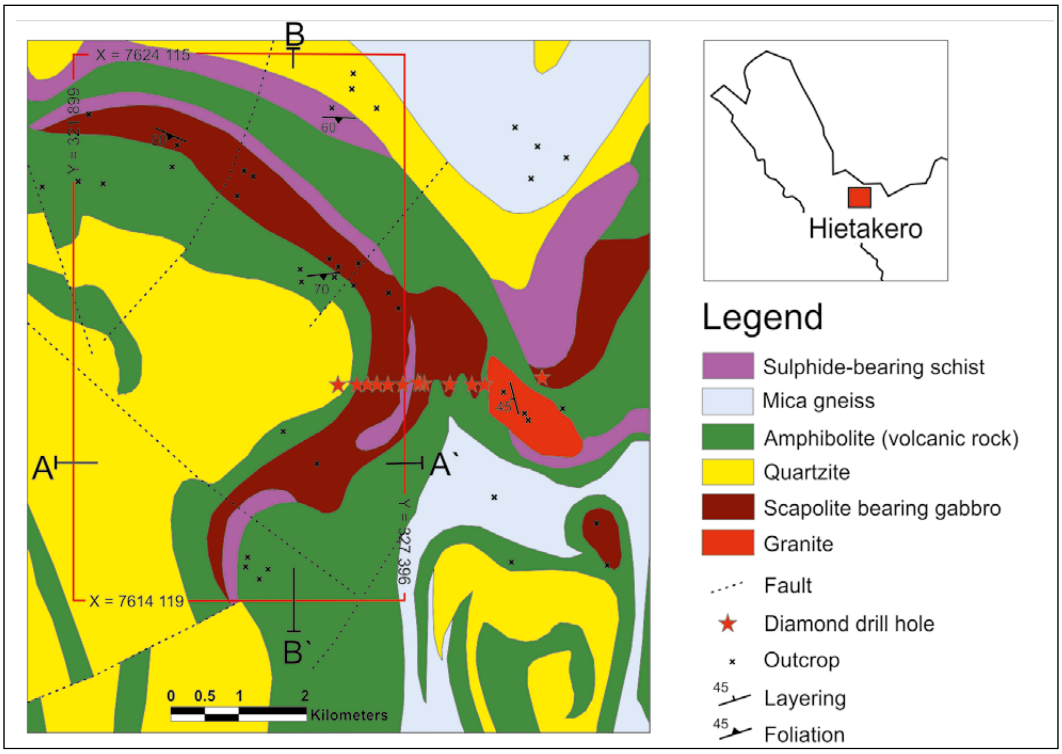

Fig. 2. Simplified lithological map of the Hietakero area. The 3D modelled area is indicated by a red box. The lithological map is redrawn after the digital bedrock database of Finland (Bedrock of Finland – DigiKP). For cross-sections along profiles A-A´ and B-B´, see Fig. 5.

Vähäkurkkio area

The Vähäkurkkio area (Fig. 3) represents the Lätäseno Group overlying the older rocks of Archaean basement and supracrustal rocks of the Ropi Group. The stratigraphic section of the Lätäseno Group is unclear, but the rocks show a transition from a continental to a marine sedimentary depositional environment. The basal conglomerate and laminar arcose quartzite in the western part of the area indicate a continental environment, whilst the carbonate-scapolite- and sulphide-bearing volcanoclastic sediments suggest a marine environment. Furthermore, the pillow structures in the mafic lavas provide evidence of a marine environment. This type of transition in sedimentary facies indicates transgression during which the sea level rose relative to the land. The Vähäkurkkio area is characterized by a N–S-trending strike of layering with a mainly moderately (30–45°) eastwards-dipping axial plane.

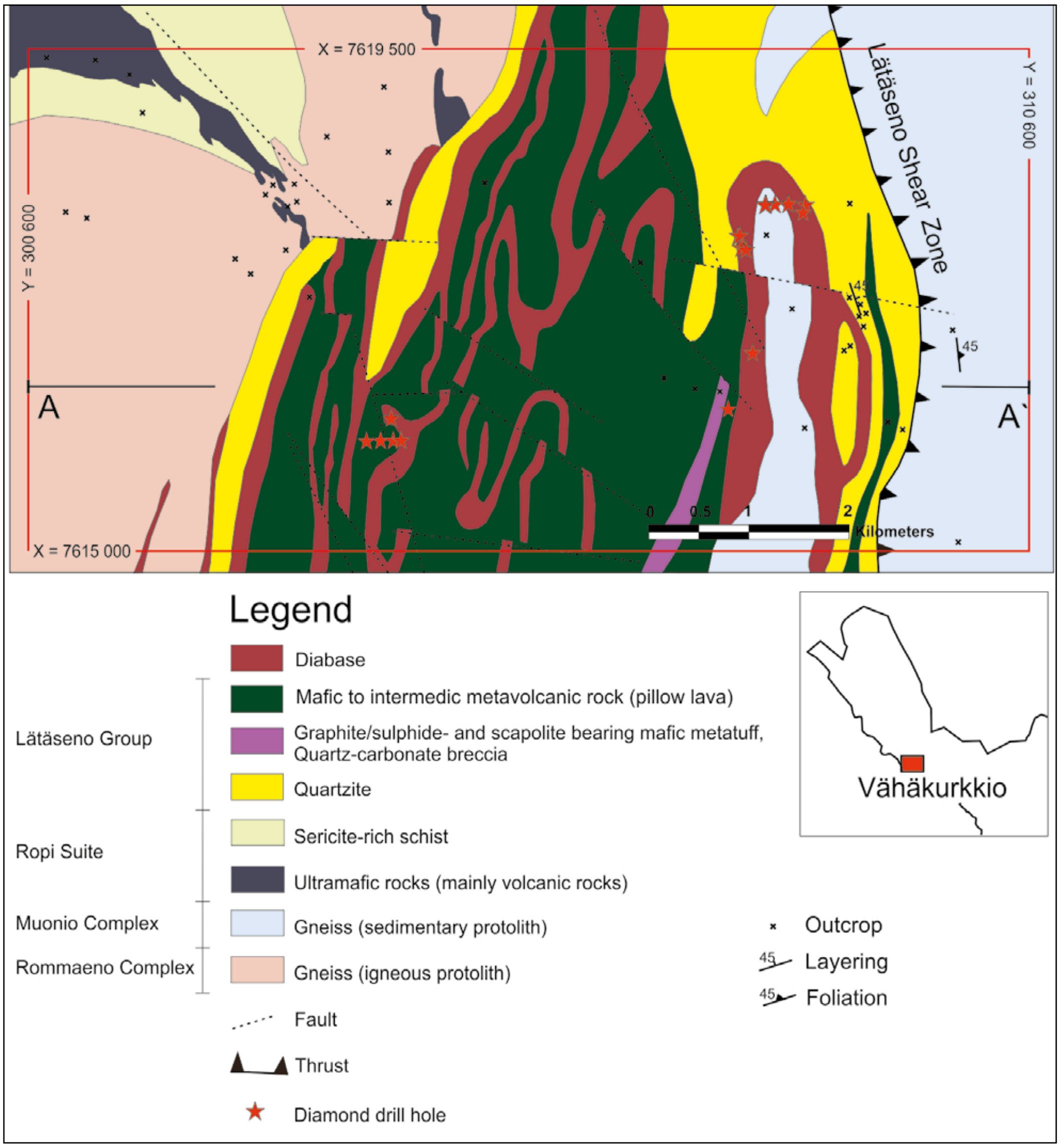

Fig. 3. Simplified lithological map of the Vähäkurkkio area. The 3D modelled area is indicated by a red box. The lithological map is redrawn after the digital bedrock database of Finland (Bedrock of Finland – DigiKP). For cross-section along profile A-A´, see Fig. 9.

MATERIALS AND METHODS

Geophysical data

The geophysical data used in the modelling included airborne EM, magnetic and ground gravity measurements and their inversion results. Geophysical maps and various derivatives were also used in 3D geological interpretations. Electromagnetic data were derived from the time domain SkyTEM survey that was performed by the Danish contractor SkyTEM Surveys Aps between 23 August and 7 September 2012. The survey also included magnetic measurement. An airborne magnetic survey of the Hietakero area and ground gravity surveys of both modelling target areas were conducted by GTK. Magnetic and gravity 3D inversions were carried out using UBC-GIF inversion software (Li & Oldenburg 1996, 1998).

Electromagnetic data and inversions

The time domain electromagnetic method involves measurement of the EM transient, which is dependent on the electrical conductivity structure of subsurface. The flight direction of the SkyTEM survey was E–W, and the line spacing was 100 m in the Vähäkurkkio and 200 m in the Hietakero area.

Inversion results of the electromagnetic data were provided by the contractor. The inversion was performed as a regularized, damped, least-squares inversion on individual sounding data along the profiles with a one-dimensional (1D), multi-layer model with 30 layers. In the inversion, the thickness of the layers was constant and layer resistivities were optimized in order to fit the measured data. The thickness of the uppermost layer was 5 m and the depth to the deepest layer boundary was 500 m. The resistivity of the initial model for the inversion was set to 100 Ωm. Layer resistivities were enabled to vary between 0.1–10 000 Ωm. A one-dimensional model was obtained approximately every seven metres along the flight lines. Finally, a quasi-3D conductivity model was obtained by interpolating 1D models into the 3D space.

The recorded electromagnetic signal level had a high dynamic range, indicating sharp geological boundaries in the survey area. The inversion code operates in a 1D mode and, consequently, hyperbolic artefacts caused by 3D structures could be seen throughout the area. These features are not a representation of the real geology and were thus treated carefully in the modelling.

Magnetic data and inversions

The entire land area of Finland is covered by GTK's high-resolution "three-in-one" aerogeophysical dataset, which includes simultaneous magnetic, radiometric and electromagnetic measurements at 200 m line spacing (Airo 2005). In the Hietakero area, the airborne surveys were carried out in 1983 with a flight altitude varying from 31 to 38 metres. The flight direction of the study area was E–W. The instrumentation and data processing have been described in detail in Hautaniemi et al. (2005). The SkyTEM survey also included standard magnetic measurements. The obtained magnetic data were used in the Vähäkurkkio modelling, as the survey line spacing of 100 m provided a higher resolution than that of GTK's standard airborne measurements (200 m).

3D magnetic inversions were carried out using the UBC-GIF inversion software MAG3D. The aim of inversion is to find a theoretical model that produces the measured magnetic anomalies of the target area. The mesh file defines the discretization of the 3D volume of bedrock. For the Hietakero area, a mesh containing 238 x 250 x 30 cells was constructed. A fixed horizontal dimension of 50 x 50 m and an increasing vertical dimension were used for cells. The increasing cell height limits the total number of cells and consequently decreases the duration of the inversion. The size of the Vähäkurkkio mesh was 362 x 250 x 33 cells. As the Vähäkurkkio magnetic dataset had a higher resolution, finer cells widths of 25 x 25 m were used in the magnetic 3D inversion. Prior to inversions, the magnetic datasets were processed using various techniques aimed at removing regional trends.

3D inversion can be unconstrained or constrained. Constrained inversion requires additional information on the magnetized structures and bodies. In constrained inversion, cell property values can be either fixed or allowed to vary within an assigned range. Various initial models can be used if additional information is available. Unfortunately, such information was not available in the present study. Therefore, unconstrained inversions with homogeneous initial models were used in 3D inversions. Unconstrained inversions yield a smooth structure that tends to disperse with depth, making geological interpretation unambiguous. Nevertheless, the inversion results give information on the dip directions of anomalous bodies and structures. The total sizes of the 3D models were large, containing approximately 1.8–3 million cells. The amount of magnetic data used was 26 000–33 000 values. Inversions took 10–18 hours to yield the final results using a standard laptop. In general, all inversions were successful, as the obtained models produced the measured magnetic anomalies. The inversion model susceptibilities were <0.31 SI units for the Hietakero area and <0.79 SI units for the Vähäkurkkio area.

Gravity data and inversions

The ground gravity datasets of the modelling areas were collected during 1972–2012. The regional gravity measurements were carried out at a density of one to four observations per square kilometre using Worden, Scintrex CG-3 and CG-5 gravity meters (Elo 1997, 1998). Gravity data processing, including reductions and topographic corrections, was performed using GTK's in-house developed software. The equations used for normal gravity were based on work by Kiviniemi (1980). The acquired regional gravity datasets mainly reflect large intrusions, crustal-scale structures, lithological units, and fault and shear zones.

3D inversions of regional gravity data were carried out using the UBC-GIF (GRAV3D) inversion software (Li & Oldenburg 1998). Prior to inversions, regional trends were removed from the data. The gravity data were acquired using a point spacing of 500 m to 1 km. Therefore, cell widths of 250–500 m were used, leading to a much shorter duration than that for magnetic inversions.

Geological data

In northern Finland, the glacial till cover and weathering of the uppermost bedrock limit the possibilities for direct field observations, and geological maps (such as shown in Figs. 2 and 3) are therefore actually mostly interpreted from the geophysical data. Although the data from drillings and outcrops for these maps are very sparse, the data are important, because they provide the only material directly from the bedrock. One profile has been drilled in the Hietakero area, including 13 diamond drill cores, and three profiles in the Vähäkurkkio area, comprising 20 diamond drill holes. The depth extent of these drillings is 100 m at maximum and their value is therefore comparable to outcrop observations.

Modelling

The 3D models were constructed in several steps using the GoCad ("Geological objects Computer aided design") modelling package (Mallet 1992). The steps included data importing, interpretation, model building and validation. In modelling, special emphasis was placed on 4D. In other words, the modelling was performed with emphasis on reconstruction of the geological evolution in the areas so that the model dimensions and structures would logically explain the data.

3D/4D MODELS

Hietakero area

The 3D geological model of the Hietakero area was restricted to the coordinates shown in Figure 2. The area covers 50 km^2 (5 × 10 km), for which the modelling was performed to a depth of 2.5 km. The rocks of the Hietakero area can be recognized by their geophysical features (Fig. 4). The rocks with highest densities, i.e. gabbro and amphibolite, may be recognized from the gravity data. The amphibolite shows high susceptibilities and sulphide-bearing schists can be detected from the conductive zones. Figure 5 presents the geophysical inversion and lithological models along two cross-sections (the locations of these sections are shown in Figs. 2 and 6). The results of the gravity and aeromagnetic inversions may be used to delineate the contacts of the gabbro and amphibolite and the dip of the contacts. The conductive zones occur on the sides of magnetic zones, while the gravity inversion indicates a shallow depth for this folded sequence.

The 3D geological model (Fig. 6) was constructed by considering the relationship of the geophysical inversion results with the observed fold interference pattern and the geochemical similarity of gabbro and amphibolite. It is likely that the geological evolution of the Hietakero began with the sedimentation of quartzites and eruption of volcanic rocks. This was followed by a tilting episode during which the gabbroic intrusion comagmatic with volcanic rocks was emplaced. The tilting episode is required to explain why the gabbros and related conductive zones have not been detected everywhere in the fold structures (see Fig. 5). Subsequent folding episodes resulted in the distinct fold interference pattern of the area, characterized by orthogonal sets of folds (Fig. 7).

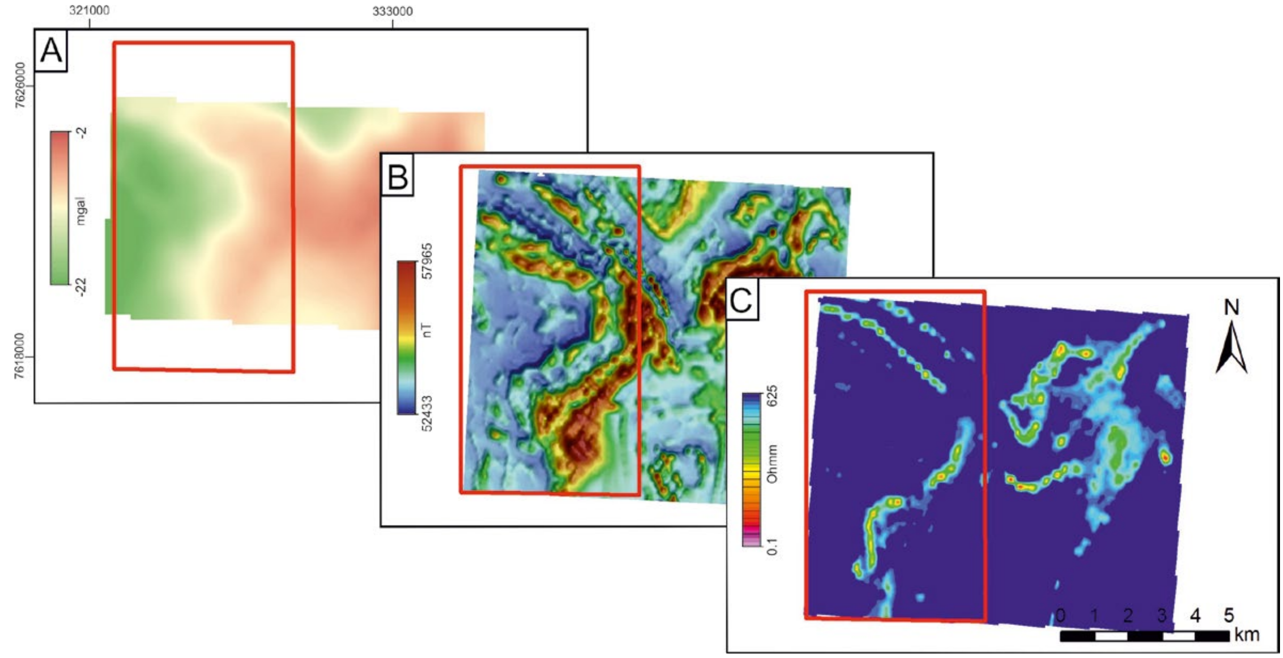

Fig. 4. Geophysical maps of the Hietakero area, with the 3D modelled area indicated by a red line (A. gravimetric, B. magnetic and C. conductivity). The 3D modelled area is indicated by a red box.

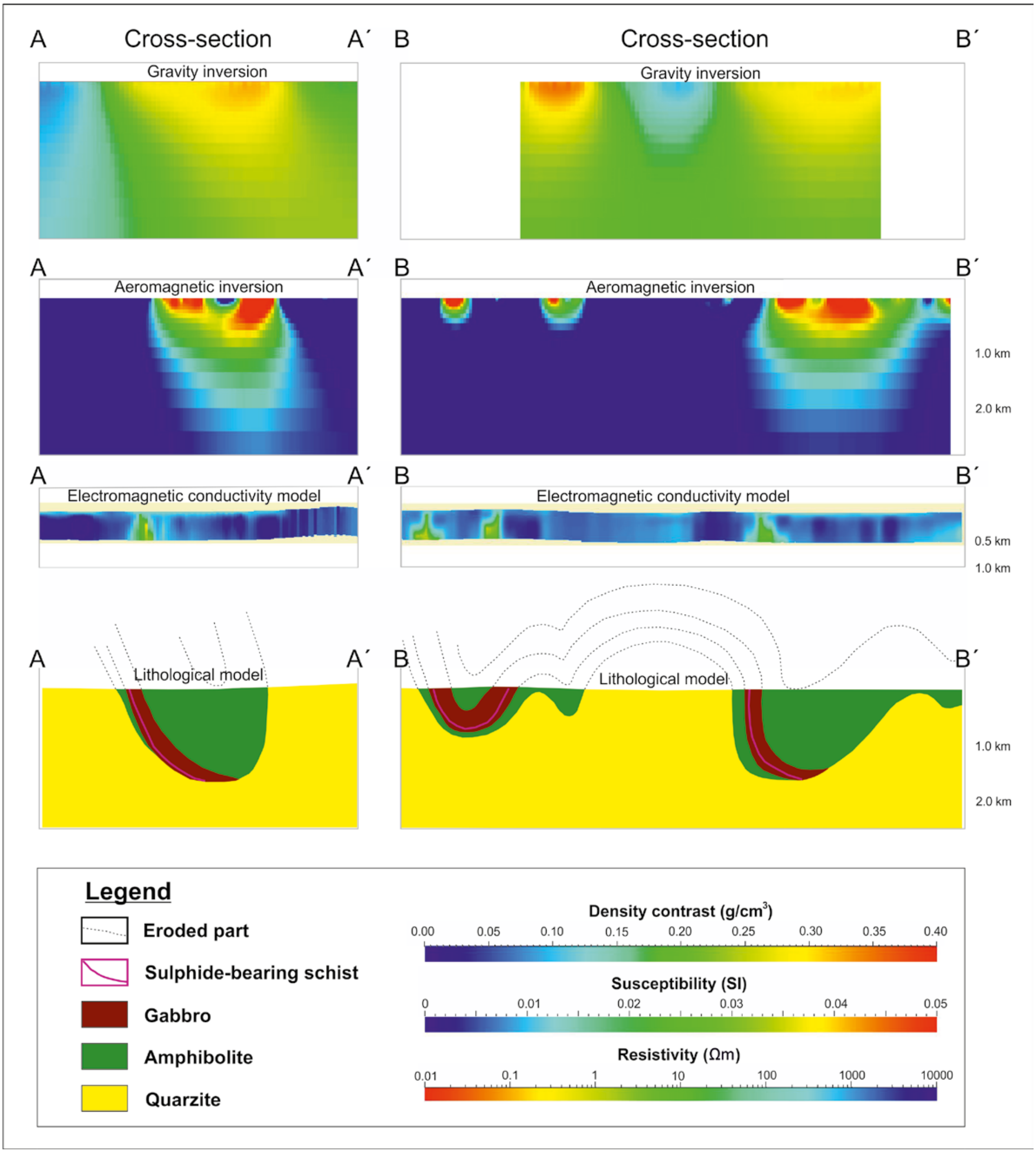

Fig. 5. Gravity and aeromagnetic inversions, an electromagnetic conductivity model and a lithological model of the Hietakero along cross-sections A-A´ and B-B´. The locations of the cross-sections are marked in Figs. 2 and 6.

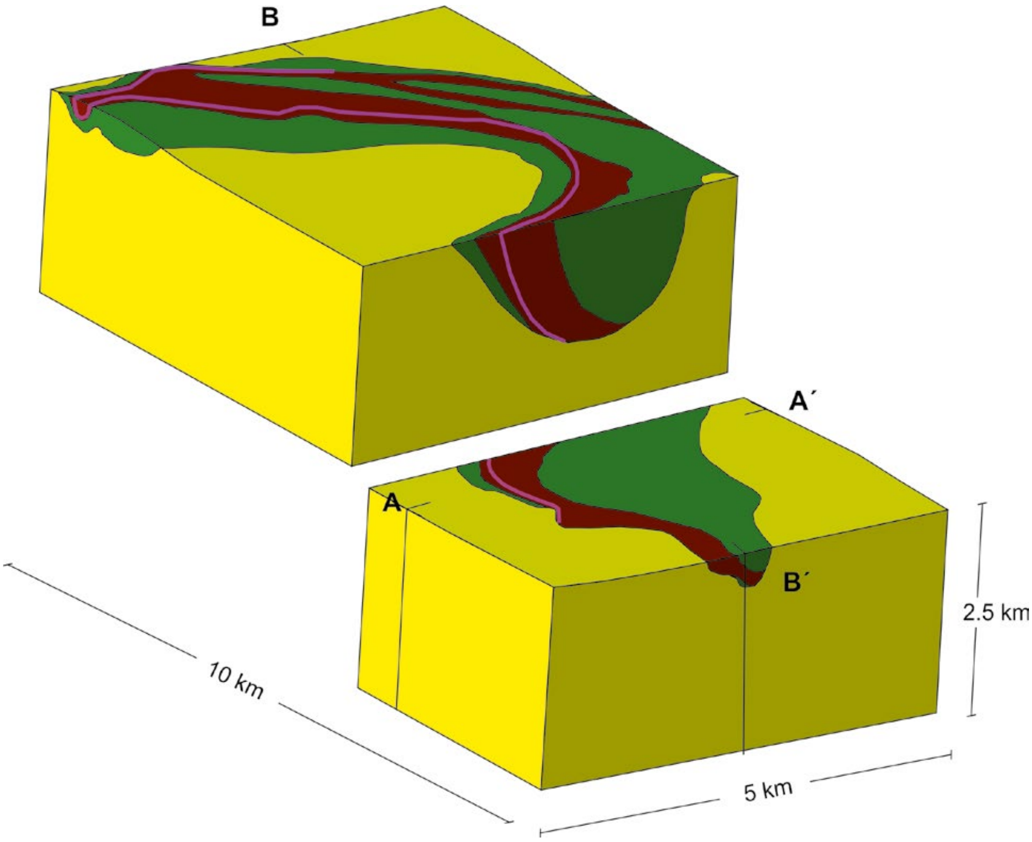

Fig. 6. The Hietakero 3D model area viewed from the southwest. The cross-sections A-A´ and B-B´ are shown by the aeromagnetic inversion, electromagnetic conductivity model and lithological model in Fig. 5. The locations of the cross-sections are marked in Fig. 2.

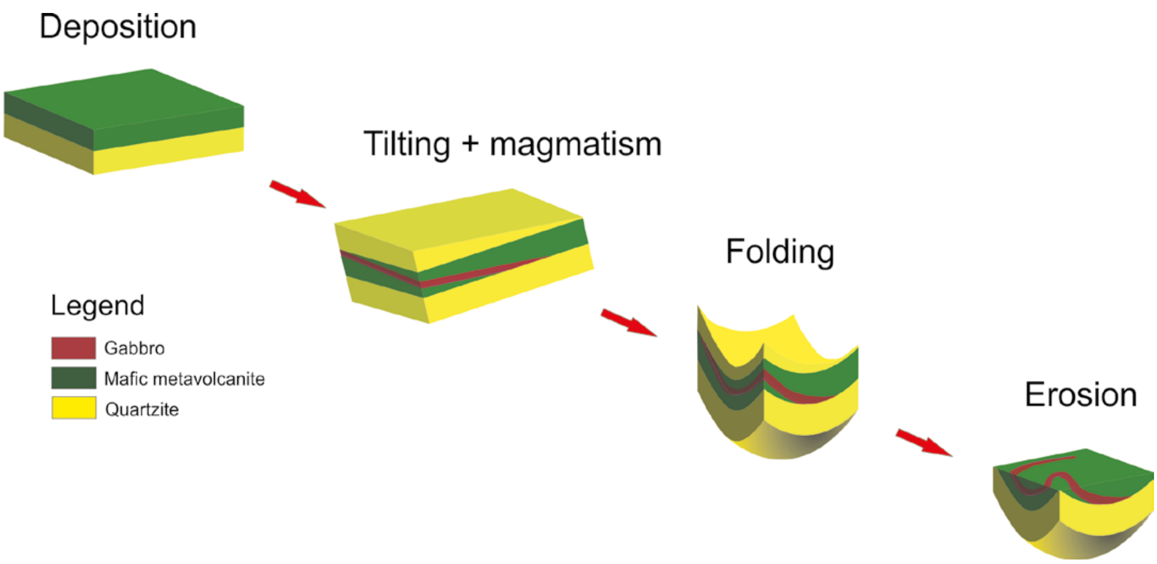

Fig. 7. Schematic diagram showing the structural evolution of the Hietakero area.

Vähäkurkkio area

The 3D geological model of the Vähäkurkkio area was restricted to the coordinates shown in Figure 3. The area covers 45 km^2 (10 × 4.5 km) and was modelled to a depth of 2.5 km. The Vähäkurkkio area can be divided into two parts on the basis of geophysics (marked with a white line in Fig. 8). In the western part of the belt, the magnetic anomalies are continuous, because they are generated by mafic dykes. In contrast, the anomalies in the eastern part are more scattered and display characteristics of intensively folded rocks (Fig. 8A). It is therefore likely that the anomalies of the eastern part are due to magnetite-rich layers of tuffagenous rocks rather than dykes as earlier interpreted (see map of Fig. 3). The presence of magnetite-rich layers of tuffagenous rocks in the eastern part has been revealed at least at the sites of recent diamond drillings (drilling sites are indicated in the map in Fig. 3). These drillings have also confirmed that the tuffagenous rocks contain various amounts of graphite and sulphide minerals (see Konnunaho et al. 2013), which explains why the rocks are more conductive in the eastern part (Fig. 8B). The regional Bouguer data (Fig. 8C) indicate that although the areal extent of the LSB is relatively large, the schist belt itself does not show a distinct positive anomaly. In contrast, it shows only a local maximum in a larger-scale gravity minimum.

Figure 9 presents cross-sections of the geophysical and lithological 3D models of the Vähäkurkkio area (the locations of these sections are indicated in Figs. 3 and 10). The 3D gravity inversion indicates that the depth extent of supracrustal rocks in the Vähäkurkkio modelling area is very shallow. It also shows that structurally the basement forms an antiform. The antiform is confirmed by observed dip directions in the supracrustal rocks of the Ropi Suite in the west and Lätäseno Group in the east. The dip directions are also visible in the aeromagnetic inversion and electromagnetic conductivity

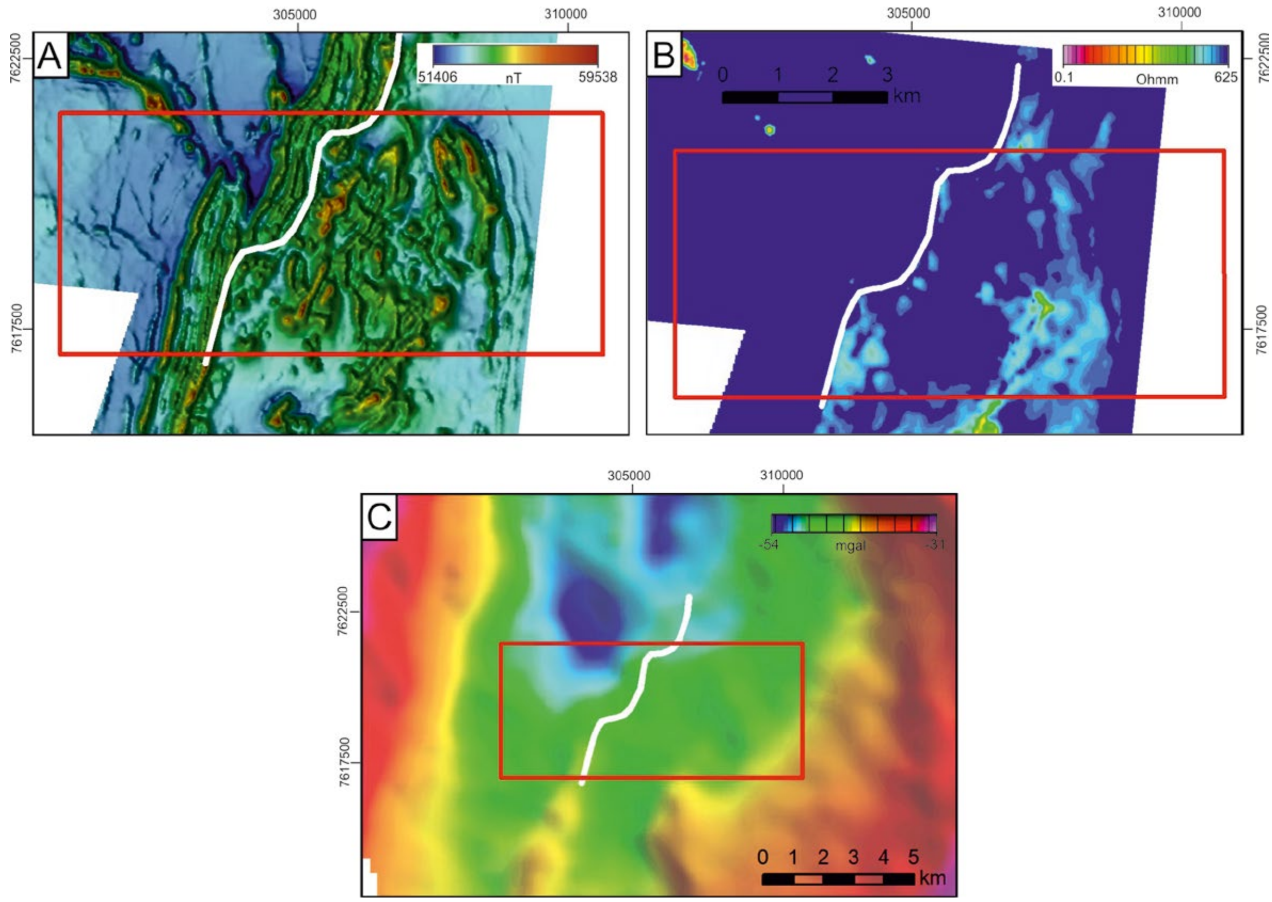

Fig. 8. Geophysical maps of the Vähäkurkkio area, with the 3D modelled area indicated by a red box (A. magnetic, B. conductivity and C. gravimetric). The white line represents a border marking geophysically distinct parts of the modelling area (see text for further explanation).

model. Aeromagnetic inversion indicates the shallow depth of the schist belt fairly well.

The 3D geological model of Vähäkurkkio (Fig. 10) was constructed by considering the relationship of the very shallow and folded section of formations showing transgression with the results of geophysical modelling, i.e. gravimetric and aeromagnetic inversions and the electromagnetic conductivity model. The geological evolution of the Vähäkurkkio area is envisaged as the folding of a volcano-sedimentary sequence that was deposited during transgression. The vergence of folding is due to later thrusting from the east along the shear zone presently known as the LSZ (Fig. 11).

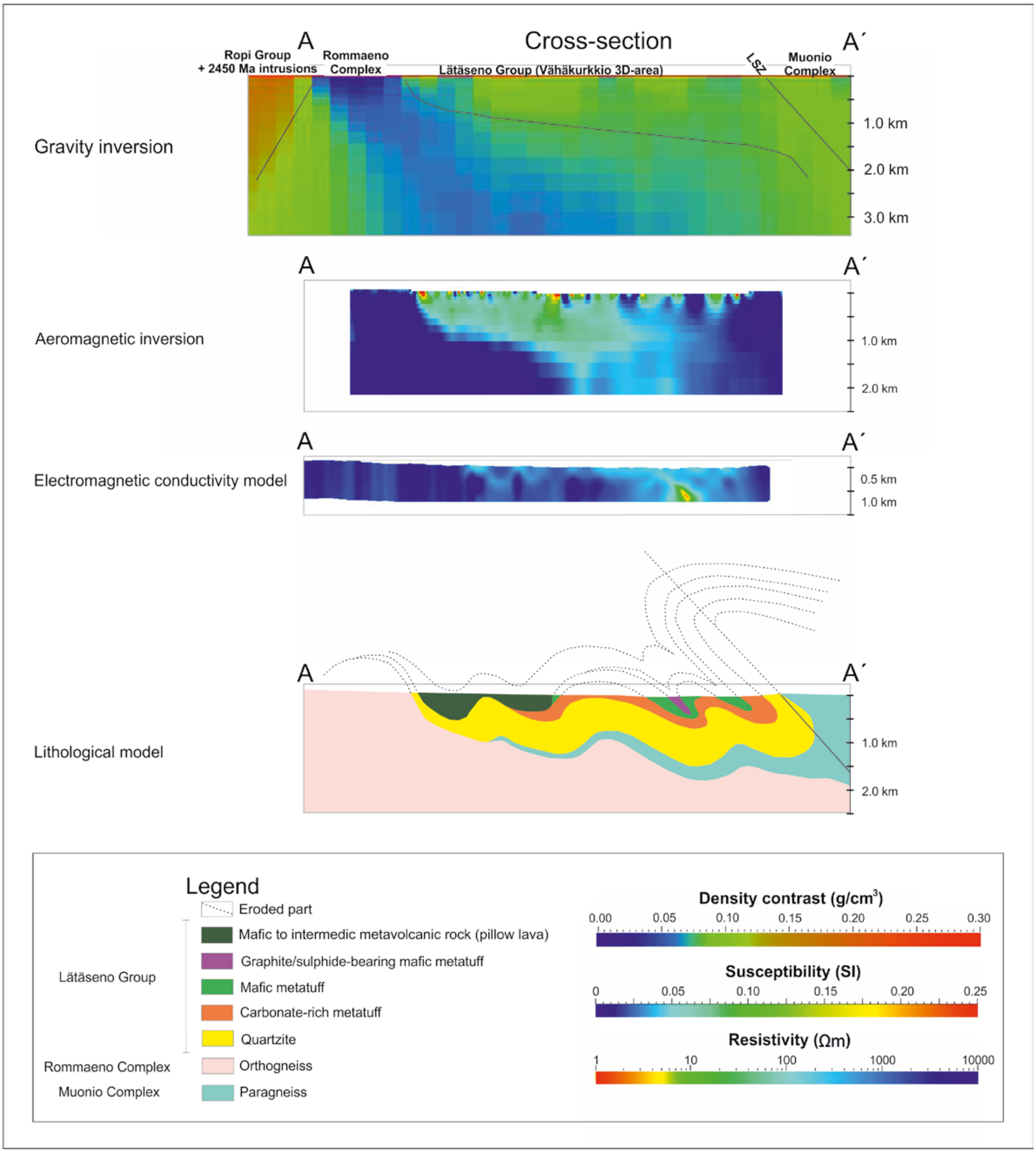

Fig. 9. Gravity and aeromagnetic inversions, electromagnetic conductivity model and lithological model along cross-section A-A´. The location of the cross-section is marked in Figs. 3 and 10.

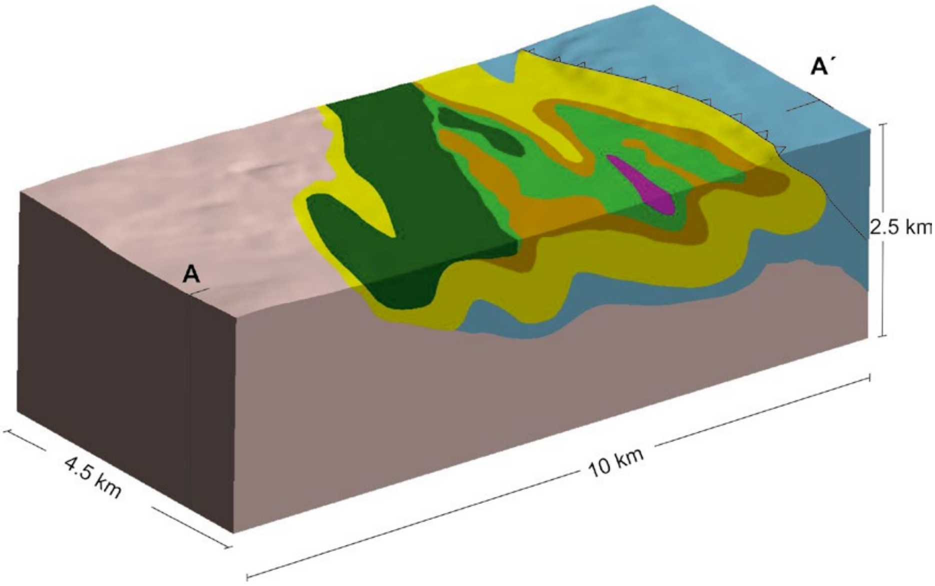

Fig. 10. The Vähäkurkkio 3D model area viewed from southwest. The cross-section A-A´ is shown by the gravimetric inversion, aeromagnetic inversions, electromagnetic conductivity model and lithological model in Fig. 9. The location of the cross-section is marked in Fig. 3.

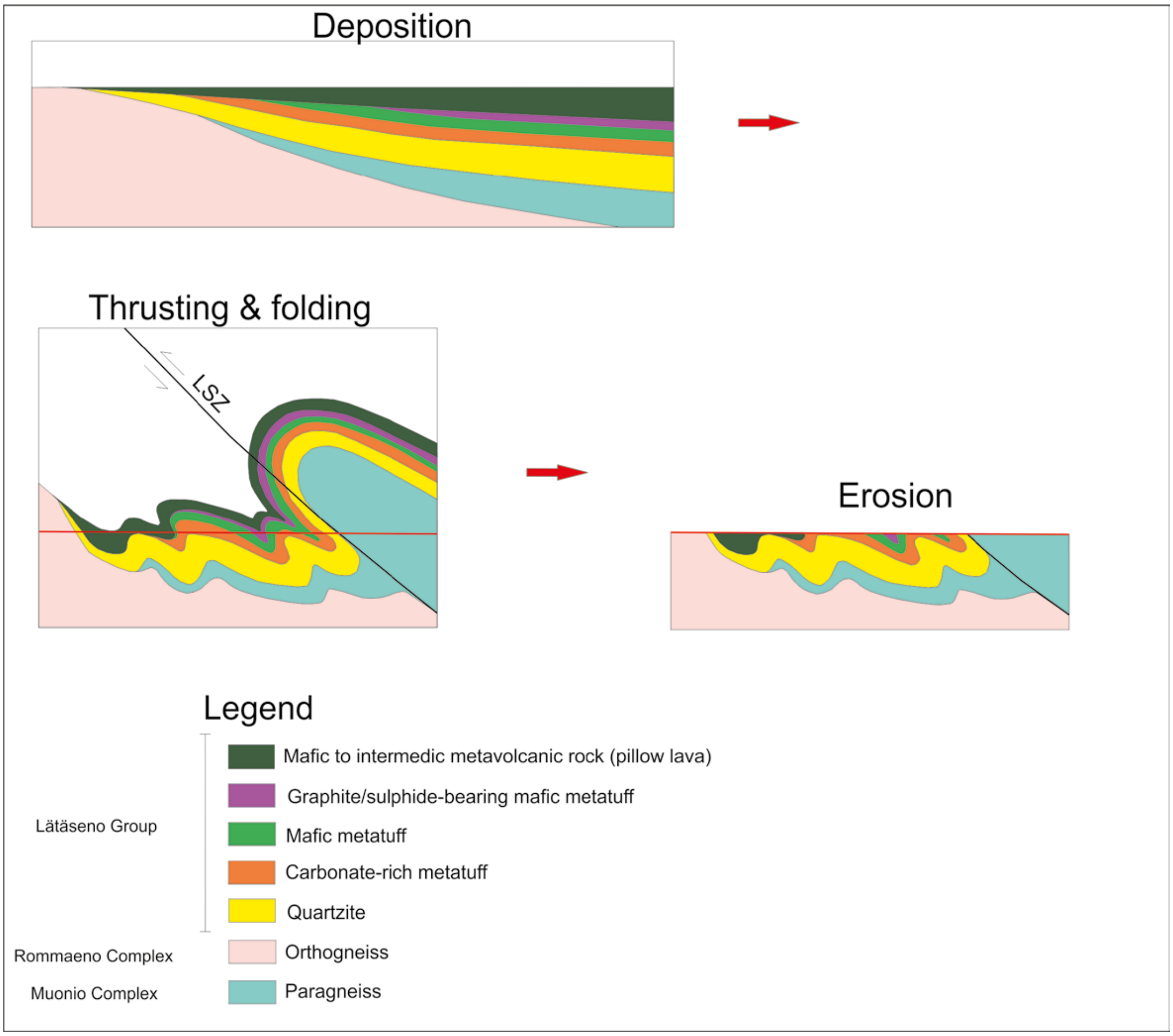

Fig. 11. Schematic diagram showing the structural evolution of the Vähäkurkkio area.

DISCUSSION & CONCLUSIONS

3D potential field inversion provides a tool for modelling, because it displays features required by the geophysical data from the modelling area. In addition to geophysical inversions, the modelling should make use of data from mappings and drillings when available. However, in many areas in Northern Finland, geophysical methods provide the only available data for the modelling.

Ideally, a 3D model is in harmony with the data. However, in the reconstruction of large-scale models, a good approach is to add a process-oriented view in modelling. By including the geological evolution of the model area, the model comes to include a historical statement and it is easier to test geological questions, for instance, by drilling.

ACKNOWLEDGMENTS

We would like to thank our both reviewers with sincerest gratitude. The first author would like to thank Tuomo Manninen for stimulating discussions on the stratigraphy and geology of Lätäseno Schist Belt.

REFERENCES

Airo, M.-L. (ed.) 2005. Aerogeophysics in Finland 1972-2004: Methods, System Characteristics and Applications. Geological Survey of Finland, Special Paper 39. 197 p.

Bedrock of Finland – DigiKP. Digital map database [Electronic resource]. Espoo: Geological Survey of Finland [accessed 11.2.2014]. Version 1.0. Available at: http://www.geo.fi/en/bedrock.html

Bergman, S., Kübler, L. & Martinsson, O. 2001. Description of regional geological maps of northern Norrbotten County (east of the Caledonian orogen). Geological Survey of Sweden. 110 p.

Eilu, P. 1984. Enontekiön Palovaaran-Järämän alueen geologiaa. Unpublished M. Sc. thesis, Department of Geology, University of Turku. 106 p. (in Finnish)

Elo, S. 1997. Interpretations of the gravity anomaly map of Finland. Geophysica, 33, 51–80.

Elo, S. 1998. Gravity investigations of the Geological Survey of Finland 1995-1997. Bulletin d'Information - Bureau Gravimétrique International 83, 59–63.

Hautaniemi, H., Kurimo, M., Multala., J., Leväniemi, H. & Vironmäki. J. 2005. The "three in one" aerogeophysical concept of GTK in 2004. In: Airo, M.-L. (ed.) Aerogeophysics in Finland 1972-2004: Methods, System Characteristics and Applications. Geological Survey of Finland, Special Paper 39, 21–74.

Idman, H. 1988. Ropi. Geological map of Finland 1: 100 000, Pre-Quaternary Rocks, Sheet 1832. Geological Survey of Finland.

Kantti, J.-P. 2002. Kaamajoen gabronoriitti-intruusio Enontekiöllä. Unpublished M.Sc. thesis. Department of Geology, University of Turku. 115 p. (in Finnish)

Kiviniemi, A. 1980. Gravity measurements in 1961-1978 and the results of the gravity survey of Finland 1945-1978. Publications of the Finnish Geodetic Institute 91.

Konnunaho, J., Heikura, P., Hulkki, H., Törmänen, T. Peltoniemi-Taivalkoski, A., Sarala, P., Manninen, T. & Salmirinne, H. 2013. Mineraalipotentiaalin arviointi raportti Enontekiö Käsivarsi. Geological Survey of Finland, archive report 7/2013. 156 p. + 6 appendices. (in Finnish with English abstract)

Lehtovaara, J. J. 1994a. Kilpisjärvi. Geological map of Finland 1: 100 000, Pre-Quaternary Rocks, Sheet 1823. Geological Survey of Finland.

Lehtovaara, J. J. 1994b. Halti. Geological map of Finland 1: 100 000, Pre-Quaternary Rocks, Sheet 1842. Geological Survey of Finland.

Lehtovaara, J. J. 1995. Kilpisjärven ja Haltin kartta-alueiden kallioperä. Summary: Pre-Quaternary rocks of the Kilpisjärvi and Halti Map-Sheet areas. Geological Map of Finland 1: 100 000, Explanation to the Maps of Pre-Quaternary Rocks, Sheets 1823 and 1842. Geological Survey of Finland. 64 p.

Li, Y. & Oldenburg, D. W. 1996. 3-D inversion of magnetic data. Geophysics 61, 394–408.

Li, Y. & Oldenburg, D. W. 1998. 3D inversion of gravity data. Geophysics 63, 109–119.

Mallet, J. L. 1992. GOCAD: a computer-aided design program for geological applications. In: Turner, A. K. (ed.) Three-dimensional Modelling with Geoscientific Information Systems. Mathematical and Physical Sciences 354, Series C, 123–141. Kluwer Academic Publisher, Springer NATO ASI.

Matisto, A. 1959. Enontekiö. The General Geological Map of Finland 1:400 000. Pre-Quaternary Rocks, Sheet B8. Geological Survey of Finland.

Matisto, A. 1969. Enontekiö. General Geological Map of Finland 1:400 000, Explanation to the Map of Rocks, Sheet B8. Geological Survey of Finland. 78 p. + 1 appendix.

Ruotsalainen, A., Laine, E.-L. & Niemi, S. 2013. Potentiaalikenttien 3D-inversiosta GTK:ssa. Sovelletun Geofysiikan XIX Neuvottelupäivät, 24.-25.9.2013, Eurajoki, Abstraktikokoelma. 43 p. (in Finnish)

Sorjonen-Ward, P. & Luukkonen, E. J. 2005. Archaean rocks. In: Lehtinen, M., Nurmi, P. & Rämö, T. (eds) Precambrian Geology of Finland. Key to the evolution of the Fennoscandian Shield. Elsevier. Developments in Precambrian Geology, Vol. 14, 19–99.