



Structural interpretation of airborne geophysical data: examples from Finland

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Title of report Structural interpretation of airborne geophysical data: examples from Finland Rakennetulkintoja lentogeofysikaalisen aineiston pohjalta: esimerkkejä Suomesta			
Abstract This report summarizes geophysical structural interpretations that have been conducted during several years and consider different parts of Finnish bedrock. Qualitative lineament interpretations were based on mainly airborne magnetic data. Regional gravity data were used to complement identification of regional structures. Visual inspection of lineaments was made from processed data sets including different versions of gradient and filtered data. Specific interest was laid on systematic trends and parallel structures in regional data sets: aeromagnetic and gravity data throughout whole Finland. Great deal of the work have been made as background information for different GTK projects and they were never published anywhere. Some of these interpretations are presented here to accomplish the whole picture although they have been earlier published in GTK internal report series. Raportti on yhteenvedo vuosien varrella toteutetuista geofysikaalisista kallioperän rakennetulkintoista eri puolilta Suomea. Kvalitatiiviset lineamentitulkinnat pohjautuvat havaintoihin systemaattisista suuntauksista ja yhdensuuntaisuuksista geofysikaalisissa aineistoissa. Tässä esitetyt tulkinnat on tehty pääasiassa käyttäen alueellisia aineistoja: painovoima- ja magneettisista aineistoista, jotka kattavat koko Suomen. Suuri osa työstä on tehty osana tai taustaselvityksinä GTK:n eri hankkeiden ja projektien toimintaa eikä niitä ole missään julkaistu. Osa tulkintoista on julkaistu aiemmin GTK:n sisäisissä sarjoissa ja referoitu tässä kokonaiskuvan takia.			
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1 INTRODUCTION

Motivation

Qualitative interpretation of bedrock structures has for years been based on visual inspection and integration of structural indications from different geophysical data sets. This report presents a brief summary of unpublished results of geophysical interpretations linked with several projects of the Geological Survey of Finland (GTK), starting from the 1980'ies. In practice the same structural information can nowadays be identified by using up-to-date semi-automatic methods, although in that context there is a risk that also geophysical signatures not related to geology may inadvertently be enhanced.

Purpose

In addition to structural lineament interpretations and tectonic trends presented over several study areas in Finland, also the general country-wide lineament trends inferred from different geophysical data sets are summarized at the end of this report. In order to outline both continuous and discontinuous structural indications in geophysical data sets, interpretation procedure has been based on the following steps as a common practice:

- 1) determination of provinces representing continuous geophysical patterns which result from different kind of deformation style and tectonic stress – these features correspond to geological shape-lines;
- 2) outlining of province boundaries, which may be shear zones or fault and fracture zones;
- 3) checking of intersecting lineaments;
- 4) searching systematic and parallel trends in lineament strikes or deformation patterns;
- 5) comparison of parallel regional boundaries or lineaments;
- 6) geological validation to look for geological reasons: mineralogical changes, metamorphic boundaries, type of faulting etc.

Data sets

Interpretations in this report are mainly based on the country-wide airborne geophysical data sets including magnetic, multi-frequency electromagnetic and gamma-ray spectrometry data provided by GTK (Hautaniemi et al. 2005, Moore 2008, Airo et al. 2011). Together with the Geodetic Institute of Finland, GTK has launched Bouguer-anomaly data of Finland (Elo 1997). The National Land Survey provides the digital elevation model (DEM) over Finland. Aeromagnetic, gravity and DEM data are here compared to seek and analyze regional tectonic trends and major lineaments over Finland. These structures can further be extended to the whole Fennoscandian shield.

All the databases used in the figures of this report are referred to as:

Airborne geophysical data © GTK

Regional gravity data © GTK and GI

Digital bedrock database of Finland © GTK

Mineral deposit database © GTK

Methods

Integrated interpretation of different processed geophysical datasets, together with DEM data is widely used for identifying structural bedrock blocks and their internal structures. Here the



main structural trends and block boundaries were interpreted mainly from horizontal derivative (HD) or tilt derivative (TDR) of upward-continued aeromagnetic data and Bouguer-anomaly data. Geophysical lineaments were hand-drawn by using Oasis software by Geosoft and by line-drawing in ArcMap. Aeromagnetic data were originally acquired along flight lines 200 m apart and at 35 m nominal flight altitude. This kind of data is too detailed to extract regional tectonic and structural features that appear as long-wavelength geophysical anomalies, so that aeromagnetic data was upward-continued to 3 or to 8 km to remove local variation and to compare better with regional gravity data, whose station spacing is ~5 km and interpolated cell size 2 km.

Methodological background

The use of gradient and filtered magnetic and gravity data became popular in structural interpretation as the survey and computer technology improved in the 1980-1990's. In those days I found directional horizontal derivatives to be effective in mapping systematic trends in GTK's aeromagnetic data and applied them widely in structural and tectonic interpretations from various parts in Finland, i.e. interpretation of south-eastern Finland (Airo 1999a), Kuhmo and Häme dykes (Airo 1999b), eastern Finland in 2002, Misi-Raajärvi area in 2001-2004, and Central Finnish Lapland from the 1980ies to 2005 (Airo 2007). Later the tilt derivative has become popular and found to be even more effective and has widely been applied (see references for TDR: Verduzco et al. 2004, for more information and comparison see e.g. Pilkington & Keating, 2004). In several projects for structural interpretation in Finland, TDR of upwards continued magnetic data combined with TDR of gravity data has been used for delineating boundaries of structural bedrock blocks. A good example is the interpreted structures of the Häme volcanic belt in South Finland (Airo & Leväniemi 2012).

2 CONTINUOUS OR DISCONTINUOUS GEOPHYSICAL FEATURES

Continuous magnetic anomaly signatures in high-resolution surveys can be related to ductile geological 'shape-lines' which are thought to describe internal structural features and fabrics of different rock types. The magnetic patterns mainly reflect those geological features that were created during the latest deformational episodes when the magnetic minerals were redistributed. In favourable conditions new magnetic material was created which increased the total magnetization of rocks in two ways: magnetic susceptibility increased and new components of remanent magnetization. In Finland the magnetic anomaly patterns were influenced strongly and widely by the enhanced role of the remanent magnetization that was acquired during Proterozoic metamorphic events. In this category, systematic, repeated, curved, ductile features are regarded as corresponding to late fold structures. On magnetic maps the fold axes form linear trends which often can be recognized as pronounced fractured zones. Later deformation processes, such as chemical alteration, development of foliation or any tectonic episodes under lower temperatures may have disturbed the continuous magnetic signature in the already cooled crust. Fractured patterns, weakened anomaly amplitudes and crosscutting lineaments reflect the brittle deformation stage that updated the magnetic picture of metamorphosed terrains (Fig 1).

Extensive, ductile, continuous magnetic shape-lines delineate magnetic provinces with well-defined contacts. Inside a structural magnetic province the magnetic signatures may show sys-

tematic patterns, but along the province boundaries the systematic, repeated magnetic patterns are disturbed. The province boundaries and contacts are generally structures that are revealed by regional gravity minima associated with reduced magnetization. This is because the shear and fault zones commonly contain weakly magnetic low-density minerals. Tilt derivatives of magnetic and gravity data were used to enhance these structures.

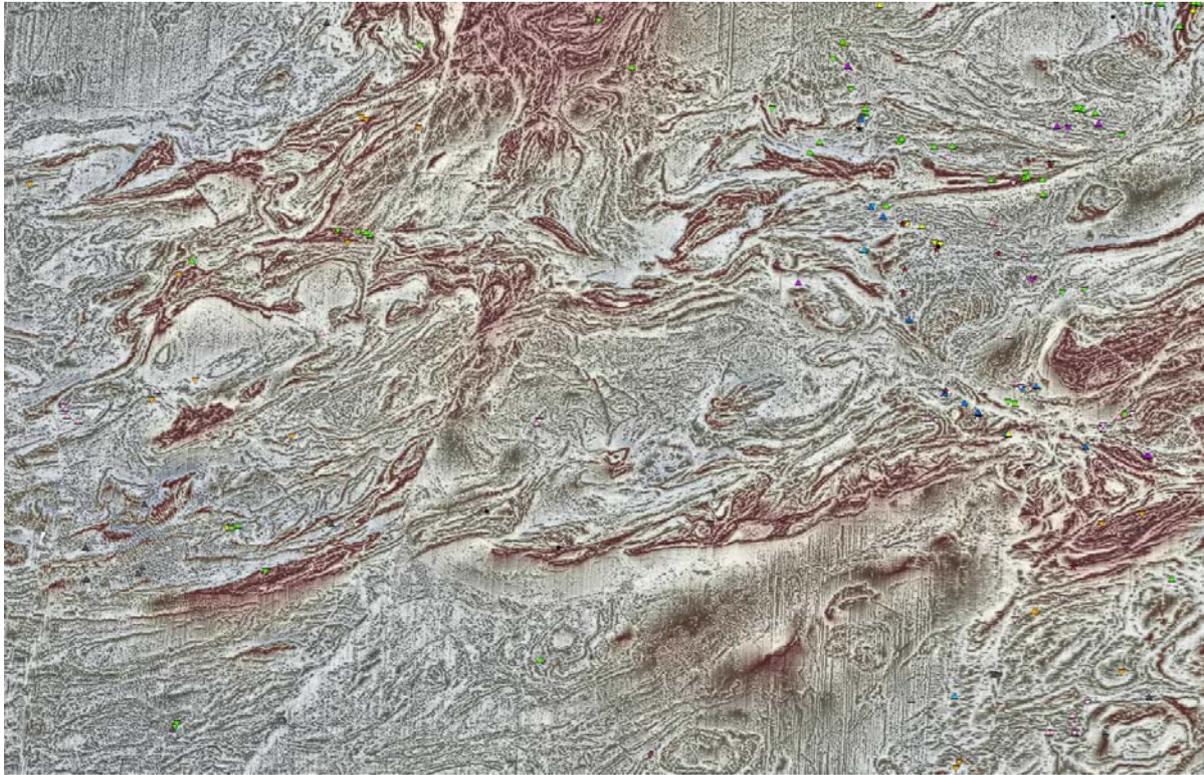


Figure 1. Magnetic tilt derivative can be related to structural patterns of bedrock. Continuous, plastic deformation shape-lines are disturbed by non-magnetic, narrow lineaments that are fault and fracture zones. The red anomalies indicate increased magnetic field intensity. Small coloured dots represent different known ore occurrences from GTK's mineral deposit database. Some of them are located along shape-lines corresponding to bedding, and some of them along fault zones.

The country-wide regional gravity data (~5 km station spacing) mainly represents the long-wavelength part of the gravity field. The revealed structures can be interpreted to reach deep in the crust. The major zones of decreased gravity field and its gradients represent contacts of crustal blocks and the outline of geological complexes in southern Finland (Fig. 2). Gravity gradients along the contacts of geological complexes 1) delineate crustal provinces having different mean density, 2) reflect the variation of specific gravity between different main rock-forming minerals, 3) are due to subsurface rocks or formations of higher density, and/or 4) the change in metamorphic grade. Many known mineral occurrences tend to be located along or in the close-by the second-order fracture zones that are related to the main province boundaries. The most pronounced and parallel boundary zones in Fig. 2, striking NW are the Raahe-Laatokka zone and the outlines of the Satakunta sandstone.

Linear structures in regional geophysical data can be related to crustal weakness zones that represent surface projections of deep crustal structures. By closer look they are composed of

groups of several smaller lineaments with directional variation but having almost similar orientations, like the NW trend as illustrated in Fig. 3. A more detailed view is given in Fig. 4, where the NW trend (green lines) controls the division of the granitoid area (red) into blocks. The aeromagnetic data displays magnetic anomalies due to diabase dykes and dyke swarms both parallel to the NW trend but also in a deviating direction.

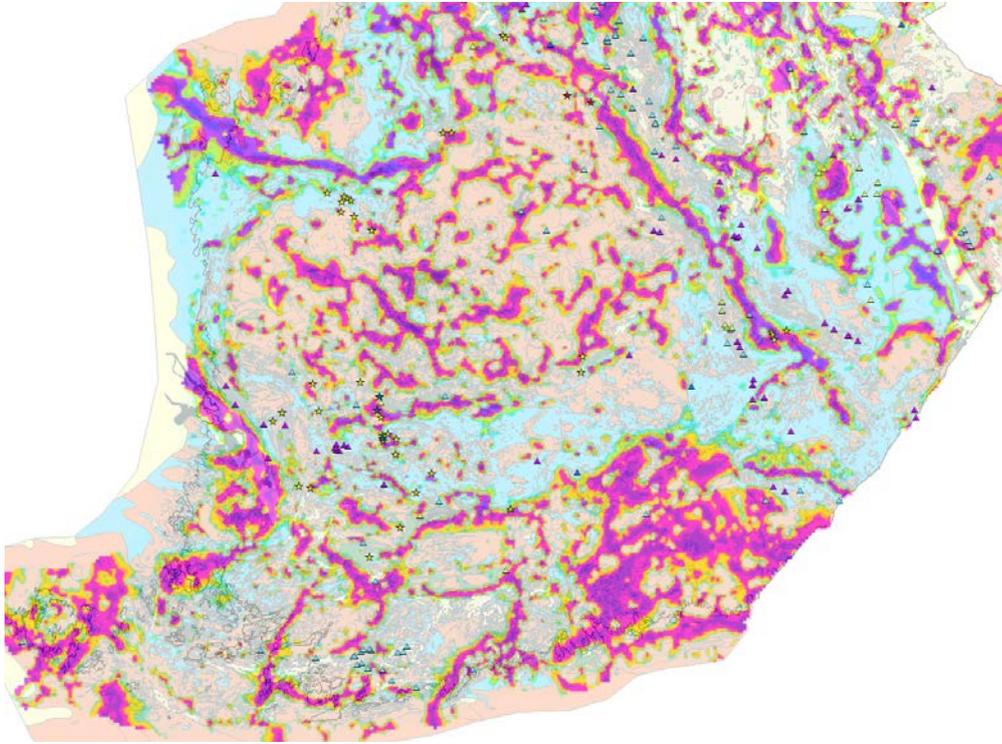


Figure 2. Example of province boundaries observed in gravity data, southern Finland. Tilt derivative of gravity data outlines the main geological complexes.

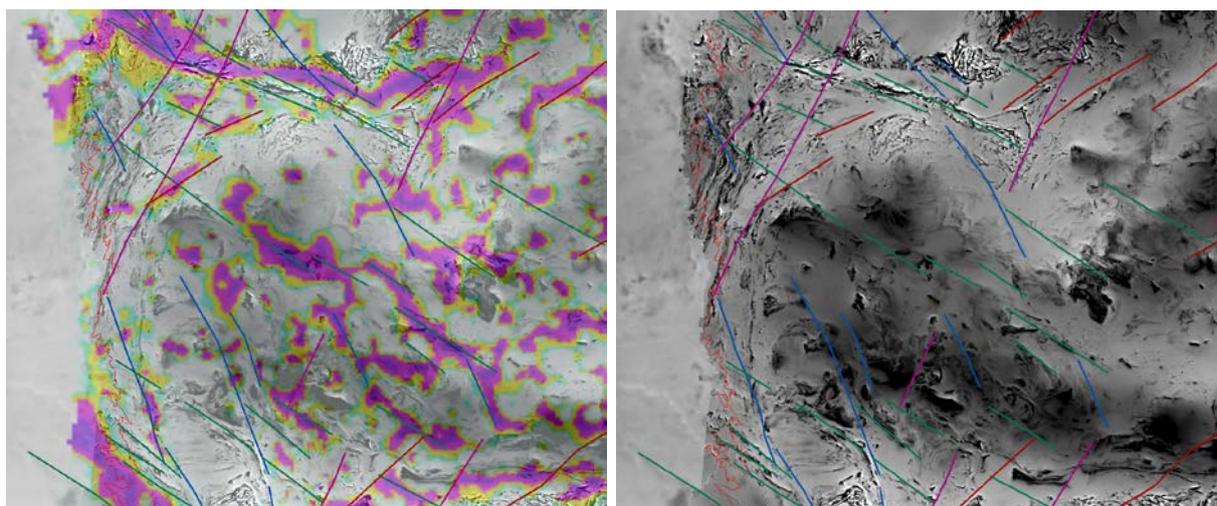


Figure 3. Detail of Fig. 2 (left) and the corresponding aeromagnetic map (right) showing how the regional gravity gradients are composed of groups of lineaments.

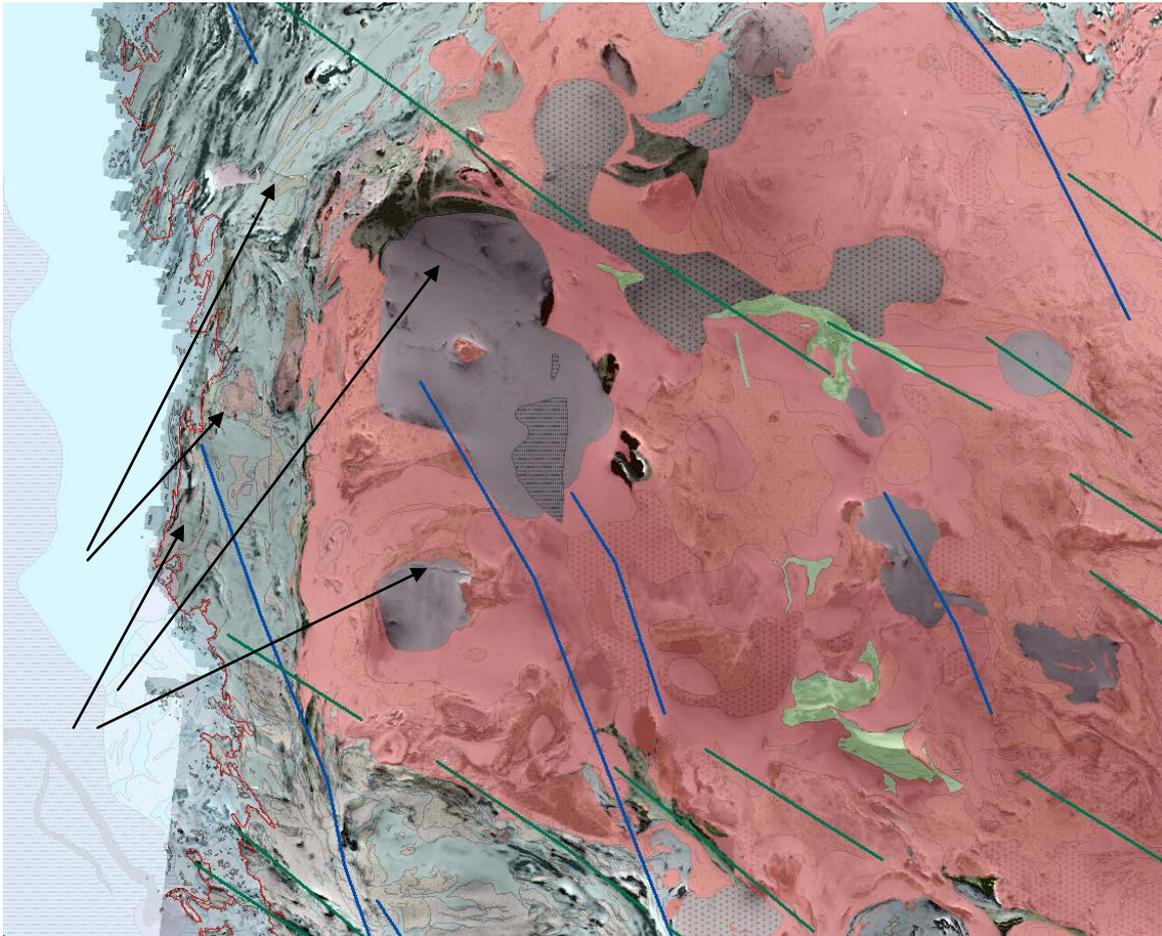


Figure 4. Detail of aeromagnetic map of an area in Fig. 3 with geological complexes as background. Diabase dyke swarms are indicated by arrows.

3 INTERPRETED STRUCTURAL TRENDS

3.1 South Finland

Geophysical structures with gold potential were studied in connection of different projects concentrating on the Pirkanmaa and Häme belts in southern Finland. The known gold occurrences are commonly located along the boundaries of geophysical provinces that can be recognized by their well-oulined by magnetic and gravity gradients. The tectonic trends observed in the Häme and Pirkanmaa belts were compared with more regional trends over the Fennoscandian shield. It was found that the same trends are repeated within the whole shield area, both in geophysical and in geological maps. They form major lineaments or they are connected to lithological contacts (Airo & Leväniemi 2012). The connection of mineral occurrences to controlling lineament systems and the more detailed structures such as second-order faults related to the main province boundaries was verified but their relationship requires further analysis of lineaments and their geological significance. Figure 5 is an example of the relationship of mineralization with brittle fracturing in a detailed fold structure.

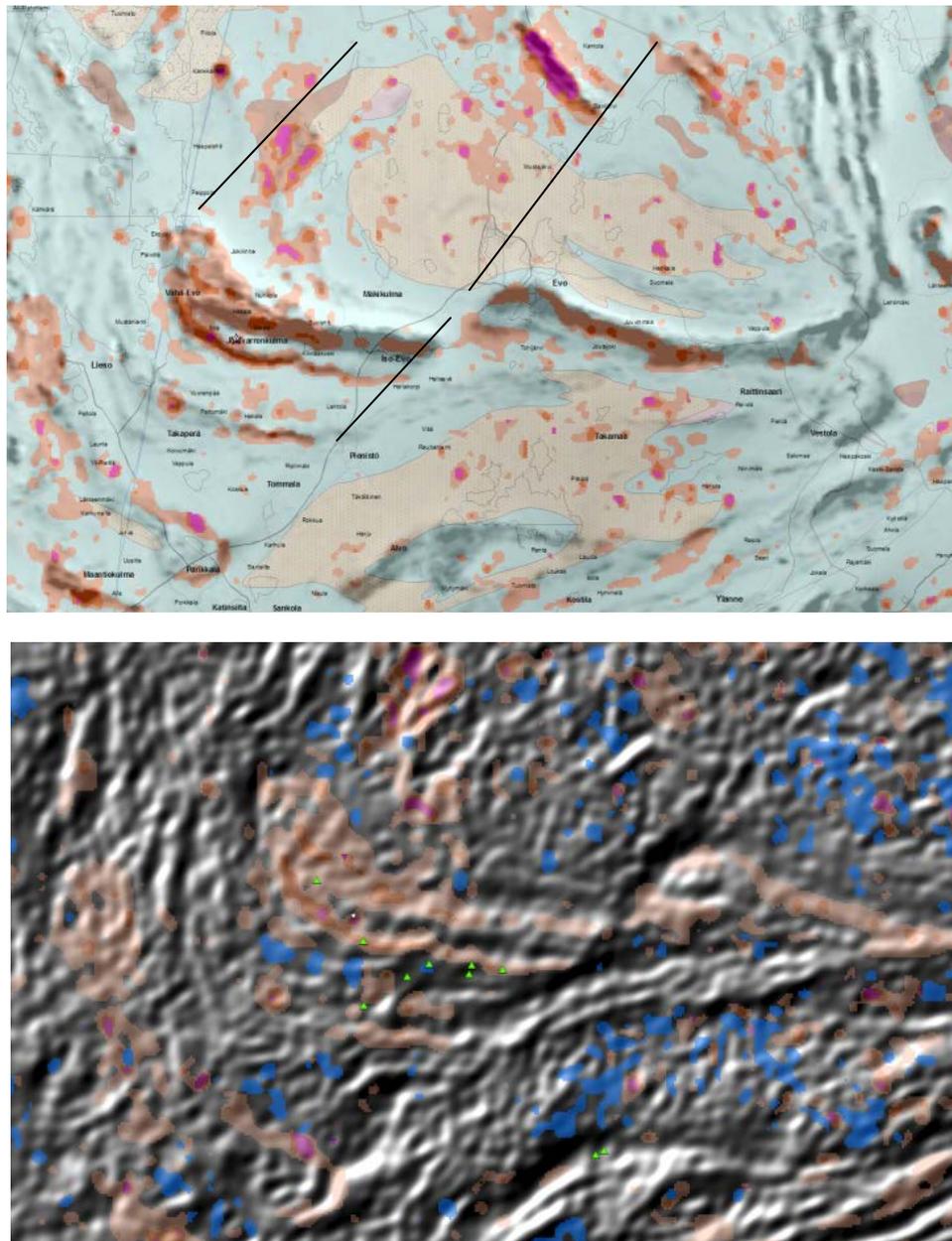


Figure 5.

Above: Magnetic anomalies (dark grey) associated with electrical conductivity (red to orange) suggest that ferrimagnetic monoclinic pyrrhotite is the main magnetic mineral in the anomalies within mica gneiss. Geophysical anomalies enhance the fold structure whose fold axis plane is directed NNE-WSW. The folded pattern is interrupted at its eastern side by a fault that is parallel to the fold axis plane.

Below: The tilt derivative of magnetic data (grey) overlaid by classification of electromagnetic data (red = conductivity, blue = resistivity) enhances the structural detail. The known mineral occurrences are located along minor fracture zones connected to the main fault. These are either related to 1) the main foliation direction in the fold pattern or 2) fractures parallel to the fold axis plane.

3.2 Central Finnish Lapland

The summary presented here is based on several interpretations made for Central Finnish Lapland and the Kittilä greenstone belt since the 1980'ies. They have been presented and reported in several occasions, and reviewed in Airo (2007).

Airborne magnetic and electromagnetic (AEM) data were interpreted in combination with regional gravity data and digital elevation model (DEM). The analysis of the so-called 'Sirkkaline' revealed a series of fracture and fault zones having systematic N60W orientations (Figures 6-7). This trend can be followed across the Central Lapland from Russia to Sweden. These structural patterns are enhanced where they associate with lithological contacts, which occur on aeromagnetic maps as zones of weakness and brittle fracturing. Well-developed fault and fracture systems striking N40E and N70E infered from aeromagnetic data crosscut the main direction.

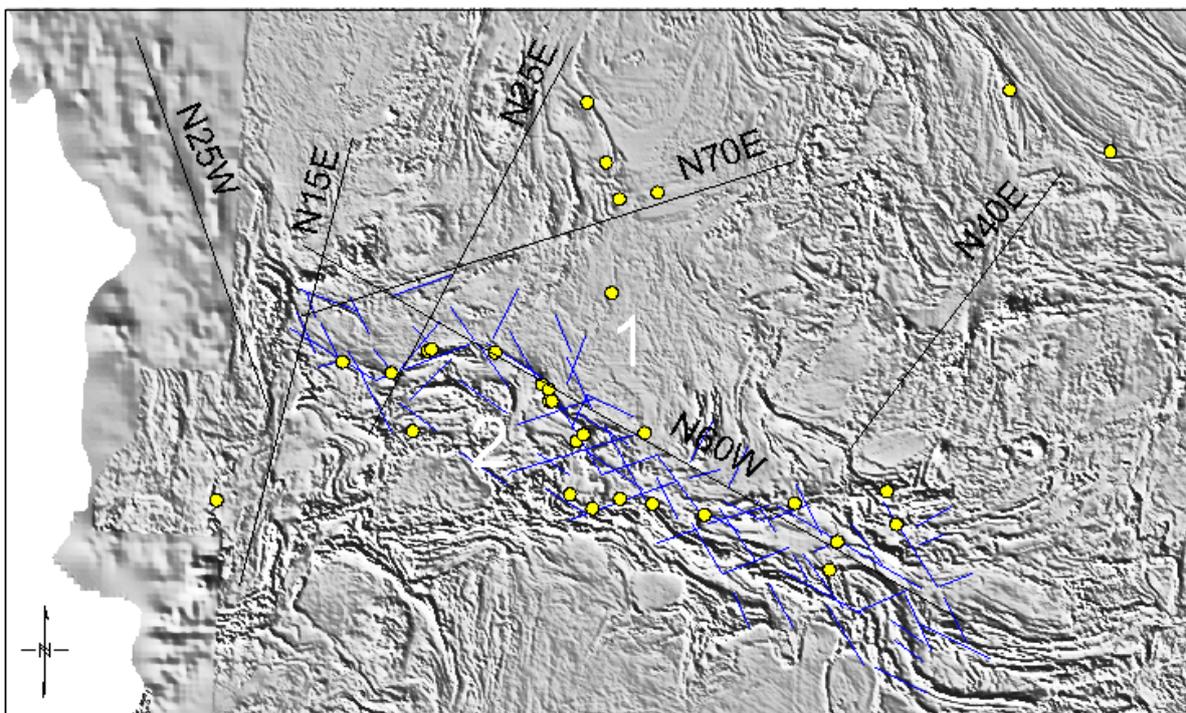


Figure 6. The N60W directed Sirkka trend in aeromagnetic data. It is composed of several parallel thrust faults (blue lines in direction N60W) which are interconnected by second-order faults. The main trends of these faults are repeated over the whole greenstone belt area (Airo 2007).

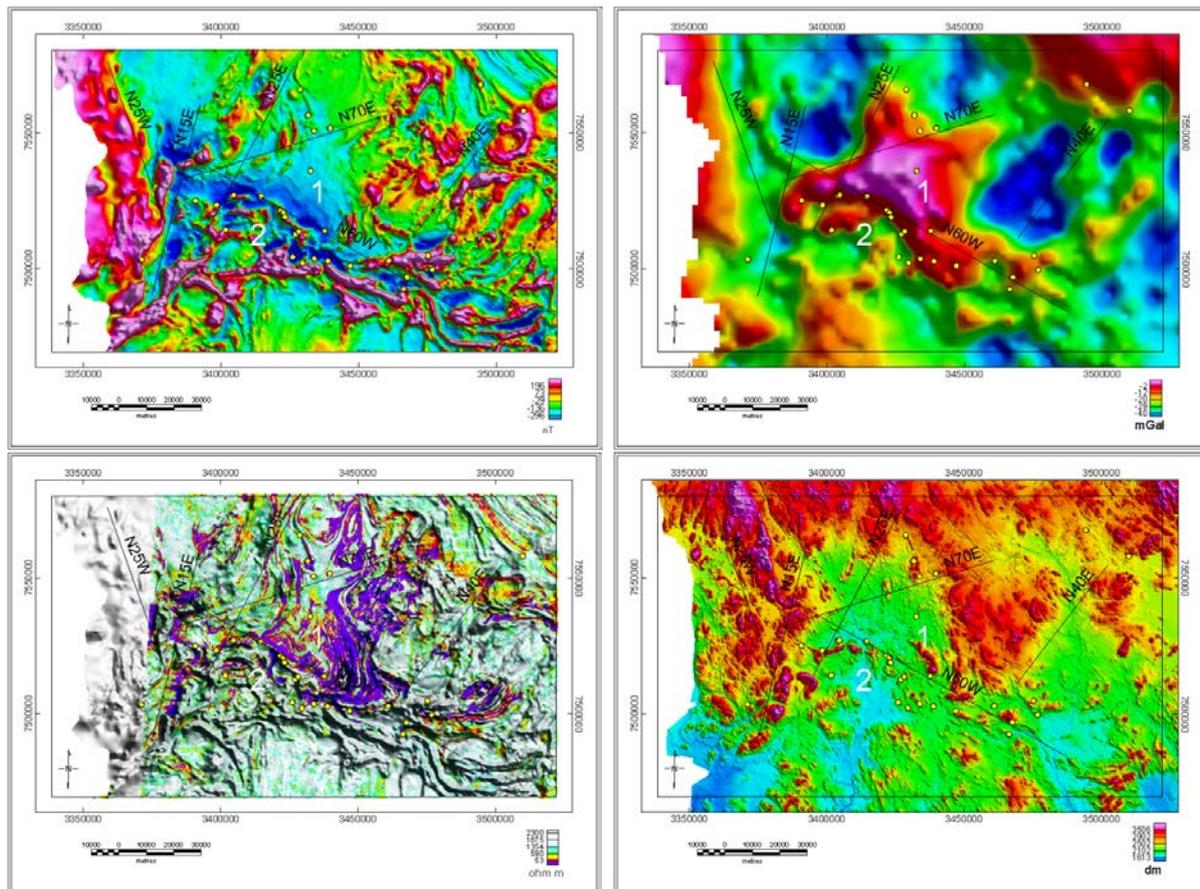
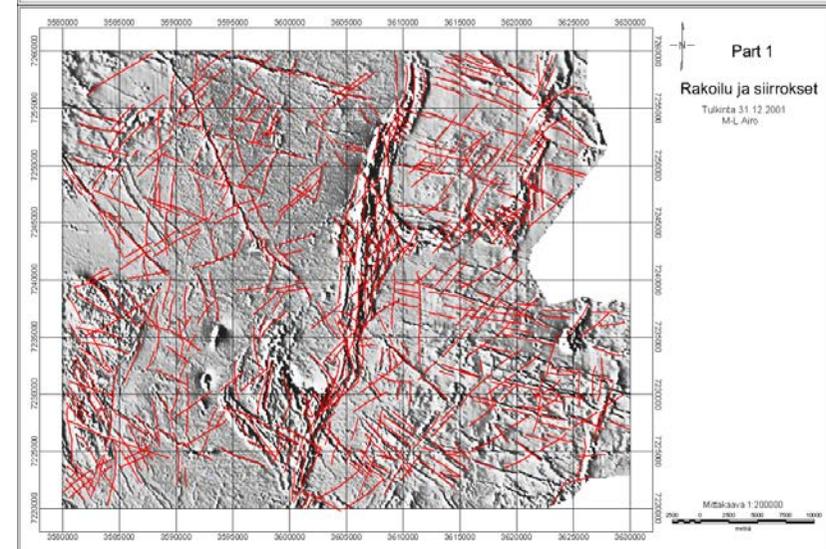
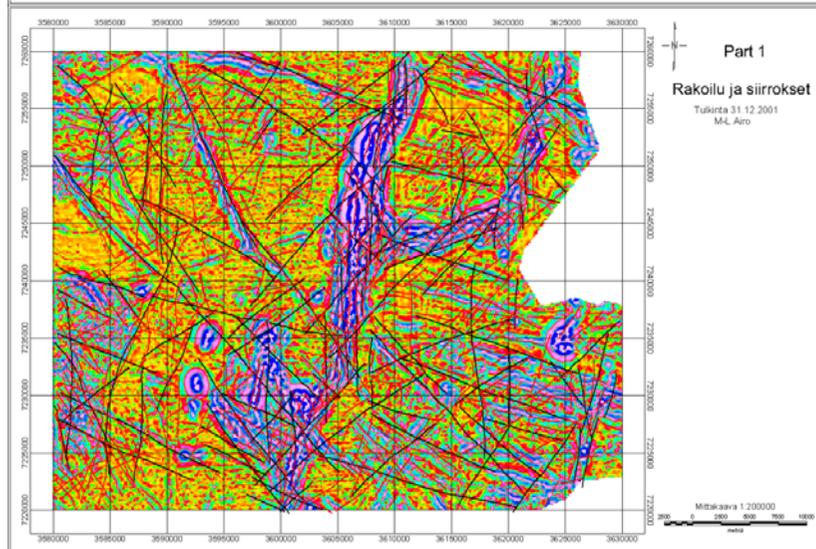
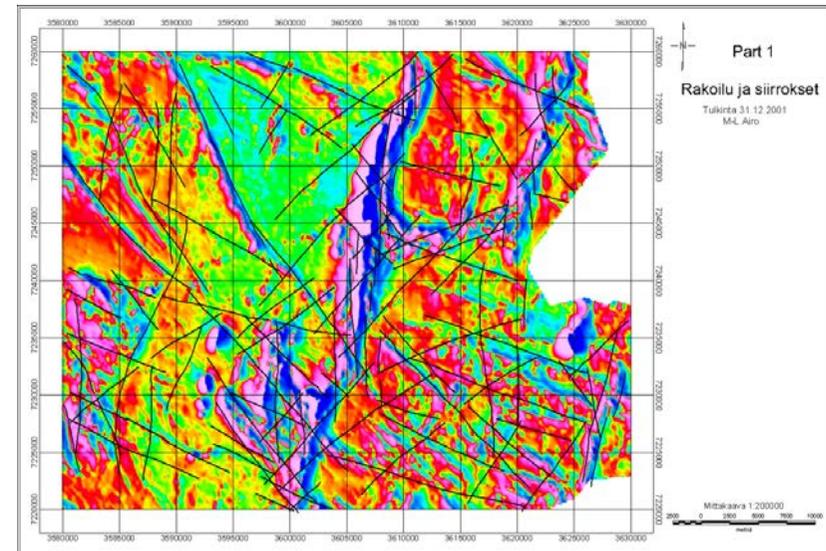
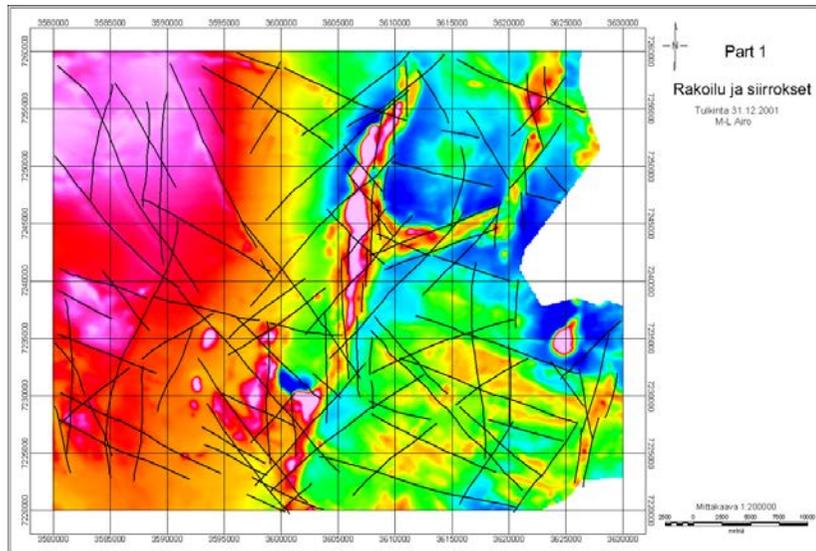


Figure 7. The N60W directed Sirikka trend in aeromagnetic and gravity data sets (above), airborne electromagnetic and elevation data (below).

3.3 Eastern Finland

Interpretation of fault and fracture patterns around the Kuhmo greenstone belt in eastern Finland were made in 2002 for GTK's project 'Arkeiset alueet' (= Archean areas). Visual inspection of lineaments was based on vertical and horizontal derivatives of magnetic field. The inferred structural patterns largely mirror the patterns typical for greenstone belts in Russia east of this study area. The fracture and fault zones in eastern Finland were later injected by mafic dyke swarms. The lineament analysis was made separately on 4 areas. Figure 8 displays an example of the various materials and the interpreted discontinuous features.

Figure 8. (next page) Fault and fracture trends around Kuhmo greenstone belt, inferred from processed aeromagnetic data (TMI, horizontal derivative upwards-continued, vertical derivative, horizontal derivative). Interpretations were made in 2002.



3.4 Southeastern Finnish Lapland and Misi-Raajärvi area

Airborne geophysical data, regional gravity data, digital elevation data and petrophysical data were used to interpret the structure of southeastern Finnish Lapland (Airo 1999a). The most prominent structures in the area are the north-south (NS) trending major block boundary, called as the Hirvaskoski shear zone (HSZ), the Ailanka fracture / shear zone directed north-west-southeast and the northeast trending depression covered by Kuusamo schist belt. The NS trending HSZ was modeled to be associated by a major vertical block movement with eastern side up for several kilometres. This must mean a severe difference in the erosion level between the crustal blocks east and west of HSZ. The NS trend is repeated elsewhere within the Archean block, for example the Pajala shear zone in Sweden. This and other important trend directions are repeated in the Misi-Raajärvi area.

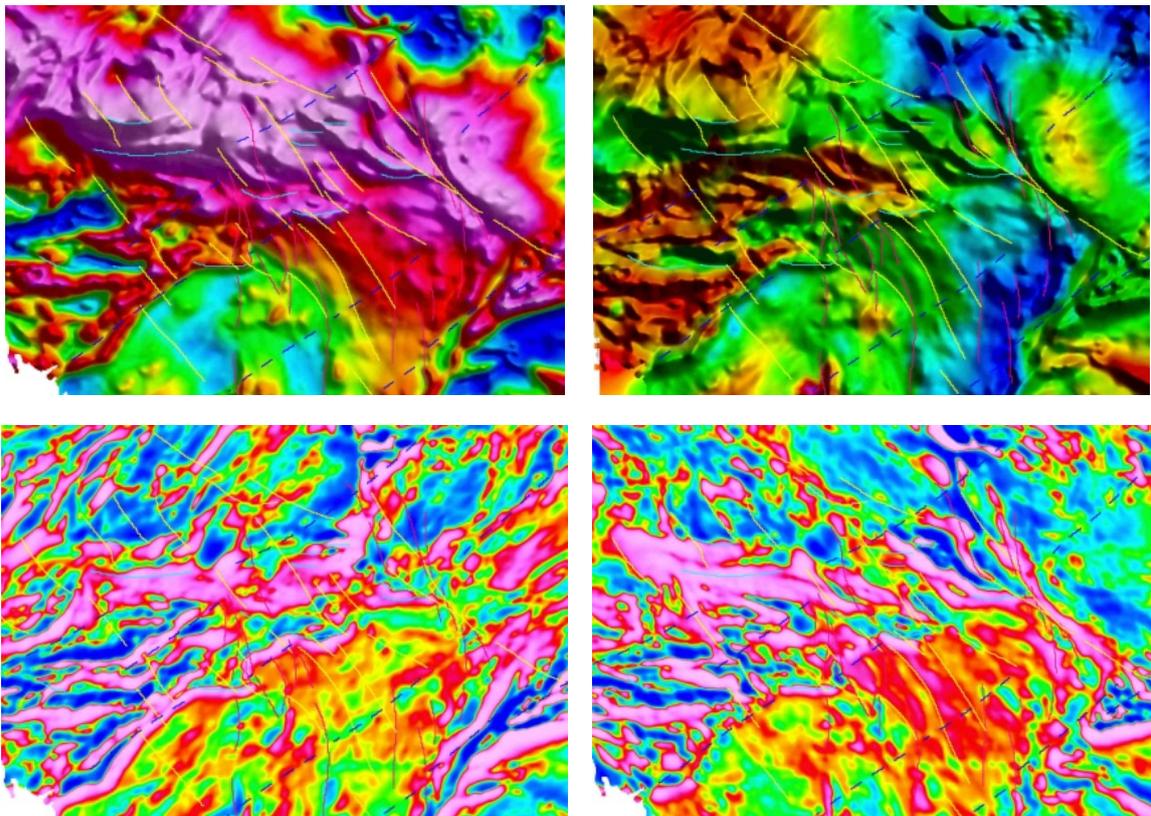


Figure 9. Examples of combinations of processed aeromagnetic and gravity data revealing structural information of southeastern Finnish Lapland.

Above: shaded relief of upward-continued aeromagnetic data combined with 1) left: magnetic total intensity (in colours) and 2) right: gravity data.

Below: directional horizontal derivatives of upward-continued aeromagnetic data. Different derivative directions enhance certain structural directions.

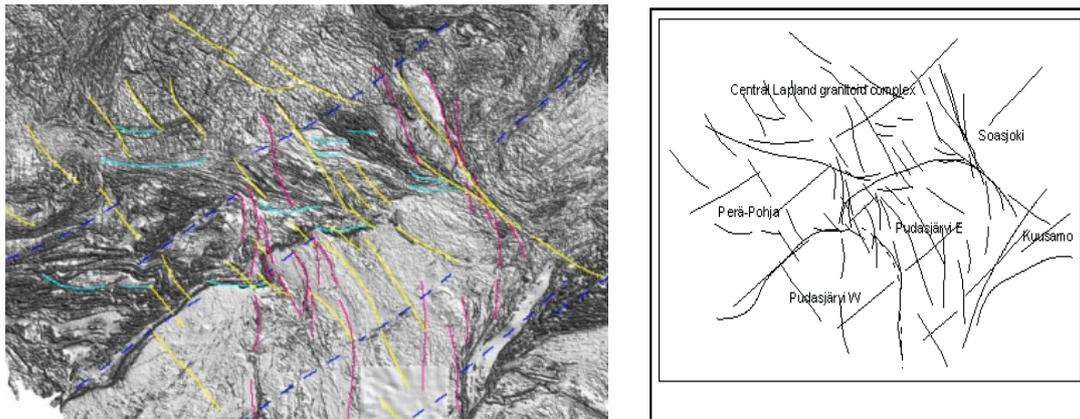


Figure 10. Regional geophysical trends around Misi-Raajärvi area. Interpretations from 2001-2004.

The interpretations of Misi-Raajärvi area were made during 2001-2004 in a project called: 'Suomen rautaoksidi-kupari-kultamalmit' (Finland's Fe-oxide-copper-gold deposits). Study areas were Misi-Raajärvi, Kolari and Perä-Pohja and regional structural features were interpreted from magnetic and gravity data. The results were introduced in project seminars. Integration of directional horizontal derivatives revealed structural patterns with different strikes (Figures 9-10). These were combined to build a tectonic summary. The NS striking patterns in the Archean Pudasjärvi block tend to apply more NW direction when they meet the Central Lapland granitoid complex. The NW trending older deformation in the granitoid area is cut and interrupted by these NE trending younger faults. The major structural patterns across the Central Lapland granitoid complex are enhanced by magnetic tilt derivative in Figure 11.

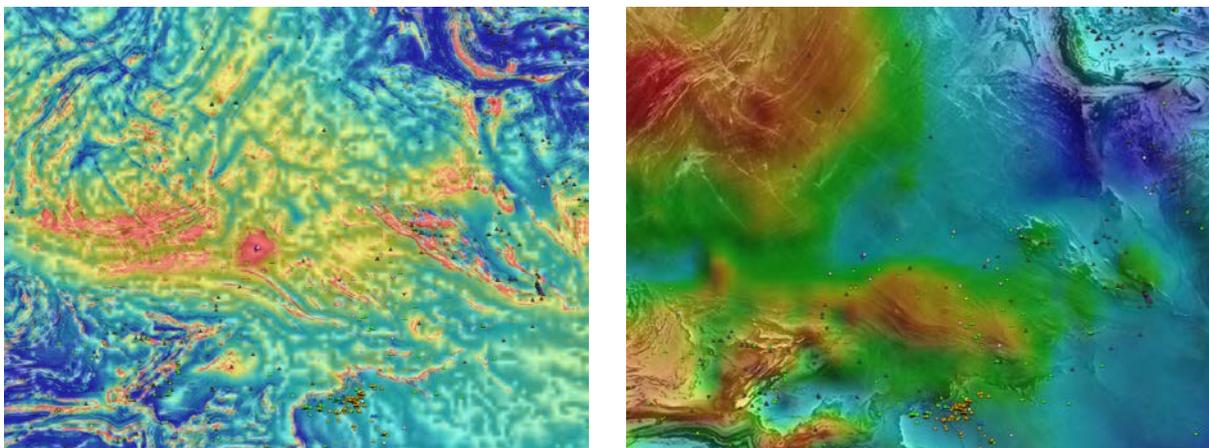


Figure 11.

Left: Structural patterns in the Misi-Raajärvi area as indicated by magnetic data (total magnetic intensity in red-blue colour scale + tilt derivative of upwards-continued (1 km) magnetic data). Ore showings: grey = Fe, green = Cu, yellow = Au, orange = U.

Right: Magnetic anomaly data (in grey) enhanced by gravity data in red-blue scale. Notice the NE trending structures cut by later fault and fracture zones within granitoid and the combined gravity anomalies.

4 SUMMARY OF THE REGIONAL STRUCTURAL TRENDS IN FINLAND

The major gravity gradients and minima in regional data represent zones of structural discontinuity and they often reveal contacts or boundaries of crustal blocks, fault or shear zones. From the nature of regional gravity field these structures can be interpreted to reach deep into crust. They may also have their background in variation of mineralogy, due to changes in metamorphic degree or style, or they may be related to weakness zones subtle to intrusion of granitic magma. The structural trends inferred from gravity gradient data can also be verified from aeromagnetic data. In general, the "low-altitude" aeromagnetic data reflects shallow and near-surface structural features in comparison with the country-wide gravity data in Finland. To extract near-surface information from gravity, more detailed gravity surveys are needed. In order to compare with regional gravity, the aeromagnetic data were here continued upwards to 3 and 5 km. The low-altitude (nominal terrain clearance 35 m, flight line spacing 200 m) aeromagnetic grid (50 m cell size) was used to interpret more near-surface, detailed structures.

Figures 12-13 illustrate lineament trends drawn on the basis of the most prominent gravity minima and the associated gravity gradients. There are two series of northwest-southeast trending lineaments, namely the west-northwest (WNW) and the northwest (NW) trending structures (Fig. 12). These deep features are not necessarily obvious in surface anomalies but they are occasionally represented as magnetic surface anomalies along the crustal province boundaries. Similarly, there are two series of the other prominent structural trend, northeast to southwest, as shown in Fig. 13, namely the northeast (NE) and the north-northeast (NNE). In southern Finland this trend is found, e.g., as contacts of granitoids or as NE-trending sheared internal patterns in granitoids. Additionally, the north-south trending (N-S) major structures, often representing shear zones, may be related to either of these predominating NW or NE structures (Fig. 13). Based on geophysical modelling using regional gravity, regional magnetic and regional petrophysical data, the NS trend at Kuhmo greenstone belt and at Hirvaskoski shear zone is associated with vertical block movement. The east-west (EW) trend is very prominent in magnetic surface anomalies along block contacts in southern Finland, but not noticed in gravity data as efficiently. Reasons for this are, for example, that the density contrast between adjacent crustal blocks is too small, and that the magnetic anomalies have very shallow, narrow sources.

Figure 14 compares the regional gravity lineaments with the outlines of the main geological complexes in Finland. Most of the contacts are controlled / revealed by either the NW or the NE –trending gravity lineaments. These orientations also seem to control the shapes of geological provinces in the Archean complex. Figure 15 illustrates how the known mineral occurrences are located along or close to regional gravity gradient and zones of minima.

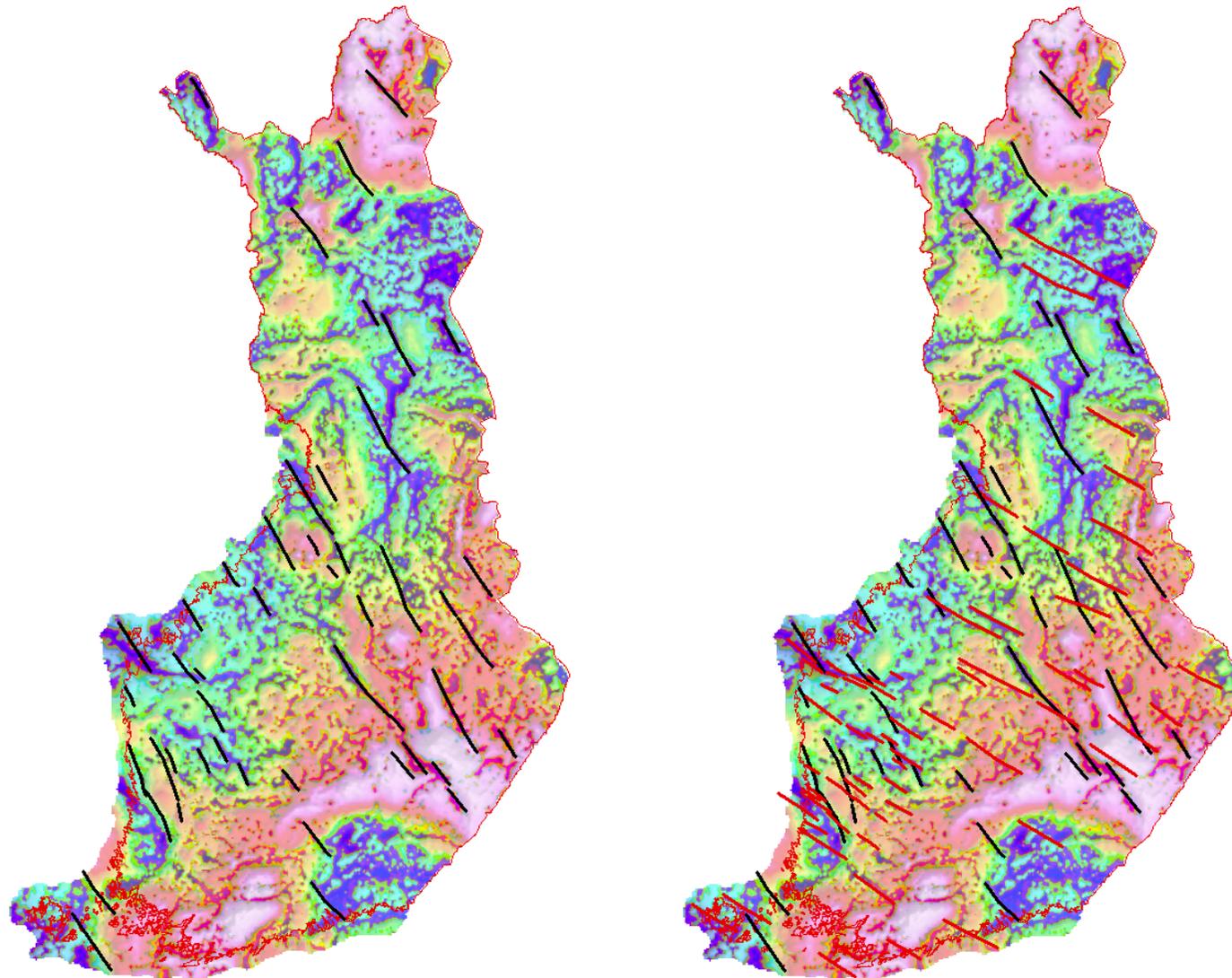


Figure 12. Major northwest-southeast trending lineaments in gravity data. Left: northwest trend (NW); right: west-northwest (WNW) and NW trends.



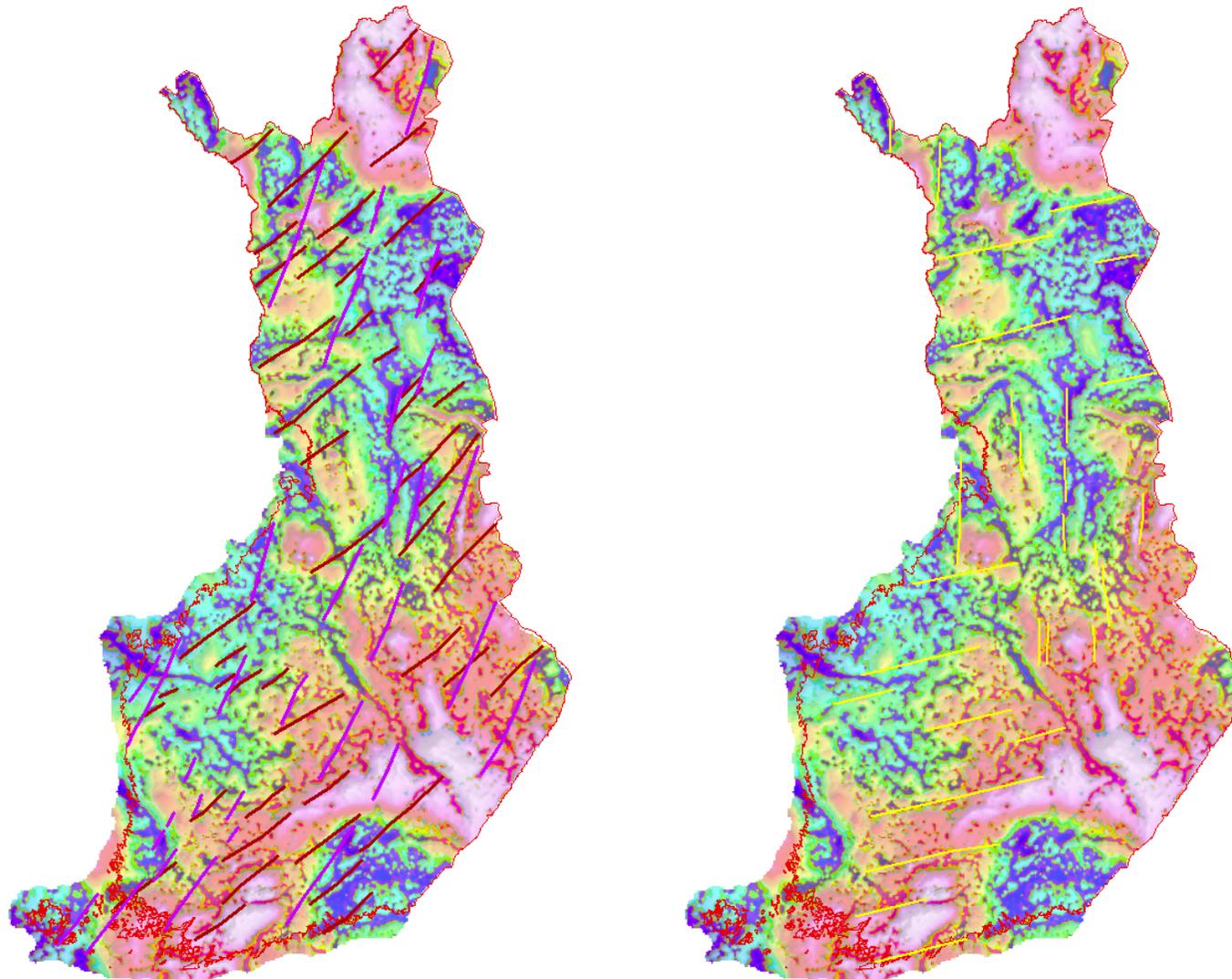


Figure 13. Left: Major northeast-southwest trending lineaments in gravity data: NE and NNE trends. Right: N-S (north-south) and E-W (east-west) trends.





Figure 14. Gravity gradient trends compared with geological complex boundaries. Left: NW, WNW, NS, EW; right: NE, NNE, EW, NS.



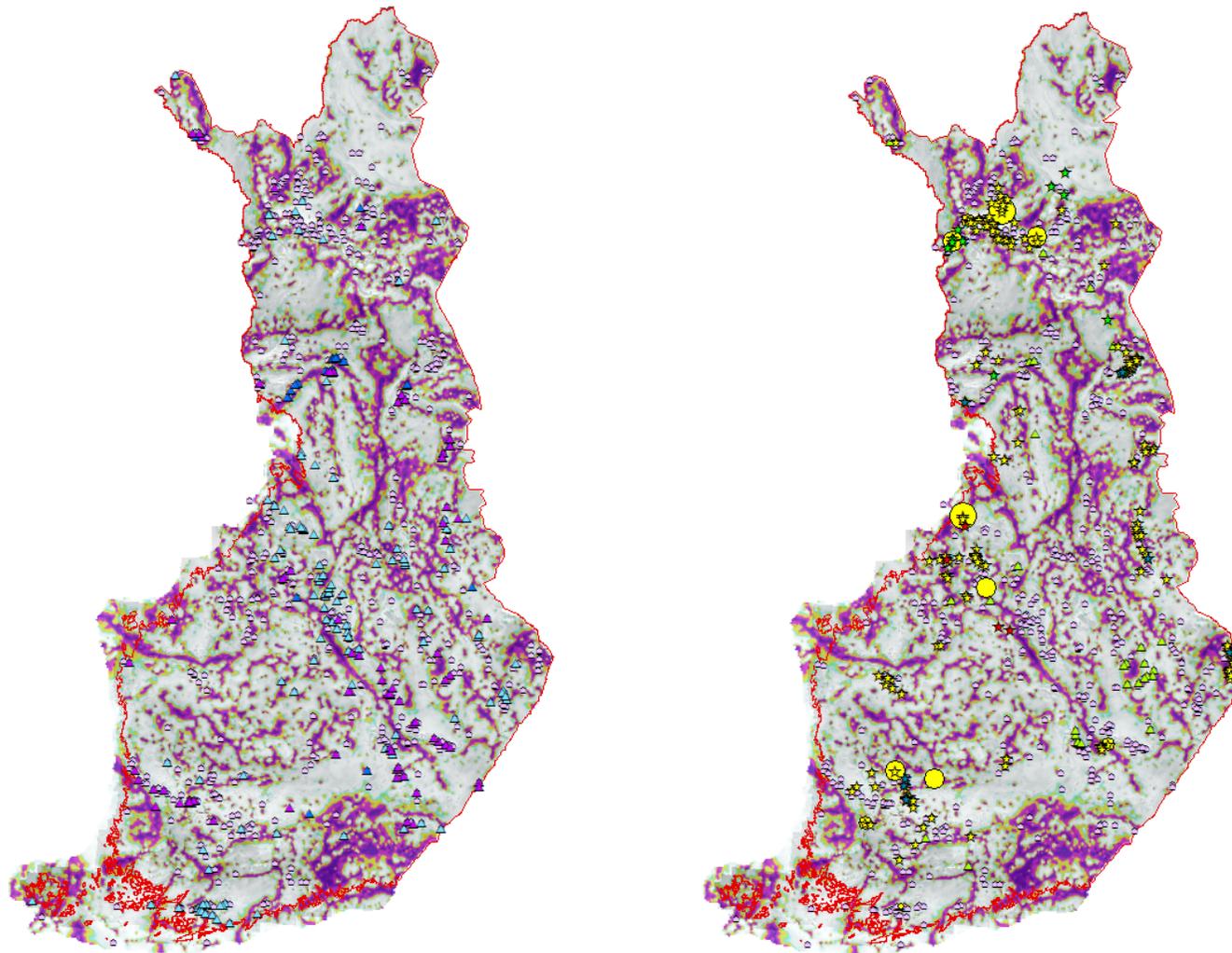


Figure 15. Gravity gradients (tilt derivative TDR) and 1) Ni-, Zn- and PGE-occurrences from mineral database (left); 2) Au- and Cu-occurrences (right).



5 REACTIVATED CRUSTAL WEAKNESS ZONES

The previous figures illustrated how the regional lineament trends in magnetic and gravity data correspond to the outline of the main geological complexes in Finland. The same lineament trends can be followed across the whole Fennoscandian shield area, both eastwards in Russia and westwards in Sweden and Norway. The systematic parallel trending of lineaments suggests their simultaneous formation and their continuation over the whole Fennoscandian shield suggests that they were formed in tectonic or deformation episodes that touched the whole shield. Since their first formation at the continental break-up, the same crustal weakness zones have been repeatedly been reactivated during younger tectonic episodes. Reactivation at different times is verified by, e.g. mineral deposits or intrusions which originate from different geological times but whose location / emplacement is controlled by the deep faults or shear zones connected to the main crustal block boundaries.

Figure 16a shows how the interpreted major lineament trends are related to regional gravity data. There are two main northeast trends (blue and green lines), two main northwest trends (red and orange lines) and the north-south trending structures in the northern part of the Fennoscandian shield. These structures correspond to deep crustal province boundaries and fault zones. In Fig. 16b the distribution of enhanced Cu in till (green) is outlined by two series of these lineaments.

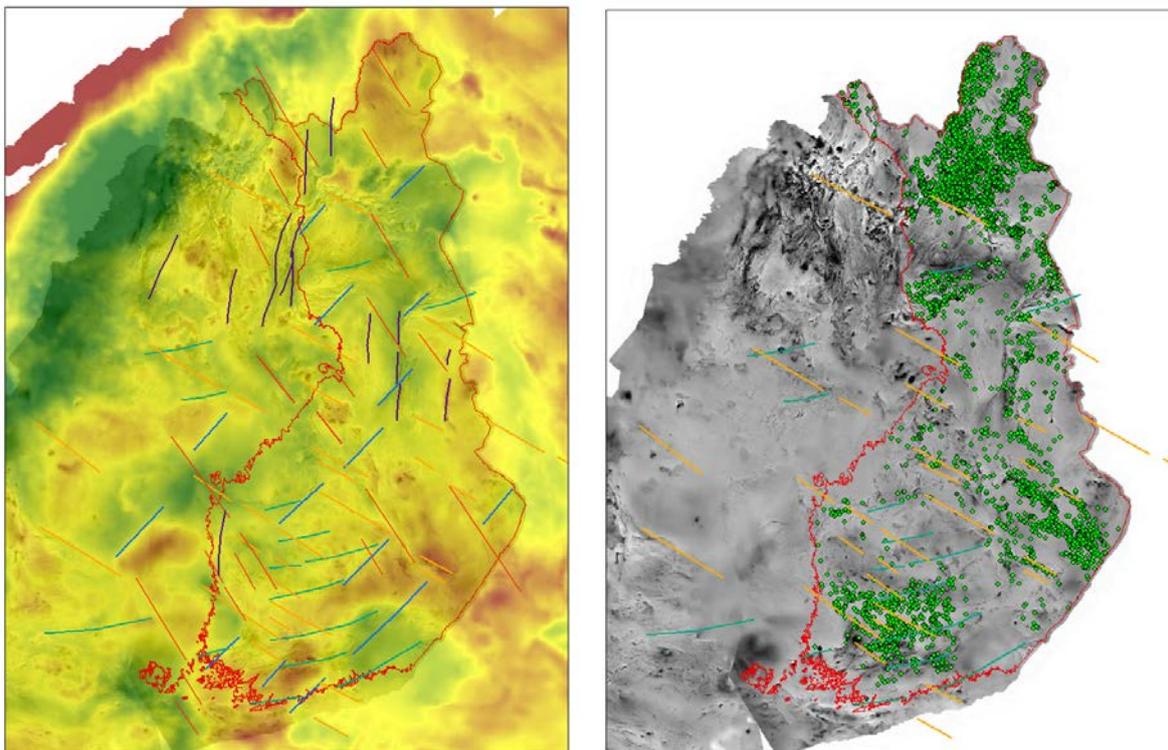
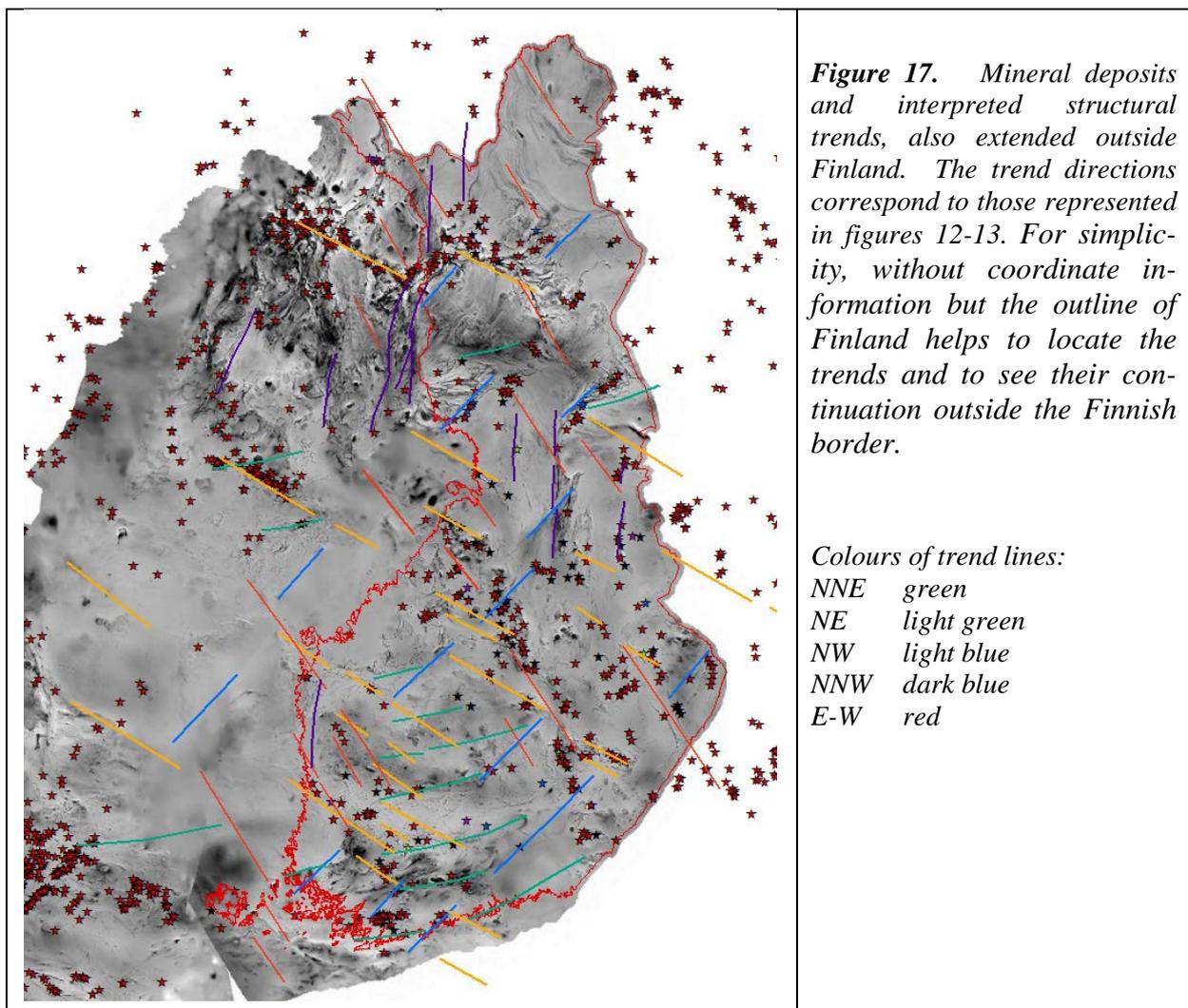


Figure 16. a) Fennoscandian shield Bouguer-anomaly data and the interpreted main structural trends. b) Aeromagnetic map with till geochemical data (enhanced Cu) compared with two lineament trends.

5.1 Implication: mineral deposits

The spatial relationship of known mineral deposits in the Fennoscandian shield with the interpreted main lineament trends is suggested in figure 17 with the aeromagnetic map of the Fennoscandian shield as background. The structural trends were interpreted in 2010-2012 by comparing different digital databases provided by GTK. The orientations of magnetic anomaly in the Archean province east of Finland, due to Archean greenstone belts, are controlled by the interpreted NW and NNW trends. The same general anomaly orientations are typical also to the Kuhmo province on the Finnish side, but the NS trend becomes more important, i.e. the NS trending Kuhmo greenstone belt and the Hirvaskoski shear zone which represents an extensive zone of vertical crustal movement (e.g., Airo 1999a). The NW and NNW trends also outline the Central Finland granitoid complex and these are the two orientations that control the Raahela-Laatokka zone. The NW trending lineaments west of Finland, in Sweden, are associated with several base metal and iron occurrences in Kiruna district and Skelleftebelt (Fig. 17). The NE, NNE and EW trends control the form of near-surface and shallow magnetic anomaly patterns in southern Finland. Northwards the EW trend seems to represent also the outlines of deeper anomaly sources. The EW and NW trends together follow the northern contact of the Central Lapland granitoid area.



5.2 Implication: ring structures

Many of the ring structures observed in aeromagnetic and gravity data of the Fennoscandian shield seem to exist in close vicinity with the interpreted regional lineaments. Such are for example carbonatite and kimberlite pipes in eastern Finland and in Russia, which are related to the EW trend that crosscuts the main NW trending block boundaries of the Karelian craton (Fig. 18). The very young age of carbonatite and kimberlitic intrusion indicate that these structural weakness zones have been repeatedly reactivated during the Proterozoic. The banded anomaly patterns in Fig. 17 denote magnetic tilt derivative and the blue-green-yellow-red colour scale represents Bouguer-anomaly data. Low values (in blue) correspond to low density felsic to intermediate rocks whereas the red areas are related to rocks of mafic to ultramafic composition or a higher metamorphic grade (granulite facies). The EW trending lineament which unites intrusions Kovdor and Apatity, is related to a wide zone of declined magnetization which represent to supracrustal rocks of the Archean age (Digital map database © GTK).

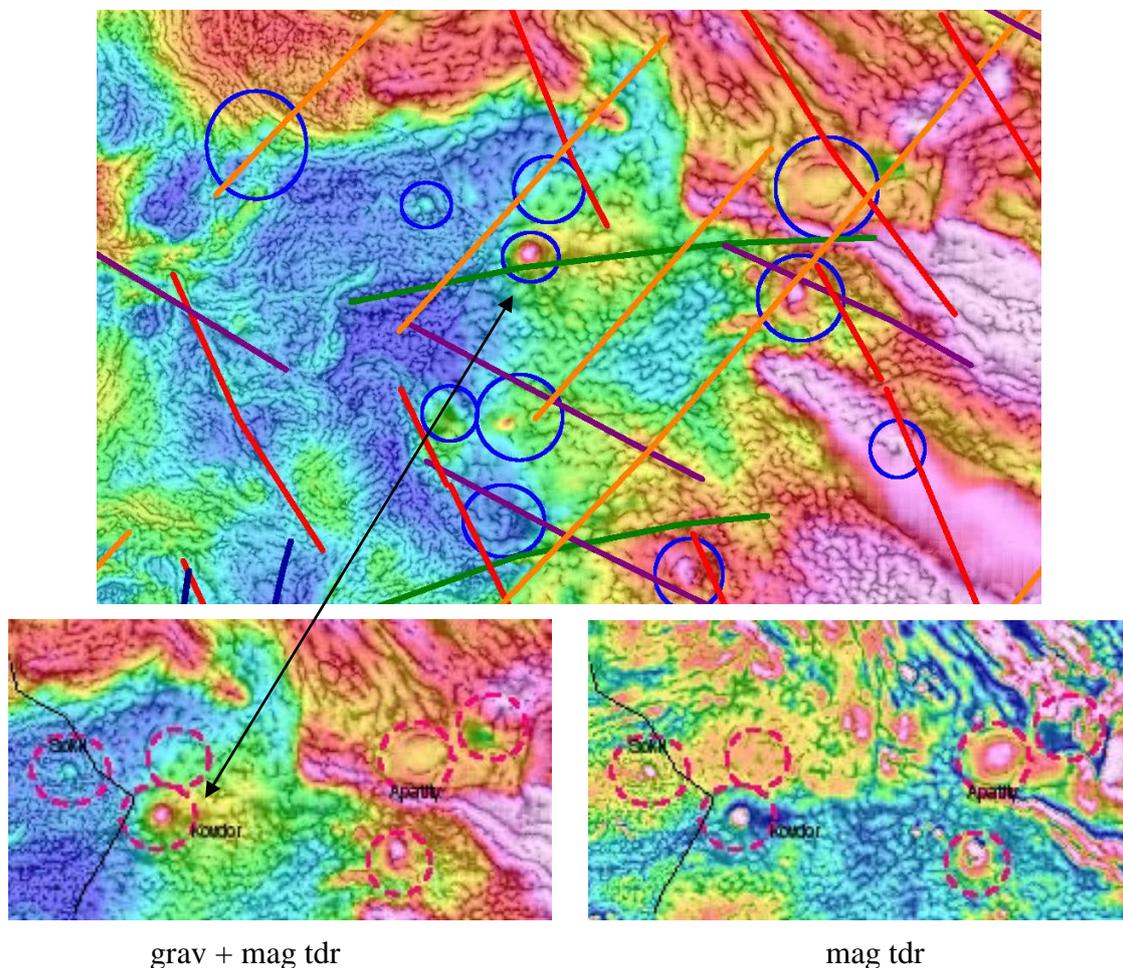


Figure 18. Ring structures observed in aeromagnetic (tilt derivative) + gravity data (in colours), northern part of the Fennoscandian shield, compared with the interpreted geophysical lineament trends.

6 SUMMARY

This report summarizes results of lineament interpretation from several different projects and it gives only brief comments or observations. Part of the results is published elsewhere and the source publications are found in the list of references. A great deal of the interpretations is only found in the author's file stores or presentations. These are available for further use by contacting the author.

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