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AIRBORNE MAGNETIC METHOD: SPECIAL FEATURES AND REVIEW ON APPLICATIONS

by
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This article describes the main characteristics of the aeromagnetic component of the low altitude survey system of the GTK and discusses future strategies in magnetic data reduction. A second part outlines opportunities for the use of the magnetic survey data. The system was initiated in 1972 and has been used basically the same way until today. Special aeromagnetic features of this second National aerogeophysical programme are as follows: 1) The system was aimed at refining earlier nation-wide measurements at 150 altitude. Hence, it became a low altitude survey (30m) that was equipped with a transverse horizontal gradiometer for improved resolution between survey lines (the first operational system globally). 2) No tie lines were used, because the magnetic sources were too close. 3) Transient and secular corrections were planned to reduce the data to a single event of time (1965.0), hence allowing a free choice of anomaly definition (DGRF 1965.0 was used) and offering an easy opportunity for a global contribution. The following features were developed to facilitate the use of the data since 1980: 4) Grey-tone anomaly display was designed for visual interpretation of the maps. 5) Supplementary nation-wide petrophysical mapping provided a link between magnetic anomalies and geological characteristics of the sources. 6) Supplementary international data reduction and exchange between nearby areas supported regional and crustal scale understanding of the sources. Strategically, high-quality results and easy access to data caused user demand and funding to extend the programme to the whole country, although a minor part only was originally planned for refinement.

Key words (GeoRef Thesaurus, AGI): geophysical surveys, geophysical methods, airborne methods, magnetic methods, magnetic anomalies, magnetic field, magnetic survey maps, petrophysics, Finland

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BACKGROUND

Between 1951 and 1972, the Geological Survey of Finland (then GTL, now GTK) carried out the first national aerogeophysical mapping programme at a nominal altitude of 150 m above terrain (high altitude survey). The spatial variation of total magnetic field was measured by a flux-gate magnetometer along traverses of separation 400 m on land and 500 m in the coastal waters and the Finnish economic zone. The flight-time variation of the Earth's magnetic field was recorded at a local base station. Data was processed by analogue methods to hand-drawn anomaly contours of floating base level. In 1968–69 the absolute base levels were determined by proton magnetometer profiles, measured at 40-km intervals in a NS-direction for the whole country. Since then the anomalies have been presented as graphically and numerically compiled IGRF-65 anomalies (Puranen & Kahma 1949, Marmo & Puranen 1966, 1990, Korhonen 1980, 1991, Ketola 1986, Peltoniemi 2005, *this volume*, Fig. 1). The measurements were complete by 1972 and the map drafting by 1980. The aeromagnetic maps were considered highly useful in mineral prospecting and bedrock mapping. To facilitate interpretation and further add to the value of geophysical maps, an assortment of petrophysical measurements from lithological samples was introduced in GTL (Puranen et al. 1968). A national petrophysical archive was established at 1972 (Puranen 1989).

Originally, a low altitude survey of one third of Finland was presented as an alternative for the high altitude survey of whole country (Puranen & Kahma 1949). Finally, parallel to the high altitude program, the GTL and mining companies made supplementary low altitude surveys to serve mineral prospecting in the 1960's. The Outokumpu Company developed a computer-based processing system for its digital airborne data since 1968, having both higher quality and drafting speed of geophysical maps (Ketola et al. 1972). At the GTL a computer was applied to transform the Decca co-ordinates of high altitude flights over the sea to rectangular co-ordinates. To study alternatives for future geophysical mapping, numerical filtering tests were done for digitised high altitude data. Although some more details could be found by applying high pass type filters, computer enhancement of high altitude data could not replace more detailed measurements in prospecting (Korhonen 1970).

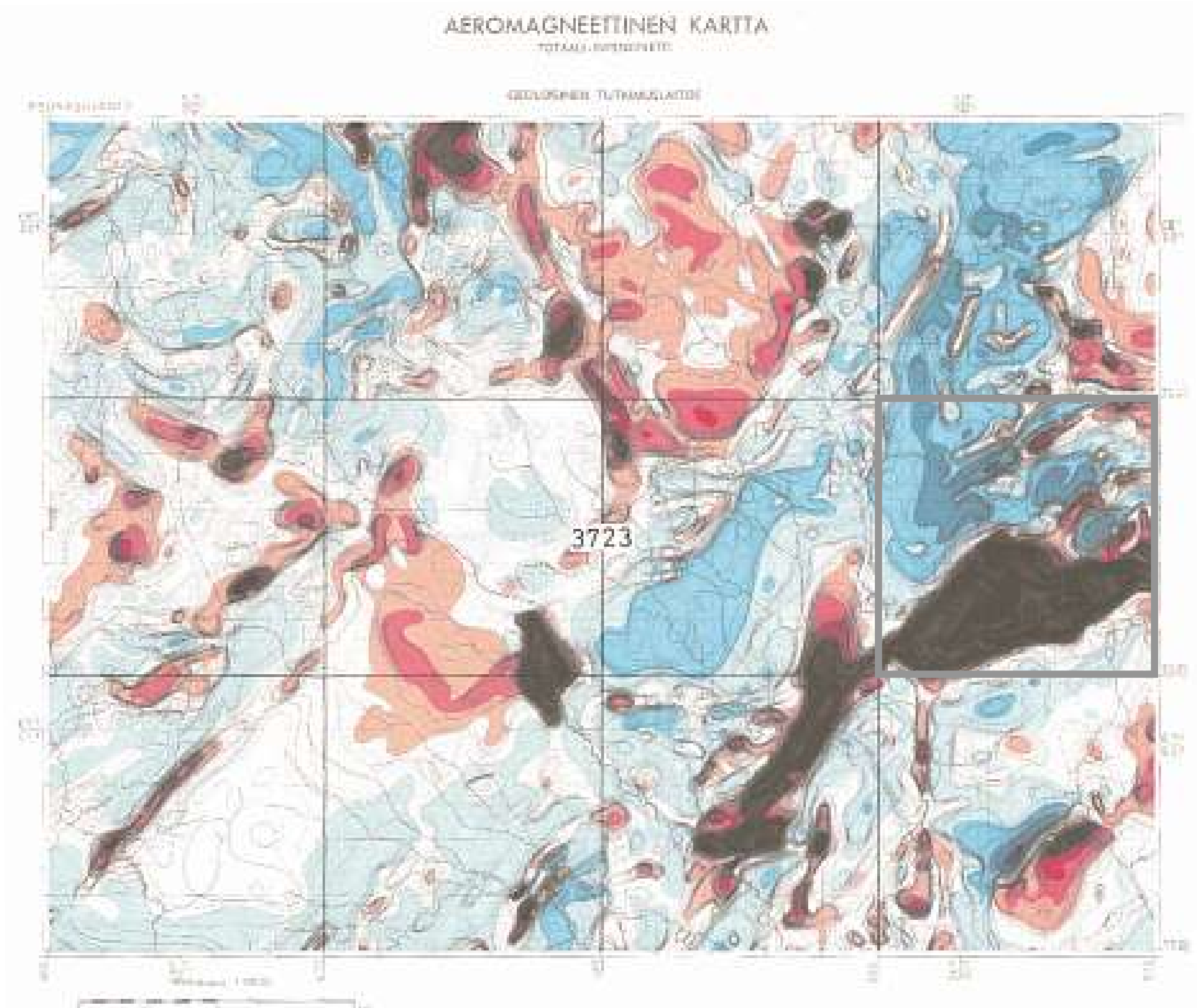


Fig. 1. Aeromagnetic Map, IGRF-65 Anomalies of High Altitude (150m) Survey, Sheet 3723, Peurasuvanto, Original Scale 1:100 000. Red colours 100, 300 500, 700 nT, blue colours –100, –300, –500, –700 nT. Sheet 3723 11, Kuusi-Lomavaarat, marked as a grey rectancle.

LOW ALTITUDE MAPPING

In 1972 GTL started a second national airborne geophysical mapping programme at a nominal altitude of 30 m above the terrain. Track separation was 200 m. The programme was aimed for prospecting of sulphide and U-Th ore deposits. Hence the requirements of electromagnetic and radiometric measurements were dominating in determining the flight parameters and the mounting of the instruments at the aircraft. (Peltoniemi 1982, 2005, *this volume*). The menu was completed with two proton magnetometers, one in the aeroplane (tail beam) and another at the magnetic base station. The aim was that the mutual consistency of survey lines would be assured by tie lines, flown 5 km apart from each other. The system was based on digital data registration, data processing and map drafting. Original and processed digital data was aimed to store systematically for future use. An example of a resulting 1:20 000 -scale map is shown in Figure 2.

A visual comparison of combined effects of sampling and processing of magnetic component at both mapping programmes is presented in Figures 3a–b. Gradients of the sets are made comparable by continuing the low altitude data upwards 100 m. The sampling rate of the high altitude data set is c. 20 effective stations/km^2. A combined effect of coarser sampling and manual map drafting has permanently left out some details from the map. The sampling rate of low altitude data set is 400 stations/km^2. Digital processing may suppress or emphasise details upon needs. Even as smoothed by upward continuation the low altitude set provides a wealth of new details to be interpreted geologically.

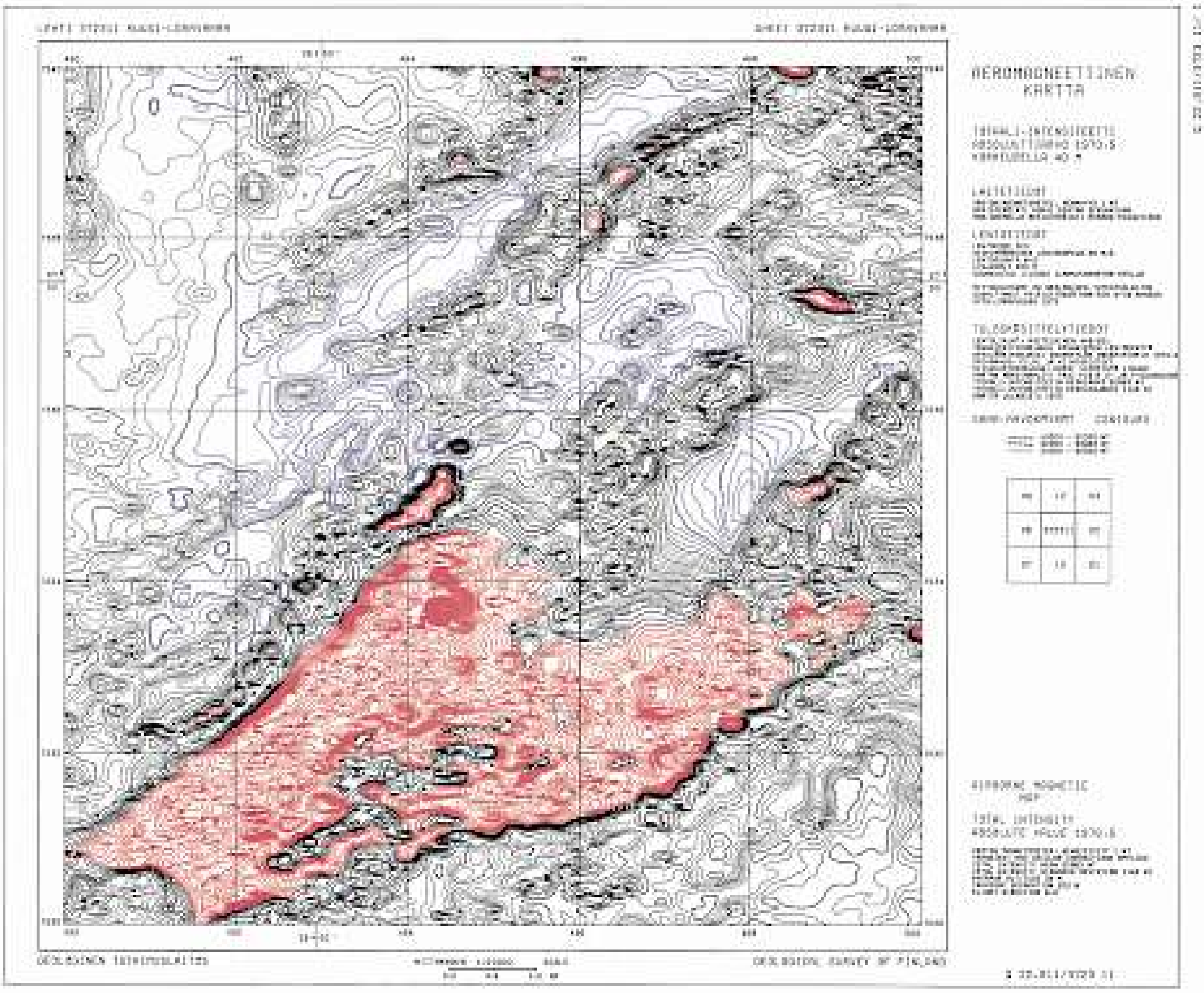


Fig. 2. Aeromagnetic Map, Absolute Total Intensity of Low Altitude (30m) Survey, Sheet 3723 11, Kuusi-Lomavaara, Original Scale 1:20 000. Coloured by DGRF-70, red +500 nT, blue –500 nT. A test print 1974.

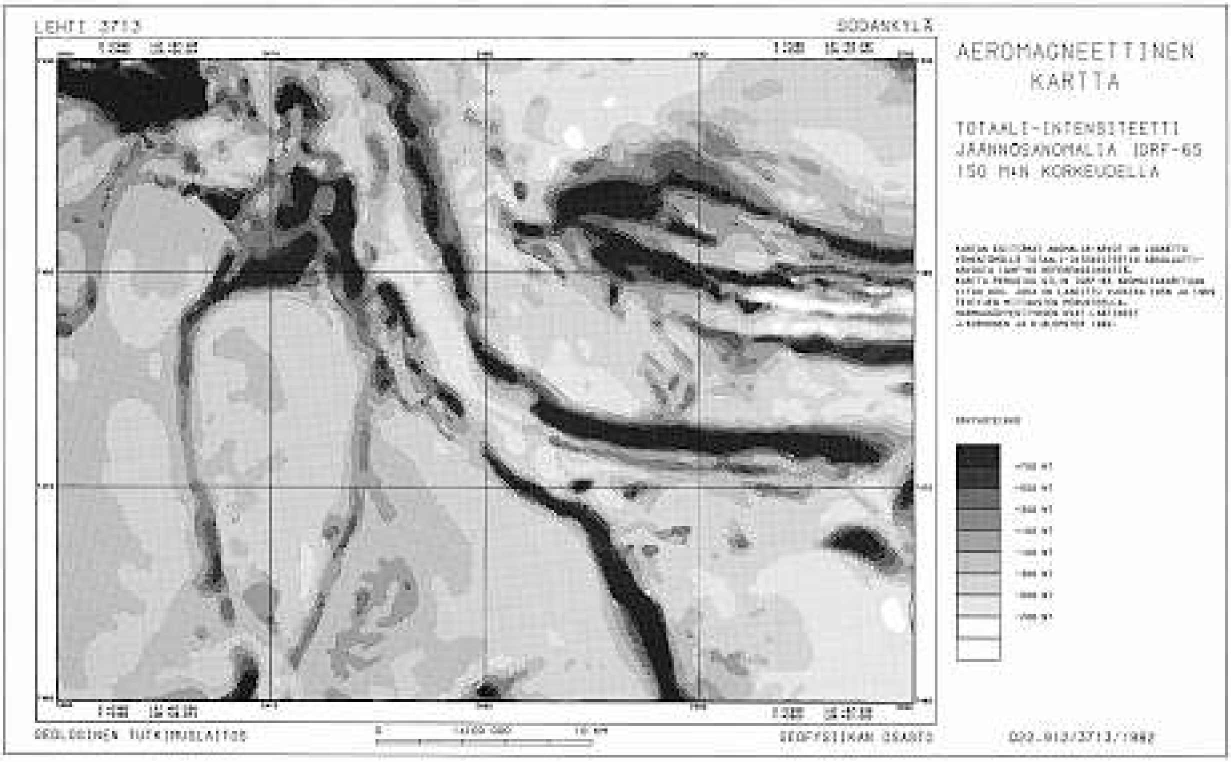


Fig. 3a. Aeromagnetic Map, Total Intensity, IGRF-65 Anomaly of High Altitude Survey (150m), Sheet 3714, Sodankylä. Original Scale 1:100 000. A reproduction of coloured IGRF-65 anomalies of Finland in hand drafted grey scale levels at 200 nT intervals.

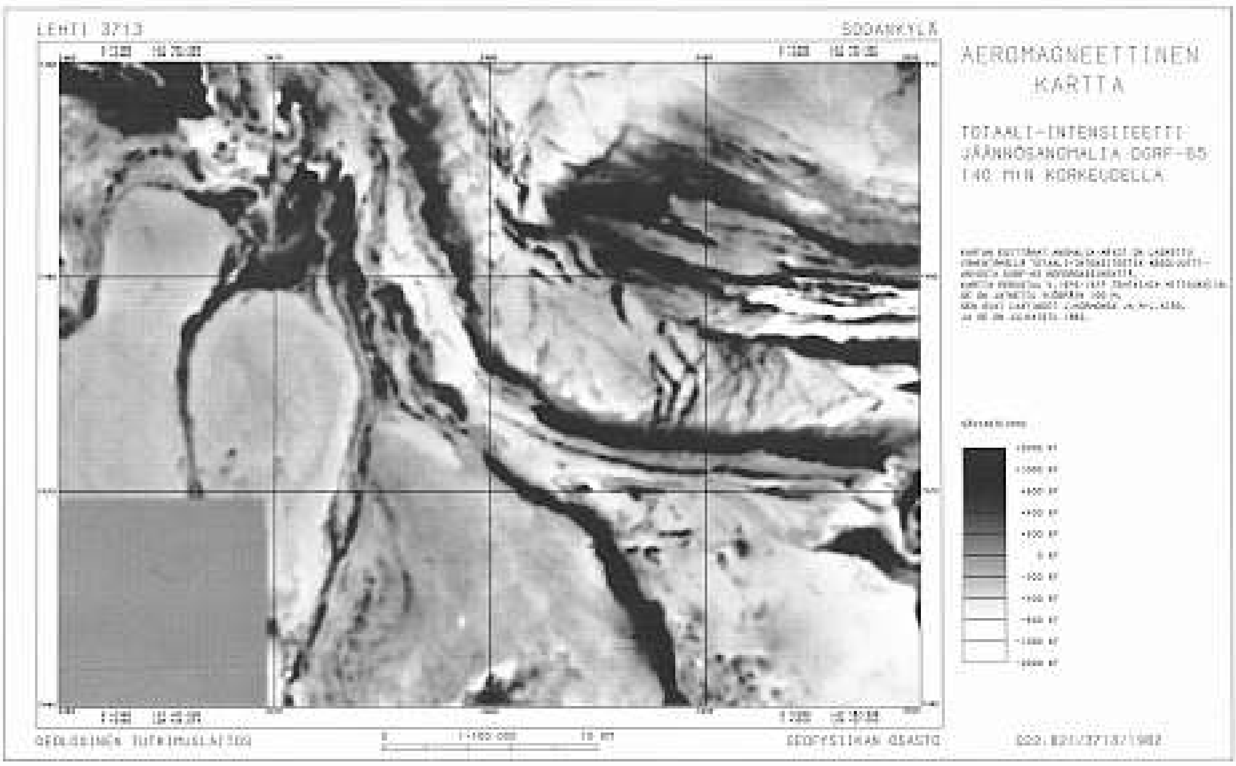


Fig. 3b. Aeromagnetic Map, Total intensity, DGRF-65 anomaly of Low Altitude Survey (30m), continued upwards 100m. Sheet 3714, Sodankylä, Original Scale 1:100 000. Digital grey scales by film plotter at c. 40 nT intervals.

BASIC PLANNING OF THE LOW ALTITUDE FLIGHTS

Changing from the old high altitude measurements to the new, low-altitude programme at GTL took place contemporarily with an administrative transition in which GTL obtained a new Director General, Dr Herman Stigzelius, a former inspector of mines at the Ministry of Trade an Industry, the Ministry hosting GTL. It became policy to initiate and develop automatic data processing (ADP) and geochemical mapping of the soil at the GTL.

A working group was established to outline the needs of ADP and, together with the State Computing Centre, prepare a development plan for the years 1972–1976 (Puranen and Korhonen 1970). Freely translated, the plan describes aerogeophysical measurements as follows:

"The most important goal of the aerogeophysical low altitude mapping will be producing series of aerogeophysical equal anomaly, profile and interpretation maps for the needs of mineral prospecting and geological mapping. The observations will be made at an aeroplane or helicopter, transformed to digital format and stored on a magnetic tape. The data will be checked and divided in files organised in national map sheet divisions. The values will be used to computer-draw equal-anomaly and profile maps. These maps will be interpreted both by interactive and semi-automatic methods and will establish different series of interpretation maps."

"Planning of the project will be started in 1971 and the first equal-anomaly and profile maps are to be made by 1973. Thereafter planning of interpretation systems will start. The final year of the project cannot be fixed now because its contents will be transformed depending on the registration and interpretation methods developed."

"The measurements can be processed more effectively and for varying purposes by computer rather than by traditional methods. Producing various interpretation map series is, in fact, impossible without ADP, because the number of staff and costs would otherwise be too high. The project will increase the reliability and speed of geophysical interpretation. As compared to the present system, the results will be essentially more useful in mineral prospecting and geological studies."

Afterwards we saw that what happened closely followed this outline. Special features of the aeromagnetic system were developed to solve problems encountered in the surveying. Development of these methods still continues. Of the other tasks of the ADP plan, the geochemical mapping and computer education of the staff started immediately. Some objectives were understood to be useful in the future, but without any given time schedule. Most of them were accomplished in due time. Finally a pre-Quaternary geological map was printed by ADP-methods (Silvennoinen et al. 1988). In the beginning ADP at the GTL was specialist's work done by main frame computers. Gradually ADP became everybody's tool based on commercially available software and without major programming and computer capacity limitations.

DATA PROCESSING

Alternatives were studied to buy data processing systems from GeoMetrics or from the State Computing Centre and some of the computer plotting of maps would be done at the GTL. Available computer and data media capacities were determinative factors in all system planning. Finally, a disc-operated HP2100 computer was bought for time-sharing daytime and batch processing of magnetic maps and till geochemical data outside of office hours. Images were made using an electrostatic dot-matrix plotter (Versatec). Radiometric and electromagnetic measurements were processed separately on a UNIVAC 1108 of the Ministry of Education. At the end of 1974, an HP3000 series II main frame computer with an advanced file management system was purchased. Later it was updated to a Series III and another similar one was bought. Maps were plotted with two pen plotters (Calcomp) that were regularly updated. In 1981, processing was moved to a Digital VAX 11-series computer, where all methods were merged under disk file management in 1984.

The magnetic component was processed as sequential files from one magnetic tape to another. Simple metadata of path, including information on flight, profile, program version and date was included as a header of each tape file and further summarised as catalogues. The job decks including parameters were stored on library tapes. The main phases of production of basic equal anomaly maps 1:20 000 were: 1) picking data from data logger tape and checking format, 2) finding sporadic values and data gaps, 3) correcting for these or rejecting unreliable parts, 4) correcting for short and long term variation of the Earth's magnetic field and for fields caused by the aeroplane, 5) merging co-ordinates, 6) computing horizontal gradient, 7) interpolating to a 50 m x 50 m grid, 8) formatting grid data for map drafting, 9) computer drafting equal-anomaly map files and 10) plotting these on a transparency off line.

Further stages of map production were made specifically for interpretation. Computer processing took place between direct access disk files and their metadata headers as follows: 11) Combining the 1:20 000 scale map grids to 100 000 scale map grids, 12) subtracting the DGRF-65 normal field to obtain anomalies, 13) converting and scaling anomalies to 8-bit grey tone files, 14) plotting these off line with an Optronix 1000 film plotter of the State Technical Research Centre, 15) drafting the films on repromedia at J.Ferin Co, and 16) storing data on library tapes and book-keeping of these products.

Programs were written on FORTRAN IV for HP3000 MPE-operating system. Main part of the software was designed and tested at the processing group. Thereafter, the bulk of the work was to prepare the jobs, let the computers do the processing, make intermediate checks and interact when manual work was necessary. An important part in long term was to obtain and analyse magnetic control information from field measurements to calculate best possible control parameters to get consistent data sets from one area and year to another.

By the end of 1980's the GTK had become one of the largest producers of graphic data processing in Finland. As usual in the 1970's, the need for computer capacity increased more rapidly than new main frame capacity could be bought. To save operated CPU-time and tape station resources, and compile the maps rapidly the main part of the processing of magnetic maps was designed for running the jobs as long batches outside office hours. By two batch-processing computers and two pen plotters, 24 map sheets could be completed in one weekend instead of the two months required for parallel processing with other activities. The base station data were pre-processed by time-sharing in office time.

Initially, Juha Korhonen made programs and processed data to maps, assisted by Tuula Laine for base station data. Later on, Meri-Liisa Airo took responsibility of the processing. Co-ordinates were obtained from the processing group for radiometric data. Maps were monthly released to the public. Finally, 88 magnetic tape series of 1972–1980 data products and corresponding metadata archives were forwarded to the processing group at the new VAX system. The later stages of magnetic processing have been described by Hautaniemi et al. 2005 (*this volume*).

SPECIAL FEATURES OF REGISTRATION OF THE MAGNETIC FIELD

Short term consistency: The Auroral zone is a major source of geomagnetic disturbance in Finland, especially in the north. Hence, lateral variation of temporal changes of magnetic field was considered when collecting reference information for magnetic surveys. The short-term magnetic variation was corrected using data registered at a magnetic base station that was installed in the survey area (Fig. 4). The base station was taken to represent field variation within a radius of about 30 km, taking care that no measurements are made during magnetically disturbed times. Allowed magnetic variation parameters were predefined for the field crew to check the magnetic 'weather' from a monitor station at the airbase prior to each flight. More recently, forecasts of magnetic weather by solar-terrestrial observatories have been used as well.

Tie lines: Although the programme was started with measurement of magnetic tie lines, this practice was stopped after being shown to be useless. The accuracy of xyz-position at tie knots was too low when compared with the sharp variation of magnet-

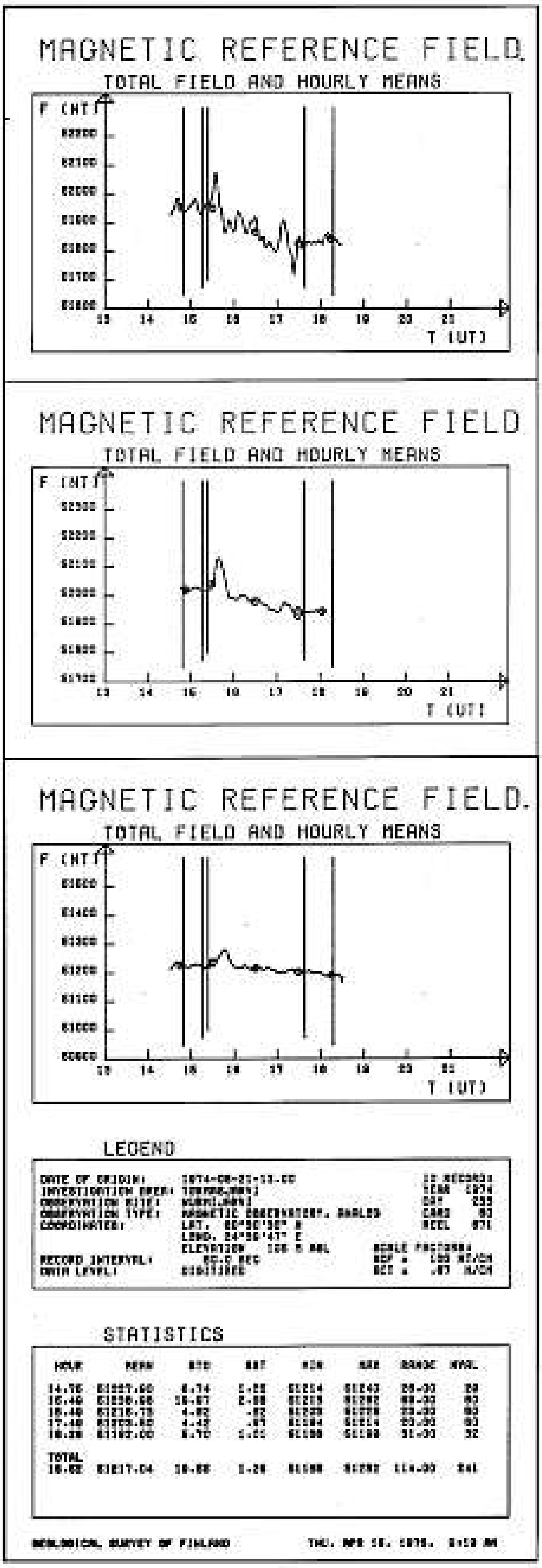


Fig. 4. Geomagnetic total field variation during flight 60 in 1974 in Törmäsjärvi area (Lat=66.0). From bottom up: a) Nurmijärvi geomagnetic observatory (Lat=60.5), b) base station at Oulunsalo airport (Lat=65.0), c) Sodankylä geomagnetic observatory (Lat=67.3).

ic anomalies due to close distance to the nearest magnetic sources. Careful corrections for base station data and directional aeroplane effects gave more accurate results. Hence, by skipping the tie lines, capacity reserved for profile measurements could be saved. Savings were used to increase the annual area surveyed by five per cent, equalling to one production year in a twenty years period.

Long term consistency: The aim was to produce a nation wide map set in which the levels of magnetic total intensity would fit together, independently of time and of registration, and further be reliably merged with any other corresponding data set in NW-Europe or globally. Hence the main field part of the measured total field was corrected to correspond to epoch 1965.0. The correction was based on secular magnetic variation at nearby geomagnetic observatories and tied to the level of the magnetic base station as described in appendix 1 (Fig. 5). It was supposed that the anomaly component doesn't change considerably upon changes in main geomagnetic field, and hence can be neglected.

Line spacing: It was known already at the planning stage that, at an altitude of 30 m above the ground and using line spacing of 200 m, the sharpest, near-ground parts of the anomalies would be poorly represented across the lines. Nothing could be done about this, however, because of economic reasons and planned schedule of the refinement programme. In 1975, after facing this fact on maps in practice, sampling was improved by installing two magnetometers, one on each wingtip, instead of just one at a wingtip or on the tail, as in 1972–74. This double profile configuration became the first operational horizontal transverse gradiometer system globally (Figs. 6a–b).

Anomalies: The basic result quantity from the magnetic measurements is magnetic total field reduced to 1965.0 (absolute magnetic total intensity). This gradually increases from south to north from 50000 to 53000 nT over the Finnish territory, making it difficult to colour the maps with a single scale and to interpret anomalies in regional terms. Hence, for combining survey-areas and facilitating interpretation of crustal sources of anomalies, a normal field, defined as DGRF-65, was subtracted from the absolute total intensity (IAGA 2003, Fig. 7a–c). Processed in this way, via absolute total intensity, anomalies of different registration years fitted together well. The remaining regional anomaly range was typically from –400 to +800 nT. However, long wavelength components lower than or equal to order and degree ten in global spherical harmonic ex-

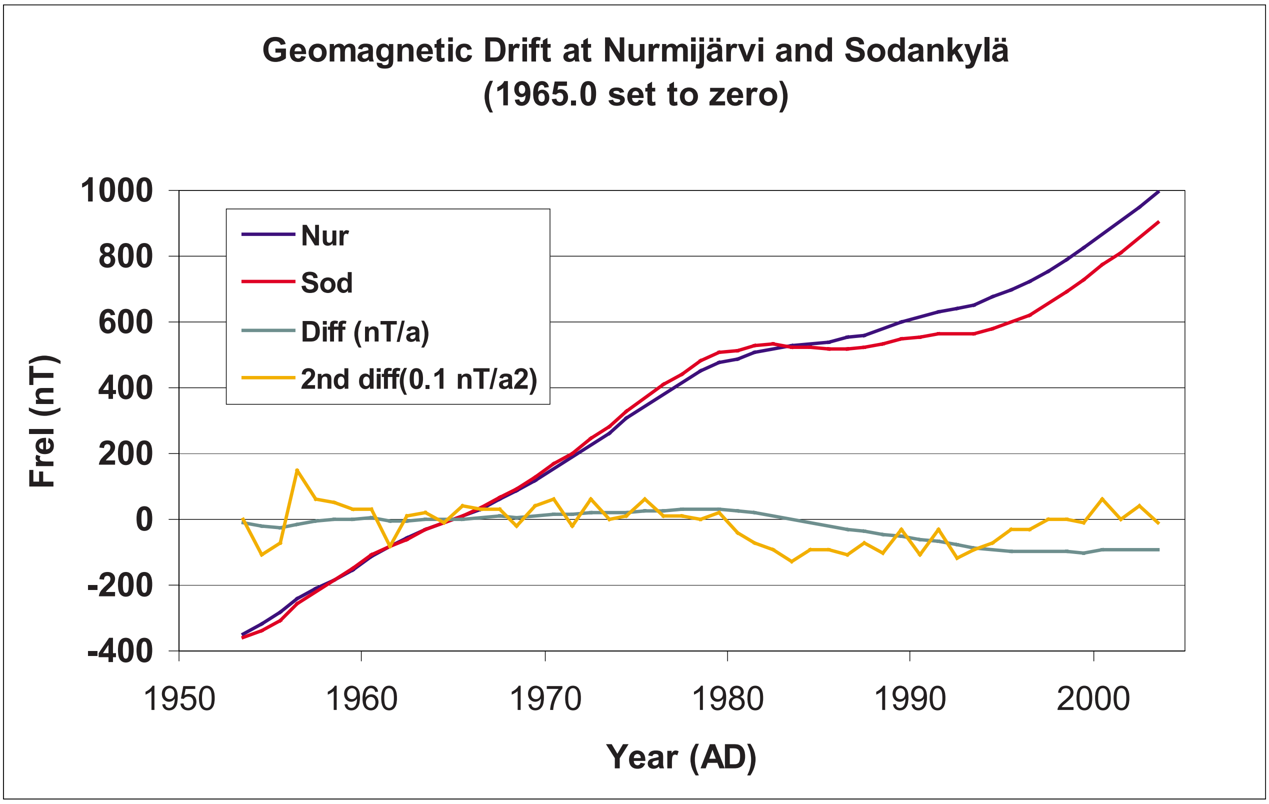


Fig. 5. Relative geomagnetic change in total field at and between Nurmijärvi and Sodankylä geomagnetic observatories 1953–2003. Averages at the reference year 1965.0 are set to zero.

Fig. 6a. Transverse horizontal gradiometer installed at DC-3 (1975–1980 surveys). Photo: GTK archives

Fig. 6b. First and second transverse horizontal gradiometers installed at DeHavilland Twin Otter (1984–1988 surveys). Photo: GTK archives

a) b) c)

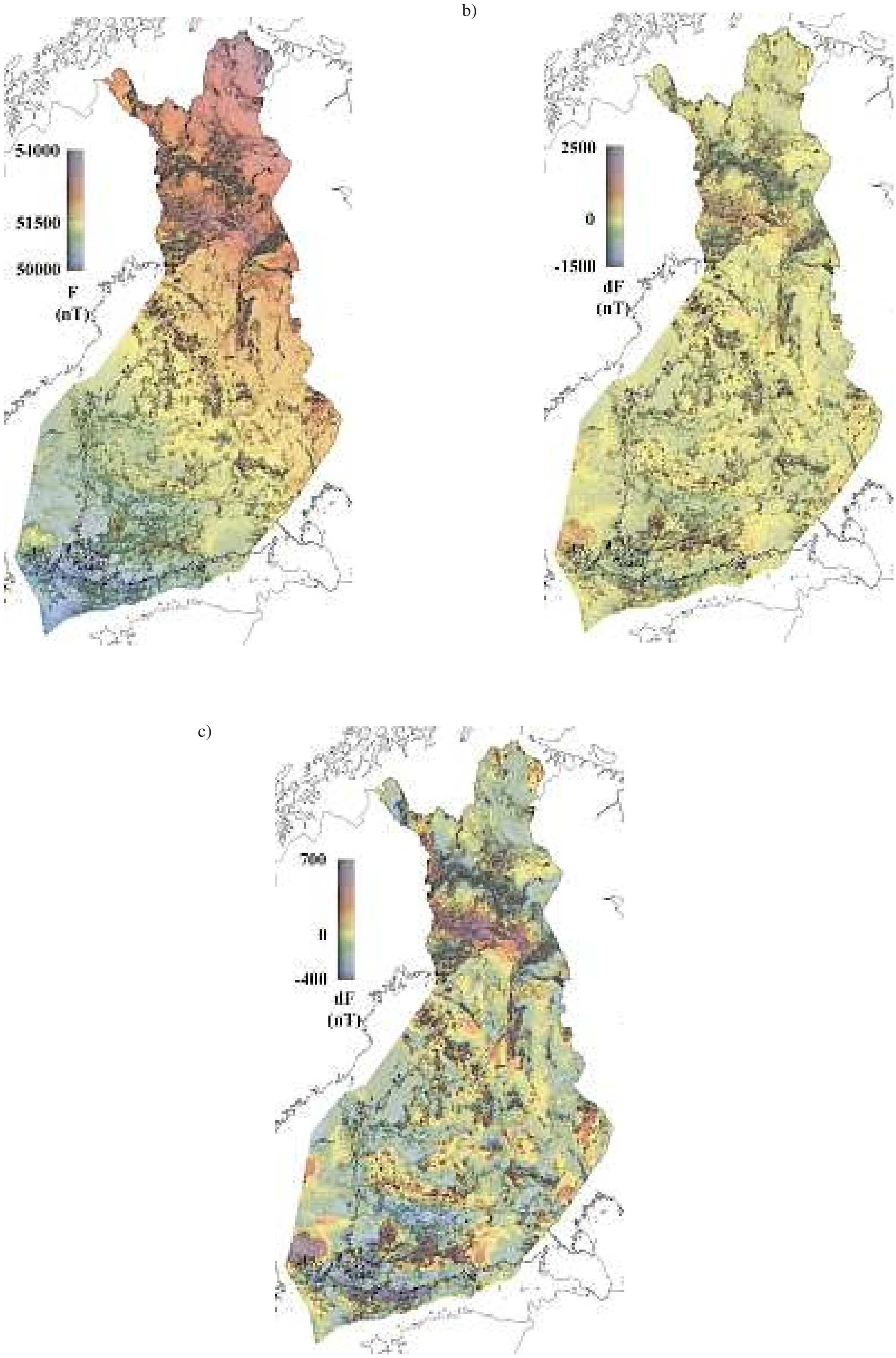


Fig. 7–c. Magnetic High Altitude Survey (150 m) anomalies of Finland in different scales, red positive, yellow zero, blue negative, grey positive horizontal gradient. a) total field in total field range (zero 51 500 nT), b) DGRF-65 anomaly in total field range (–1500 … 2500 nT), DGRF-65 anomaly in anomaly range (–400 + 700 nT).

pression were cut off in this anomaly definition. To obtain continental and global scale anomalies of longer wavelength than 2600 km some other normal field definitions must be used. In this data set any digitally defined, GIS-based normal field is easy to apply because the absolute total intensity data is retained, the secular variation data from geomagnetic observatories is available and the present normal field grid and its definition coefficients are known.

Graphic display: At the first stage, the absolute total intensity was represented as equal anomaly maps coloured with reference to DGRF-65 value at the centre of each 1:20 000 scale sheet). Besides their use in geological studies these maps were originally planned to establish an analogue safe archive to numerical grid values of absolute total field in 50nT accuracy class, in case of eventual loss of digital data. For interpretation, these maps were combined as DGRF-65 anomalies in grey-scale (grey tone maps) at a scale of 1:100 000 from 1980 (Korhonen 1983) (Figs. 8, 9a). The latter presentation became popular because of its good visual properties and economic price. More recently users have started to prepare coloured and enhanced maps individually for each problem and area using database for low altitude airborne geophysics of the GTK as the source of the data.

National coverage: Although the program was started to re-fly key areas for mineral prospecting only, the concept was soon extended to cover the whole country. The main reason for this was that the low altitude survey brought in new useful detail for geological studies, independent of region and purpose. The maps were considered so useful to region-

Fig 8. Magnetic High Altitude Survey (150 m) IGRF-65 anomalies in grey scales (50 nT interval, dark positive), original scale 1:2 000 000. The first grey tone map at the GTK in 1980, a by product of printing the Magnetic Anomaly Map of Finland (Korhonen 1980)

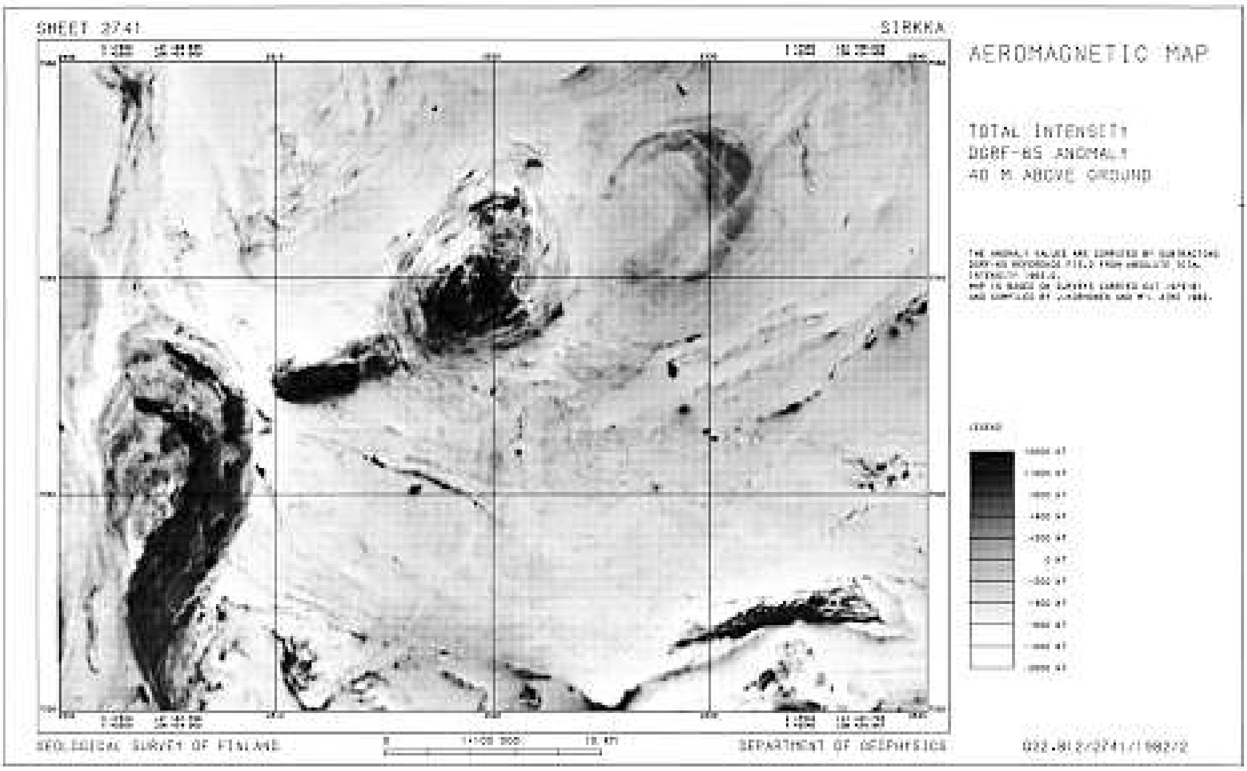


Fig. 9a. Aeromagnetic map, total intensity of DGRF-65 anomaly, 30 m above ground. Sheet 2741, Sirkka. Standard grey tone map, based on total intensity an its horizontal gradient. Original scale 1:100 000.

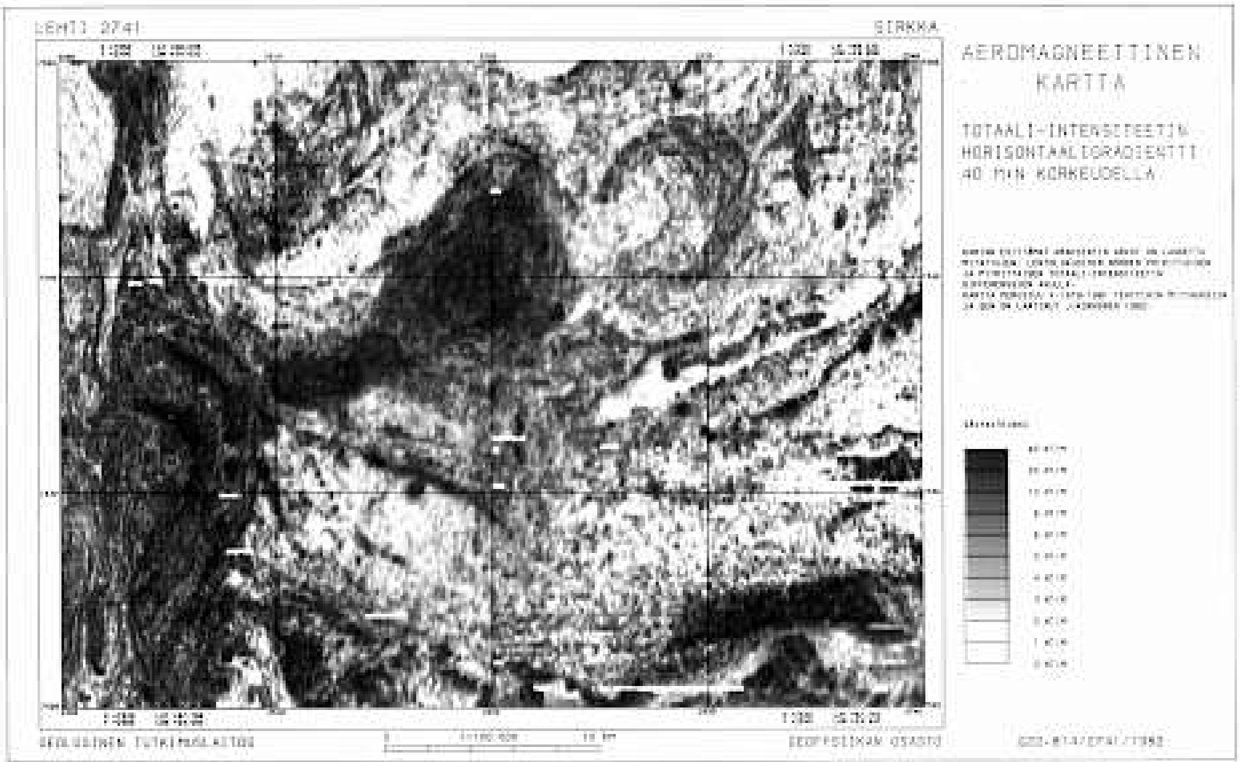


Fig. 9b. Aeromagnetic map, horizontal gradient of total intensity, 30 m above ground. Sheet 2741, Sirkka. Special grey tone map, presenting intensity of horizontal gradients that were used to compile map 9a. Original scale 1:100 000.

al geological activities that the availability of new maps could influence on scheduling a new geological project. In turn, the need for countrywide overviews arose (Fig. 10a–b).

Regional and Global coverage: To facilitate interpretation of the long wavelength anomalies, GTK exchanged a 1 km x 1 km grid of DGRF-65 anomalies of high altitude data with the neighbouring countries to have access up to 200 km outside the borders of Finland. In these compilation processes similar schemes of reduction as applied at GTK have been shown to be useful so far. Independently collected and reduced national matrices fitted with each other without any major forcing, like in examples of

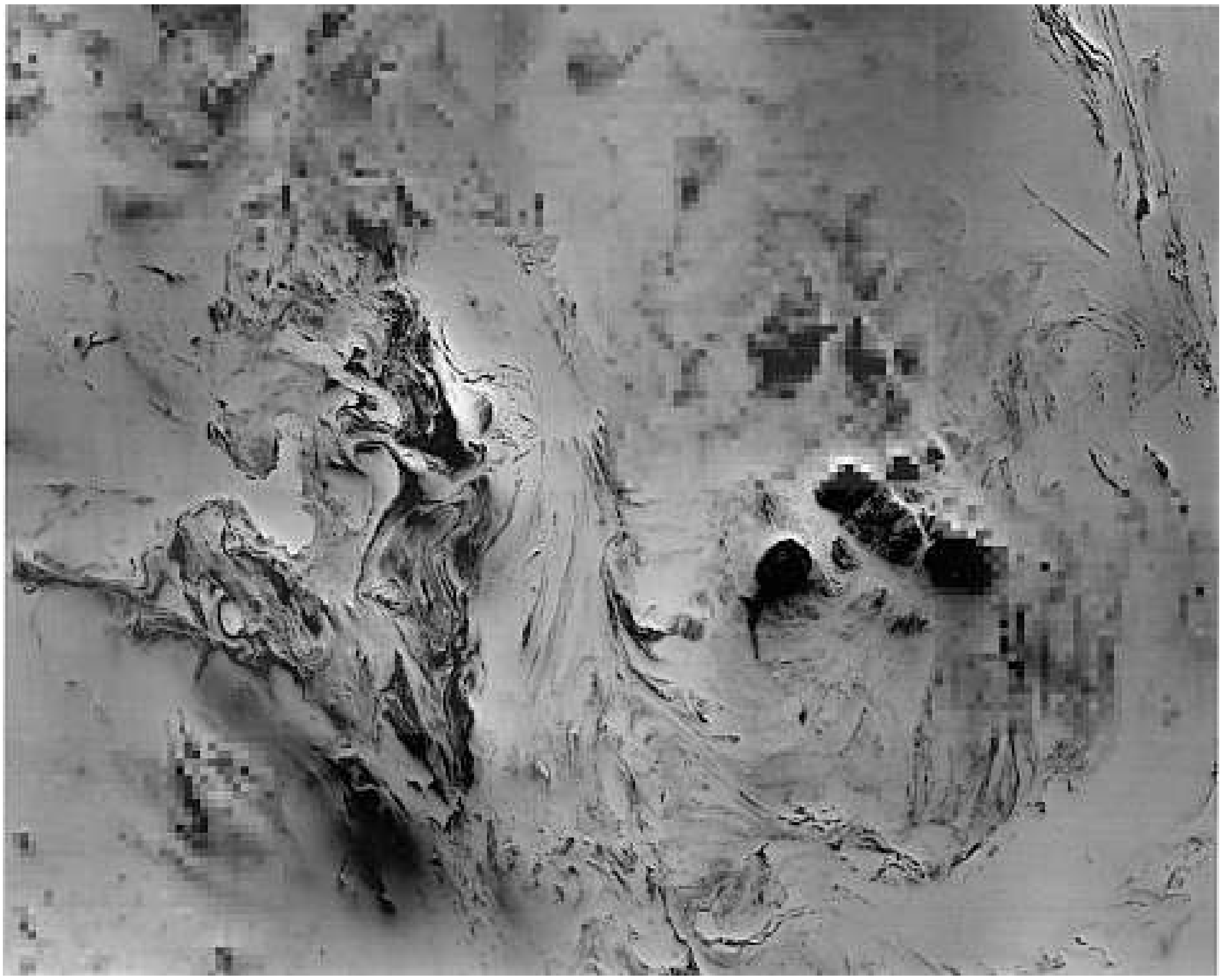


Fig. 10a. Digital combination of high and low altitude aeromagnetic grids of GTK, in grey tones at c. 40 nT intervals. Map Sheet 33, Iisalmi. Height of the map area is 120 km. Major squares represent 1 km x 1 km grid. Edited from original scale 1:400 000.

Figures 11a–b. The Finnish anomaly field would be further joined together with a global database collected by IAGA on a 5 km x 5 km grid (Korhonen 1997).

Petrophysics: GTK has covered whole country by petrophysical measurements on hand specimens and drill cores. The national petrophysical database consists of bulk densities and basic magnetic properties of 131 000 samples. The purpose is to rapidly provide values for first approximations of petrophysical properties in geophysical modeling and geological interpretation of anomalies over any area of Finland.

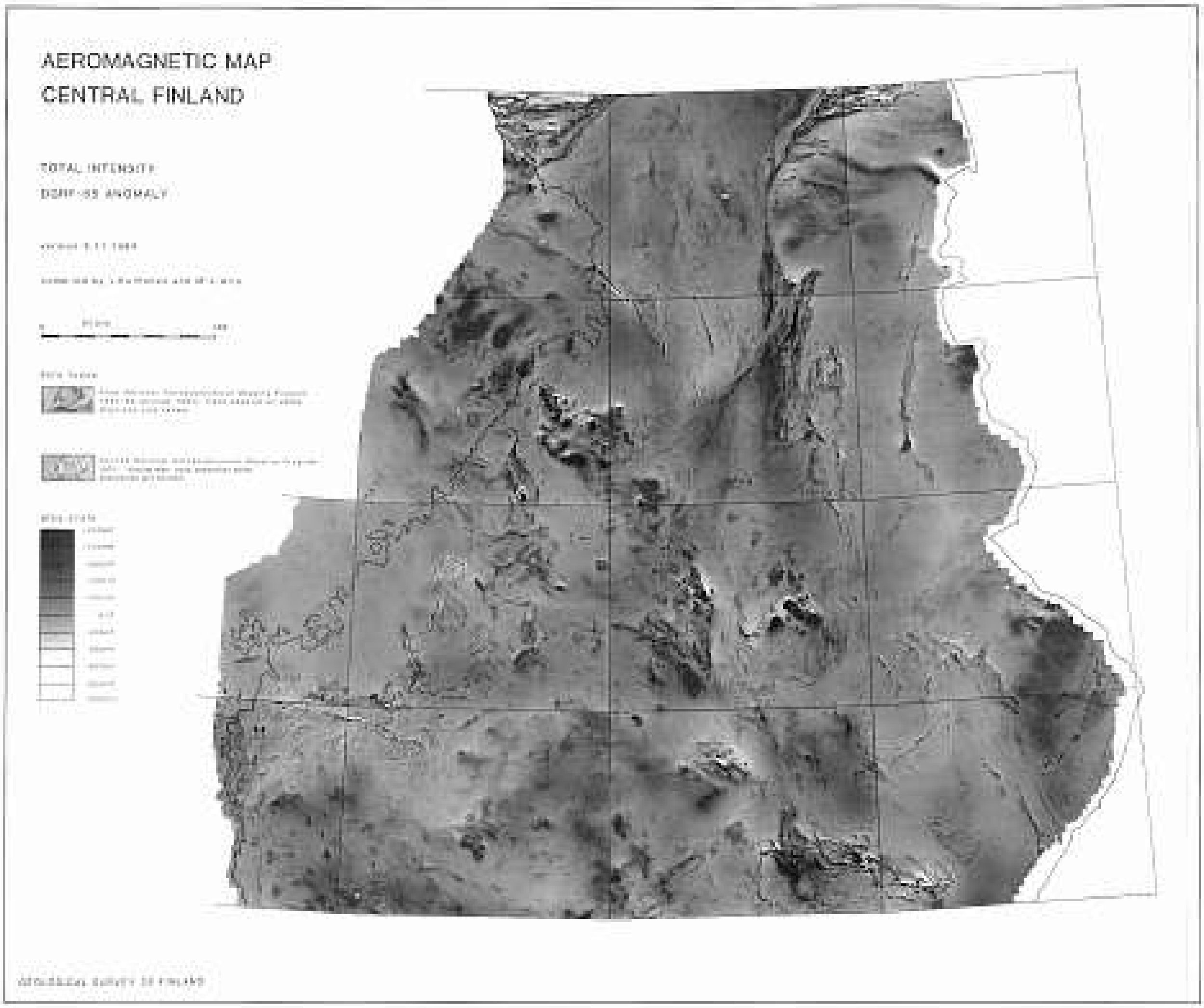


Fig. 10b. Aeromagnetic map, Central Finland, DGRF-65 anomalies of total intensity in grey tones at c. 40 nT intervals. The map was prepared as a collage of digitally combined of low and high altitude grids of 1:400 000 map sheets (e.g. Fig. 10a). Compiled by J.Korhonen and M-L. Airo in 1984. Presented in exposition of GTK at 54th SEG meeting in Atlanta 1984. Height of the map area is 480 km. Edited from original scale 1:400 000.

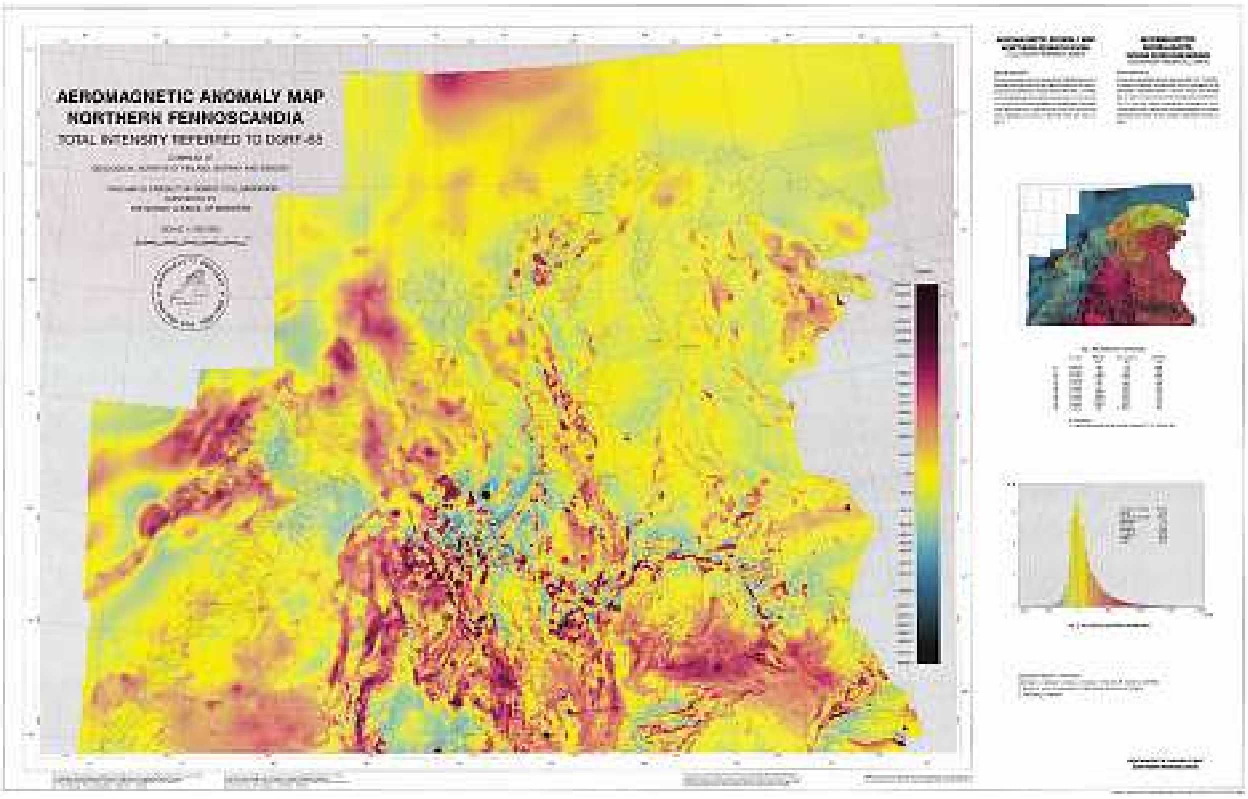


Fig. 11a. Aeromagnetic Anomaly Map, Northern Fennoscandia, Total Intensity Referred to DGRF-65. Original scale 1:1 000 000 (Korhonen et al. 1986).

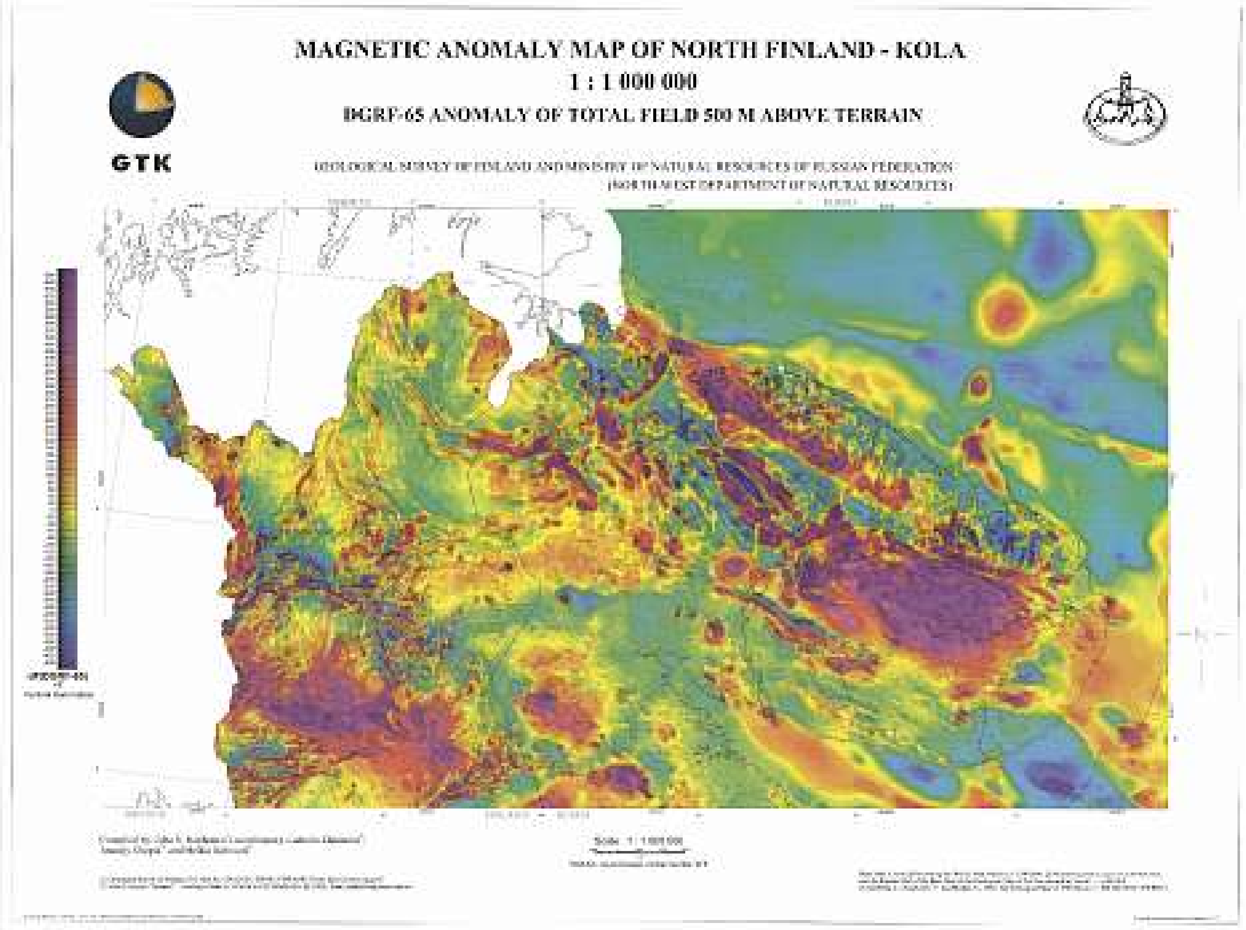


Fig. 11b. Magnetic Anomaly Map, North Finland – Kola, DGRF-65 Anomaly of Total Field, 500 m above terrain. Original scale 1:1 000 000 (Korhonen et al. 2001a).

TRANSVERSE HORIZONTAL GRADIOMETER

The characteristics of electromagnetic and radiometric measurements defined the flight altitude to be as low as possible. The average distance to magnetic sources in low altitude data was estimated by the nominal flight altitude 30 m, added with mean soil thickness of 4 m in Finland. Hence the minimum half width of anomalies caused by geological near surface sources was supposed to be less than 25 m. It was well understood that a flight line configuration of 200 m track-separation greatly under-samples such features across the profiles (Korhonen 1970). A 50m track separation would have been necessary to adequately sample the anomalies in both dimensions. However, there were no economic possibilities to do this at all. The programme was started with one magnetometer in the tail of a De Havilland Twin Otter. Map drafting procedures produced oblique linear anomalies as 'chains of pearls'. In this situation it was suggested again to fly with closer line spacing, but the proposal was considered impossible to accept. In fact, alternatives were studied so as to essentially lower the total costs, even by cancelling part of the new programme. However, the new magnetic maps were considered to be essentially more useful than the previous high altitude maps, and cheaper per unit area than making ground based measurements. Because the survey seemed to be worth its price, the Ministry of Trade and Industry agreed to continue, and later even to extend the programme.

Meanwhile, the Twin Otter had crashed on a passenger flight in wintertime, and low altitude surveys were continued using a DC3. On the new platform the electromagnetic system was co-axial and the magnetometer was moved to the left wingtip. The innovation was to mount a second magnetometer on the right wingtip, hence providing a double profile of track separation 24.5m at a single price. This second magnetometer was built from system spare parts. With the skills of the instrumentation team it worked with minimal problem from the first test flight onwards (Fig. 6a). Due to close distance to the sources this simple measurement was capable of identifying maximums and minima between flight lines by calculated horizontal gradients and determining directions of equal anomalies at the flight lines (Figs. 12a–b).

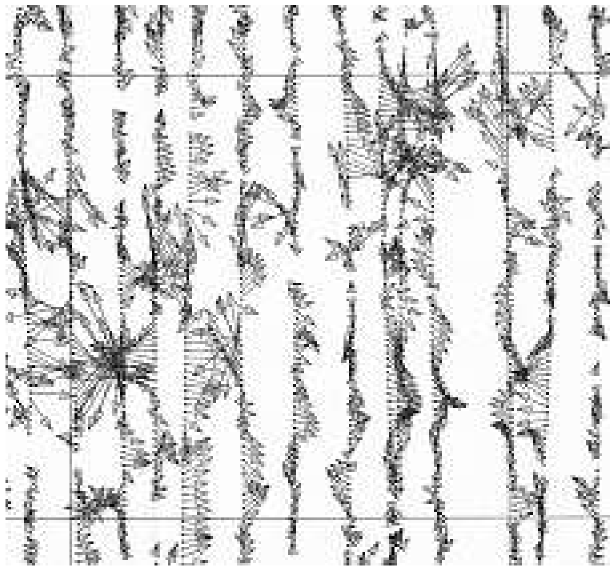


Fig. 12a. Horizontal gradient vectors calculated from DC-3 data 1978. Flight lines are in NS-direction and 200 m apart from each other. The distance between co-ordinate lines is 2 km.

Fig. 12b. Directions of equal anomalies at maximum gradients (lines), total field maximums (circles) and minima (crosses) calculated from DC-3 data 1978. Flight lines are in NS-direction and 200 m apart from each other. The distance between co-ordinate lines is 2 km.

Directional aeroplane corrections were calculated for both magnetometers by data registered at the Emäsalo magnetic rose site that was measured from the air a few times per year. An interpolation algorithm for gridding by gradients was adapted from the manual of the contouring program GPCP II (Calcomp 1972). From the pair of two wingtip profiles, both horizontal components of gradient were calculated at each data station and were used to linearly extrapolate the total field to the grid point. Estimates from various stations were weighted inversely by their square distance. Data from three closest profiles in a radius of 400 m were used in the calculation. The interpolation scheme produced more isotropic and geologically looking anomaly patterns from two magnetometer data than from one magnetometer only (Figs. 13a–b.) It placed anomaly highs and lows mostly between flight lines, although it did overestimate values in high gradient cases. This latter could have been avoided by a more complicated version of the procedure. However, the interpolation was kept simple to compile the maps in a reasonable time.

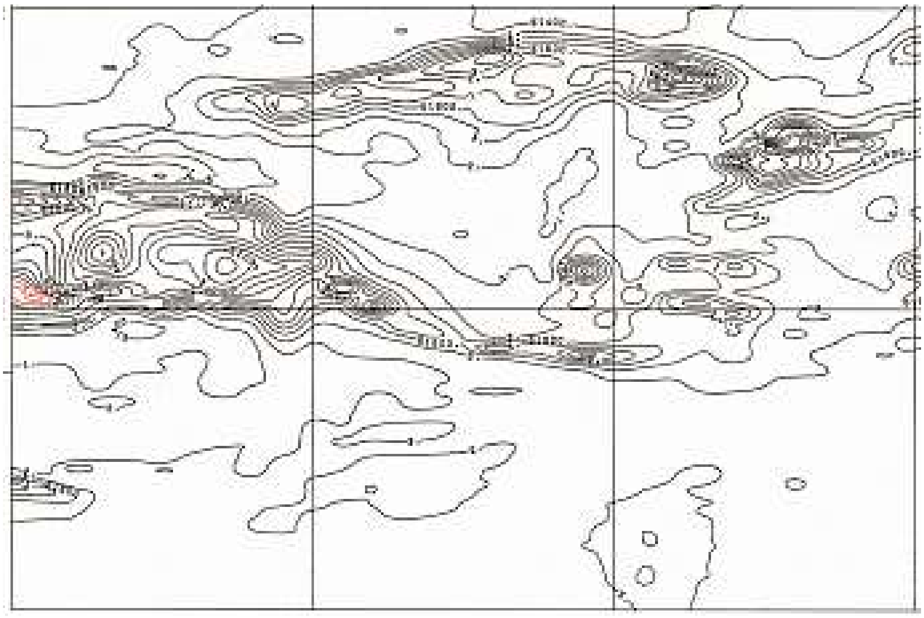


Fig 13a. Magnetic total intensity, equal anomalies at 50 nT intervals, compilation of left magnetometer, Sheet 3344 07, Hiidenvaara. Coordinate lines are 2 km from each other. North is to the left.

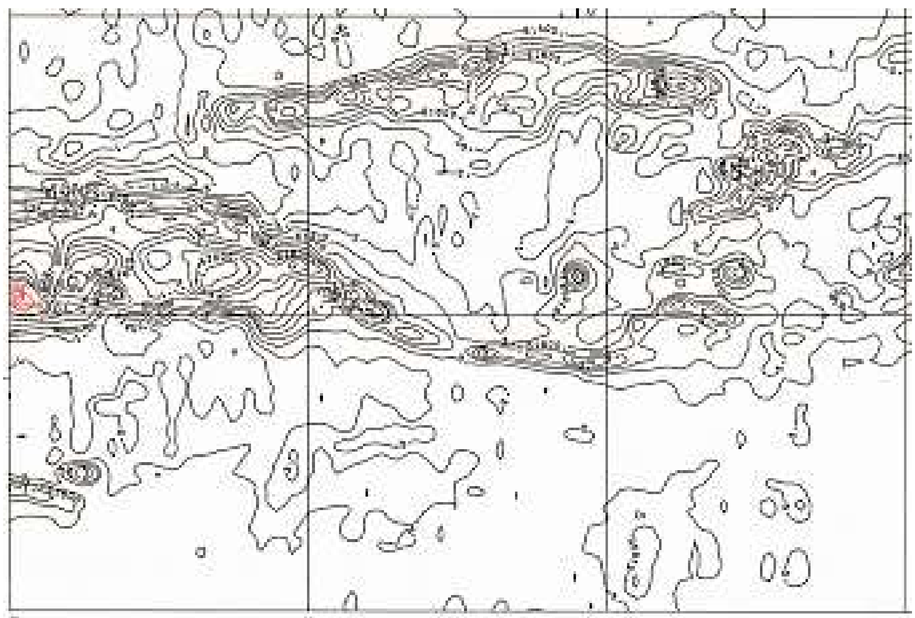


Fig 13b. Magnetic total intensity, equal anomalies at 50 nT intervals, compilation of both magnetometers, Sheet 3344 07, Hiidenvaara. Coordinates are as in Fig 13a.

To test the method, the details of the gradient based total intensity maps were compared with both ground measurements of GTK and low altitude flight survey of the Outokumpu Company. In Korsnäs area, the gradient-based system on track separation of 200 m (400 stations/km^2) indicated ground anomalies closer than a single magnetometer flight of track separation 125 m (320 stations/km^2), both having an effective along track station spacing of 25 m. The grid values created by the gradient interpolation scheme were better nearer the flight lines than in mid areas, as might be expected.

Development ideas included using the gradient vectors in identifying different source types, and assisting in automated interpretation. Second transverse gradient could help in interpolating grids of the first gradient for interpretation (Figs. 9a–b). Longitudinal gradient measurement could help in correcting for short-term magnetic variation near crustal-scale conductors and along long profiles. Furthermore, a tensor gradient configuration was an attractive idea, but far beyond the possibilities of a national mapping team with underlined practical goals (Korhonen 1984, 1985). A three magnetometer transverse system was tested in the Twin Otter 1984–1988 (Fig. 6b). It was abandoned because of an unavoidably high noise level from electromagnetic sources in one of the sensors.

More recently, old survey areas have been re-covered to complete a more dense line spacing down to 50 m for mineral prospecting. In fact, a sufficiently dense data sampling is one of the basic requirements to distinguish between potential field sources exposed at the bedrock relief surface and deeper unexposed sources above the drilling depth of normal prospecting (c. 500 m). A few uncovered map sheets of the programme on land area are planned to survey in 2005–2006.

GEOLOGICAL APPLICATIONS OF MAGNETIC MAPS

In the 1970's, geologists used magnetic anomaly maps at scales 1:20 000 (10 km x 10 km squares) and 1:50 000 (collected to 20 km x 30 km rectangles) where total intensity was presented as 50 nT equal-anomaly lines. The former were used to visually interpret anomaly sources and geological structures locally, the latter to see overall geological elements of a survey area. Maps were drafted with 10 or 2 nT contour line intervals when more detail was required. Starting in 1981, map-sheet grids were merged to 1:100 000 scale matrices (40 km x 30 km) on a 50 m x 50 m grid, DGRF-65 anomalies were calculated and grids were drafted via film to greytone repro-paper or transparency. Altogether 131 map sheets were released up to 1985. Following the general trends of computer data processing, the drafting of special maps was transferred to project groups and finally to the GIS-groups of the Survey.

The maps and grids have been used as one of the basic materials in bedrock mapping, mineral resource assessment, mineral prospecting and studies of groundwater reservoirs, both in the public and the private sectors. Interpretation of maps, both visually and numerically, was normal but practice varied in organisations using the data. (e.g. Aarnisalo et al. 1983, Rekola & Ahokas 1986, Kuosmanen 1988, Säävuori et al. 1991, Ruotoistenmäki 1992, Airo 1999, Arkimaa et al. 2000, Pesonen et al. 2000).

A programme to create a total of 342 map sheets of pre-Quaternary geology at 1:100 000 scale was initiated at the Geological Survey in 1946. Aerogeophysical maps were planned to assist in that work because continental Finnish bedrock is for 97 per cent covered by Quaternary formations like till, clay, peat bogs and lakes. Since then, 14 maps have been prepared without aerogeophysical information, 104 by using high-altitude maps, and 105 based on low altitude data. Quality and outlook differences between these groups clearly exist. Geologically interpreted magnetic patterns and anomaly boundaries have been introduced to bedrock maps. Hence, the amount of detail at and continuity of geological formations is greater on newer geological maps. Some of the older maps have been revised in connection with newer projects. Besides this national mapping programme geological maps are made topically, independent of map sheet borders. In these compilations the overview characteristics of magnetic maps have shown to be most useful. The conventional wisdom of the geologist in their work is that magnetic data is considered to be inferior only to geological field observations.

Aeromagnetic maps have been used in the planning of some major engineering projects in bedrock, like the Päijänne freshwater tunnel (120 km), underground fuel storage, nuclear power plants and nuclear waste disposal sites. In addition, the maps established a reserve of quality background information in various geology-related investigations, like environmental evaluation, land use planning and geo-medical studies. They have been especially valuable in geological-geophysical-geodetic research. Guides and articles on the use of the data have been published mainly in Finnish. (e.g. Marmo & Puranen 1966, 1990, Korhonen 1983, 1993, Peltoniemi 1988, Airo 1999).

In 1980, GTK established a team to build background for interpretation of aerogeophysical data. Its work included conducting a national petrophysical sampling programme in 1980–1991, compiling aeromagnetic grey tone maps and multinational map sets, writing articles for geological use, arranging workshops and taking part in geological mapping and research projects. One of its major recommendations for future was to build a geophysical crustal model for Finland and surrounding area to become a tool for digital retrieval of previous work and new interpretation of geophysical data (e.g. Korhonen 1992b, 1997, 1999).

PETROPHYSICS

Measurements of physical properties of rocks as an aid to geophysical map interpretation started at GTL in 1953. Systematic measurement of regional sample sets and drill cores was carried out since 1963 (e.g. Puranen et al. 1968). Basic quantities measured were density, susceptibility, and intensity of remanent magnetisation plus – optionally –vector components of the latter, thermal dependence of susceptibility, electrical conductivity, IP-effect, porosity, P-velocity and thermal conductivity. The petrophysical database was established in 1973 and consists presently of 171 000 data records (Puranen 1989, Säävuori & Hänninen 1995). A petrophysical programme covering all of Finland was initiated in 1980 (Korhonen et al. 1989, 1993, 1997). The laboratory was computerised in 1982 and two new laboratories were built at regional offices. Three Finnish universities established their own petrophysical laboratories. A temporal-spatial summary of Finnish, Norwegian, Swedish and Estonian data of Precambrian rock properties was presented on maps of the Fennoscandian Shield (Korhonen et al. 2002a–b). A major part of the digital continental petrophysical data globally has been collected in this area (Korhonen & Purucker 1999). Application of petrophysics in interpretation is described e.g. in Airo 2005 (*this volume*).

Local magnetic anomalies are due to the ferrimagnetic population which relative proportion in geological formations varies regionally from a few per cent to almost 100 per cent and is c. 25 per cent on average (Fig. 14a). The bulk density of ferrimagnetic rocks varies, corresponding to acid compositions at major positive regional anomalies and to basic compositions at many local anomalies (Fig. 14b). The mapping allows estimation of regional variation in intensity of magnetisation of the ferrimagnetic population and total population (Figs. 14c–d). The Q-value varies typically from 0.1 to 20 on sample level and from 0.8 to 8 between major rock types (e.g. Fig. 1 in Korhonen 1993). Scatter diagrams of magnetic properties indicate typical lithology by density and mineralogy by ferrimagnetic Q-value for magnetic anomaly sources (Fig 15a–b). Average magnetic properties of major upper crustal units differ, exhibiting apparent temporal trends across geological history of the Shield as indicated by summaries in Korhonen et al. 2002a–b.

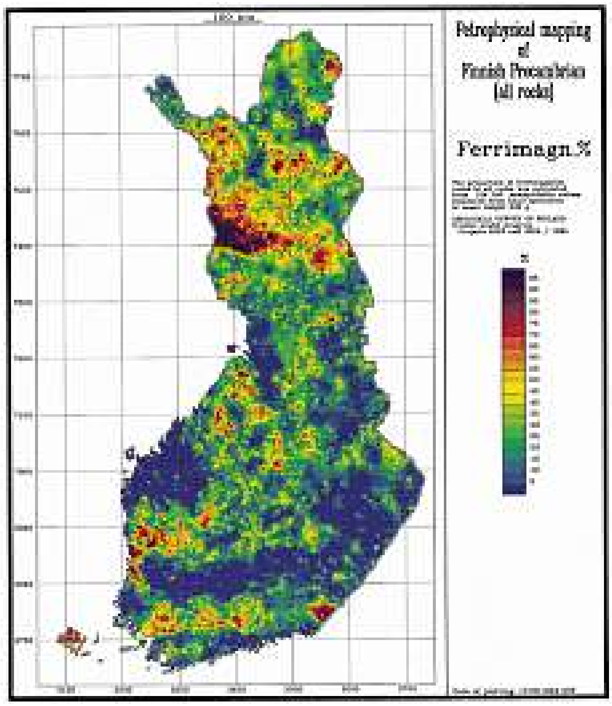


Fig 14a. Percentage of ferrimagnetic rocks in Finland, Original Scale 1:4 000 000. Petrophysical mapping by GTK, 1994.

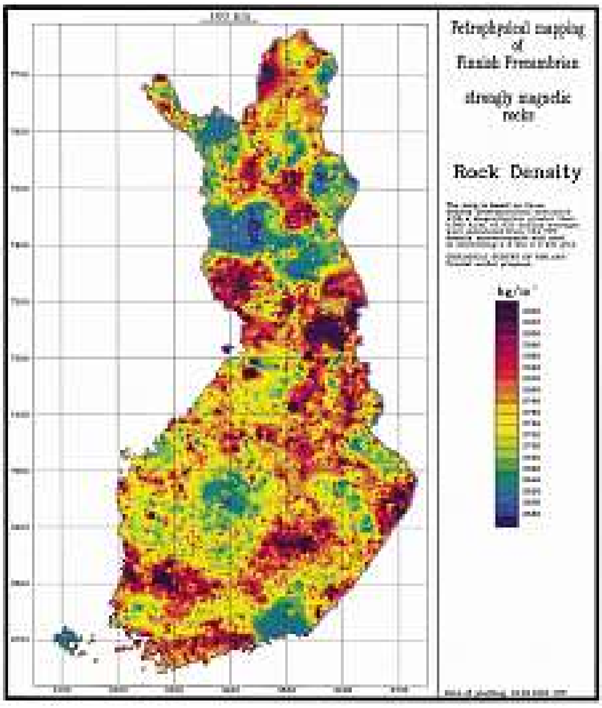


Fig 14b. Bulk Density of ferrimagnetic rocks in Finland, Original Scale 1:4 000 000. Petrophysical mapping by GTK, 1994.

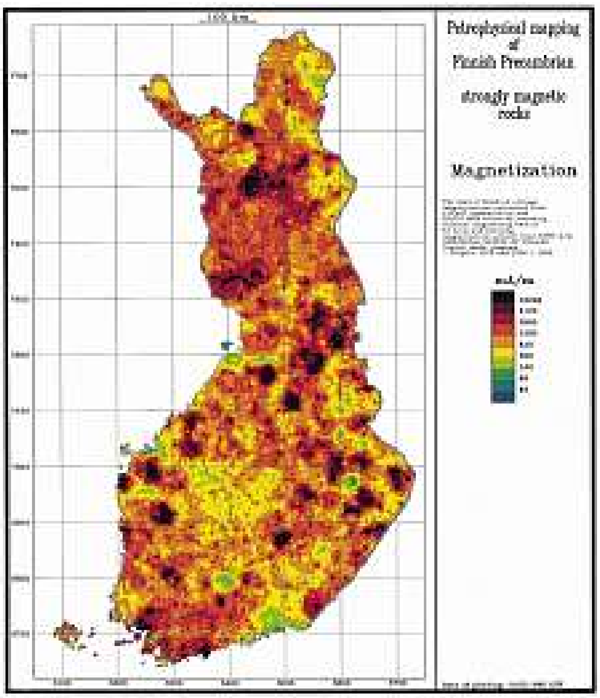


Fig. 14c. Magnetization of ferrimagnetic rocks in Finland, Original Scale 1:4 000 000. Petrophysical mapping by GTK, 1994.

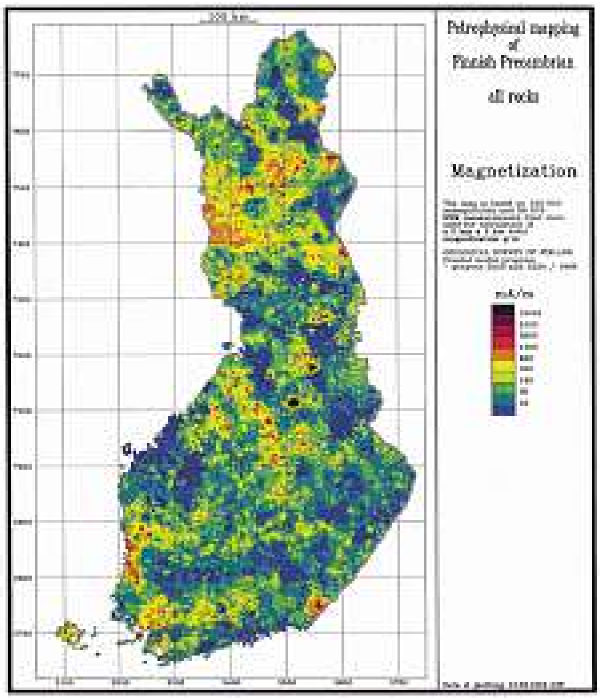
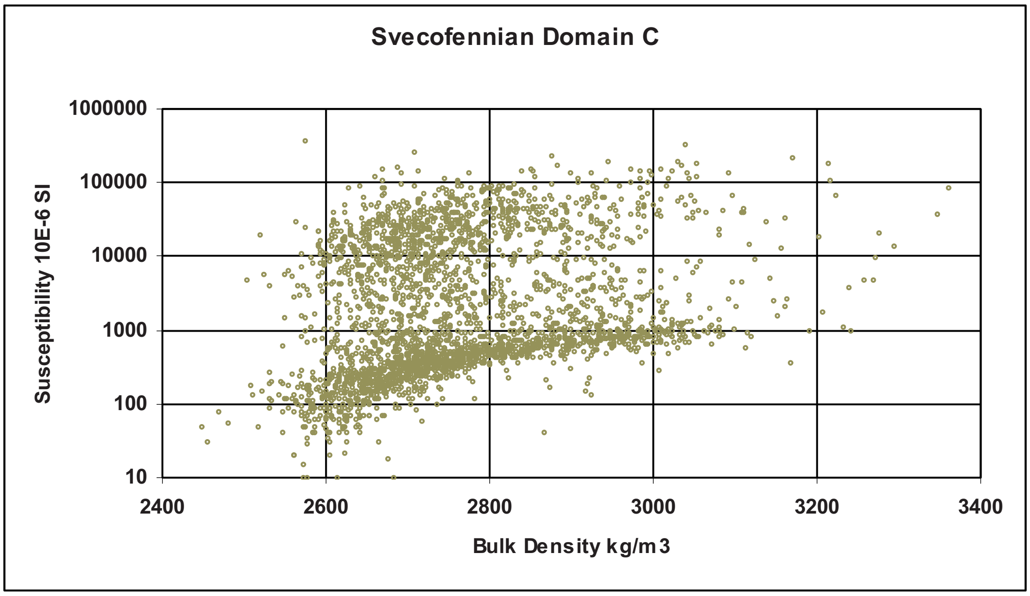


Fig. 14d. Total magnetisation in Finland, Original Scale 1:4 000 000. Petrophysical mapping by GTK, 1994.



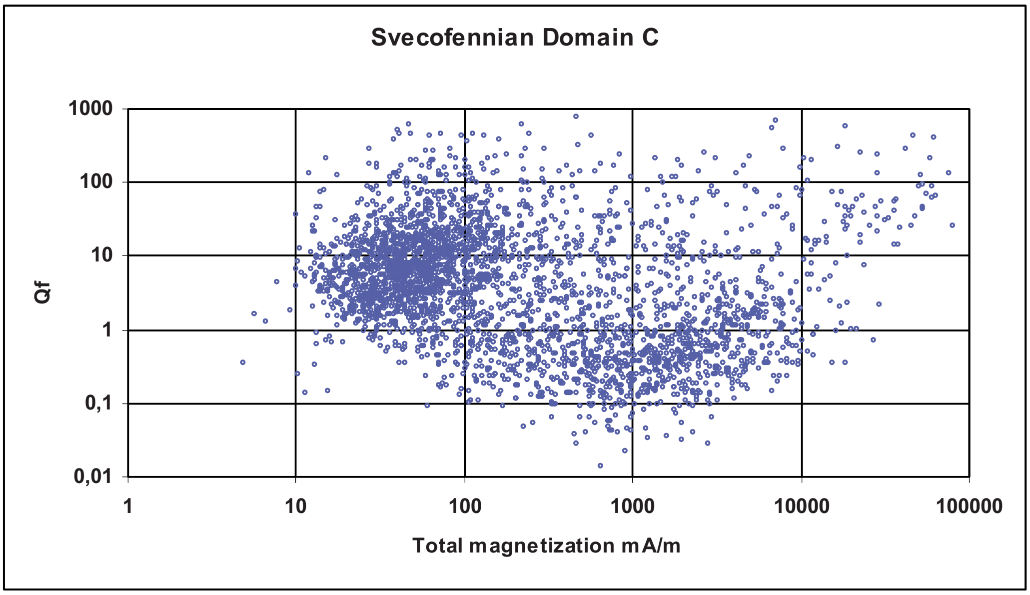


Fig. 15a–b. Petrophysical scatter diagrams from database FINPETRO. Primitive arc complex of Central Finland (1.93–1.87 Ga) as defined by Korsman et all. 1997). a) bulk density versus magnetic susceptibility; concentration of ferrimagnetic sources (k>2000) to bulk densities around 2700 kg/m^3 corresponding to rocks of intermediate composition (top), b) total magnetisation versus ferrimagnetic Q-value (H=41A/m); concentration of ferrimagnetic sources (J>0.2A/m) to Q-values less than 1, corresponding to coarse grained magnetite (bottom).

MULTINATIONAL MAPS

High altitude anomalies digitised on 1 km x 1 km grid were used as overview material, in data sales and in bi- and multinational data exchange. The reduction procedure for temporal variation proved to be adequate to combine national data sets, originally compiled independently. Existing geomagnetic observatory network in the area of participating countries at NW Europe was a necessary requirement to successful compilation. Minor warping has been done locally to adjust data sets to the most reliable grid.

Data versions and corresponding small-scale maps based on Finnish Magnetic High Altitude Grid for the Finnish part include:

- FINMAG 00 (1978): Incomplete land IGRF-65 grid.
  - Ladoga-Bay of Bothnia Zone (Elo et al. 1968).
- FINMAG 01 (1980): Complete land IGRF-65 grid, except eastern border zone, part of Baltic Sea data was included.
  - Magnetic Anomaly Map of Finland 1:2 000 000 (Korhonen 1980)
  - Magnetic Anomaly Map of Northern Fennoscandia 1:1 000 000 (Korhonen et al. 1986)
  - Magnetic Anomaly Map of Finland, Atlas of Finland, Geology, Map 26a (Korhonen 1992a) 1:5 500 000
  - Local Magnetic Anomalies of Finland, Atlas of Finland, Geology, Map 26b (Korhonen 1992a) 1:5 500 000
  - Magnetic Anomaly Map of the Arctic Area 1:5 000 000 (Verhoef et al. 1996)
- FINMAG 02 (1993): Eastern border zone was completed by measurements in 1993; complete Finnish DGRF-65 grid of land area and economy zone in the Baltic Sea.
  - Magnetic Anomaly Map of Central Fennoscandia 1:1 000 000 (Ruotoistenmäki et al.1996)
  - Magnetic Anomaly Map of Europe 1:5 000 000 (Wonik et al. 2001)
- FINMAG 03 (2001): DGRF-65 anomalies; BEAR98-levels were applied to anomalies of economy zone; Fits with the surrounding national grids of Norway, Sweden, Russia and Estonia.
  - Magnetic Anomaly Map of Central Finland Karelia 1:1 000 000 (Korhonen et al. 2001a)
  - Magnetic Anomaly Map of North Finland – Kola 1:1 000 000 (Korhonen et al. 2001b)
  - Magnetic Anomaly Map of the Fennoscandian Shield 1:2 000 000 (Korhonen et al. 2002) (Fig. 16)
  - Magnetic Anomaly Map of Gulf of Finland and surrounding area 1:1 000 000 (Korhonen et al. in prep)
- FINMAG 04 (2007, in prep): WDMAM-2007 anomaly definition for 5 km x 5 km grid extended to 1 km x 1 km grid.
  - World Digital Magnetic Anomaly Map 1:50 000 000, (IAGA and CGMW, in prep for 2007).

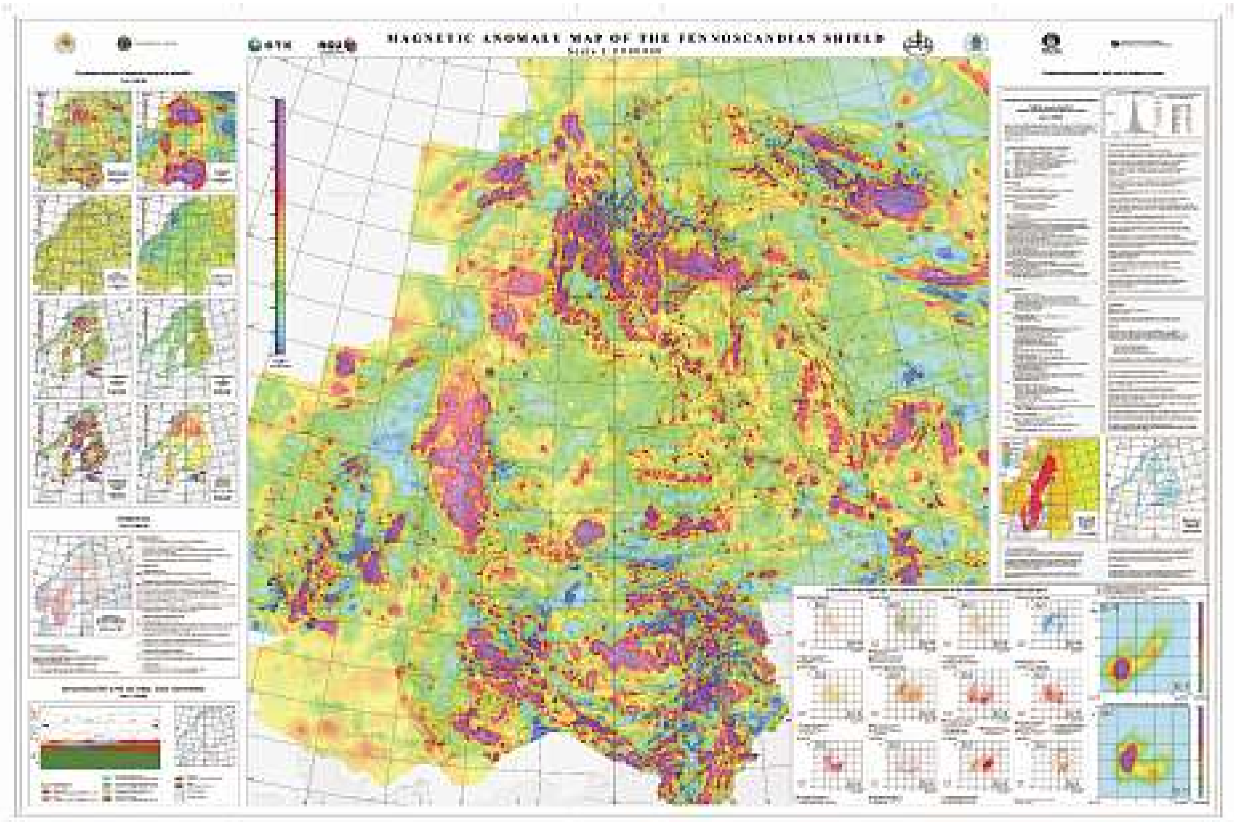


Fig. 16. Magnetic Anomaly Map of the Fennoscandian Shield, DGRF-65 Anomaly of Total Field, Anomaly continued upwards 500 m above ground. Original scale 1:2 000 000. Korhonen et al 2002.

DISCUSSION

Recently, a global model of geomagnetic variation, the Comprehensive Model (CM), became available for reduction of aeromagnetic data (Sabaka et al. 2002). In the NW-Europe the CM is based on the same observatory data as the reduction system of GTK. Hence a comparison between results obtainable via the CM and from the system of GTK would be useful to understand the accuracy of the reductions in practice, considering that basic assumptions are valid as defined in Appendix 1.

The map reduction procedure was based on the assumption that temporal variation of the Earth's main magnetic field can be traced by and corrected for geomagnetic observatory variation. This is not completely true in a strict sense, however. A geomagnetic observatory records the entire magnetic field at its site, including the lithospheric anomaly. The changes in the core field cause changes in the anomaly field, immediately in the induced part and with some time lag in the remanent part. All these are seen as a secular change of the main field, although the lithospheric part may be quite local. Changes in the direction of inducing field may change anomaly effects at observatories more than changes in its intensity. For example, the Sodankylä geomagnetic observatory is situated in a regional low north of a major regional high anomaly, and Nurmijärvi observatory at the southern slope of a regional high, both being susceptible to temporal changes in anomalies.

Although the drift of crustal anomalies is likely from the physical nature of the magnetic field, there's no definitive scientific evidence that these changes have truly occurred at the observatories (McMillan and Thomson 2003). This is why GTK carried out, in 1998, together with the EUROPROBE BEAR-project, a country wide reconnaissance survey based on magnetometer network, for comparison with Finnish low altitude data since 1972. Especially it was intended to see whether it was possible to detect local temporal components in the magnetic absolute field, and if so, to estimate how much this change would contribute to the observatory means and further countrywide anomaly levels over time. It was expected that change since 1972 would be of the order of 10–20 nT at most. The study is to be completed.

Problematic is that the longest wavelength anomaly components are regularly missing from grids and maps because of the overlapping bandwidth definition of most normal field models. A spatial model of the crustal field sources should be made to understand what the smoothest part of the crustal contribution may be and what could be its effect on change of crustal anomalies in time.

The Earth's magnetic field is rapidly decreasing since 1000 AD. The quadrupole term energy of spherical harmonics of IGRF may be equal to the dipolar anomaly term energy 50 years from now (e.g. Gianibelli et al. 2004) should the changes continue at the current rate. It follows that, close to the present dipolar and quadrupolar anomalies, the intensity and direction of the magnetic field may change considerably. Some time in the future the direction of the main field would reverse. With a change of direction of the Earth's main field, magnetic measurements aimed for global correlation should be presented with reference to the time of observation, not reduced to a common epoch by present methods. Regional compilations could be made by reduction of the data by assumptions of the effective vectoral magnetisation of lithospheric blocks.

Regional sampling may provide local estimates of magnetisation near crustal surface (E.g. Lahtinen and Korhonen 1995) and occasional deeper lithospheric values may be obtained from xenoliths but it is impossible to extend sampling to cover the whole lithospheric depth. In fact, necessary lithospheric scale magnetisation and its time dependence can be determined by geophysical models of lithospheric units only, jointly with geomagnetic, gravimetric, seismic, geothermal and geoelectric information. Finally, the modelling groups would end with spatially varying standard lithospheric models, accepted more or less globally. The Fennoscandian Shield is currently one of the most well covered areas of the globe for lithospheric modelling and hence would become one of the type areas both for reduction techniques and for characteristics of geophysical sources.

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APPENDIX

Time dependent reductions for aeromagnetic measurements

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18.1.1973 (in Finnish)
Geological Survey of Finland
English translation with *explanations*
by Juha V. Korhonen

Reductions are calculated to tie airborne measurement of magnetic total intensity (F_{rec}) made at time moment t_2 to a fixed time epoch, denoted by t_0. The reduced value is called the **absolute value** of the magnetic field at that epoch ($F_{abs}(t_0)$). The reductions include both correction for the annual change in the Earths main field (**secular variation**) within the survey area and correction for the variation in the magnetic field during the measurements (**transient variation**). The change in the intensity of induced magnetic anomalies due to change of inducing magnetic field is neglected.

Secular variation is calculated as a difference between observatory magnetic field values (F_{obs}) at time epochs of t_1 and t_0. The difference between the secular variations in the observatory and in the survey area (dF_{sec}) is added to the value of observatory secular variation to obtain the secular variation to be used in reductions for the survey area.

The transient variation is corrected by using magnetic field values (F_{stat}), recorded by a fixed magnetic ground station near the survey area. The drift of the magnetic field in the aeroplane during the flight is assumed to be the same as the drift in the magnetic ground station between a fixed time epoch t_1 and time moment of measurement t_2.

In addition a correction will be applied to remove the effect of magnetic field caused by the aeroplane (dF_{dir}). This varies in flight direction.

The correction formula (1) is the following:

(1) $F_{abs}(t_0) = F_{rec}(t_2) - (F_{obs}(t_1)\text{-}F_{obs}(t_0)+dF_{sec}(t_1,t_0)) - (F_{stat}(t_2)\text{-}F_{stat}(t_1)) + dF_{dir}$

$F_{abs}(t_0)$ absolute magnetic total field intensity reduced from the moment of recording to epoch t_0.

Values for the quantities are calculated as follows:

$F_{rec}(t_2)$ magnetic field value recorded in the aeroplane (original survey data)

$F_{obs}(t_0)$ magnetic field average of undisturbed days for the epoch of absolute reduction, obtained from the annual reports of the observatory (e.g. 1970.5). *(1965.0 was used for the Finnish low altitude survey)*

$F_{obs}(t_1)$ average total field for an epoch of one hour (e.g. 9.00–10.00 UT), calculated from H and Z component observatory magnetograms. *(Averages for several hours were used. Later on the observatories started to deliver digital F-data, that was used instead of magnetograms.)*

$dF_{sec}(t_1,t_0)$ difference of secular variation between observatory and survey area, calculated from secular variation tables or interpolated from maps. *(This was calculated from secular variation polynomials provided by the Geomagnetic Department of the Finnish Meteorological Institute*)

$F_{stat}(t_1)$ magnetic field average calculated from total field values in the ground station *(The same time epoch, one hour or several hours, was used for all t_1 calculations in the same ground station and survey area)*

$F_{stat}(t_2)$ magnetic total field value at the time moment t_2, interpolated from ground station measurements *(the airborne measurements were made at 0.5–0.25 sec intervals and the ground station recordings at 10–sec intervals depending on the instrumentation and survey specifications)*

dF_{dir} correction for magnetic field caused by aeroplane in the flight direction of the profile (see M.Puranen and L.Kivekäs, 13.12.1972)
(fully automatic magnetic corrections for aeroplane direction, pitch, roll and yaw was applied since 1994)

t_0 time interval (epoch) of a year, e.g. some internationally agreed reference year, denoted by its average time expressed in year and one or more decimals

t_1 time interval (epoch) of magnetically silent hour, or several hours, during the survey, used to tie together secular and transient variations, and denoted by its average time in hour and decimals

t_2 time moment of measurement of magnetic field value in aeroplane, considered as a sharp point of time unlike the t_0 and t_1 that are time periods

In practice the reductions are made as a computer run for each of the survey flights. The corrections are grouped to consist of two terms: the first one is a constant for each profile ($F_{corr}+F_{dir}$) and the second one depends on time ($F_{stat}(t_2)$).

The constant reduction term is calculated as follows:

(2) $F_{corr} = +(F_{obs}(t_1)-F_{obs}(t_0)+dF_{sec}(t_1,t_0)) - (F_{stat}(t_1) - F_{base})$

F_{base} selected technical level of magnetic field presentation *(a value of 50000 nT was used for 16-bit computers)*

In each measurement point the correction is calculated as follows:

(3) $F_{abs}(t_0) - F_{base} = F_{rec}(t_2) - (F_{corr}-dF_{dir}) - F_{stat}(t_2)$

$F_{stat}(t_2)$ is interpolated from ground station values nearest to time t_2.

The input of the data can be done as follows:

Data 1. Magnetic tape of pre-checked airborne magnetic field values and time for each

Data 2. Correction file, consisting of constant correction and directional corrections for each profile in Data 1.

Data 3. Magnetic file of pre-checked ground station records or alternatively a total field file digitized from observatory magnetograms and made absolute.

Result Magnetic tape containing absolute magnetic field intensities
(together with all other information).

These formulas have been used since 1973 to present (2005). The level differences indicate an accuracy normally better than $\pm$ *5 nT*