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Some Highlights of Finnish Research in Solid Earth and Applied Geophysics in the 20th Century

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Abstract

The development of non-seismic aspects of solid Earth geophysics in Finland is described along five major lines: geomagnetic research at observatories, applied geophysics to assist mineral prospecting and geological mapping, geothermal research, and induction studies. Finally examples of high-quality work on numerical modelling of electromagnetic geophysics are given.

The paper describes first some key results from the earliest Finnish geomagnetic recordings, the development of the Finnish geomagnetic observatory system and its present state.

Geophysical field measurements have been used in mineral prospecting in Finland since the early 1910's. New techniques have quickly been adapted, magnetic, electromagnetic and systematic airborne measurements soon became standard tools of applied geophysics. In addition the development of petrophysics, palaeomagnetism and other branches are briefly described.

Geothermal research since the first measurement in 1960 and induction studies since late 1970's have brought new insights about the geological history of the Finnish crust and upper mantle. Studies of geomagnetically induced currents in power lines and oil pipes and examples of numerical modelling of electromagnetic fields are finally described.

Solid Earth and applied geophysics have developed well in Finland. Continuous vital registrations, good national co-operation between university, research institutions and industry, together with active participation in international projects have kept Finnish Solid Earth and applied geophysics on a high international level.

1. Introduction

Solid Earth geophysics is a wide branch of geophysics covering physically different techniques, such as geomagnetism, geothermics, gravimetry, radioactivity, seismology, and research on the deep interior of the Earth (mantle and core). In addition geochronology, geodynamics, tectonics and volcanism are the major branches tying together geological and geophysical studies on the structure and dynamical behaviour of our planet. Broadly speaking also applied Geophysics, prospecting of natural resources (gas, oil, minerals, groundwater) and the study of the environment are dealing with the Solid Earth.

This report will discuss briefly induction study aspects of geomagnetism, applied geophysics and geothermics, since the history of seismology is covered by *Luosto and Hyvönen* (2001). Geomagnetic observatory registrations started in Finland more than 150 years ago as described by *Simojoki* (1978) and *Nevanlinna et al.* (1992). Applied geophysics has been a vital part of Finnish ore prospecting since the beginning of the 20th century (*Ketola,* 1986). Geothermal studies started in Finland in the 1950's (*Kukkonen,* 1989a) and electromagnetic (EM) lithospheric research in the late 1970's (*Hjelt,* 1982). These branches will be covered in chronological order. Because of space limitations and since not all relevant archive material has been available this summary should be considered only as an introduction to a more complete history of Solid Earth Geophysics in Finland.

2. *The geomagnetic observatories in Finland*

The electromagnetic (EM) radiation and energetic particle emission from the Sun changes the ionospheric current systems causing in turn short-term time variations of the Earth's magnetic field. The variations have serious effects on telecommunication and can induce harmful currents in powerlines and gas pipelines. The currents induced in the bedrock give on the other hand information about the crust and upper mantle. Continuous monitoring of the time behaviour of the geomagnetic field has been a vital component of ionospheric studies, prediction of radio wave propagation and many other applications.

2.1 *The overall history of the magnetic observatories*

Registration of the Earth's magnetic field at a network of sites was started in the 1840's following an initiative and plan by C.F. Gauss. Today there are about 200 geomagnetic observatories all around the world. The beginning of Finnish geomagnetic observatory recordings in 1846 in Helsinki has been described in detail by *Simojoki* (1978) and later by *Nevanlinna et al.* (1992).

Table 1. The Finnish geomagnetic observatories.

Time of operation	Helsinki 1844–1912	NGO 1952–	SGO 1913–	OUJ 1992–
Geograph N		60° 30.5'	67° 22' 09"	64.52°
Geograph E		24° 39.3'	26° 37' 47"	27.23°
Geomagn N		57° 43.8'	63.67°	–
Geomagn E		113° 28.8'	120.44°	–
Geomgn N, corr		56° 49.2'	63.4°	60.6°
Geomgn E, corr		102° 31.2'	108.9°	106.9°
L-value		3.3	5.2	4.3
Altitude [m asl]		105	178	

Presently there are are two permanent observatories in Finland: Nurmijärvi and Sodankylä. The Finnish Academy of Science and Letters established the Sodankylä Geophysical Observatory (SGO) in 1913. Since 1 August, 1997 it is a part of the University of Oulu. Besides research, the observatory performs routine geophysical measurements at its different stations. The magnetic registrations are published in the series *Sodankylä Geophysical Observatory, Publications.*The first yearbook appeared in 1921 covering the 1914 registrations summarized by Keränen (Table 2).

The Nurmijärvi Geophysical Observatory [NGO] was founded at the lake Sääksjärvi about 40 km north-west from Helsinki. NGO started recording the Earth's magnetic field in April 1952. The registrations are published as yearbooks (*Magnetic results. Finnish Meteorological Institute*). The first yearbook covered the 1953 data.

In 1992, after several years of preparations, continuous magnetic field registrations were started on December 6th at the Oulujärvi field station (OUJ) of the University of Oulu as a joint venture with NGO (*Pajunpää et al.,* 1998). Because of its geographical location at the southern edge of the auroral zone, the station has been an important element of the semipermanent registration network IMAGE (*Sucksdorff et al.,* 2001, this volume). Today the OUJ station is a part of the Oulu unit of SGO. Since 1990's the magnetic recordings from four Finnish magnetic permanent stations, SOD, OUJ, HAN and NUR, are available in a single data bulletin both in printed and electronic form (*ftp://space.geo.fi/pub/finbull*).

Table 2. Editors of the SGO data publications, Sodankylä Geophysical Observatory, Publications (until 1997 Verö ffentlichungen des geophysikalischen Observatoriums der Finnischen Akademie der Wissenschaften).

No	**Editor**	**Year of data**
1–4	J. Keränen	1914–1917
5–7	E.R. Levanto	1918–1920
8–13	H. Hyyryläinen	1921–1926
14–34	E. Sucksdorff	1927–1944
36–37	M. Seppänen and E. Kataja	1946–1947
38	T. Hilpelä	1948–1949
39–55	E. Kataja	1950–1971
57–62	E. Kataja	1972–1977
64–68	E. Kataja	1978–1982
69–75	E. Kataja and J. Kultima	1983–1989
77–83	J. Kultima	1990–1996
Sodankylä Geophysical Observatory, Publications		
84	H. Nevanlinna	Polar Year 1882–1883
85–	J. Kultima	1997–

2.2 *Helsinki Geomagnetic Observatory – A restudy of old data*

A remarkable work of great scientific and cultural significance has been the restudy of the Helsinki geomagnetic recordings by Nevanlinna and coworkers (*Nevanlinna and Ketola,* 1992, 1993 and 1994; *Nevanlinna et al.,* 1992). The data consisted of 10 minute visual observations of declination obtained by an Gauss' unifilar declinometer. The interval of observations were increased from 10 minutes to 1 hour in 1857. Measurements of the vertical magnetic component Z ceased 1851, probably because of systematic creep error of Z-recordings. (*Nevanlinna and Ketola,* 1993; *Seppinen,* 1988). Horizontal and declination data were noted until the end of the observatory activity, 1912.

A total of 1 010 300 observations of declination were digitized and transformed into 3-hour K-indices and daily Ak-amplitudes. The homogeneity of the data allowed extension of long activity series (like *aa)* backwards at least two sunspot cycles. The magnetic activity was on the same level as the activity at Nurmijärvi 1953–1992, although the number of large storms is greater in the latter data set. Storm occurrence peaked both during the rising and falling parts of the sunspot (Carrington) cycle 9 (*Nevanlinna et al.,* 1992).

The analysis of the 1854–1880 declination data showed an annual secular variation increase by + 8.5' per year and a small quasi-sinusoidal variation with an amplitude of 3' and a period of about 25 years. The coeval Oslo magnetic observatory data exhibit similar behaviour. The numerically determined three-hour K-indices correlated well with Mayaud's *aa*-indices for the period 1868–1880 (*Nevanlinna and Kataja,* 1993). The largest magnetic storm appeared on Sep 2–3, 1859. The storm was so intense, that the corresponding A-value could not be determined (*Nevanlinna and Ketola,* 1993). The completing analysis of the 1880 to 1909 data retained the stability of secular change (eastward drift of 7.2' / year.) being however twice the present day value. The complete Helsinki data now covers 5 solar cycles and the annual Bartels musical diagrams the years 1844–1909. Solar cycle, annual and semiannual waves and 27-day solar rotation periods can be clearly identified from spectral analysis of the data (Fig. 1). Some signature of intermediate periods (1.5 to 4–6 years) were found in both Helsinki and Nurmijärvi activity data (*Nevanlinna and Ketola,* 1994). A similar analysis and presentation of data has later been carried out for the Sodankylä registrations during the Geophysical Polar Year 1882–83 (*Nevanlinna,* 1998).

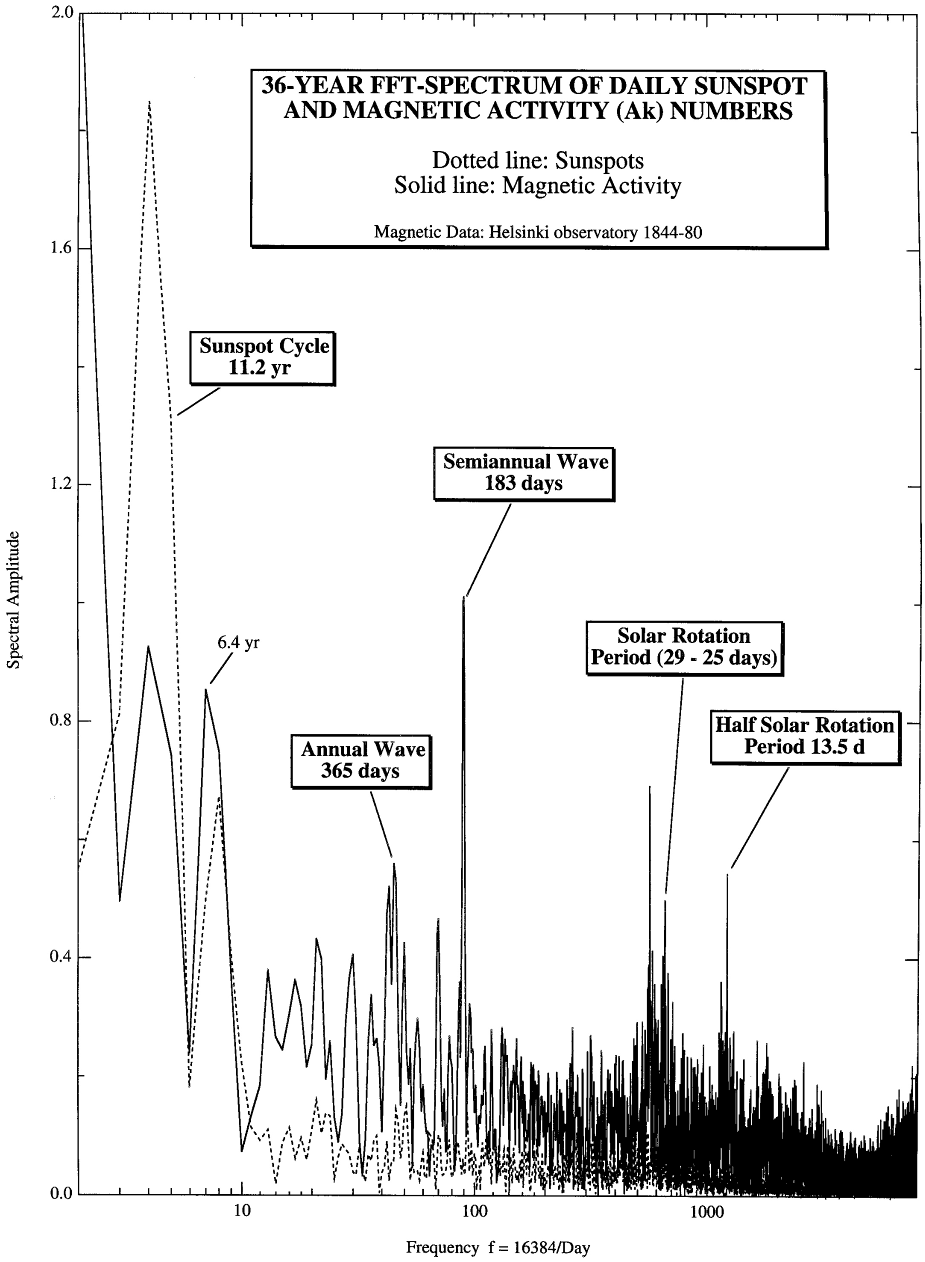

Fig. 1. FFT spectra of a) monthly and b) daily Ak-values from the Helsinki geomagnetic observatory (1844–1880) and sunspot numbers (*Nevanlinna et al.,* 1992; courtesy: H. Nevanlinna).

2.3 Sodankylä Geophysical Observatory [http://space.sgo.fi]

The construction of the observatory started in 1912 and it was inaugurated in the fall 1913. Both geomagnetic and meteorological observations were performed routinely. Systematic observations of aurorae were started in mid-1920's. In 1949 the Finnish Meteorological Institute (FMI) started its own Meteorological Observatory [from 2001–01–01 onwards the Lapland Observatory] as a neighbour to SGO. Seismic registrations at Sodankylä started in 1956, ionospheric soundings in 1957 and EISCAT ionospheric radar registrations in 1981. With continuously developing new activities and high quality of work, the Observatory area has become the landmark and source of pride for the whole region.

Before the second world war the number of observatory buildings had increased to 11. The buildings were destroyed by retreating German troops in 1944. Rebuilding commenced in 1946, the new main building, designed by the famous Finnish architect Vivi Lönn, was inaugurated in 1951 (Fig. 2a). (*Simojoki,* 1978; *Turunen,* 1993). It has since many years been out of use and a new main building (Fig 2b), jointly with the Lapland Observatory of FMI, will be finished in 2001.

Fig. 2. Two main buildings of the SGO. a) The old is one of the few remaining examples in Lapland of the work by the architect Vivi Lönn (photo: Jyrki Manninen). b) The new to be in augurated in June 2001 to serve both SGO and the Lapland Observatory of FMI, is an example of modern Finnish wooden building architecture (photo: Timo Turunen).

Today the magnetic instrumentation of SGO consists of three sets of digital variometers with sampling rates of 2 Hz, the Polish and Russian Photoelectric Torsion Magnetometers PSM and RM and the Danish Fluxgate magnetometer FG. The classical LaCour analogue registrations with photographic recording were operated continuously for 82 years until the end of 1995.

In 1945 new absolute and variation rooms were built (Fig. 3), 250 m WWN from the original location of the absolute house. The present absolute and base line instruments are the proton precession magnetometer Elsec type 770 and an fluxgate declinometer & inclinometer Elsec type 810.

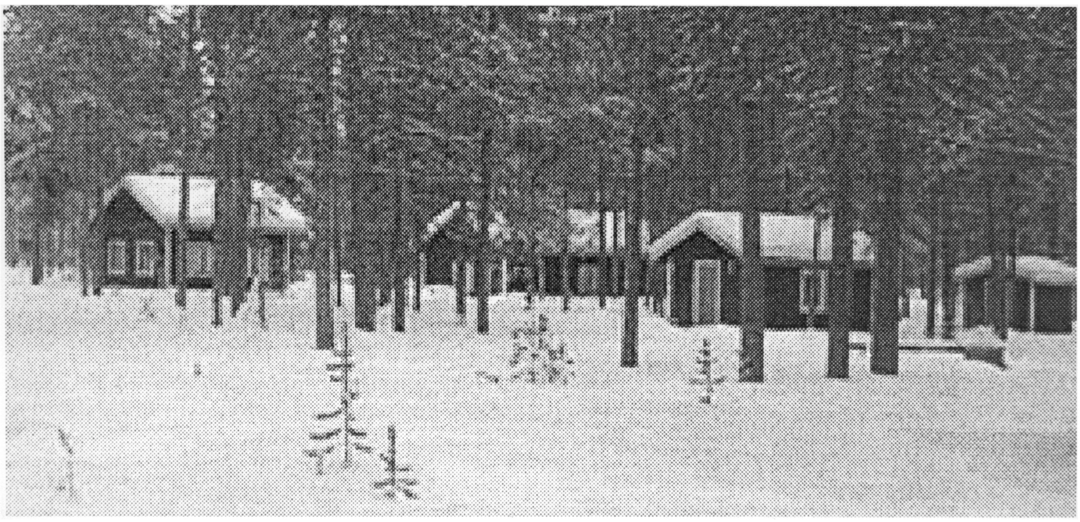

Fig. 3. Magnetic observatory registrations require (magnetically) quiet and homogeneous surroundings. The huts are built without a single piece of metal. (SGO, photo: Jyrki Manninen.)

The Oulujärvi magnetometer station OUJ has absolute and variation rooms built in 1992 and it is equipped with a Danish FGE magnetometer. With the exception of some baseline drifts, the data are very close to observatory quality.

Telluric and magnetic data from a four station array at distances of 30 km around the observatory proper were analysed by *Kauristie et al.* (1990). A large-scale 3D induction anomaly was recognized, but for the periods 100–2500 s the field was practically homogeneous over the array. Similar studies were performed around the Nurmijärvi Observatory, where a similar homogeneity of the field and a conductivity anomaly outside the array were identified (*Jankowsky et al.*, 1986).

Table 3. Directors of SGO (*Kataja*, 1973).

Jaakko Keränen	1913–1917	
Heikki Lindfors	1917–1918	
Elias R Levanto	1918–1921	
Heikki Hyyryläinen	1921–1927	
Eyvind Sucksdorff	1927–1945	
Mauno Seppänen	1945–1947	
Tauno Hilpelä	1948–1950	
Eero Kataja	1950–1992	
Tauno Turunen	1992–	on leave 1998–2002
Jorma Kangas	1998–2002	

Several person with great contribution to Finnish geophysics have served as directors of SGO (Table 3; *Kataja,* 1973). During the first years and after the second world war the periods of office were short. But the contributions of J. Keränen, E. Sucksdorff, E. Kataja, T. Turunen and J. Kangas to the development of geomagnetic research in Finland are too wide to be included in this review.

2.4 Nurmijärvi Geophysical Observatory [http://www.geo.fmi.fi/MAGN/nur.html]

Today the Nurmijärvi geophysical observatory (NGO) is running two digital magnetometers and two-component pulsation magnetometers of the Oulu and York Universities. Samples are taken every second of all three components of the field, and the results are delivered to the international scientific community (see Fig. 4). The Seismological Institute of the Helsinki University has one of its seismic recording stations (FNUR) in the area. An automatic MILOS weather station is operated by the Finnish Meteorological Institute, as well as an equipment for monitoring radioactivity. The water level of the lake Sääksjärvi is followed for local needs.

To control the secular change, magnetometer readings are checked weekly by an absolute measurement. It is performed in another building by using a non-magnetic theodolite (to detect the direction of the field), a fluxgate instrument and a proton magnetometer (to measure the total amplitude).

The calibration facility contains three component coils on concrete pillars, built in 1986, and a high quality temperature testing system for magnetic sensors (Fig. 5). The field in a volume of the size 18×25×30 cm at the centre of the square coils (size 1.6 and 2.2 meters), is homogenous with an accuracy of 0.001 %. The errors in the orthogonality are less than 1'. The variation room comprises a Danish suspended flux gate magnetometer (FGE) and a Polish torsion photoelectric magnetometer. The total field is measured with the Polish proton precession magnetometer PMP-7. The coil constants are checked once or twice a year with an accuracy of 0.01 % and the temperature stability of the coil constants are -25 ppm/°C for the X component and – 20 ppm/°C for the Y and Z components. The automatic control and measuring system for the calibrations was built in the middle of 1990's in co-operation with the Lviv Centre of Space Research Institute in Ukraine.

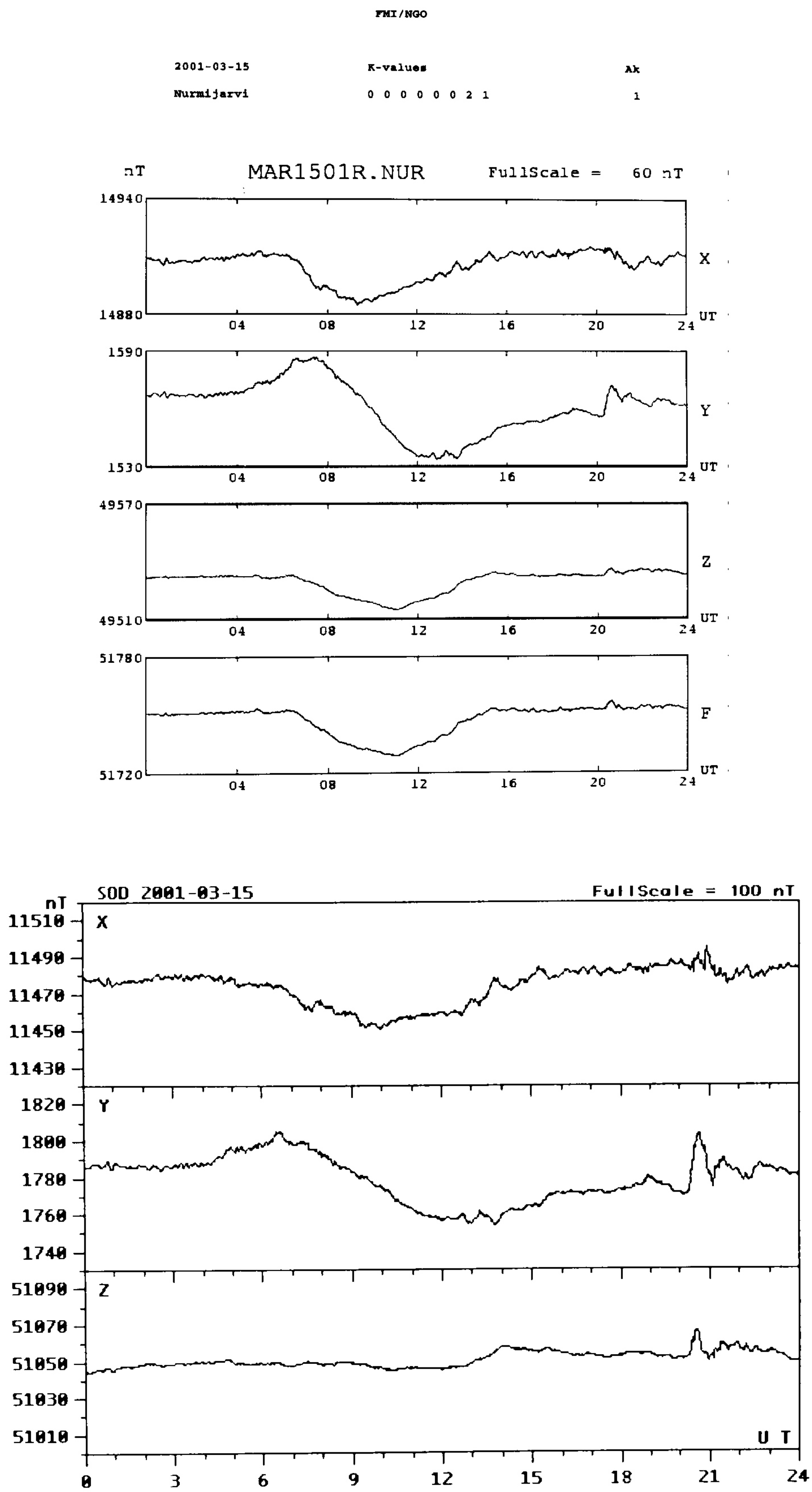

Fig. 4. Real time magnetograms for Thursday 15th of March 2001 recorded at a) Nurmijärvi and b) Sodankylä observatories.

Fig. 5. Kari Pajunpää inside the calibration coil at magnetic test laboratory of the Nurmijärvi Geophysical Observatory (photo: Nanni Akkola).

The magnetic cleanliness measuring and a demagnetizing system comprises a rotating table, which can carry devices with weight up to 30 kg and dimensions up to 0.5 m. The system operates at two different frequency ranges (50 Hz and 1–8 Hz respectively). Software fits a one-dipole model to the data with an accuracy of 5 % for the dipole moment and 0.5 cm for its position. At the center of the coils, magnetic field amplitudes between 3,000 μT and 0.1 μT are obtainable. At 50 Hz small objects with "hard" magnetism can be studied in field > 10,000 μT.

The Nurmijärvi observatory is also an active partner in the IMAGE magnetometer network and NGO operates and maintains eight IMAGE stations. (For further details, see *Sucksdorff et al.,* 2001, this volume.)

2.5 Secular variation studies

The absolute measurement equipment of NGO has also been used at special measurement points to record the secular change at a regional scale in Finland. The measurements are performed annually at each site. Since Finland is located on the fringes of one of the largest regional anomalies of the global geomagnetic field, the secular change in declination is remarkable (Fig. 6). The FMI/GEO has also regularly produced versions of the global IGRF and the global secular variation maps (e.g. *Korhonen, K.,* 2000), which are updated every 5 years. During recent years, secular change measurements have been performed in Estonia to derive magnetic charts for the country (*Nevanlinna et al.,* 1998).

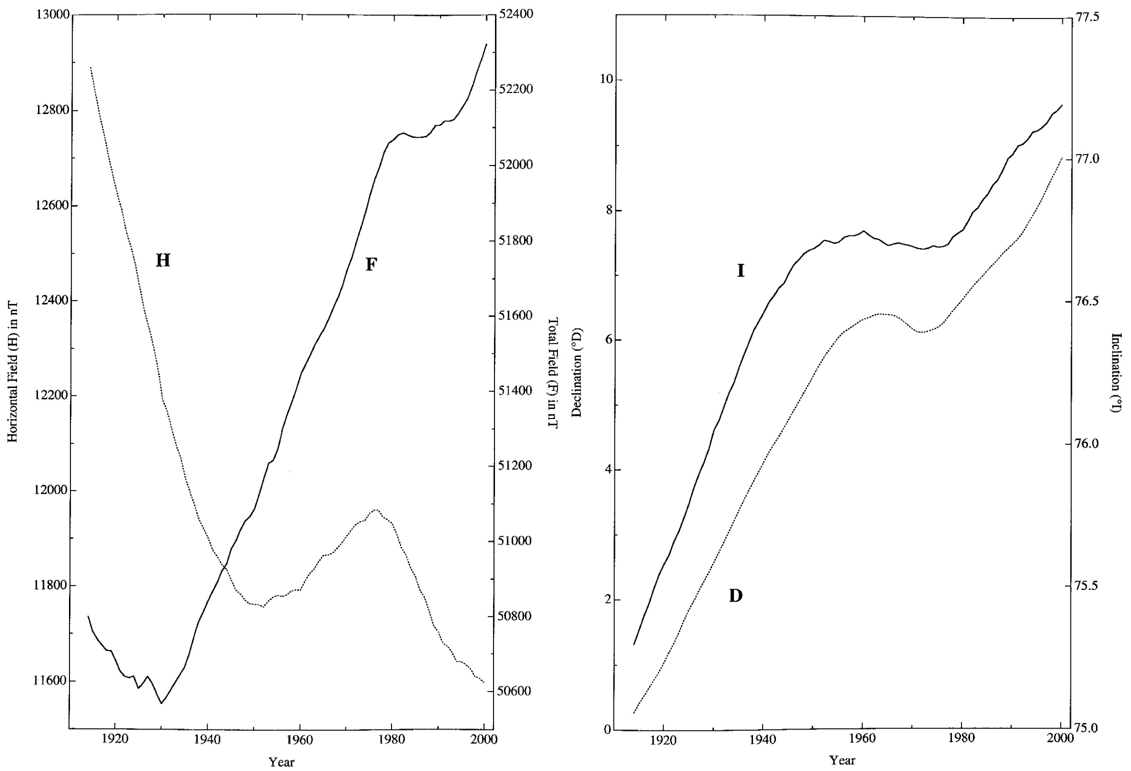

Fig. 6. Secular variation in Sodankylä 1914 to 2000 a) total field and horizontal component, b) declination and inclination (courtesy: H. Nevanlinna).

2.6 *Observatory days*

The co-operation between geophysical observatories and the scientists working in the fields of geomagnetism and aeronomy has been very fruitful in Finland. A key instrument in this development has been the National Days of Geophysical Observatories. The format of meetings was free and varying, with topical key lectures, preliminary presentation of research results, discussions, resolutions, planning of new projects and participation in international scientific endeavours. Some of the meetings have focused on important topics, most typically on technical problems related to observatory registrations proper. Much of the rise in Finnish space research has originated from the discussions during these meetings.

The Days started in 1961 on the initiative of prof Jaakko Keränen. The 13 participants represented both geomagnetic and seismic observatories. Only the two first meetings were held in the Helsinki region, thereafter mainly at Sodankylä, but also in Oulu and once during the first hectic days of EISCAT in Utsjoki, Kevo (*Sucksdorff,* 1961; *Pellinen,* 1993). The role of the Days during the last 5–6 years has been in the shadow of the boom in space science research.

3. Applied geophysics

Applied geophysics was during many years almost synonymous with ore prospecting geophysics. The physical properties of the subsurface are studied using magnetometric, gravimetric, radioactive and a great variety of geoelectromagnetic techniques. The main methods have with slight modifications found increased use in new applications, mainly in environmental studies. Only few methods have been invented in Finland, but remarkable development has taken place in instrumentation and especially in the modelling and data inversion techniques. Much of this work has started as MSc. theses at the University of Oulu and the Helsinki University of Technology. Because of space limitations only major trends of this work are discussed.

3.1 Early applications of geophysics in ore prospecting

Ketola (1986) presented a detailed history of Finnish prospecting geophysics until the first years of the 1980's. His review shows that magnetometry as well as electrical and electromagnetic methods were utilized in prospecting very early. Ketola writes: "The impulse to start developing geophysics in Finland came from the investigations conducted on the Outokumpu Cu ore deposit and the Petsamo Ni-Cu ore deposit in the period 1908–1934 under the direction, first, of the Geological Bureau* and then, from 1918 onwards, the Geological Commission*. These investigations included more geophysical measurements than is probably realized."

Until 1940 geophysics were referred to as instrumental methods and measurements were made mainly on specific targets. Systematic geophysical ground surveys started in Finland during the 1940's, and systematic airborne measurements in 1954. The need for geophysical data was rapidly growing when the exploration department of Outokumpu Co was established in 1951 and when Otanmäki Oy started exploration in Vuolijoki in 1952. Geophysics played a remarkable role in the discovery of the Kotalahti Ni-Cu deposit in 1954, the Zn-Cu-bearing Pyhäsalmi pyrite deposit and the inventory of the Otanmäki Fe-ore area from 1950 to 1960. The Geophysics Department of the Geological Survey of Finland (GSF) was established in 1963. (*Ketola,* 1986; *Annala,* 1960; *Kuisma,* 1985; *Autere and Liede,* 1989).

3.2 Magnetic surface measurements

The magnetic method has been used in prospecting for iron ores in Sweden as early as in 1630's. The mining compass was in general use both in Finland and Sweden in the 18th and 19th centuries. The needle of the compass was pivoted as to allow

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* both predecessors of today's Geological Survey of Finland (GSF).

measuring the inclination of the magnetic field. The compass was replaced by the Thalen-Tiberg magnetometer at the end of the 19th century. Then the intensity of the vertical and horizontal components of the field could be determined with an accuracy of 150 nT. The first systematic magnetic surveys were made by Axel Tigerstedt at Orijärvi in 1889 (Fig. 7) and Jussarö in 1898, by Emil Sarlin in the Porkonen-Pahtavaara area in 1900–1901 and by Otto Trüstedt in Outokumpu, where by the end of 1919 60.000 observations were taken. Eero Mäkinen, Aarne Laitakari and Adolf Metzger conducted 27.500 observations in the Pahtavuoma area and Mäkinen estimated the ore tonnage from the data. (*Ketola,* 1986).

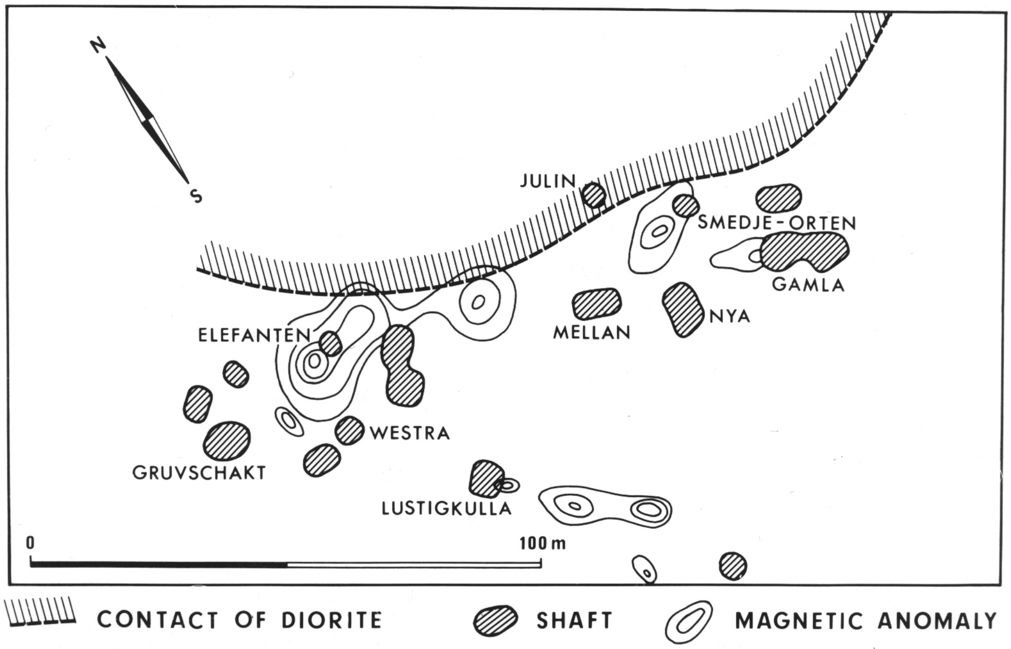

Fig. 7. O. Trüstedt published in 1909 a map from the Orijärvi region with magnetic anomalies based on measurements of A. Tigerstedt in 1889 (courtesy: M. Ketola).

The Geological Commission bought in 1923 the first Schmidt balance and detailed investigations were possible with an accuracy of 5–10 nT, Petsamo nickel ore being one of the major targets in the 1930's. Since 1935 the newly established company Suomen Malmi conducted both magnetic and electrical surveys, names such as Maunu Puranen and Heikki Paarma among the investigators. (*Ketola,* 1986).

In 1947 the first Finnish magnetometer was built. The Arvela magnetometer was a versatile and fast modification of the Tiberg balance and the Thalen-Tiberg magnetometer. Some years later it was complemented by the Jalander direct reading flux-gate magnetometer. This lightweight instrument was also a commercial success, several hundreds were sold by 1986. In the late 1970's a Jalander miniature magnetometer came on the market. (*Ketola,* 1986).

In the early 1960's, the Askania torsion (vertical component) magnetometer became the major instrument in systematic magnetometric surveys. In the early 1970's proton magnetometers came into use and from then on the total magnetic field. was measured (*Ketola,* 1986).

The need for magnetic three-component and susceptibility measurements in boreholes was dictated by the structure of the Otanmäki iron ore. First tests in mine shafts were performed 1952–53, but the first borehole magnetometer was designed in 1955 by S. Hämäläinen. Academician E. Laurila played a key role in developing further instrumentation for the needs of the mining companies. (*Ketola,* 1986; *Hjelt and Fokin,*1981). Interpretation was soon developed (*Levanto,* 1959; *Ketola,* 1986; *Turunen,* 1978) and it became one of the first and succesful themes of Scientific-technical co-operation between Finland and the (then) USSR. (*Hjelt and Fokin,* 1981)

3.3 Electrical and electromagnetic methods

Electrical methods were pioneered in both Petsamo and Outokumpu areas. In Outokumpu the electrical reflectometric method of Daft and Williams was tested as early as 1910. In 1916 alone, 10.000 points were measured using a newer variant, the equipotential method. Also small scale laboratory modelling was developed at the Geological Bureau. In the following ten years or so, disputes over patents and the rights to measured data were intense. The use of linear source electrodes became the major variant used. (*Ketola,* 1986).

The first test with the so called electromagnetic intensity method was done in 1925 at Jalovaara and Pitkäranta by professors H. Brotherus and V. Ylöstalo from the Helsinki University of Technology. After reconstruction the instrument was tested at Outokumpu and soon it became the main electrical method also in Petsamo (Fig. 8). The instrumentation used a 1000 x 500 m cable loop, a current stabilized AC generator at frequencies 50–10.000 cps. (*Ketola,* 1986; *Väyrynen,* 1929).

The new EM methods, Turam and Slingram, developed in Sweden in the 1920's were not used in Finland until after the Second World War. Jalander, who had participated in the EM tests in Petsamo in the early 1930's, started instrumental tests already in 1935 and built an improvised Turam system in 1943. Between 1945 and 1947 the Aijala and Metsämonttu ore deposits were identified using the Turam technique (*Jalander,* 1982 in *Ketola,* 1986) and more than 200.000 points were measured using this method between 1945 and 1950. (*Ketola*, 1986).

The first Slingram tests were made in Vihanti in 1946 by the Geological Committee with an instrument purchased from Sweden. A similar instrument was obtained by Outokumpu in 1952, but the necessary field crew of 5 men and the short life of the cables made the use of the instrument difficult in forested terrain. Between 1953 and 1957 a lighter, a two-man Slingram unit was constructed at Outokumpu Oy together with the Technical Research Centre of Finland. Later this technique – utilizing loops as transmitting coil and receiving coil at fixed distance – was to become for years the major EM method of ground prospecting in Finland. (*Ketola,* 1986).

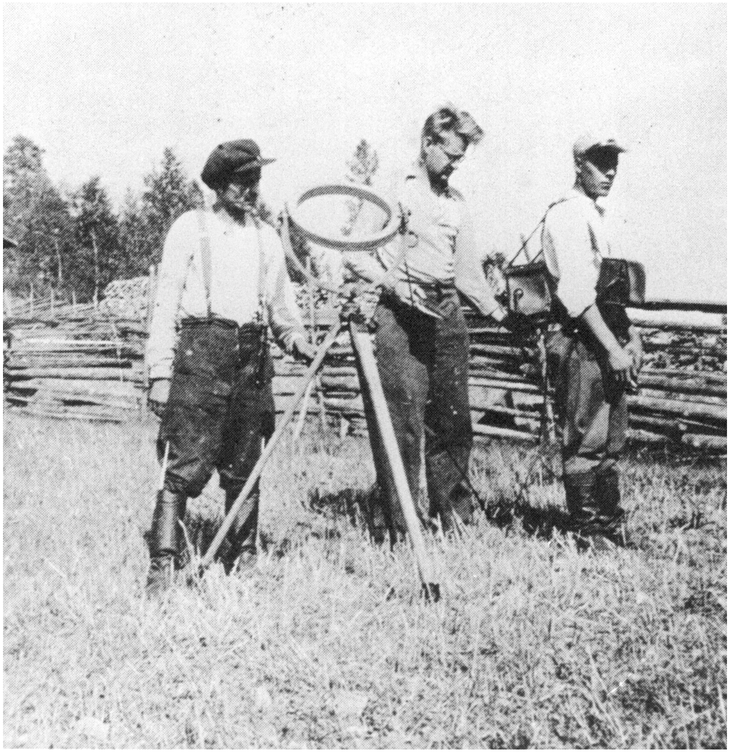

Fig. 8. Electromagnetic measurements using the intenisty method (*Ketola,* 1986*;* courtesy: M. Ketola).

The first Finnish one-man EM instrument was designed already in 1953 by V Rönkä (*Ketola,* 1986), who later became the founder of the well-known Canadian EM instrument company Geonics Ltd. Several versions were designed over the years and also manufactured by Outokumpu Co. In the instruments the transmitter and receiver dipoles are ferrite rods oriented so that the primary field at the receiver dipole was close to zero (e.g. *Rekola,* 1972). The distance between the dipoles was of the order of one meter.

In the 1960's theoretical work and instrumental prototype (nicknamed UNILOOP) was made at the Physics Department of the Outokumpu Co (*Hjelt,* 1968a). The primary field was compensated by an additional coil, which turned out to be too temperature sensitive for field conditions. A second prototype was operating in the time domain (*Korteila,* 1969). Field tests showed unexplained negative signals, which later were learnt to be caused by the clayey ground at the test site. The work resulted also in theoretical development of calculating transient fields (*Hjelt*, 1968b; 1971a; 1971b). A change of company policy for instrumental production interrupted this promising development in transient EM systems.

An important trend in ground EM methods started at the end of the 1970's, the use of multi-frequency systems to create a depth sounding effect. A great variety of instruments have been used in Finland (*Ketola,* 1986; *Hjelt et al.,* 1990a). They ranged from the so called "multifrequency Slingrams" to various transient systems. Several frequencies and a wide range of coil separations were in use.

The first commercial time-domain or transient EM system was tested in 1975 by Rautaruukki in Oravainen using the Russian MPP-instrument. (*Ketola,* 1986). The University of Oulu also acquired such a system (*Heikka,* 1981), but the large transmitter loop (200 to 600 m each side) and the heavy weight of the instrumentation required a larger field crew than a University department could afford. A modernized version of MPP, the Australian SIROTEM was purchased by Suomen Malmi Oy, which also used the Canadian PEM system having a “slingram-size” transmitter loop. Both instruments are equipped with borehole sensors. After short tests, Outokumpu Co purchased the Geonics EM37 instrument in 1984. (*Ketola,* 1986). The multifrequency SAMPO-GEFINEX system was constructed jointly by the Outokumpu Co and the GSF.

The induced polarization (IP) technique is able to give information about the chemistry of the subsurface. The first equipment in Finland was purchased by Outokumpu in 1962 and the Tervola Cu-Au deposit was discovered with this method in 1964 (*Ketola,* 1986). Later the method has been studied intensively (*Peltoniemi,* 1973) and GSF has adapted strongly its multifrequency variant (*Vanhala,* 1997). Borehole variants of the IP technique have also been used in Finland.

3.4 Audiomagnetotellurics (AMT)

The audiomagnetotelluric (AMT) method utilizes the energy of distant lightning discharges. The energy is propagated as a plane wave all over the world. Following field experiments in 1974, the University of Oulu acquired its first analogue AMT instrumentation in August 1976. After successful tests at sites of the mining companies Rautaruukki and Outokumpu (*Pelkonen et al.,* 1979; *Hjelt et al.,* 1990b) the technique became popular in studying deeper parts of known ore deposits. In Kolari (Rautuvaara) and Miihkali areas the orebearing conducting structures could be followed down to about one kilometer below the surface (*Hattula,* 1977; *Pelkonen et al.,* 1979). The small distance between measuring points was a part of the success story at Miihkali. Subsequently Outokumpu Co purchased its own ECA 541-0 instrument (*Lakanen,* 1986).

In Sulitjelma, Norway, a horizontal ore layer (mean thickness 3 m) was studied to establish the extent of the layer and to identify possible new horizons late in 1978. The ore horizon could be traced at a depth of 900–1000 m, even below another, blanketing conducting ore layer at 400–500 m. All AMT results were subsequently confirmed by drilling (*Pernu,* 1979). Also this company continued AMT applications using own instrumentation. Later Pelkonen did extensive modelling work at the Norwegian Technical University in Trondheim to provide results for 2D interpretation (*Pelkonen,* 1984).

The AMT source field signal often decreased below the noise level at 1–2 kHz, frequencies relevant for studying the higher parts of ore-bearing structures. Following a successful AMT field measurement in Hungary by P. Kaikkonen and J. Tiikkainen in

1982 (*Ádám et al.,* 1984), a joint Oulu-Sopron instrument project was created to study the source field (*Ádám et al.,* 1988).

Some of the source field problems could be overcome by controlled source techniques. In 1983, P. Kaikkonen and S.E. Hjelt, during their research visit to Hungary, were thoroughly introduced to the interpretation technique of the multi-frequency EM method MAXIPROBE. Successful field tests were made by the Hungarian Research Institute ELGI at the earlier AMT profiles in Kolari and subsequently GSF joined the Fenno-Hungarian co-operation in EM geophysics. Since the MAXIPROBE instrument was not commercially available, Outokumpu Co and GSF started a national instrument project in the late 1980’s. The resulting SAMPO-GEFINEX equipment has since then replaced the AMT technique in most deep ore studies.

3.5 The VLF technique

The VLF method uses the fields of the worldwide navigation and time signal system. The transmitters operate in the frequency range 10–30 kHz and the plane wave field of the transmitters was available practically everywhere and at any time. One of the mostly used and versatile instruments was designed by Geonics Ltd. The first equipments were purchased by GSF in 1968 and Outokumpu Oy in 1969. The first versions measured the tilt of the induced magnetic field, but later the option to measure the electric field (the so called R-option) was added and allowed to determine the apparent resistivity. At the University of Oulu the VLF resistivity value was used to complete and calibrate the high-frequency part of AMT soundings.

Numerical modelling to assist 2D interpretation was introduced by *Kaikkonen* (1979, 1980a, 1980b, 1980c). The six-point linear Karous filter (*Karous and Hjelt,* 1983) was useful as a first approximation of the current system induced in the subsurface. The filter became very popular and at least the Swedish company ABEM integrated it into their VLF instrument. Successful case histories on the use of VLF and VLF-R measurements can be found in *Hjelt et al.* (1985, 1990c).

3.6 Airborne geophysical mapping

Airborne geophysics grew from the instrumental development that had taken place during World War 2. Finnish airborne geophysics followed rapidly the international trends. The major ore exploration organizations, Outokumpu Oy and Rautaruukki Oy had own equipment which were used for low altitude measurements and direct prospecting purposes. GSF started a countrywide systematic high altitude (150 m) aeromagnetic survey for general geological mapping in 1951. The measuring system was expanded in 1954 by adding of electromagnetic and gamma radiation instrumentation (Table 4).

Table 4. Systematic use of airborne geophysics (*Peltoniemi*, 1998).

METHOD	**First year of use**		
	Finland	**Sweden**	**Canada**
Magnetic	1951	1948	1947
Electromagnetic	1954	1954	1950
Gamma radiation	1956	1954	1948

After various experiments with air- and carborne moving EM instruments, the first airborne geophysical survey was performed by GSF in 1954. A new flux-gate magnetometer and a patented electromagnetic system (*Puranen and Kahma,* 1949 in *Ketola,* 1986) were installed in a Locheed Lodestar aircraft (Fig. 9) and a systematic surveying from 150 m altitude started. Finland was the first country in the world to establish such a survey. The EM system was sold in mid-1950's to Canada and became known as the Hunting Canso system. The transmitting coil was wound around the body of the aircraft and the receiver sensor was placed in an aerodynamically shaped bird towed behind the plane.

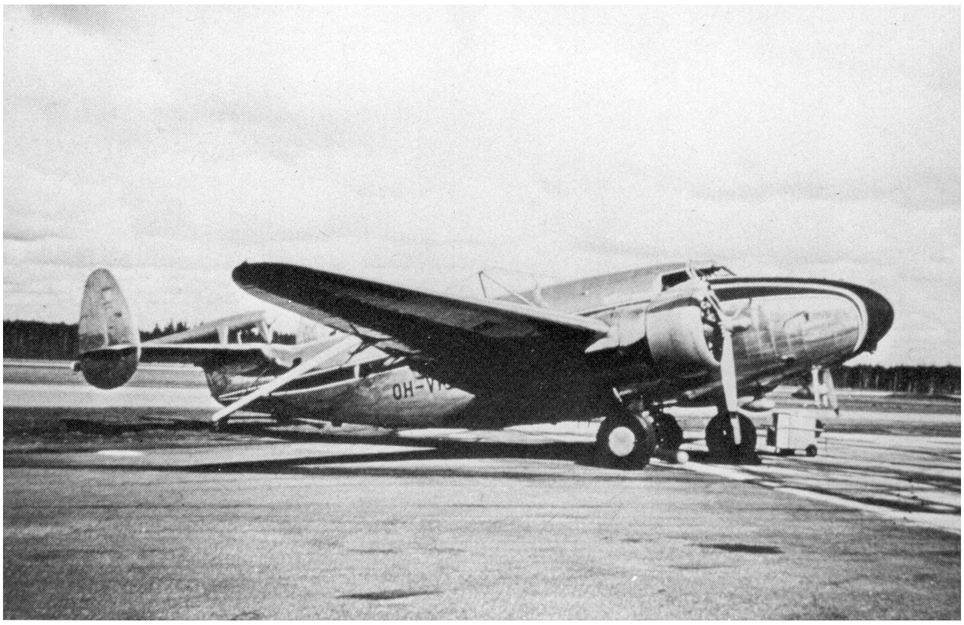

Fig. 9. The Locheed Lodestar plane and the airborne EM system of GSF used from 1953. (*Ketola,* 1986; courtesy: M. Ketola.)

Radiometric measurements were added to the survey in 1972 when the new low-altitude (30–50 m) survey programme of GSF started using a Twin Otter aircraft. At the same time the EM coil geometry was changed into a vertical coplanar coil geometry (often called the "wing-tip" system), which has the best horizontal resolution for vertical or subvertical conducting veins. After only one summer survey season the plane crashed and during 1973–1980 GSF had to use a DC-3 aircraft equipped with a vertical coaxial system. At the early 1980's GSF again was able to use a Twin Otter plane and the "wing-tip" geometry. The various measuring geometries and measuring quantities are summarized in Tables 5 and 6 and are described in detail by *Peltoniemi* (1982; 1998) and *Ketola* (1986). The practical use of aerogeophysical maps was early described by *Marmo* (1964) and later by e.g. *J. Korhonen* (1993) and *Airo* (1999).

Table 5. Platforms used for airborne geophysics in Finland (*Peltoniemi*, 1982, 1998).

Airplane	Instrumentation	Equipm/Operator	Years
Lockheed Lodestar		GSF /Velj Karhumäki (Karair Oy)	1954–1972
De Havilland Twin Otter DHC-6	EM, M, R	GSF / Karair Oy	1972; 1980–
Douglas DC-3	EM, M, R	GSF / Karair Oy	1973–1979
Cessna 185	Magnetic Aeromagnetic Gamma	Rautaruukki Oy	1955– 1966–79 1968–79
Pilatus Turbo Porter	Magnetic EM Rotary Field	Outokumpu Oy	1957– 1959–79
		Finnprospecting Oy	1965–1985

Table 6. Measuring geometries of airborne EM systems used in Finland (*Peltoniemi*, 1982, 1998).

Years	Tx-Tx dist/geom	Tx orient	Rx orient	Flight height	Fq (Hz)	Measured
1954–59	150	Horiz	Inclined	150		Im
1960–71	250 m coplanar	Inclined	Inclined	150		A, phase
1972						
1973–79	25 m coaxial	vert	vert		3200	Re, Im
1980–96	21 m coplanar	vert	vert			
1997–					3100, 14200	Re, Im
1960–1970 Outokumpu	rotary field	vert & horiz	vert & horiz		880	Re, Im

The airborne electromagnetic (AEM) data collected by the Geological Survey of Finland have been compiled into a surface conductance map of Finland (*Peltoniemi et al.,* 1992). These data in the form of 1:100000 profile maps are useful in delineating near-surface conducting structures and to study the internal structure of the surface expressions of deeper conductors (e.g. *Korja and Koivukoski,* 1994; *Korja et al.,* 1996b).

Later three magnetometers were mounted at the extremes of the aircraft, allowing the calculation of the horizontal gradient vectors with a subsequent huge improvement in the quality of aeromagnetic maps (Fig. 10). For further details the reader is referred to the files and reports of GSF and two recent reports by *J. Korhonen and Säävuori* (2000) and *Airo and Ruotoistenmäki* (2000).

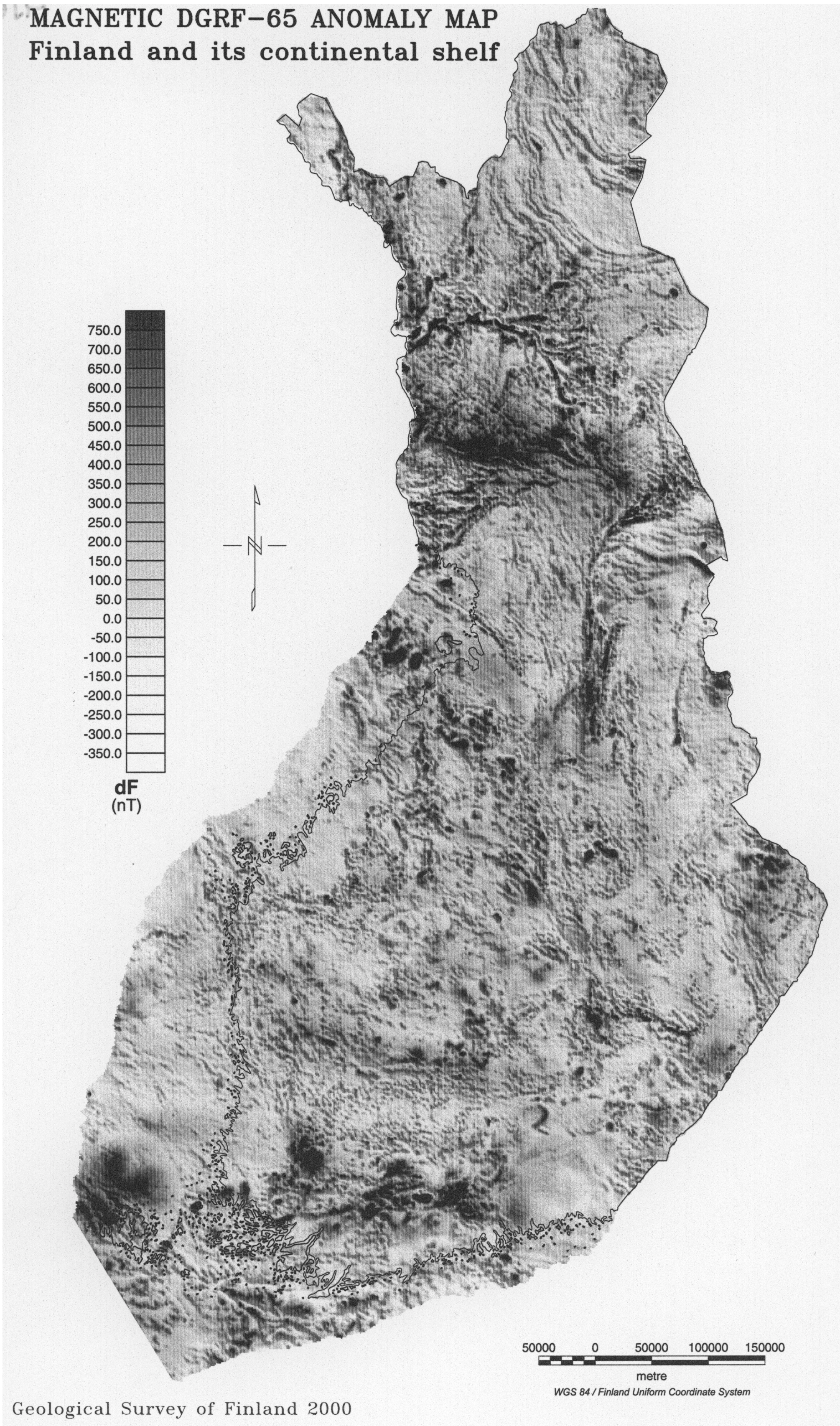

Fig. 10. The aeromagnetic map of Finland. (*J. Korhonen*, 2000; courtesy J. Korhonen.)

Before GSF started low-altitude flights many mining companies conducted their own airborne surveys to fulfill the rapidly increasing demand for regional data (e.g. *Ketola et al.*, 1971). Since the end of 1950's these surveys used a variety of transmitter-receiver configurations, but the vertical coplanar coil geometry gained the greatest popularity. The geometry was used in low-altitude surveys by Finnprospecting Ky and Suomen Malmi Oy, which were the major contractors for the mining companies in the 1970's. In 1965 Otanmäki Oy and Outokumpu Oy tested the INPUT transient technique at the Bothnian Bay off coast at Raahe and later in the 1970's at the Hannukainen iron ore (*Ketola,* 1986). The ore deposit was well delineated, but this worldwide popular aeroEM system never was adapted to systematic use in Finland.

3.7 Applied gravimetry

In 1946 the Geological Survey requested the Geodetic Institute to apply a gravimetric survey to prospecting. T. Honkasalo measured some profiles across the Lampinsaari formation in Vihanti. Due to encouraging results GSF purchased a Boliden gravimeter in 1947. Finland obtained its first Worden gravimeter in 1954–55, which gradually improved the efficiency of gravimetric surveys in exploration. Several variants of levelling tubes were developed to speed up and to reduce the costs of field work. (*Ketola,* 1986). Today the gravimeter system of GSF is equipped with a GPS option. The discovery of the Kemi Cr ore deposit in 1959–60 was to a great deal based on gravimetric and residue anomaly maps. (*Ketola,* 1986).

Regional anomaly map coverage has been extended to the Nordic countries in co-operation with the Surveys of the neighbours (e.g. *Elo,* 1989; *Ruotoistenmäki et al.,* 1997; *J. Korhonen et al.,* 1999). A more recent example of gravity inversion work at GSF can be found in *Elo* (2000).

3.8 Petrophysics

Determination of the physical properties of rock samples (petrophysics) was started early at the GSF. The first portable susceptibility meter was acquired back in 1954 (Fig. 11). In 1971 Maunu Puranen started the development of petrophysical instrumentation together with his son Risto Puranen. The versatile equipment was a prerequisite for systematic petrophysical mapping of the whole country. Sampling and measurements has produced an immeasurably valuable database on magnetic susceptibility, remanent magnetization, density and electrical conductivity values of wide range of rocks (e.g. *R. Puranen,* 1976; *M Puranen and R. Puranen,* 1977; R *Puranen et al.,* 1992, 1993; *Korhonen,* 1987: *Airo and Ruotoistenmäki,* 2000). According to a recent questionnaire the majority of the world's petrophysical data are in the database of GSF (*Korhonen and Säävuori,* 2000).

Fig. 11. Field susceptibility meter designed by GSF in the 1970's. (*Ketola,* 1986; courtesy: M. Ketola.)

3.9 Palaeomagnetism [based on information from J.J. Pesonen]

Palaeomagnetic studies allow to measure the drift of continents and provide the geomagnetic intensity beyond magnetic observatory records. In Finland palaeomagnetic research was started by Professor Maunu Puranen at the Geological Survey of Finland in late 50's. His determination of the palaeomagnetic pole of the 1.88 Ga old Ylivieska gabbro (*Puranen,*1960) was one of the first Precambrian pole determinations in the world.

The challenge was soon taken up by professor K.J. Neuvonen at the Geology Department of the University of Turku, who soon produced remarkable results on the mafic dyke swarms (*Neuvonen,*1966). The first apparent polar wander path of Fennoscandia (*Neuvonen,*1974) indicated that our bedrock has been located at shallow palaeolatitudes in warm climates during most of the Precambrian. His laboratory operated for more than 25 years and some of his instruments have been moved to the new Palaeomagnetic Laboratory at the University of Helsinki.

L.J. Pesonen, who after finishing his studies in Toronto returned to Finland in 1978, continued to develop the palaeomagnetic laboratory at GSF. His first series of investigations culminated in a benchmark paper on the Fennoscandian palaeomagnetism (*Pesonen and Neuvonen,* 1981), where the connection of Scandinavia with Laurentia during the Precambrian was demonstrated. Scandinavian Palaeomagnetic Workshops were initiated in 1986 by Pesonen and have been held since then every fourth year. The first Workshop was associated with the EGT Polar Profile Meeting (*Pesonen et al.,* 1989). Pesonen has been the leader of the Scandinavian palaeomagnetic group of the IGCP 257, mafic dyke swarms-project and since 1989 the regional compiler of the Fennoscandian palaeomagnetic data base. This data base was the first published part of the Global Palaeomagnetic Data Base. The most well-known result of the Finnish palaeomagnetic studies is the Fennoscandian drift map produced and refined several times by Pesonen and coworkers. A new model for the birth of the supercontinent Rodinia (*Mertanen and Pesonen,*2000) is the culmination of this research. (See also Fig. 12.)

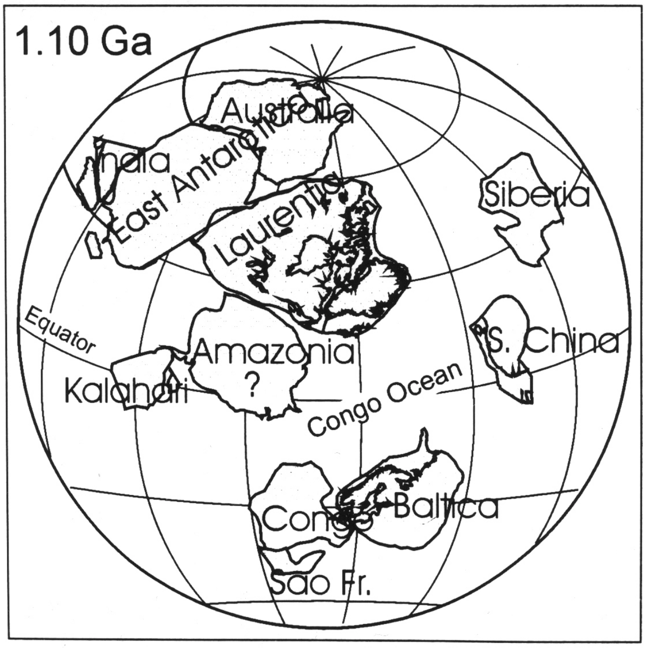

Fig. 12. The location of the Earth's continents 1.10 Ma ago (*Mertanen and Pesonen,* 2000).

Over the years the laboratory at GSF has been continuously improved with the acquisition of a superconducting SQUID magnetometer in 1991 revolutionizing the laboratory measurements. Continental drift of Fennoscandia, archaeomagnetism, quaternary palaeomagnetism to date lake sediments, meteorite magnetism and study of Precambrian geomagnetic field reversals have become the focus of research at GSF. The internationally recognized laboratory is presently run by S. Mertanen. She has extended the studies of Scandinavian rocks to Russian Karelia (*Mertanen et al.,* 1999) and developed new techniques relevant for dating of hydrothermal events associated with gold deposits.

Lately the study of meteorite impact structures have given useful new material on the crustal and biological evolution of the Earth. Initiated by professor Thure Sahama in 1967 investigations on the Lappajärvi structure by M Lehtinen was the start of a new branch of Solid Earth research. The first and succesful Fennoscandian meteorite impact conference in Lappajärvi and Espoo (*Pesonen and Henkel,* 1992) was followed by several European activities, first ERGTIP (European Research Group of Terrestrial Impact Processes) from 1991 to 1994, then an ESF Network activity from 1993 to 1997 and finally the ESF Impact Programme “Response of the Earth to Impact Processes, 1998–2003”.

Presently nine impact structures have been identified in Finland by using high-resolution airborne geophysics, drilling and detailed petrographic investigations to document shock features in the rocks (Fig. 13). The newest results indicate the potential of meteorite impact studies in finding economic deposits and in providing new insight into measures of erosion of the Fennoscandian shield (e.g. *Pesonen et al.,* 1999; *Pesonen et al.,* 2000b).

Fig. 13. The meteoritic impact craters identified in Finland by the end of 1999. (Courtesy: L.J. Pesonen.)

3.10 Other applications

A multitude of practical applications of geophysics to study other resources than ores and many new targets have been studied recently by various organizations. Examples can be found in e.g. *Ketola et al.* (1975), *Tammenmaa et al.* (1976), *Aarnisalo et al.* (1982), *Saarilahti* (1982), *Poikonen* (1983a, b), *Kuittinen et al.* (1985), *Saksa* (1985), *Rouhiainen* (1987), *Saksa and Korkealaakso* (1987), *Suomen Malmi Oy* (1988), *T. Jokinen and Lanne* (1996), *Maijala et al.* (1998).

4. Geothermics [based on information obtained from I. Kukkonen]

Following a suggestion in 1956 by P. Eskola, M. Puranen initiated geothermal studies at the Geological Survey of Finland in late 1950's. The first borehole temperatures were measured in 1960 in a 1021 m deep hole through the Jotnian Muhos sandstone formation at Liminka.

A temperature-sensitive copper coil resistor was used in the early 1960's and a thermistor instrument from 1964 to 1984. In 1984 a new equipment constructed by a P. Järvimäki and K. Sulkanen ws taken into use. A temperature-sensitive micro circuit (AD 591) provided an absolute accuracy of 0.1 °C and a resolution of 0.01 °C. The shortened time constant of the probe allowed more detailed down-hole logs, required in studies of groundwater flow effects.

Järvimäki (1968) was the first to present heat flow density (HF) and temperature gradient data in Finland. Due to the scatter of the data no firm conclusions about regional variations of HF were possible. Later *M. Puranen et al.* (1968) concluded, that the results were in agreement with results of HF measurements in other Precambrian areas. *Järvimäki and Puranen* (1979) reported geothermal data from 18 holes, most of them drilled for mineral exploration or in deep mines. The results were uncorrected for palaeoclimatic effects and radiogenic heat production rates were not determined. A slightly extended data set (24 holes) was presented in the Geothermal Atlas of Europe by *Kukkonen and Järvimäki* (1992).

To obtain heat flow information from the borehole temperature data one needs to know the thermal conductivity of the rocks intersected by the hole. Based on the divided bar method, an equipment was constructed at the GSF in 1964 (*Järvimäki*, 1968) and has been in use since (although with technically updated components; *Kukkonen*, 1989a). A summary of the thermal conductivity measurements of ca. 2800 drill core samples together with density and magnetic properties were reported by *S. Peltoniemi* (1996) and *Kukkonen and S. Peltoniemi* (1998).

The oil crisis in 1973 brought also geothermal energy into focus. *Kivekäs* (1978) made a survey on Finnish rapakivi granites and found their heat production potential to be uneconomically low. Maps of crustal radiogenic heat production were compiled by *Vaittinen* (1986) using airborne gamma ray spectrometric data and *Kukkonen* (1989a; 1993) from glacial till analysis. While the cold Finnish bedrock is not feasible for geothermal electricity production, heat pumps have been installed in shallow boreholes, soil and lakes for producing low-cost energy for space heating. The number of such applications in Finland is currently around 10,000 of which ca. 1,000 are borehole installations (*Kukkonen*, 2000).

Orivuori (1976) obtained exceptionally low HF and ΔT values at the 2600 Ma old Siilinjärvi carbonatite intrusion. This initiated more detailed studies on the role of groundwater flow on HF data and on the postglacial temperature effects (*Kukkonen,* 1987, 1988, 1995). Since prospecting for nuclear vaste disposal sites started in Finland, several new holes became available (*Kukkonen,* 1989a). It was clearly demonstrated that fresh surface groundwater (meteoric water) dominates in the uppermost few hundred meters of the bedrock, whereas more saline waters are encountered at deeper levels.

The role of convective heat transfer in measured heat flow values was studied and discussed by *Kukkonen* (1987, 1988, 1995, 1998) and *Kukkonen and Safanda* (1996). Groundwater flow effects on vertical variation of HF are strongly limited by the available driving force (topographic flow gradient) and the hydraulic permeability of the bedrock. The deep heat flow signal from the deepest drill hole in Finland at the Outokumpu area is modified in the uppermost crust by palaeoclimatic effects and refraction of heat due to thermal conductivity contrasts.

In 1989, the geothermal data from 35 drill holes at 32 sites were published (*Kukkonen,* 1989a, b). The HF data were corrected for palaeoclimatic effects, and the correlation between heat flow and radiogenic heat production of the rocks based on drill core analyses was also presented. The lowest HF values (below 30 mW/m^2) are encountered in the Archaean and Early Proterozoic areas in eastern and northern Finland, whereas the highest values (50–70 mW/m^2) are found in the Early Proterozoic migmatitic granitoids and Middle Proterozoic rapakivi granites in southern Finland. The latest geothermal data summary is based on 46 sites and 53 drill holes (Fig. 14; *Kukkonen,* 2000).

In the 1990's geothermal studies were extended to cover the southern margins of the Fennoscandian Shield (*Jõeleht and Kukkonen,* 1996, 1998; *Kukkonen and Jõeleht,* 1996), as well as the eastern and northern parts of the Fennoscandian Shield in Russian Karelia and the Kola Peninsula (*Kukkonen and Clauser,*1994; *Kukkonen et al.,* 1998). Co-operation was extended to the Urals in the framework of the EUROPROBE programme (*Kukkonen et al.,* 1997). All these studies have revealed considerable vertical variations in measured heat flow density, mainly caused by palaeoclimatic disturbances due to glacial cold climatic periods, previously underestimated in their amplitude.

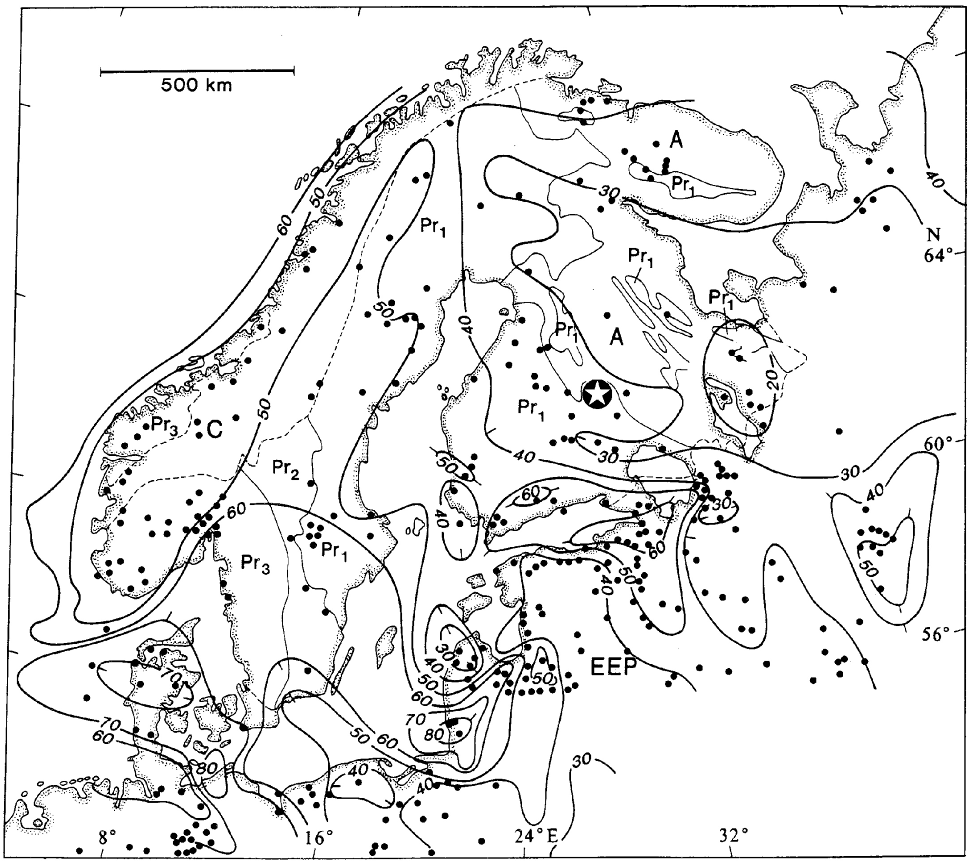

Fig. 14. Heat flow density (mW m^{-2}) map of the Fennoscandian Shield; A – Archaean; Pr1...3 – Proterozoic; C – Caledonides; EEP – East European Platform. The star shows the location of a kimberlite pipe. (*Kukkonen and Peltonen,* 2000).

New forward and inverse techniques to calculate the lithospheric temperatures were developed in the late 1990's using the random modelling and Monte Carlo techniques (*Jokinen and Kukkonen,* 1999a, 1999b, 2000; *Jokinen,* 2000). Due to uncertainties in heat production rate, thermal conductivity and boundary conditions the accuracy of the calculated temperatures at 50 km depth is only about ± 100–120 K. Additional constraints of the temperature values at greater depths was provided by the kimberlite-hosted mantle xenoliths discovered in eastern Finland in the 1990's. The geotherms could be constrained to depths of about 250 km in the upper mantle. The most recent estimate of the minimum thickness of the lithosphere is ca. 250 km below the central Fennoscandian Shield. (*Kukkonen and Peltonen,* 1999, 2000; *Kukkonen et al.,* 1999; *Jokinen and Kukkonen,* 2000).

A combination of seismic, geothermal, density and earthquake data have been used by *Kaikkonen et al.* (2000), *Moisio and Kaikkonen* (2000) and *Moisio et al.* (2000) in studies of the rheological properties as well as stress and deformation conditions of the Finnish lithosphere.

5. *Electromagnetic induction studies of the lithosphere*

5.1 *Introduction and methodological comments*

Electromagnetic (EM) methods are versatile tools in obtaining the lateral as well as the vertical distribution of the conductivity σ within the Earth. The conductivity depends in a complicated way on the mineralogical composition, amount of fractures in the bedrock, content and nature of pore fluids and the temperature of the bedrock. The first use of EM techniques in Finland was in ore prospecting very soon after the invention of the first DC and AC methods during the 1910's and 1920's (*Ketola,* 1986).

Crustal EM research is one of the youngest areas of Solid Earth Geophysics. The theory of its main technique, magnetotellurics (MT), was published simultaneously in France by L. Cagniard and in Russia by A.N. Tikhonov in 1953. In Finland crustal EM started in 1980. In magnetotellurics (MT) two or more components of the Earth's magnetic field and the horizontal geoelectric field are measured simultaneously. From the data both the horizontal and the vertical distribution of the electrical conductivity can be obtained. In magnetometer array or magnetovariational (MV) studies all three components of the magnetic field are registered simultaneously at several sites. Such studies are used to identify crustal conductors and to determine regional conductivity.

To study the electrical properties of the deep crust and the upper mantle low frequency electromagnetic fields have to be utilized. High frequency ground and/or airborne data are useful in constraining the effects of near-surface conductivity variations. Temporal changes of the ionospheric and magnetospheric current systems create suitable natural source fields for MT at periods above some tenths of a second. *Osipova et al.* (1989) used the equivalent current method to show that close to the source region in Northern Scandinavia the magnetic field depends only weakly on the Earth's conductivity for periods greater than 15 minutes. For shorter periods (AMT; the audio range: 1 to 0.0001 s) lightning discharges in the atmosphere produce the source field.

5.2 *Crustal EM (Induction) research starts in Finland*

The start of Deep Crustal EM geophysics in Finland can be traced back to mid-1960 and early 1970. In his travel report from the Mining Congress in Freiberg, June 1963, professor Heikki Paarma (at that time chief geologist at the Rautaruukki Oy Prospecting Department) proposed that test and research using telluric methods should be started in Finland (*Paarma*, 1964). He based his proposal on a presentation at the meeting by Prof. Antal Ádám (*Hjelt,* 1982). In 1970 Dr H. Korhonen and prof. M.T. Porkka wrote the first funding proposal to start magnetotelluric (MT) studies in Finland.

Drs Ádám and J. Verö visited Finland in 1973, which was the start of a long a fruitful Finnish-Hungarian co-operation. Theoretical sounding curves for the Muhos sandstone formation as an introduction to AMT studies were calculated by *Ádám* (1973) (Fig. 15). Upon the advice of Dr Ádám, contacts were established with Centre des Recherches Géophysiques, Garchy (France) an institute established for Prof Cagniard. Scientists from Garchy measured the first field AMT data in 1974 using a French scalar, high-frequency instrument (*Benderitter et al.,* 1975, 1978). In August 1976, the University of Oulu acquired its own equipment ECA 541-0 and a more modern version ECA 542-0. The AMT technique became a popular tool in deep ore prospecting.

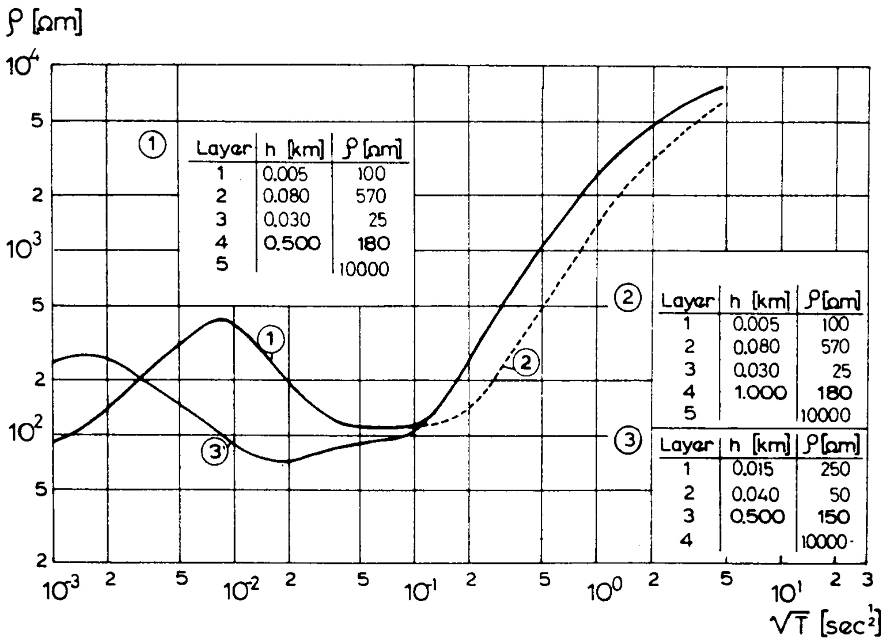

Fig. 15. Theoretical AMT sounding curve for a three-layer Earth with parameters typical for the Muhos sandstone formation at Oulu (*Ádám,* 1973).

In 1978 deep EM research in general and MT specifically was added to the minutes of co-operation between the Academy of Finland and the Hungarian Academy of Sciences. After thorough preparations with mutual visits between Oulu and Sopron, a three-person team from Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences (GGKI/MTA) in Sopron arrived in Finland in June 1980 with analogue field equipment. The Academy of Finland-funded project “Electromagnetic Deep Research” started.

The field sites of the Hungarian deep MTS in 1980 were prepared by the Oulu team, lead by P. Kaikkonen, using 4–20 AMT-soundings to locate electrically homogeneous sites. Originally 3 deep MT soundings were planned, one on each side of the Ladoga-Bothnian Bay Zone and one within the zone. The excellent field conditions allowed 5 soundings to be completed (Fig. 16). Later the line connecting the MTS sites became known as SVEKA, the first Finnish DSS profile and a part of the world-class Geotraverse GGT/SVEKA.

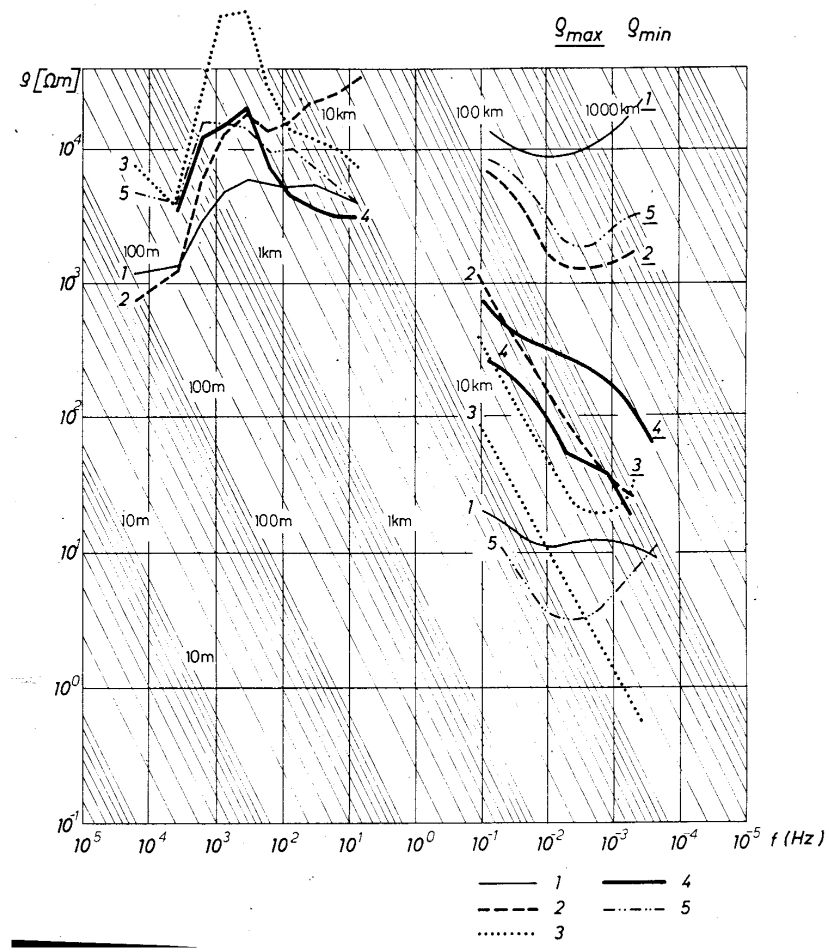

Fig. 16. First five field MTS curves measured in Finland 1980 with depth lines in km (*Ádám et al.,* 1982).

Several co-operative efforts followed: a comparison of the deep EM results from the Finnish Precambrian and the young Mesozoic-cainozoic Pannonian Basin in Hungary, instrumental development for synoptic monitoring of AMT source fields as well as both numerical and analogue EM modelling. Lack of funding and personnel in Finland dropped the monitoring from the research agenda at Oulu. The Hungarian ELGI organization, the Geophysical Department of the GSF and Rautaruukki Oy joined later the Finnish-Hungarian co-operation. This lead to subsequent multi-frequency instrumental development.

Long-period MTS in the Kuhmo region in 1981, using Bobrov analogue stations, marked the start of the six years long project "Development of the Geoelectric Model of the Baltic Shield". This was Project 13 of the co-operation between the Academy of Finland and the Soviet Academy of Sciences. The first stage of project 13 ended in 1983, but has continued until today's date with scientific themes changing every 3 years. The role of numerical modelling has continuously increased in importance. In the 1990's field work has concentrated on studies related to the registration of the geoelectric field of moving ocean water (*Palshin et al.,* 1996, 1997, 1999).

In 1984 the University of Oulu acquired its first own deep-EM instrument with 5 channels. MT-groups in Finland, Sweden and Denmark utilized similar equipment. Thus the Scandinavian MV and MT data form a comprehensive and unified set. In Finland, MT studies have continued throughout the 1990's. The profiles across the crustal conductive structures, obtained by MV array studies, are numerous and the Finnish crustal geoelectric data set is globally unique both in quality and coverage.

An extensive magnetometer array work followed the first MT soundings. The arrays covered Finland between latitudes 60 and 66.5°N (e.g. *Pajunpää,* 1984, 1986, 1987, 1989; *Pajunpää et al.,* 1983). The corresponding area of Central Sweden was covered later, but this data has not been processed and analysed to the same extent. Later data from the EISCAT magnetometer cross and its successor, the IMAGE array (*Sucksdorff et al.,* 2001, this volume) have been utilized to have a better control on the source field in MT and MV array studies.

This array research was actually initiated at a lunch meeting during the 1976 Induction Workshop in Sopron, which at least J. Untiedt, U. Schmucker, B. Olafsdottir, R. Hutton and S.E. Hjelt participated in. The array work utilized the same Gough-Reitzel instruments as in the IMS project 1976–79 (*Küppers et al.,* 1979). The Braunschweig magnetometers were recalibrated immediately after the IMS and 31 of them were used in 7 dense arrays (30–40 km station separation) from 1981 to 1985 in Finland and later also in Sweden (*Pajunpää,* 1989).

In Finnish Lapland and on the Kola Peninsula frequency soundings (FS) in 1983 made use of the energy from a magnetohydrodynamic (MHD) generator located at the Fisher Island of the Kola Peninsula. These unique geoelectric investigations were started in 1983 and the distribution of average crustal resistivity covering the NW part of the shield was obtained (*Heikka et al.,* 1984; *Velikhov et al.,* 1983, 1986; *Kaikkonen et al.,* 1988; *Vanyan et al.,* 1989; *Zhamaletdinov,* 1990; *Zhamaletdinov et al.,* 1993).

5.3 Major results of crustal induction studies in Finland

The deep EM research of the Fennoscandian Shield has proceeded almost ideally methodologically. MV arrays for regional mapping and MT soundings across anomalous zones have been completed by controlled source techniques, allowing a variation in the depths of investigation and lateral resolution. The surface conductors have been traced from the unique airborne EM data available in Finland. Thus it has been possible to focus from large-scale, elongated structures with dimensions of the order 100 km and more to small-scale (few meters) local structures.The conductivity models were continuously refined, from the first sitewise layered (1D) models via 2D profile cross-sections to regional 2D and 3D descriptions of the conductive subsurface.

Pernu (1973) presented the first Finnish MTS curve based on Sodankylä observatory data. The 1980 MTS data were digitized and analyzed in Sopron. Strong electrical anisotropy of the crust could be only partly explained by effects of conducting schistbelts (Fig. 16; *Ádám et al.,* 1982).

Jones (1981, 1983) and *Jones et al.* (1983) used the original IMS array data for crustal structural studies in Scandinavia.. The first results indicated a thinning of the lithosphere towards the northern edges of the Fennoscandian (Baltic) Shield and the existence of a conductivity anomaly around the Kiruna ore area (*Jones,* 1982). *Pajunpää* (1984, 1986, 1987, 1989 and *Pajunpää et al.,* 1983) identified several long crustal conductors and a general horizontal distribution of electrical conductivity in the southern and central parts of Finland.

Subsequently *Pajunpää* (1987, 1989) divided the middle and lower crust of Southern and Central Finland into five geoelectrically different blocks. In Central Finland the blocks are surrounded by narrow, highly conducting bandlike formations in the midcrust, with their upper boundary being often 6–10 km below the surface. The resistivities are typically 5–10 Ohm-m. The greatest anomalous crustal regions have an conductance of 20.000 Siemens and more. The lower crust is well conducting in most parts of the Shield. The bandlike anomalies could be connected to corresponding anomalies in the Russian parts of the Baltic Shield. (Fig. 18, *Hjelt and T. Korja,* 1993, *T. Korja,* 1993).

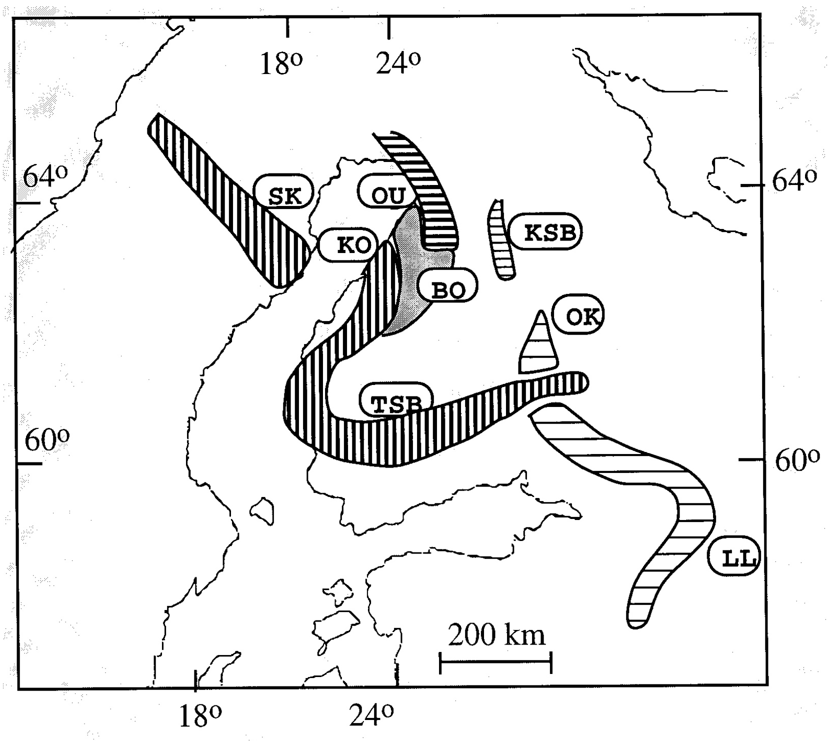

Fig. 17. Upper and middle crustal conductors in the Fennoscandian Shield based on MV, MT, MHD and AEM data. Names of the anomalies: BO = Bothnian; KO = Kokkola; KSB = Kuhmo Schist Belt; LL = lake Ladoga; OK = Outokumpu; OU = Oulu; SK = Skellefteå ; TSB = Tampere Schist Belt (*Korja and Hjelt,* 1998).

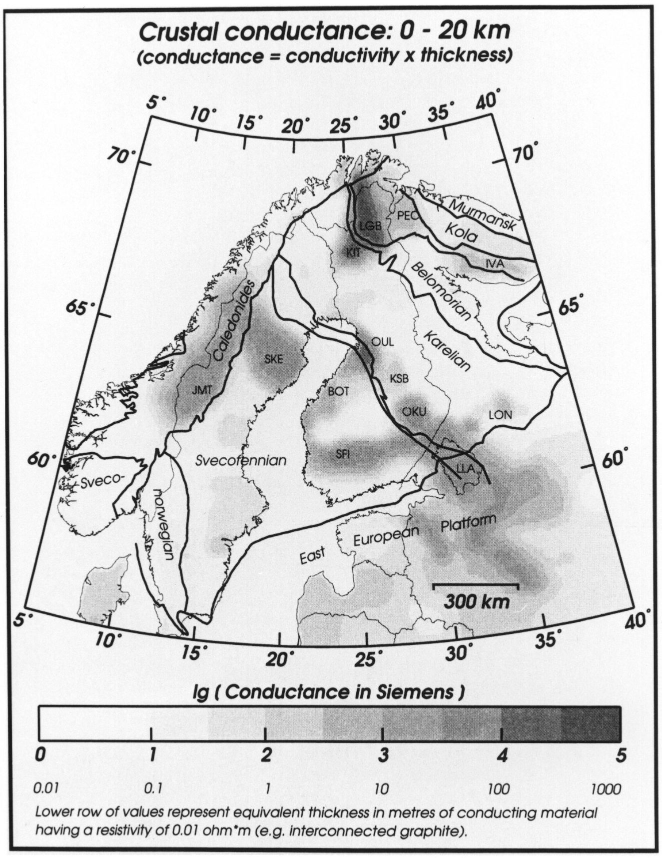

Fig. 18. Upper crustal conductivity in Fennoscandia (*Korja and BEAR WG,* 2000).

The present models of crustal electrical conductivity in the Fennoscandian Shield (Figs. 17 and 18) are based on magnetovariational (e.g. *Jones,* 1981; *Rokityansky,* 1982; *Pajunpää,* 1987) and magnetotelluric (*Ádám et al.,* 1982; *Golod et al.*, 1983; *Jones et al.*, 1983; *Korja et al.*, 1986; *Korja et al.*, 1989; *Korja,* 1990; *Pernu et al.,* 1989; *Vaaraniemi,* 1989; *Korja,* 1993; *Hjelt and Korja,* 1993; *Korja and Hjelt,* 1993; *Korja and Koivukoski,* 1994; *Korja et al.*, 1996b; *Korja and Hjelt,* 1998) data, whereas airborne electromagnetic mapping all over Finland (*Peltoniemi,* 1982, *Peltoniemi et al.,* 1992) has provided important information about near-surface structures, e.g. the possible surface expressions of deep conductors. Locally AMT soundings (*Kaikkonen and Pajunpää,* 1984), ground VLF-R and airborne VLF mapping (*Hjelt et al.,* 1990c; *Korja et al.,* 1996a), DC dipole-dipole profiling (*Pernu,* 1991), controlled source soundings, e.g. frequency and DC-soundings in the northeastern part of the shield using magnetohydrodynamic data (*Velikhov et al.,* 1986; *Vanyan et al.,* 1989; *Zhamaletdinov,* 1990), and self potential measurements (*Korja et al.,* 1996a) have also produced data for crustal studies.

Several crustal EM projects produced new background information to support new strategies of ore prospecting. The Outokumpu crustal anomaly was problematic to investigate because of the high conductivity of the surface structures. The measurements in 1983 were financed by the Ministry of Trade and Commerce. Detailed studies of the structure of the Tampere schist belt started in August 1986, the project was lead by Teuvo Pernu and financed also by the Ministry of Trade and Commerce (*Pernu et al.,* 1989). Also in the investigations of the Suhanko massif deep EM techniques were important (*Pernu et al.,* 1986).

Summaries pertinent to the Northern Segment of the European Geotraverse (EGT) were published by *Hjelt* (1987a, 1992); *Hjelt and Vanyan* (1989); *Korja* (1990); *Korja et al.* (1989); *Hjelt et al.* (1992). Magnetometer array (MV) and magnetotelluric profiling (MTP) data were completed by controlled source measurements (*Velikhov et al.,* 1986). Simultaneous operation of EGT and Project 13 led to tremendous synergetic advantages in studies of the Baltic (Fennoscandian) Shield. Detailed MT profiles [from Finland POLAR (*Korja et al.,* 1989); OULU I & IV (*Korja et al.,* 1989, *Vaaraniemi,* 1989) and SVEKA (*T. Korja,* 1990; *Korja and Koivukoski,* 1994)] were included in the the EGT/N Segment results. The SVEKA MT profile is only partly inside the full EGT/N window, but was included in order to emphasize the lateral variability and differences among the geoelectrical cross-sections.

Toivo Korja has extensively discussed the tectono-geological explanations for the conductivity structures (*Korja,* 1990; *Korja et al.,* 1996a; *Korja and Hjelt,* 1998; *Korja et al.,* 2000). The Fennoscandian Shield is characterized by several elongated belts of conductors separating more resistive crustal blocks. Most of the belts can be recognized as orogenic conductors and seem to indicate places where crustal masses have once collided and been sealed together. The belts have a complicated internal structure with mainly graphite- and sulphide-bearing metasedimentary rocks. They serve as tectonic markers of terrain boundaries and the blocks as transparent windows for probing the deeper crust and lithosphere. Most conductors are located in the upper and middle crust without continuation into the lower crust. The crust of the younger (Palaeoproterozoic Svecofennian) part of the Shield seems to be more conductive than the older (Archaean) lower crust.

The conductivity of the lower crust of the Fennoscandian Shield is laterally homogeneous and anisotropic at several locations. Even the upper mantle may be electrically anisotropic. The conductivity of the lower lithosphere has not yet been determined reliably. The asthenosphere is poorly or not at all conductive resembling electrically the lower lithosphere.

5.4 The electrical asthenosphere

Jones (1983) explained some of the early IMS data by the presence of an electrical asthenosphere in the range 115 to 185 km below the northern Fennoscandian Shield. This result has been challenged by source field modelling (*Osipova et al.,* 1989). Also early MT-soundings in northern Karelia seemed to be free from disturbing surface conductors. The average resistivity curve for this region was suggested by *Kaikkonen et al.* (1983) to have a surface resistivity of 10^4–10^5 Ω m, decreasing to 100 Ω m at a depth of about 150 km, which is typical also for most other shield regions.

The presence of an asthenospheric conductive layer can be detected only if its conductance is greater than 1000 S (*Vanyan,* 1984).

During the 4th Electromagnetic Induction Workshop in Murnau (Germany) in 1978, professor L.L.Vanyan proposed to start a joint Finnish–Soviet ELAS-project in order to intensify the studies on the Baltic Shield. A draft for such a program was developed at the Soviet ELAS-meeting in Suhumi in April 1979 by professors M.N. Berdichevsky, S.-E. Hjelt and L.L. Vanyan. The program proposal was submitted simultaneously to the Soviet Academy of Sciences and the Academy of Finland. In 1980 both Academies decided to add the joint project number 13, "The development of the deep geoelectric model of the Baltic Shield" into their scientific co-operation scheme. (*Vanyan & Hjelt,* 1994). ELAS, The Electrical Properties of the Asthenosphere, was at that time an ad-hoc-operated project of the IAGA Working Group I–3 (later I–2), but evolved later into an interassociation (IAGA and IASPEI) effort (*Hjelt,* 1987b).

During the first joint field season 1981 a long-period Bobrov-type station IZMIRAN 5 was operated in the Kuhmo region. The instrument became later the property of the University of Oulu. The registration of signals from the MHD generator "Khibiny" on the Rybatchy (Fisher) Island had started in the USSR already in 1976 on the Kola Peninsula. The registrations were extended into Finnish territory at the end of 1982. Analogue field instruments from Apatity and filters developed at Oulu were used during the first field campaigns. Later digital MT stations were used. (*Hjelt and Vanyan,* 1989; *Vanyan and Hjelt,* 1994).

The existence of the electrical asthenosphere below the Finnish bedrock remains open. A new approach in studying the lithosphere-asthenosphere boundary is the 1998 ultradeep array measurement of the SVEKALAPKO / BEAR Working Group (for further information, see http://pcland3.phys.spbu.ru/index.html).

5.5 Numerical modelling related to induction studies

The scientists of project 13 developed and studied independently at several organizations a variety of numerical approaches to induction modelling. Results were discussed and compared during regular visits of the project scientists and the exchange and implementation of computer programs was successful. The first collection of articles (on numerical modelling) was published as Report No. 7 of the Report series of the Department of Geophysics, University of Oulu (*Hjelt and Vanyan,* 1983). It was soon followed by Report No. 8, articles from the First Project Symposium held in Oulu in October 1983 (*Hjelt,* 1984). A Second Project Symposium took place in Petrozavodsk in May 1984 and the articles from that symposium were published in Russian in the series of the Karelian Branch of the Soviet Academy of Sciences (*Golod,* 1986). A jubilee symposium was held in 1991 (*Kaikkonen,* 1992).

Numerical modelling problems ranged from the calculation of the effects of ionospheric current sources on MT sounding (*Osipova et al.,* 1989), via 2D modelling of EM profile measurements across interesting crustal conductivity anomalies, to thin sheet approximations of the electric fields. The latter approximation was used not only to produce field estimates covering the Fennoscandian Shield (e.g. *Kaikkonen, 1983a,* 1998), but for a variety of other tectonic environments, Kamchatka, Rheingraben, the Pannonian Basin and India (*Kaikkonen et al.,* 1984, 1985; *Ádám et al.,* 1990; *Arora et al.,* 1993).

Following a resolution at the 1985 General Assembly of IAGA (international Association of Geomagnetism and Aeronomy) an international computer program library, ILONEM, was established in Oulu in 1987. This facility, lead by P. Kaikkonen, was intended as a center providing a computer program library for test and reference purposes, particularly for scientists from institutions with small computer facilities. More than 25 visitors from 13 countries worked at Oulu during the most active period of the center from 1985 to 1987. In addition, scientists at ILONEM modelled and solved induction problems submitted by researchers from developing countries. The activities gradually have declined with the increased availability of free software over the Internet.

6. Environmental effects of geomagnetism (GIC research) [abridged from original text of Risto Pirjola, FMI]

6.1 Definition of geomagnetically induced currents (GIC)

Time variations of the geomagnetic field affect technological systems, especially at high latitudes, where geomagnetic storms are the largest and most frequent. The impacts, geomagnetically induced currents (GIC) flowing in electric power transmission systems, oil and gas pipelines, telecommunication cables and railway systems are the ground end of the complicated space weather chain starting from the Sun.

GIC effects were first observed about 150 years ago when early days' telegraph operators found that at times their systems were inoperative and at other times they even did not need the battery to be connected (*Boteler et al.,* 1998). The first GIC problems in power systems were observed during the large magnetic storm in March 1940 (*Davidson,* 1940). Power system transformers are saturated by GIC, and the possible consequences extend from distortions of the sinusoidal waveforms to permanent damage of transformers and a blackout of the entire network (*Kappenman and Albertson,* 1990). A final understanding that GIC constitute a potential risk to electric power transmission was obtained from the catastrophe that occurred in the Hydro-Quèbec system during the magnetic storm in March 1989.

The only failures that have been caused by GIC for sure in Finnish systems have occurred in the tele-equipment in September 1909 and in February 1958 (*FMI*

Observations, 1909; *Nevanlinna et al.,* 2000). However, the largest research efforts made in Finland concern the high-voltage power system and the natural gas pipeline.

6.2 GIC in the Finnish high-voltage power system

The large magnetic storm in August 1972 with its GIC impacts in North America, the northern location of Finland and the rapid growth of the 400 kV grid in the latter part of 1970’s (including the loops in southern and central Finland) were obvious reasons for starting active research of GIC in the Finnish high-voltage power system. By an initiative of Dr. Antti J. Pesonen from the Imatran Voima Oy (IVO) power company and Prof. Christian Sucksdorff from the Finnish Meteorological Institute (FMI), a meeting was held in September 1976 to evaluate common interests and to establish a GIC collaboration. Joint studies of GIC between FMI and the IVO and Fingrid Oyj power companies started in 1977. The GIC recordings and other data thus cover already more than two eleven-year sunspot cycles. However, observations of GIC at different times are not necessarily comparable because of great changes in the power line configuration.

The Huutokoski 400 kV transformer is the main GIC measurement site in Finland (Fig. 19). Recordings were started in the earthing lead of the transformer in February 1977 (*Pirjola,* 1983). As the end station of a 400 kV line, Huutokoski was thought (correctly) to experience large GIC values. A model calculation of GIC at this site was also considered easy. A neutral point reactor was installed at Huutokoski in the middle of the 1980's. The large resistance caused by this reactor and changes in the position of the station in the configuration of today's 400 kV system decreased the GIC values at Huutokoski. Subsequently recording ended at the early 90’s.

Presently GIC are recorded in the Pirttikoski, Rauma and Yllikkälä 400 kV transformers. The largest GIC one-minute mean value (about 200 A) ever measured in the Finnish power system occurred in the earthing lead of the Rauma 400 kV transformer on March 24, 1991. The correlation, between GIC and the time derivative of the geomagnetic field simultaneously measured at the Nurmijärvi Geophysical Observatory in southern Finland, is clear (Fig. 20).

Modelling efforts to calculate GIC in the Finnish 400 kV system were started in the beginning of the 1980's. *Lehtinen and Pirjola* (1985) presented exact matrix formulas for the computation of GIC driven by the geoelectric field for a discretely-earthed network, such as a power system. *Häkkinen and Pirjola* (1986) presented formulae for the surface electric and magnetic fields created by a general ionospheric-magnetospheric current system above a layered Earth. The application of the complex image method (CIM) improved numerical calculations of GIC due to different ionospheric current events (*Pirjola and Viljanen,* 1998; *Pirjola et al.,* 2000; *Viljanen et al.,* 1999).

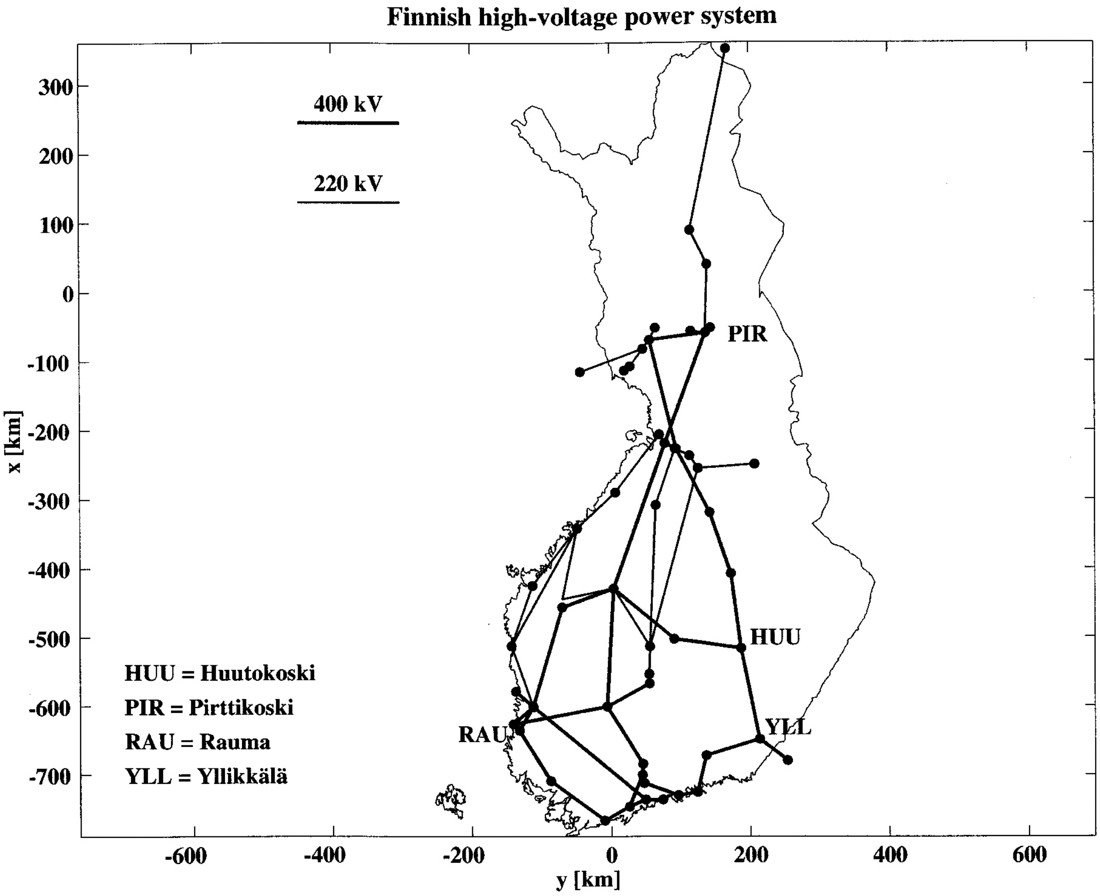

Fig. 19. The present-day configuration of the Finnish 220 and 400 kV power transmission system (*Pirjola et al.,* 2000).

Statistical estimates on the occurrence of GIC at each site of the Finnish 400 kV power system in 1985 and 1986 were based on the plane wave approximation of the geomagnetic field. Effects of changes in the power system configuration and the duration of large GIC's in the transformers were studied later (*Viljanen and Pirjola,* 1989).

In 1991 to 1992, in a new "GIC project", data were collected simultaneously at four 400 kV transformers (Huutokoski, Pirttikoski, Rauma, Yllikkälä) and in the Nurmijärvi–Loviisa 400 kV transmission line (*Viljanen and Pirjola,* 1994). The GIC in the line was obtained from the difference between two magnetometers, one close to the line and the other at a distance where no GIC signal could be detected. More elaborate models gave GIC statistics for the 400 and 220 kV grids (*Mäkinen,* 1993).

The latest statistical GIC study of the Finnish 400 and 220 kV systems in 1999 and 2000 (*Pulkkinen et al.,* 2000) was based on geoelectromagnetic data collected in the "SVEKALAPKO / BEAR" project in Finland in summer 1998 and on magnetic data produced by the IMAGE magnetometer array operating continuously in Fennoscandia and Svalbard. The simultaneous occurrence of large GIC at several transformers was also investigated.

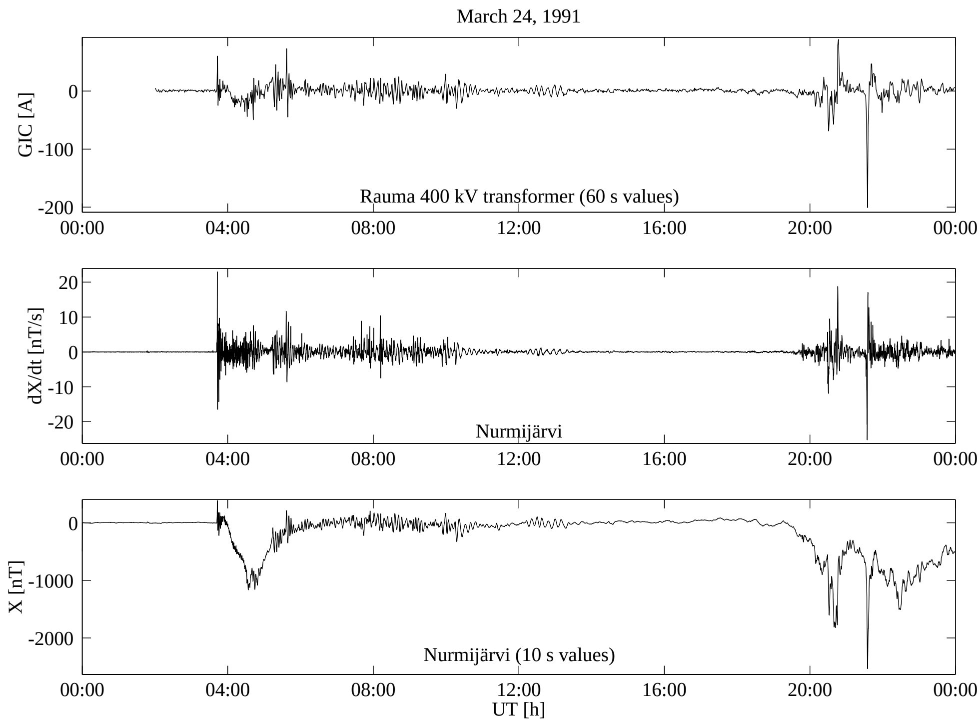

Fig. 20. GIC (positive into the Earth) in the earthing lead of the Rauma 400 kV transformer on March 24, 1991 (uppermost panel) and the simultaneous north component of the geomagnetic field (lowermost panel) and its time derivative (middle panel) at the Nurmijärvi Geophysical Observatory. (*Pirjola et al.,* 2000).

6.3 *GIC in the Finnish natural gas pipeline*

Since buried pipelines are earthed continuously, the GIC phenomenon in pipes differs from that in power line systems. A current from the pipe into the soil may enhance corrosion and may be accompanied by unwanted pipe-to-soil voltages. The Neste Oy company found in the beginning of the 1980's some unknown voltage fluctuations in the eastern part of the Finnish natural gas pipeline. The fluctuations disturbed the corrosion control and protection systems. This initiated theoretical studies of GIC in the pipeline at FMI. Later it was discovered that the fluctuations were produced by dc railways in the Soviet Union.

The discussions between Neste Oy and FMI lead to a long and fruitful co-operation on GIC between FMI and the pipeline companies Neste Oy and Gasum Oy. Neste Oy bought from FMI a statistical study of the occurrence of GIC along the Finnish pipeline and from the pipe to the soil in 1988 (*Viljanen,* 1989). A simplified model assuming an infinite pipe in a homogeneous medium and the K-index statistics at Nurmijärvi was used. Modelling was later improved by including the branches of a pipeline network (*Pulkkinen,* 1999a) into the distributed-source transmission line (DSTL) formulation of *Boteler* (1997).

A new statistical study of the occurrence of GIC and pipe-to-soil voltages in the Finnish natural gas pipeline was performed in 1998 to 1999 (*Pulkkinen,* 1999b). The study was based on GIC measurements carried out by using two magnetometers and on the DSTL theory.

7. *Modelling and inversion*

7.1 *Scale modelling*

Numerical modelling of EM systems for interpretation purposes was virtually impossible before the time of computers. Although the idea of small scale modelling had been practised in Finland already in the 1920's (*Ketola,* 1986), the dissertation of Ketola (*Ketola,* 1968; *Ketola and Puranen,* 1967) was a break-through for modelling EM systems. The thesis contains a wealth of interpretation nomograms for the horizontal coplanar (Slingram) EM system. Numerous MSc theses have been prepared and published using the small scale facility of Helsinki University of Technology.

Pernu (1991) used a waterfilled basin in the backyard of his home to measure fields of complicated conductor shapes in (less) conducting environment. Although some polarization effects were neglected in the design of the scale system, the clever use of the ground water level to get rid of the wall effects gave good qualitative results for a great variety of DC electrodes geometries.

7.2 *Numerical electromagnetic modelling*

The first desktop computer was installed at the Prospecting Dept of Outokumpu Co in 1969 (*Ketola,* 1986). *Hattula* (1970) implemented successfully a magnetic profile calculation program and it soon became a routine tool in interpretation (*Ahokas,* 1973). From 1971 S.E. Hjelt continued research as Senior Fellow of the Academy of Finland, working at and using the facilities of Outokumpu Co. A long-profile inversion program with automatic starting value determination was constructed. A 5-fold increase in speed of computation, also for the desktop system, was obtained (*Hjelt,* 1973, 1975, 1976a, 1976b). The formulae for the magnetic and gravity effects of dipping prisms (*Hjelt,* 1972, 1974) opened up possibilities for 3D interpretation of potential field data. Early descriptions of the use of the program in real structural work are found in *Hjelt et al.,* (1977), *Pernu et al.,* (1986).

From 1974 research continued at the Applied Geophysics Laboratory of the Helsinki University of Technology (HUT); experiments with using interactive graphical terminals in magnetic inversion soon started (*Lakanen,* 1975). All the experience gained in these studies and the increasing theoretical litterature formed the backbone of a unique course in Geophysical Inversion, which was first given in 1973 at HUT. With many modifications it has since then been regularly given by S-E Hjelt both at HUT and from 1975 at the University of Oulu. An international textbook (*Hjelt,* 1992a) supports the course.

A long line of numerical modelling started with the dissertation of *L. Eskola* (1976). This seminal work, where the integral equation technique and the method of subareas was used, was followed by a series of papers and culminated in a international textbook (*Eskola,* 1992). Nonlinear and inhomogeneous demagnetization of platelike bodies was studied by e.g. *Eskola and Tervo* (1980), *Tervo* (1986), DC- and IP-effects were modelled by e.g. *Eloranta* (1984), *Soininen* (1985) and *Vanhala* (1997). *Eloranta et al.* (1998) have extended the analysis using the new developments of EIT (Exact Image Theory).

The finite element method of calculating numerical EM fields has been intensively studied and developed by P Kaikkonen at the University of Oulu since 1973 (*Kaikkonen,* 1977, 1980a, b, c). In 1976 prof. David Rankin (Edmonton, Canada) visited Oulu during his sabbatical in Aarhus. Kaikkonen was invited to do post-graduate work in Edmonton, which challenge he took up in 1976. The dissertation of *Kaikkonen* (1980c) contained a remarkable set of VLF modelling results. Later extensions to MT, to many EM geometries and 3D DC problems have been published (e.g. *Kaikkonen,* 1983b; *Kaikkonen et al.,* 1984, 1985,1988; *Hvozdara and Kaikkonen,* 1994, 1996, 1998; *Hvozdara et al.,* 1987; *Pethö et al.,* 1995; *Kaikkonen,* 1998).

7.3 Inversion of electromagnetic data

A systematic study of EM inversion has at the University of Oulu has developed along three major lines. P. Kaikkonen and S.P. Sharma have successfully explored the properties of simulated annealing as a tool in global optimization and joint inversion of VLF, VLF-R, time domain EM and DC data (*Kaikkonen and Sharma,* 1997, 1998a, 1998b; *Sharma and Kaikkonen,* 1998a, 1998b, 1998c, 1999a, 1999b, 2000). Among earlier work on MT inversion and interpretation are the papers of *Marcuello-Pascual et al.* (1992) and *Weidelt and Kaikkonen* (1994).

In addition M. Pirttijärvi and S.E. Hjelt have worked on practical computer codes either running with reasonable speed in PC environment or using very approximate, but quick procedures. The latter approach has its roots in early theoretical work on a single-loop EM system (*Hjelt,* 1968, 1970, 1977). A program suitable for PC environment was prepared by M. Pirttijärvi for a conducting plate in the field of a EM magnetic dipole (*Pirttijärvi and Hjelt,* 1993). The work was funded by the Outokumpu Foundation from 1991 to 1994 and continued in the EU-project GEONICKEL, coordinated by the Outokumpu Co with GSF, HUT and BRGM (France) as partners. In 1997 the project NOIGEM (and its one-year follow-up IPEG in 2000) was funded by the Academy of Finland. This project concentrated to study the inversion aspects of conducting plates (*Hjelt and Pirttijärvi,* 2000; *Verma et al.,* 1998; *Pirttijärvi et al.,* 1998). Project partners were dr. S.K. Verma (NGRI, India), Prof MS Zhdanov (now at Univ Utah, Salt Lake City), the Dept of Mathematics in Oulu (prof. Päivärinta and his collaborators at several international institutes).

The third and newest line is the application of Bayesian statistics, Pareto optimization and fractal mathematics and joint inversion of EM and seismic data (*Kozlovskaja and Hjelt,* 2000; *Kozlovskaja,* 2000).

8. The role of international co-operation in electromagnetic geophysics

8.1 Lithospheric studies

International co-operation and projects have played a seminal role in the history of Finnish Deep EM research. Besides the binational co-operation described in Chapter 5, the participation in the multinational Electrical Conductivity of the Asthenosphere (ELAS; *Vanyan and Hjelt,* 1994), European Geotraverse (EGT; *Blundell et al.,* 1992), EUROPROBE (*Gee and Zeyen,* 1996) and Global Geotransects (GGT; *Korsman et al.,* 1999) programmes have all contained a strong component of Deep EM studies. With the exception of ELAS, the mentioned subprogrammes are European contributions to the International Lithosphere Programme (ILP).

The scientist from the Department of Geophysics/University of Oulu participated from 1980 to 1992 in the (then) largest geoproject of the European Science Foundation (ESF): the European Geotraverse (EGT). The main idea of the project was to construct a cross-section of the Earth's crust from the Mediterranean to Nordkap. The Oulu Induction Group compiled a map of 2D electrical conductivity structures of Scandinavia using uniform depth and resistivity scales and maps of reversed induction arrows for the periods 300 and 1000s. The results of these investigations have been summarized as map No. 11 of the EGT Atlas (*Blundell et al.,* 1992) and are available also in digital form on a CD-ROM disk published jointly with the report.

The idea of the "Global Geoscience Transects (GGT) Programme" was initiated at a joint meeting of IUGG ja IUGS in Tokyo in June 1985. The transects were supposed to shed light on the evolution and structure of the lithosphere. Their proposed width was 100 km, they should cross all major geotectonic units and be located so that enough geophysical crustal measurements exist. The EGT was to be one such transect, but its orientation in Scandinavia was tectonically less favorable.

A special EGT subproject, called POLAR, extended across the granulite rock unit in Lapland. These rocks have been upthrusted from the lower crust several tens of kilometers to the surface. Field data were measured and modelled at one of the first Study Centres of the EGT project in 1996. Two weeks of work by more than 60 scientists resulted in two geologically different models of the granulite structure, but paved the way for future transect type of work. The resistive granulite is underlain by a conductive layer, which can be traced down to about 15 kilometers. The basinlike geometry of the conductivity model across the Lapland Granulite Belt was, however, in good agreement with the seismic and gravity models (*Korja et al.,* 1989, *Elo et al.,* 1989 and other articles in the same volume).

Another important general outcome of EGT was to produce a new understanding of the long, well conducting zones of the crust. These ideas were further tested in the Finnish Geotransect Programme GGT/SVEKA and in the EUROPROBE programme, which emerged on the European geoscientific scene after the EGT.

Based on ideas at the end of the Academy of Finland-funded Induction projects, the Finnish Lithosphere Committee proposed in 1987 the transect GISK (Greenland–Iceland–Scandinavia–Kola) to cover tectonic regimes from a recent active one to one of the oldest ones (*Korsman and Hjelt,* 1987). This proposal did not get sufficient support in Sweden and Russia, but in Finland the line SVEKA was chosen as the backbone of a transect. Work started in the beginning of 1990's with K. Korsman and T. Korja as coordinators of geology and geophysics respectively. The preliminary results were published at the International Geological Conference 1996 and final results have recently been published (*Korsman et al.,* 1999). The conductivity model for SVEKA indicates a highly resistive upper crust and suggests the existence of a conducting layer (600–800 Siemens) at the depth of 45 km in the lower crust. Additional well conducting crustal structures are connected with the Kainuu and the Tampere schist zones. GGT/SVEKA, a combination of models from many geophysical techniques and a detailed geological and tectonical analysis, has been one of the most advanced and succesful Transects of the GGT Programme.

8.2 SVEKALAPKO – a new European success story

Preparations of a new ESF Earth Science Programme was going on during the late 1980's and the early 1990's. In 1992 the EUROPROBE Programme was officially launched by ESF. In 1993, at a meeting in Bad Herrenalb, near Frankfurt, the programme and project outlines were already rather concrete. Project Deep Europe (DE) was suggested to be a methodological framework, common for all target-oriented projects. Suitable pilot targets for DE areas were discussed with the Central Baltic Shield, Kola and Schwarzwald among the candidates. No Finnish scientists participated in the 1994 meeting, but fortunately our colleague and long-time co-operator, prof Laust B Pedersen from Uppsala took up the task to prepare a project draft on EUROPROBE research in Scandinavia.

Soon after the meeting he asked S.-E. Hjelt and T. Korja (who was doing postdoctoral research in Uppsala at that time) whether they would be willing to continue the planning, since his administrative burden had increased strongly. At the 1995 EUROPROBE Scientific Steering Committee (ESSC) meeting the first draft, called CEFES was presented. Another proposal for research in Kola was presented by J. Stephen Daly from Dublin. The ESSC decided that a new EUROPROBE project could be acceptable, if these two proposals can be integrated. So happened and after painstaking work SVEKALAPKO was accepted as one of the key projects of EUROPROBE in late 1995 (*Hjelt et al.,* 1996). Geological field work was well under way in Kola, but the geophysical key experiments, seismic tomography and the electromagnetic BEAR array started much later. Geothermal research has been going on successfully since 1996. Reflection seismic profiling has so far been completed only on the Russian target areas of SVEKALAPKO.

The first major aim of the SVEKALAPKO project is to determine the geometry, thickness and age of the lithosphere and the disposition of major lithospheric structures in the Fennoscandian (Baltic) Shield. The properties and structure of the lithosphere-asthenosphere system beneath the central shield is one of the key questions to be addressed by the induction studies. Field work of the world class BEAR subproject took place in the summer 1998 (*Korja et al.,* 2000; *BEAR Working Group: http://pcland3.phys.spbu.ru/index.html*). The largest ever long-period induction array comprised 50 long-period stations. In addition data from the semipermanent IMAGE-array gives a reasonable control of the source field question. The Finnish Induction research here again in the forefront of Solid Earth Geophysics.

8.3 Scandinavian co-operation

The tradition of Scandinavian co-operation in prospecting geophysics lead to the establishment of NOFTIG, Nordiska Föreningen för Tillämpad Geofysik (the Scandinavian Association of Applied Geophysics). Since its official establishment in 1964, NOFTIG held biannual scientific meetings at locations rotating in the Nordic countries.

Soon new topics entered the programme of the NOFTIG meetings, first oil and gas prospecting in the 1970’s, then environmental and other applications. Also sessions on crustal geophysics were held at the meetings in late 1980’s and early 1990’s. NOFTIG held its meetings in Finland in Helsinki 1970, Oulu 1978, Espoo 1985 and Oulu 1993. During the later part of the 1990’s the meetings have been poorly attended and even cancelled. It seems that NOFTIG has lost its momentum and a remarkable heritage seems to vanish.

The journal Geoexploration was started by a Nordic ad hoc group in 1963, Prof. Maunu Puranen and Toivo Siikarla being among the funding members. Soon the journal became more international and in 1970’s its publication was transferred to Elsevier. The journal was still included in the membership fee of NOFTIG. Prof DS Parasnis acted as Editor of the journal until mid-1990’s, when the journal was renamed as Journal of Applied Geophysics and its scope widened.

8.4 Scientific and technical co-operation between Finland and Soviet Union (STCFSU)

At the 5th Meeting of the Working Group for geology within the Committee of STCFSU in May 1976 in Leningrad joint study of some borehole geophysical problems was initiated. A three-year project was based on digital and analogue modelling. One of its key results was a collection of articles describing new results of modelling and inversion methodology, instrumental development and applications of borehole magnetometry. One of the most interesting theme was the modelling with the Russian analogue computer using resistivity paper and an array of electrode points. Thus also inhomogeneous magnetization effects could be modelled. The use of the equipment was demonstrated in field conditions at the Kostamus mine in the summer 1979. A comparison with numerical results of the GSF group gave new insight into the demagnetization effect in platelike bodies. (*Hjelt and Fokin,* 1981). The University of Oulu, Rautaruukki Oy and GSF were the Finnish participants. Visits and joint work with colleagues from the Production Geological Amalgamation "Sevzapgeologija" and All-Union Research Institute of Prospecting Technique and Engineering, VITR was straightforward and friendly.

The fruitful results brought in futher themes of co-operation. Similar publications exist for DC and EM methods of prospecting (*Eskola and Fokin,* 1986; *Hjelt and Fokin,* 1990).

After the changes in Russia in 1991, the co-operation between GSF and corresponding organizations in the Leningrad, Karelia and Kola has continued ao. in several projects for production of joint geophysical maps (*Korhonen et al.,* 1999).

9. *Solid Earth geophysics at Finnish universities*

9.1. *Development in Oulu*

Solid Earth education was organized at Oulu soon after the operation of the seismograph station had started in 1960. In 1963, the curriculum for the grade approbatur was accepted by the (then) Faculty of Philosophy. The teachers were Seppo Huovila, Arto Levanto, Juhani Oksman and Erkki Palosuo. The curriculum comprised of introductory courses on seismology and Solid Earth geophysics, geomagnetism and aeronomy, hydrology, meteorology and applied geophysics as well as study trips to institutions and the power stations in Northern Finland. Next year (1964) the curriculum for the grade cumlaude was accepted. The professor of Meteorology in Helsinki, L.A. Vuorela was in charge of the education in Oulu.

The first chair in geophysics at the University of Oulu was founded in 1968. [Although the proposal was made many years earlier, the chair could be founded only after the chair of geophysics had been founded at the University of Helsinki in 1966.] After long discussions the chair in Oulu was defined as Solid Earth geophysics including aeronomy – an impossible combination already at that time. The first professor was Mauno T. Porkka, who served until his retirement in 1987. He was followed by Sven-Erik Hjelt, who had acted as associate professor at Oulu since 1975, a chair originally defined with emphasis on applications. Pertti Kaikkonen followed

Hjelt as the second professor of the Department (Table 7). In 1988 the aeronomy was deleted from the definition of the main chair and applications from the other chair and both were redefined as Solid Earth geophysics. (*Hjelt et al.,* 1990d).

Table 7. Finnish University professors of Solid Earth (SEG) and applied geophysics.

Name	Years in office	University	Chair definition
Mauno T Porkka	1968–1987	Univ. Oulu	SEG & aeronomy
Sven-Erik Hjelt	1975–1987	Univ. Oulu	SEG & applications
	1988–	Univ. Oulu	SEG
Pertti Kaikkonen	1989–1998	Univ. Oulu	SEG
	1998–		
Markku Peltoniemi	1983–1998	HUT	Applied Geoph
	1998–		
Lauri J.Pesonen	2001	Univ. Helsinki	SEG

In 1994 the Faculty of Sciences was reorganized and Geophysics joined the Institute of Geosciences and Astronomy. Two years later astronomy became a part of the Institute of Physical Sciences, but Geophysics remained a part of the Institute of Geosciences.

Besides a complete curriculum in Solid Earth Geophysics a rather complete line of courses in Applied Geophysics is offered. Recently courses in environmental geophysics have become very popular, also among students majoring in other fields than geophysics. Students majoring in geophysics can since 1998 specialize in the topic of Geoenvironment. Also successful efforts have been taken in Oulu to participate in Continuing Education of School teachers. In co-operation with the Kastelli college (Kastellin lukio) a special course in introductory geophysics has been given twice as a co-operation between the teachers of physics and geography. This education is supported by a recent book in Finnish (*Kakkuri and Hjelt,* 2000) and specially designed web-page MARATON (*http://www.oulu.gf.fi*).

The research profile of the University of Oulu has been clearly defined since early 1980's. It comprises three main themes, *Lithospheric geophysics (EM and DSS soundings of the crust and upper mantle), mathematical geophysics (modelling and inversion of EM fields) and Applied geophysics* [http://www.oulu.geof.fi]. The content of the last theme varies according to the needs of society and industry. It has changed from ore prospecting to environmental problems during the last 5–7 years.

Oulu has also been an active initiator of national meetings in geophysics. The Geophysics Days were started there in 1964. In 1977 another series of national meetings (on Applied Geophysics) was initiated at Oulu by S.-E. Hjelt. The format of the meetings was meant to be informal, with presentations of preliminary data and interpretations, to discuss common research problems and demonstrate instrumental development. Gradually the meetings changed into a normal scientific format, but instrument demonstrations and institutional progress reports have remained on the agenda. Since 1978 these two-day meetings have been arranged biannually and in 1982 the Association of Mining and Metallurgical Engineers (Vuorimiesyhdistys ry) took over the responsibility of arrangement. Attempts to have joint meetings in connection with the Geophysics Days have failed several times.

Another meeting initiative was taken in 1991, when following discussions between professors Ismo Lindell and S.-E. Hjelt people working with modelling of EM fields were invited to a one-day meeting in Oulu. The meetings have been repeated at various institutions annually, but kept their one-day character. URSI has taken over the responsibility for the arrangements and the role of geophysical topics, which was strong during the first few years, has gradually diminished.

9.2 Development in Helsinki

Occational courses in applied geophysics have been given at the Helsinki University of Technology already since 1920's. (*Ketola,* 1986). A systematic education in Applied Geophysics started officially in 1963 upon initiatives of Academician Erkki Laurila and Prof. Aimo Mikkola. No chair was established then, but the studies were organized by Maunu Puranen, then leader of the Dept of Geophysics of GSF. Most teachers were employees of GSF, located only few 100 meters away from the new building of the Dept of Mining Industry. Many of them had been given special courses for engineering geology students already since 1950's. A versatile installation for performing scale model measurements of various EM systems was one of the key facilities of the Laboratory of Applied Geophysics.

In 1983 Outokumpu Foundation funded the start of an associate professorship in Applied Geophysics at the HUT (the first attempt in 1975 failed). Markku Peltoniemi has held this position since its beginning. His contribution to education of Applied Geophysics has been voluminous (the first Finnish textbook, *Peltoniemi,* 1988 as a leading example). Peltoniemi and his laboratory was key arranger of the largest international geophysics meeting ever in Finland, the 61st EAGE Conference and Technical Exhibition, 7–9 June 1999 in Helsinki. During late 1980's and the 1990's the organizational status and name of the Laboratory has changed many times. Since March 1, 2001 the old units, Laboratory of Rock Engineering and laboratory of Engineering Geology and Geophysics form one new unit called Rock Engineering. (For further information see http://www.hut.fi/Units/Geophysics/)

Various courses in Solid Earth Geophysics have been given at the University of Helsinki / Physics Department already before the independent Department of Geophysics was founded in late 1960's. The first courses date back to the 1920's. A rather complete set of courses in geodesy and Solid Earth subjects has been available thanks to many docents and experts available from the nearby research institutes (*Simojoki,* 1997).

In 1996 the Institute of Seismology and Department Geophysics started arrangements to establish a chair in seismology at the University of Helsinki. After two attempts to fill the position the faculty redefined the chair to be one in Solid Earth

Geophysics. Lauri J.Pesonen has been nominated the first holder of this chair starting from April 1st 2001 (after having worked as acting professor since March 1st 2000). At the same time Geophysics moves to new localities at the Kumpula campus, where laboratory facilities for petrophysical and palaeomagnetic research have been constructed. Starting from August 1st 2001 the history of Geophysics as an independent department will end and it becomes a part of the large conglomerate of Physical Sciences. (Additional information: http://geophysics.helsinki.fi/fingeo.html)

9.3 Postgraduate education in Solid Earth and Applied geophysics

The number of licentiate and doctoral theses has been remarkably high in Applied geophysics, partly thanks to the close co-operation between GSF and HUT. Good co-operation has also existed between the small teaching units in geophysics. The University of Oulu and the Helsinki University of Technology started already 1980's a system of biannual courses aimed at both research students' and at continuous education of people from industry and research organizations. The courses were held alternating in Oulu and Helsinki. Later, in 1990, also the University of Helsinki joined the system and the first all-national course was held at the Lammi Biological station. Most of these courses were financially supported by the Ministry of Education. The introduction of the Graduate School system in Finland in 1994 ended the funding of this effective and useful form of co-operation in post-graduate education. The Lithosphere Graduate School, a joint effort of geology and geophysics started in 1994 with great optimism, but did not get funding continued in 1998. Geophysicists have participated in the Postgraduate Schools of geohydrology and rock engineering

In 1979 the first Scandinavian Research course on EM techniques was arranged at the University of Oulu. Data were taken by the participants using several methods during field experiments. Each group interpreted the data. Peter Weidelt was the internationally most famous of the teachers.

The laboratory of applied geophysics at the HUT offers also international education as a part of the International Linkage Programme "Mining Technology and Economics".

10. Conclusions

The development of non-seismic aspects of Solid Earth geophysics in Finland has been described along four major lines: geomagnetic research at observatories, applied geophysics to assist mineral prospecting and geological mapping, geothermal research, and induction studies.

Continuous observations of the time variations of the Earth's magnetic field started in Finland in the 1840's. The earliest data have been recently brought into digital format. Some key results from the data and the development of the Finnish geomagnetic observatory system shows the importance of long, continuous and high-quality geomagnetic data sets.

Geophysical field measurements have been a vital part of mineral prospecting in Finland since early 1910's. New techniques have quickly been adapted, magnetic and electromagnetic measurements soon became standard tools of applied geophysics. Systematic airborne geophysical measurements started as early as in 1951 and have continued since then. In addition the major development of petrophysics and palaeomagnetism has been favorable in Finland. The production of Finnish geophysical maps, the creation of the Finnish petrophysical data base and recent meteoritic impact studies are examples of top quality Solid Earth geophysics. Again systematic work and high quality of data have shown their strength.

The first geothermal measurements in early 1960 and the development in research thereafter and induction studies since late 1970's have marked the start of serious lithospheric geophysics in Finland. Through successful bilateral co-operation geothermal, magnetotelluric and magnetometer array data, together with simultaneous and co-ordinated seismic research have contributed to new insights about the development of the Fennoscandian crust and upper mantle. Systematic work and active international co-operation have made Finnish lithospheric geophysics highly esteemed. Many open scientific questions are still awaiting for their solution.

The research on geomagnetically induced currents in power lines and oil pipes is another example how induction research can be applied to industrially important topics. The development in numerical modelling of electromagnetic geophysics has shown good progress and new applications are continuously noted.

The development of Solid Earth and applied geophysics in Finland has been steady and all branches are on a high international level. The continuity of vital registrations, good co-operation nationally between university and research institutions as well as with industry, active participation in international projects and collaboration with international colleagues are the backbones of the success story of Finnish Solid Earth and applied geophysics.

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