DISSERTATIONES GEOLOGICAE UNIVERSITATIS TARTUENSIS
26

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ULLA PREEDEN

Remagnetizations in sedimentary rocks of Estonia and shear and fault zone rocks of southern Finland

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following published papers, which are referred to in the text by their Roman numerals. The papers are reprinted by kind permission of the publishers.

I Preeden, U., Plado, J., Mertanen, S., Puura V., 2008. Multiply remagnetized Silurian carbonate sequence in Estonia. Estonian Journal of Earth Sciences, 57(3), 170–180.

II Plado, J., Preeden, U., Puura, V., Pesonen, L.J., Kirsimäe, K., Pani, T., Elbra, T., 2008. Paleomagnetic age of remagnetizations in Silurian dolomites, Rõstla quarry (Central Estonia). Geological Quarterly, 52(3), 213–224.

III Plado, J., Preeden, U., Pesonen, L., Mertanen, S., Puura, V., 2009. Magnetic history of early and middle Ordovician sedimentary sequence, northern Estonia. Geophysical Journal International (accepted).

IV Preeden, U., Mertanen, S., Elminen, T., Plado, J., 2009. Secondary magnetizations in shear and fault zones in southern Finland. Tectonophysics, doi:10.1016/j.tecto.2009.08.011 (in print).

Author's contribution

Paper I: The author was responsible for field work, palaeomagnetic and rock magnetic measurements, data analysis and interpretation, and the writing of the manuscript.

Paper II: The author contributed to field work, palaeomagnetic measurements and interpretation of data, and complemented the writing of the manuscript.

Paper III: The author contributed to palaeomagnetic and rock magnetic measurements, was responsible for the interpretation of mineralogical data and complemented the writing of the manuscript.

Paper IV: The author's contribution involves field work, primary responsibility for palaeomagnetic and rock magnetic measurements, data analysis, interpretation of the results and the writing of the manuscript.

ABSTRACT

The present doctoral thesis combines palaeomagnetic, rock magnetic and mineralogical studies of Palaeozoic sedimentary rocks of Estonia and Palaeoproterozoic crystalline rocks of shear and fault zones of southern Finland. The sampled central part of the Baltica plate has been tectonically relatively stable since the Precambrian. However, tectonic processes at the margins of the plate, e.g. during the Caledonian (450–350 Ma), Hercynian (350–280 Ma) and Uralian (300–250 Ma) orogenic epochs, may have influenced the inner part, by generating and reactivating the existing faults and by producing low-temperature fluid circulation. These events may be recorded in palaeomagnetic directions.

Part of the examined localities show primary magnetizations acquired at the time of rock or sediment formation. In Estonia, primary remanences were revealed in Early and Middle Ordovician carbonates where the remanence resides in magnetite. In the Palaeoproterozoic shear and fault zone rocks of Finland (titano)magnetite is the carrier of the primary remanence. In addition to the primary remanence components, the studies have revealed several secondary magnetization components in the rocks. These components are of different ages and reflect either local or regional geological processes. In the Silurian carbonates of Estonia, late Silurian to Mississippian and Mesozoic components were recorded. They are presumably of chemical origin and are carried by various magnetic minerals, e.g. magnetite, maghemite, hematite and pyrrhotite. In the shear and fault zone rocks of Finland, indications of remagnetizations due to Mesoproterozoic rapakivi magmatism and younger (Mesozoic to present) events were found. However, the most outstanding and common secondary component is of Permian age. The magnetization is of chemical origin, and according to rock magnetic and mineralogical studies hematite and maghemite are the carriers of this Permian magnetization.

A corresponding late Palaeozoic secondary magnetization has been widely recognized all over the world. It is associated not only with orogenic belts, like the Alleghenian, Hercynian and Uralian orogens, but also with stable platform areas like the Russian platform. Most of the late Palaeozoic remagnetizations, as well as the findings described in the present thesis, may be attributed to the formation of the supercontinent Pangea when the orogenic regions were formed and/or reactivated. The formation of Pangea caused also changes in the environmental conditions due to regression of the seas and/or continental uplift, which in turn produced progressive oxidation and alteration of the host rocks.

The results of this thesis are important both in the local and regional scale. They support the use of palaeomagnetic method as a dating tool for local diagenetic changes in sediments, and give evidence of the alteration of primary minerals and formation of new magnetic minerals. Moreover, this research shows that the geological history of the studied area is more complex than previously thought. In the regional scale, the detected Permian remagnetization affirms the importance and specificity of this time period worldwide.

Keywords: Baltica, palaeomagnetism, remagnetization, Permian, Pangea.

1. INTRODUCTION

During rock and sediment formation iron-bearing ferromagnetic minerals, like magnetite, hematite and pyrrhotite, can record the past direction of the Earth's magnetic field. The aim of most palaeomagnetic studies is to identify the primary magnetization component that is synchronous with the formation of the rock. The identification of this ancient magnetization is crucial for the reconstruction of the past distribution of continents and for the studies of prolonged existence of the Earth's magnetic field. In the Australian and Greenland cratonic regions, magnetized rocks as old as four billion years bear witness to the existence of a magnetic field already in the early times of the Earth's history (Lanza and Meloni 2006). Magnetic memory may sometimes carry the only evidence of the multiply evolved geological history of rocks.

Primary magnetic information may be partly or completely destroyed by secondary geological processes at any time after the formation of a rock. These processes, however, may be responsible for the acquisition of secondary magnetizations (magnetic overprints) that record the magnetic field at that time.

The rather well preserved Estonian Palaeozoic sequence is composed of Ediacaran to Devonian terrigenous and carbonate sediments, which overlie the southern slope of the Fennoscandian Shield. The entire homoclinal section is gently tilted to the south and the thickness of the Palaeozoic complex above the crystalline Proterozoic bedrock is up to 800 m (Raukas and Teedumäe 1997). This Palaeozoic complex has probably never been buried deeper than 2 km (Kirsimäe and Jørgensen 2000). The occurrence of very old (>500 Ma) unconsolidated clay in the lower Cambrian points to moderate diagenetic temperatures below 50 ˚C (Kirsimäe et al. 1999). The conodont alteration index (CAI) for Estonian lower Palaeozoic sediments is 1–1.5, suggesting maximum diagenetic temperatures from 50 to 80˚C (Männik and Viira 1990).

The studied sequence (Fig. 1) is composed of Ordovician (Floian to Darriwilian, 478.6–460.9 Ma; ISC 2009) and Silurian (Llandovery and Wenlock, 443.7–422.9 Ma; ISC 2009) limestones and dolomites. These deposits have earlier been systematically studied by sedimentological, palaeontological and stratigraphical methods and discussed in numerous works (e.g. Männil 1966; Kaljo et al. 1970; Nestor and Einasto 1997 and references therein). Detailed palaeomagnetic study of the Estonian Silurian and Ordovician sedimentary sequence of such extent is performed for the first time (Papers I–III). Previous preliminary analyses (Plado and Pesonen 2004) were aimed at testing the suitability of the rock types for palaeomagnetic measurements.

The initial aim of the present study was to improve the apparent polar wander (APW) path of Baltica in the age range from Cambrian to Silurian, but it soon became evident that most of the studied samples were remagnetized (Papers I–III) and did not carry any primary magnetic information (Papers I, II). Therefore, the goal of further research was shifted towards studies on remagnetizations by identifying their age and the remanence-carrying minerals. For these purposes several rock magnetic tests and optical investigations were carried out.

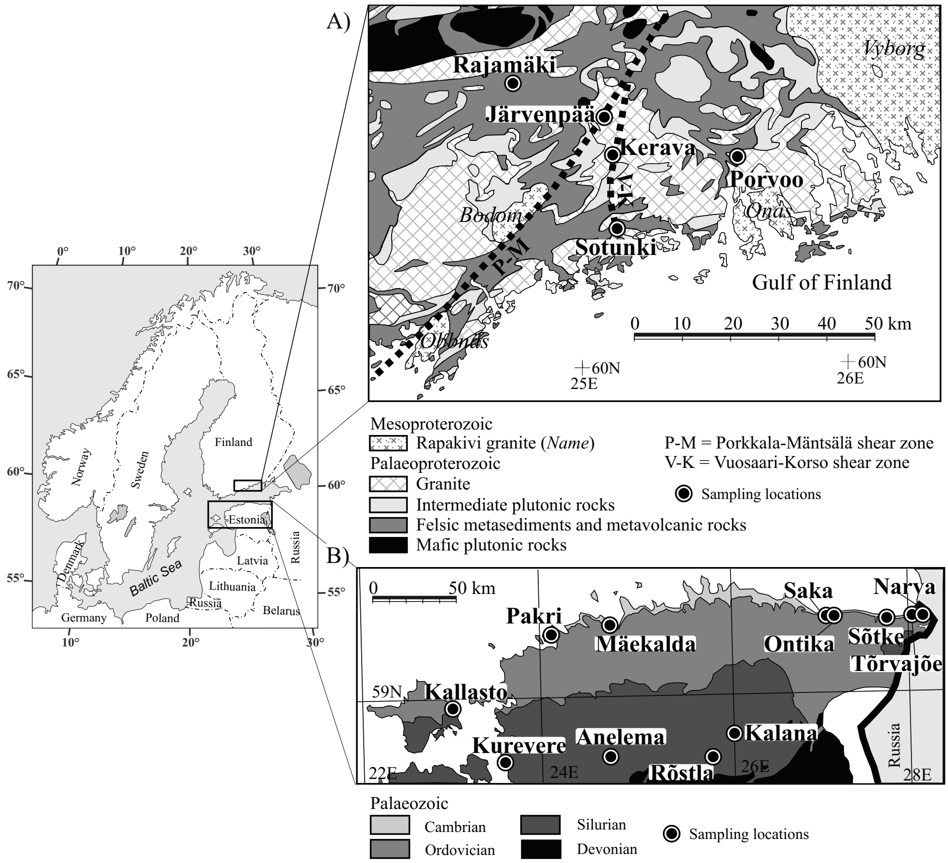

Fig. 1. Location of the study area and geological sketch maps with the sampling locations in (A) Finland and (B) Estonia.

The present thesis also includes a study (Paper IV) of Proterozoic crystalline rocks from shear and fault zones of the Helsinki region in southern Finland (Fig. 1). These zones were earlier (Elminen 1999; Mertanen et al. 2008) found to be influenced by post-formational (post-Svecofennian) events like anorogenic rapakivi magmatism (~1.6 Ga) and the Caledonian orogeny (450–350 Ma). The basement itself was formed at different stages during the Svecofennian orogeny at 1.9–1.8 Ga by oblique collision of the island arc system against the Archaean domain and due to subsequent continental deformation, metamorphism and crust-forming magmatism (e.g. Pajunen et al. 2002, 2008; Väisänen and Mänttäri 2002; Väisänen 2002). The localities along the extensive north-east to south-west trending Porkkala–Mäntsälä shear zone and the north–south trending Vuosaari–Korso shear zone (Fig. 1) were chosen for the study, because these were expected to indicate possible reactivations.

The palaeomagnetic method has proven to be a useful tool in the search for evidences of younger alterations in the rock. The main overall flaw in the interpretation of secondary magnetizations is the uncertainty associated with the timing and duration of magnetization events. Thus, another purpose of the study, in addition to determining and comparing the magnetic overprints, has been the identification of the mechanism of remagnetization and finding possible explanation to its common origin in Estonia and Finland. The final aim has been to link the remagnetizations with local and regional geological events.

This research comprises data from the following four articles presenting the results of palaeomagnetic, rock magnetic and mineralogical studies.

PAPER I

Preeden, U., Plado, J., Mertanen, S., Puura, V., 2008. Multiply remagnetized Silurian carbonate sequence in Estonia. Estonian Journal of Earth Sciences, 57(3), 170–180.

The main aim of this paper was palaeomagnetic study of Silurian sedimentary rocks and determination of the ages of secondary processes previously identified by mineralogical and lithological studies of pore and fracture fillings in the sequence. The study revealed Silurian–Early Devonian syndepositional or early diagenetic components at three locations. Late Palaeozoic and Triassic overprints were registered and they were interpreted to be related to tectonically derived low-temperature hydrothermal fluids, activated during processes that were connected to the formation of the Pangea supercontinent.

PAPER II

Plado, J., Preeden, U., Puura, V., Pesonen, L., Kirsimäe, K., Pani, T., Elbra, T., 2008. Paleomagnetic age of remagnetizations in Silurian dolomites, Rõstla quarry (Central Estonia). Geological Quarterly, 52(3), 213–224.

The paper focuses on the study of Silurian dolomites at one site with the goal of specifying the age of magnetic minerals in dolostones and establishing their post-sedimentational history. Two components of remanent magnetization were revealed. One component dates to the Late Devonian to Mississippian and is interpreted as being caused by low-temperature hydrothermal circulation due to the influence of the Caledonian/Hercynian orogeny after early diagenetic dolomitization. The other component points towards Cretaceous age and is considered to have been formed due to migration of oxidizing fluids.

PAPER III

Plado, J., Preeden, U., Pesonen, L., Mertanen, S., Puura, V., 2009. Magnetic history of early and middle Ordovician sedimentary sequence, northern Estonia. Geophysical Journal International (accepted).

In this paper Ordovician sedimentary rocks (Floian to Darriwilian carbonate sequence) of northern and eastern Estonia were studied. The main aim was to identify remanence components acquired at different geological stages, specify the sedimentational and post-sedimentational history of the area and fill the regional gap between the palaeomagnetic studies of Ordovician sedimentary rocks in Scandinavia and the St. Petersburg area. Two characteristic remanence components were identified. A south-easterly downwards directed component dating to the Ordovician was identified in the Floian and Dapingian–Darriwilian carbonate sequence. This component resides in magnetite and is regarded as primary early diagenetic in origin. A south-westerly upwards directed component with a reversed counterpart represents a Permian magnetization. The carrier of this overprint is hematite, which is of chemical origin and most likely indicates near-surface alteration by meteoric fluids, coupled with the mid-continent position of the studied area and widespread Permian regression of the seas.

PAPER IV

Preeden, U., Mertanen, S., Elminen, T., Plado, J., 2009. Secondary magnetizations in shear and fault zones in southern Finland. Tectonophysics, doi:10.1016/j.tecto.2009.08.011 (in print).

This paper presents results from the Proterozoic Porkkala–Mäntsälä and Vuosaari–Korso shear and fault zones in southern Finland. Most of the studied rocks have preserved their original remanent magnetization that was acquired during cooling of the crust in the late stages of the Svecofennian orogeny. (Titano)magnetite is the carrier of this primary remanence. The presence of secondary magnetizations indicates the vulnerability of shear zones to later reactivation. Hematite and maghemite were found to carry the most prevalent component of Permian age. Reactivation due to emplacement of the nearby Mesoproterozoic (~1.6 Ga) rapakivi granite was also recorded.

2. PALAEOMAGNETISM AND REMAGNETIZATION

In this chapter some common terms used in geomagnetism and palaeomagnetism (see Butler 1998; McElhinny and McFadden 2000; Tauxe 2005 and references therein) are described and defined.

There exist two main types of magnetization: induced magnetization and remanent magnetization. When material is exposed to a magnetic field H, it acquires an induced magnetization (J_i) that is typically in the direction of the present geomagnetic field. Remanent magnetization (J_r) is the permanent magnetization of the material and exists without the external field. It is so-called natural remanent magnetization (NRM), and its direction is usually different from the outer field. The total magnetization of the material is the vector sum of these two components: $J = J_i + J_r$.

The Earth's magnetic field (geomagnetic field) is essentially dipolar and is believed to be driven by dynamo processes. In the dynamo theories, fluid motion in the Earth's core involves the movement of the conducting material, thus creating a current and a self-enforcing field. On the geological time scale the study of the geomagnetic field requires some model for use in analysing palaeomagnetic results, so that measurements from different parts of the world can be compared. For that purpose the Earth's magnetic field is represented by a geocentric axial dipole (GAD), where the magnetic field is produced by a single magnetic dipole in the centre of the Earth (Butler 1998). The GAD model is simple because the time-averaged geomagnetic pole and the geographic axis (rotation axis) coincide, as do the geomagnetic and geographic equators. Using the GAD model, the ancient latitude (palaeolatitude) of the sampling site may be obtained from the magnetic inclination by applying the equation $\tan I = 2\tan\lambda$ (I – inclination, λ – palaeolatitude). This simple model has been used in palaeomagnetism for studying the Earth's geomagnetic field and continental movements since the 1950s (Irving 1964).

The essence of palaeomagnetism is that a record of the ancient magnetic field is locked in a rock. For example, if rocks in different regions of the globe have the same age, the polarity of their remanence must be the same aside from the petrographic facies. Likewise, the remanence directions must concur at the very same point, which corresponds to the magnetic pole for this age (Lanza and Meloni 2006). As direct measurements of the Earth's magnetic field extend back for only a few centuries, palaeomagnetism remains the only way to investigate ancient field behaviour. Most of the geological information that can be obtained from the magnetic study of a rock is found in the small fraction of ferromagnetic minerals it contains. The main task of palaeomagnetic studies is thus successful separation of remanent magnetization components. This is crucial for the reconstruction of the distribution of continents in the geologic past and for understanding plate tectonic processes.

The extremely strong remanent magnetization of some rocks was noted as early as the late 18th century from their effect on the compass needle. The first studies of the direction of magnetization in rocks were made by Delesse and Melloni in the 1850s. They both found that certain lavas were magnetized parallel to the Earth's magnetic field. David (1904) and Bruhnes (1906) discovered materials that were magnetized opposite to the Earth's field. They speculated that the Earth's magnetic field has reversed its polarity in the past. The following studies by Mercanton (1926) and Matuyama (1929) supported the argument that reversely magnetized rocks were found all over the world. For the sake of clarity the term *reverse* is always used to indicate the polarity of the Earth's magnetic field in the sense when it is opposed to the present-day situation. The field reverses its polarity at a rate which looks random as the polarities have remained constant for time periods of the order of 100 kyr to 1 Ma. However, several superchrons (long periods when no reversal takes place) have been observed like the Cretaceous Long Normal, the Jurassic Quiet Zone (predominantly normal) and the Kiaman Long Reversed, which last more than 10 Ma years.

The NRM of a rock depends on the geomagnetic field and on the geological process during the formation of the rock and its subsequent history. In the following two main processes responsible for the primary magnetization in rocks are described (after Butler 1998; McFadden and McElhinny 2000). Thermoremanent magnetization (TRM) is mainly produced in igneous rocks by cooling from above the Curie temperature (T_C) in the presence of a magnetic field. Thermoremanent magnetization is formed at certain blocking temperatures T_B, and grains of different composition and size will each have different blocking temperatures. This type of remanence can be stable over geological time and resistant to effects of magnetic fields after original cooling. In sedimentary environments, rocks become magnetized in quite a different manner than in igneous bodies. Detrital grains are already magnetized, and these particles become aligned with the magnetic field while settling in the water column. When deposited, they retain a detrital (or depositional) remanent magnetization (DRM). In sedimentary rocks, also post-depositional remanent magnetization (pDRM) has to be taken into account. The formation of sedimentary rocks from sediments is long and complex, caused by physical and chemical processes (like the action of turbulent water, laminar flow, bioturbation and compaction) that widely vary according to the depositional environment. The complexity of the process is reflected in magnetization as well (Tauxe 2005).

Primary magnetic information can be partly or completely destroyed by a secondary magnetic overprint, acquired at any time after the formation of a sediment or a rock. The earliest identifications of magnetic overprints have been shown since the 1960s. Creer (1968) was one of the first to give the "remagnetization hypothesis", suggesting that remagnetization resulted from secondary iron oxides (hematite) in red beds. The hypothesis was challenged by McElhinny and Opdyke (1973), who reported an overprint from the Ordovician limestone in New York, USA. The carrier of this secondary magnetization was magnetite that could not have been formed by oxidative weathering as was shown by Creer (1968). Since the 1980s, studies of remagnetized rocks have got more popular (Zwing 2003), and it has become evident that remagnetizations may be widespread.

All secondary NRMs can be potential geological signals, which record the Earth's magnetic field during e.g. regional uplift, metamorphism, igneous intrusion event or fluid penetration (Dunlop 1979). The recognition of pervasive remagnetization of NRM is essential for a correct interpretation of palaeomagnetic data and has also important geodynamical implications. Rocks are not closed systems once they have been formed and later geological processes may partially or completely overprint the primary NRMs. Several possibilities for secondary magnetization exist: viscous remanent magnetization (VRM), thermoviscous magnetization (TVRM), partial thermoremanent magnetization (pTRM) and chemical remanent magnetization (CRM).

Viscous remanent magnetization is gradually acquired during exposure to an external magnetic field, thus resulting from the action of the geomagnetic field long after the formation of the rock. In naturally acquired VRM, the acquisition time can be up to 10^9 yr or even longer, but from the palaeomagnetic viewpoint, this VRM usually is undesirable noise. Moreover, rocks of palaeomagnetic interest may suffer intervals of reheating, possibly resulting in contact or burial metamorphism, which unpins the NRM of mineral grains at the lower end of the spectrum of unblocking temperatures and rocks will acquire a secondary partial thermoremanent magnetization pTRM or TVRM (Dunlop and Özdemir 2001). In principle, the pTRM or TVRM can be removed by thermal demagnetization at a time-temperature combination, which is equivalent to that at which the rock acquired the pTRM or TVRM (Neél 1949).

Chemical (or crystallization) remanent magnetization (CRM) results from the formation of a magnetic mineral below their blocking temperatures in the presence of a magnetic field. The CRM processes produce secondary magnetizations, which are mainly related to the alteration of a pre-existing ferromagnetic phase (such as oxidation that usually happens on the grain surface and along cracks), but also to the growth of new magnetic minerals within the rock. A ferromagnetic mineral forms below its Curie point, and while in TVRM blocking temperature is important, in CRM it is the blocking volume (Lanza and Meloni 2006).

3. MATERIAL AND METHODS

3.1. Sampling

Eighty-eight block samples were taken from the Early to Middle Ordovician horizontally-bedded carbonate sequence at seven outcrops along the northern coast of Estonia (from west to east: Pakri, Mäekalda, Saka, Ontika, Sõtke, Tõrvajõe and Narva) (Paper III and Fig. 1B). Altogether 47 block samples and additional 103 drill cores were collected from the Silurian sequence of lime- and dolostones of Llandovery and Wenlock age at five localities (Kallasto, Kurevere, Anelema, Rõstla and Kalana) (Papers I and II and Fig. 1B).

In southern Finland, samples were taken from five localities in the Helsinki area, (Rajamäki, Järvenpää, Kerava, Porvoo and Sotunki) (Paper IV and Fig. 1A). The collected 8 block samples and 112 drill cores represent granites, gneisses, mylonites and tectonic breccias of Palaeoproterozoic age (1.9–1.8 Ga).

The samples were taken either with a gasoline powered drill (Fig. 2A) in the field as 2.5 cm diameter cores or as oriented blocks which were drilled in the laboratory. Independent orientation of the cores or block samples was obtained by sun and/or magnetic compass (Fig. 2B). In the case of block samples, several drill cores (2 to 6) per sample were drilled. Up to 35 samples were taken from each site and 1–4 specimens of the length of 2.2 cm were cut from each core in the laboratories at the Geological Survey of Finland (GSF) and University of Tartu.

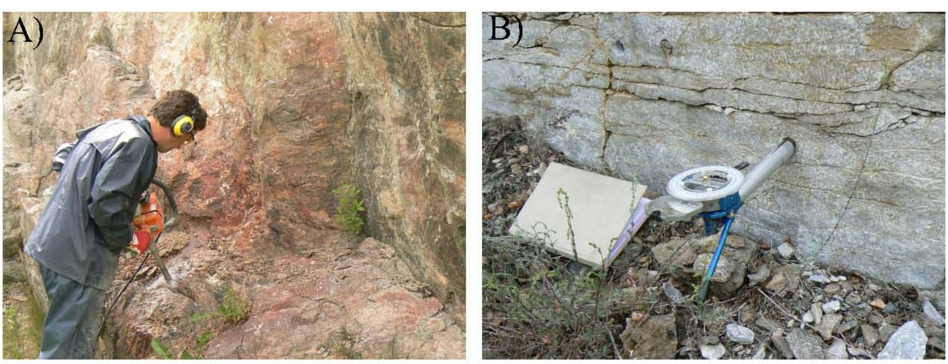

Fig. 2. (A) Sampling at Rajamäki with the gasoline drill. (B) Core orienting with sun and magnetic compass at Kallasto.

3.2. Petrophysical measurements

Before palaeomagnetic studies the petrophysical properties of the rocks most be known as they are informative about the remanence stability and can help in detecting mineralogical alterations. Measurements of NRM, magnetic susceptibility (χ), Koenigsberger ratio (Q-value) and density were carried out for each rock specimen at the laboratories of the University of Tartu, University of Helsinki and GSF. The porosity of Rõstla samples was studied also in some specimens at the Department of Geology, University of Tartu (Paper II).

Rock density was determined by the Archimedes principle by weighing the specimens in air and water. For sedimentary rocks it is an apparent density as weighing is neither water-saturated nor oven-dried, which would remove the effect of pores. Susceptibility is a measure of the ability of the rock to get magnetized in the presence of an external weak magnetic field. In the GSF it was measured at room temperature using a home-made apparatus working at a frequency of 1025 Hz and alternating field of ca. 130 A/m. Susceptibility gives the first indication of the amount of magnetic minerals in the specimen and allows distinction between the specimens of predominantly dia-, para- or ferromagnetic character. The NRM in rock specimens is generally of multi-component nature, consisting of two or three superimposed components. The Koenigsberger ratio is defined as the ratio of remanent magnetization to the induced magnetization in the Earth's field. In general, Q-value is used as a measure of the rock's capability of maintaining stable remanence.

3.3. Palaeomagnetic methods

To study the origin of the remanence components, alternating field (AF) demagnetization up to a peak field of 0.16 T or thermal demagnetization up to a temperature of 680 ºC were used. In some cases when AF demagnetization was insufficient to demagnetize the sample, the process was continued thermally. For thermal demagnetizations, a magnetically shielded oven was used (home-made in the GSF, TSD-1/Schonstedt Instrument Co. at the University of Helsinki). After each demagnetization step the intensity and direction of the magnetization were measured with a 2G-Enterprises superconducting SQUID magnetometer (RF model in the GSF, and DC model at Solid Earth Geophysics laboratory of the University of Helsinki). Automatic settings were used, which allow the measurement in three orthogonal positions with the sensitivity of 0.03 mA/m. Individual NRM measurements were subjected to a joint analysis of stereographic plots, demagnetization decay curves and orthogonal demagnetization diagrams (Zijderveld 1967). Line segments with maximum mean angular deviations of 10° were identified prior to separating the components with principal component analysis (Kirschvink 1980). Fisher (1953) statistics was used to calculate mean remanence directions. Virtual geomagnetic poles (VGPs) were calculated for each remanence component and plotted on the APW path by using the GMAP2003 program of Torsvik and Smethurst (http://www.geophysics.ngu.no).

3.4. Rock magnetism

To get knowledge on remanence carriers, different rock magnetic methods were used. The methods involve usage of isothermal remanent magnetization (IRM) and/or determination of Curie temperatures. The magnetic carriers were identified according to coercivities and Curie temperatures (Table 1).

Table 1. Composition, maximum coercivities (McElhinny and McFadden 2000) and Curie temperatures (T_C) of some ferromagnetic minerals (Dunlop and Özdemir 2001).

Mineral	Composition	Max coercivity (T)	T_C (°C)
Magnetite	Fe_3O_4	0.3	580
Maghemite	γFe_2O_3	0.3	590–675
Hematite	αFe_2O_3	1.5–5	675
Goethite	$\alpha FeOOH$	>5	120
Titanomagnetite	$Fe_{2.4}Ti_{0.6}O_4$	0.1–0.2	150–540
Pyrrhotite	Fe_7S_8	0.5–1	320

3.4.1. Isothermal remanent magnetization method

After demagnetization of the NRM of the sample, IRM was acquired in stepwise fashion. It is often used to measure the intrinsic coercivity spectrum as different ferromagnetic minerals reach the saturation value in different fields (Table 1). The IRM was produced by the Molspin impulse magnetizer (with the maximum available field of 1.5 T) at the Geophysics laboratory of the GSF.

3.4.2. Lowrie test

The interpretation of the magnetic mineralogy can be considerably improved by stepwise thermal demagnetization of the acquired IRM, proposed by Lowrie (1990). It was used to employ different coercivity and thermal unblocking temperatures characteristic of the most common ferromagnetic minerals. At first, IRMs were given along three axes in the following order: (i) 1.5 T in the z-direction (diagnostic for hard magnetic carriers), (ii) 0.4 T in the y-direction (diagnostic for intermediate magnetic carriers), (iii) 0.12 T in the x-direction (diagnostic for soft magnetic carriers). Then specimens were thermally demagnetized step by step up to 680 °C. After each step magnetic susceptibility and remanent magnetization were measured. Finally, the magnetization of each orthogonal axis was plotted against the temperature.

3.4.3. Thermomagnetic measurements

To determine the Curie temperature of ferromagnetic minerals (Table 1) magnetic susceptibility values were measured against the temperature in air or argon gas. This was done using an Agico CS3-KLY3 Kappabridge at the Geophysics laboratory of the GSF and at the Solid Earth Geophysics laboratory of Helsinki University. During the measurements, small amounts of powdered specimens are heated from room temperature up to 700 °C and cooled back to room temperature, and susceptibility is monitored during the whole process.

3.4.4. Hysteresis measurements

For mineralogical indications and for identification of domain states of the magnetic carriers, hysteresis properties were measured in selected specimens using a Princeton Measurement Corporation's MicroMagTM3900 model Vibrating Sample Magnetometer (VSM) in the Solid Earth Geophysics laboratory of Helsinki University. Measurements were performed at room temperature using a maximum field of 1 T. A small chip or capsulated powder of rock was placed under sinusoidal motion by mechanical vibrations within a uniform magnetic field. When an external magnetic field is applied to a ferromagnetic mineral, the ferromagnetic material becomes magnetized and when the external field is removed, the material retains some remanent magnetization. The resulting hysteresis loops show the behaviour of magnetization of a particular magnetic mineral when it is cycled through a magnetic field.

3.5. Mineralogical study

To identify the main rock-forming minerals and their relations, thin sections of several samples were examined under optical microscope and powdered whole-rock samples with X-ray diffractometry (Dron-3M diffractometer) at the Department of Geology, University of Tartu. More detailed study of magnetic carriers with the scanning electron microscope (SEM) and electron microprobe was conducted at the Geolaboratory of the GSF and at the Institute of Electron Optics in Oulu University.

4. SUMMARY OF RESULTS

4.1. Petrophysics

Magnetization of the examined carbonate rocks of Estonia is generally low. The intensities of NRM are between 0.02 and 2.26 mA/m and magnetic susceptibilities (volume normalized) range from -40×10^{-6} to 336×10^{-6} SI (Papers I–III). The studied shear zone rocks of southern Finland are weakly magnetized as well (Paper IV). The average intensity of NRM is between 0.8 and 20 mA/m and magnetic susceptibilities (volume normalized) range from 74×10^{-6} to 753×10^{-6} SI.

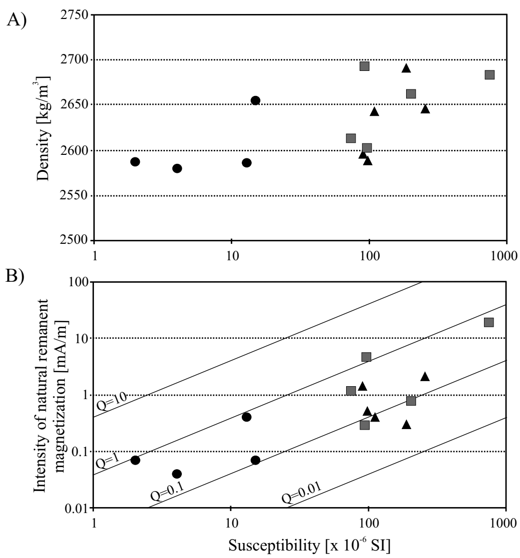

Fig. 3. Physical properties of the studied rocks (circle – Silurian, triangle – Ordovician, square – Proterozoic). (A) Density vs. susceptibility, (B) natural remanent magnetization (NRM) vs. susceptibility. Koenigsberger ratio (Q-value) is indicated by inclined lines, the intensity of NRM and magnetic susceptibility are given on a logarithmic scale.

To compare the physical properties of rocks of the studied localities, the mean values of density, NRM, Q-value and magnetic susceptibility of samples from each site were calculated and plotted (Fig. 3). The densities of carbonate and crystalline rocks are mostly between 2500 and 2700 kg m^{-3} (Fig. 3A). The main difference between the sites is that Silurian carbonates (denoted by circles) have the lowest density (Fig. 3A) and magnetic susceptibility (Fig. 3B), but these values are higher in Ordovician carbonates (triangles) and in fractured Finnish crystalline rocks (squares). The highest susceptibility was measured in gneisses and pegmatites from the site in Porvoo (Paper IV). The NRM values (Fig. 3B) show a positive correlation with susceptibilities. The lowest NRM values were recorded in Silurian carbonate rocks, probably indicating a low content of ferromagnetic minerals (Paper I). Measured Q-values range from 0.04 (Ordovician site) to 1.9 (Finnish site), falling mainly in the range 0.1–1 (Fig. 3B).

The porosity of the dolomites was measured in Rõstla (Paper II). The results showed that dolomitization had resulted in higher porosities (more than 10%) due to volume reduction by replacement of original carbonates (mainly calcites).

4.2. Palaeomagnetic results from Estonia

In the following, an overview of palaeomagnetic studies is given. The results of rock magnetic and palaeomagnetic studies are described more thoroughly in Papers I–IV. Mean values of all palaeomagnetic components found in different localities of Estonia and Finland are shown in Table 2 and Figure 4.

Table 2. Palaeomagnetic results by the studied localities.

Locality	Comp.	Polarity	*N*	*D* (°)	*I* (°)	*k*	α_{95} (°)	Plat (°)	Plong (°)	dp (°)	dm (°)
Kallasto	KO1	N	4	217.2	39.9	22.6	19.8	2.8	169.0	14.3	23.8
	KO2	N	9	29.6	33.3	15.0	13.7	43.9	162.3	8.9	15.6
Kurevere	KU1	N	4	249.3	27.1	89.3	9.8	1.9	138.4	5.8	10.6
Anelema	AN1	N	11	217.8	32.6	13.6	12.8	7.6	168.5	8.2	14.5
	AN2	R	13	225.4	–27.8	17.2	10.3	34.8	147.5	6.2	11.3
	AN3	N	16	139.7	55.2	25.0	7.5	10.2	56.8	7.6	10.7
Rõstla (Rõ)	A	N	7	60.7	7.7	14.2	16.6	18.2	139.5	8.4	16.7
	B	M	15	13.5	60.7	67.0	4.7	71.1	173.3	5.5	7.2
Kalana	KA1	N	7	53.0	56.8	61.4	7.8	50.1	124.4	8.2	11.3
Pakri (Pa)	P	N	9	144.2	63.7	136.8	4.4	18.7	49.8	5.6	7.0
	S	N	2	37.7	67.8	–	–	67.2	119.2	–	–
Mäekalda (Mä)	P	N	11	159.8	65.3	47.7	6.7	18.1	39.1	8.8	10.8
	S	R	1	235.9	–48.0	–	–	41.9	128.5	–	–
Sõtke (Sõ)	P	N	4	166.4	52.9	70.4	11.0	3.4	39.1	10.5	15.2
	S	R	3	207.2	–36.7	22.4	26.7	43.7	159.5	18.2	31.2
Tõrvajõe (Tõ)	S	R	7	212.2	–47.1	69.7	6.7	51.9	158.5	5.6	8.6
Narva (Na)	S	R	6	207.6	–45.5	153.6	5.4	52.5	165.6	4.4	6.9
Rajamäki (Ra)	A	N	6	331.4	38.6	43.3	10.3	46.3	244.8	7.3	12.2
	B	N	5	29.8	34.6	31.2	13.9	43.4	164.4	9.2	16.0
Järvenpää (Jä)	A	N	8	338.9	38.5	29.4	10.4	48.5	235.4	7.3	12.3
	B	N	9	27.9	35.8	23.6	10.8	44.8	166.8	7.3	12.5
	JR	N	10	17.5	5.0	26.9	9.5	30.5	184.6	4.8	9.5
Kerava	KE	N	10	52.6	45.1	15.4	12.7	41.2	134.7	10.2	16.1
Porvoo (Po)	A	N	10	333.7	23.1	17.2	12.0	37.9	239.0	6.8	12.8
	B	N	16	33.4	29.9	15.4	9.7	39.5	162.3	6.0	10.7
Sotunki (So)	A	N	11	335.0	40.4	24.8	9.4	48.9	241.4	6.8	11.3
	B	N	6	32.0	41.0	39.0	10.9	47.1	159.7	8.0	13.2

Comp. – component referred to papers I–IV; polarity: N (normal), R (reversed), M (mixed); *N* – number of samples revealing the component that was used for counting the average; *D* – declination; *I* – inclination; *k* – Fisher's (1953) precision parameter; α_{95} – the radius of 95% confidence about the mean; Plat and Plong – latitude and longitude of the virtual geomagnetic poles; dp and dm – semi-axes of the oval of 95% confidence of the pole.

4.1.1. Silurian sequence

The results of Silurian palaeomagnetic and rock magnetic studies are discussed in more detail in Papers I and II. The Silurian carbonate rocks are weakly magnetized (Fig. 3), but they contain different stable components (sites Kallasto, Kurevere, Anelema, Rõstla and Kalana in Table 2 and in Fig. 4A). Late Silurian–Early Devonian syndepositional and/or early diagenetic component was revealed in Kallasto, Kurevere and Anelema carbonates (Paper I). A slightly younger Late Devonian to Mississippian diagenetic component was revealed in Rõstla (Paper II). Both of these components are most probably carried by magnetite and/or maghemite. In addition, a late Palaeozoic remagnetization was identified in Anelema and Kallasto and a Mesozoic component in Kalana and Rõstla. These secondary magnetizations are mainly tied to the formation of hematite.

4.1.2. Ordovician sequence

The mean remanence components detected in the Ordovician sequences of the Pakri, Mäekalda, Sõtke, Tõrvajõe and Narva localities (Paper III) are shown in Table 2 and illustrated in Fig. 4B. Two remanence components, a primary (P) and a secondary (S) one were identified. The intermediate coercivity reversed polarity component P is present in Floian to Darriwilian glauconitic limestones and dolomites. According to rock magnetic and mineralogical studies, the carrier of the component is magnetite. On the Baltica's APW path the palaeopoles are placed on the Lower and Middle Ordovician segment. The component S, which is of high coercivity and high unblocking temperature, has both normal and reversed polarities and is best represented in Floian to Darriwilian hematite rich samples. The corresponding virtual geomagnetic pole position shows Permian age (~260 Ma) for pole S.

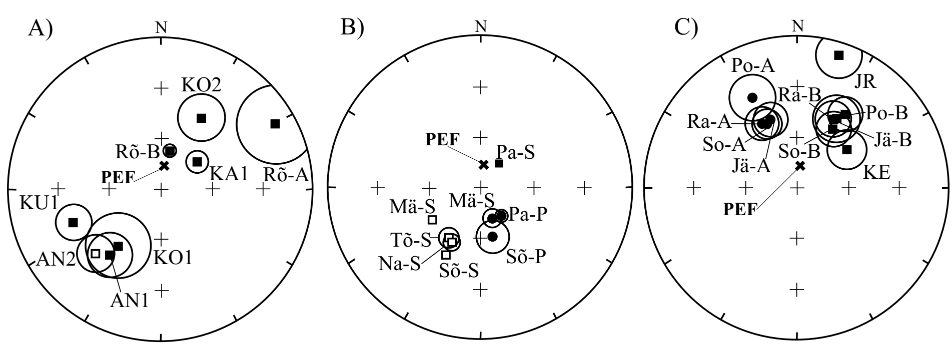

Fig. 4. Stereoplots of mean components described in the thesis. (A) Silurian, (B) Ordovician, (C) Proterozoic. See Table 2 for abbreviations.

4.3. Palaeomagnetic results of Palaeoproterozoic rocks of Finland

Two consistent remanent magnetization components were identified within the fault and shear zone rocks in four localities (Rajamäki, Järvenpää, Sotunki and Porvoo) in southern Finland (Paper IV). The component A (Table 2 and Fig. 4C) has intermediate to high coercivity and intermediate unblocking temperature, suggesting that the remanence resides in (titano)magnetite. The direction is close to the remanence commonly observed in Svecofennian age formations all over the Precambrian Fennoscandian Shield. Therefore, it most probably represents the primary Svecofennian magnetization preserved in the host rocks (Paper IV). The other common component, B, is carried by hematite and maghemite, and according to the APW path, represents a Permian magnetization (Table 2). In addition, remagnetization components due to Mesoproterozoic (~1.6 Ga) rapakivi magmatism (JR) and a Mesozoic overprint (KE) were identified (Table 2). Magnetization JR is carried by hematite and KE by maghemite (Paper IV).

5. PALAEOGEOGRAPHIC RECONSTRUCTIONS

Palaeomagnetism can be used as a relative dating tool because the palaeomagnetic poles of different ages are mostly distinct from the present-day geographic pole. In the case of Europe, for example, the Permian poles are distributed along the 45°N parallel (Lanza and Meloni 2006). Any pole position that is calculated from a single observation of the geomagnetic field is called a virtual geomagnetic pole. This is the position of the pole of a geocentric dipole that can account for the observed magnetic field direction at one location and at one point in time (Butler 1998). The term “palaeomagnetic pole” implies that the pole position has been determined from a larger palaeomagnetic data set that has averaged out geomagnetic secular variation, and thus gives the position of the rotation axis with respect to the sampling area at the time the remanent magnetization was acquired. In general, the positions of the palaeomagnetic poles from a continent vary in time and the curve joining the poles is called APW path (Lanza and Meloni 2006). Different continents have different APW paths. According to the GAD model, it is assumed that the magnetic pole has remained stationary throughout the time, which proves that continental masses have been the ones that have moved.

An APW path of Baltica (after Torsvik and Cox 2005) for the time period of 480–10 Ma is shown as an example in Figure 5. It includes the primary palaeomagnetic pole from Ordovician carbonates (Table 3) and the secondary pole of Permian age (Table 3 and Fig. 5). The Ordovician pole fits fairly close to the APW path of 480–460 Ma. The late Palaeozoic poles of the current studies (Papers I, III and IV, listed in Table 2) were divided according to the polarities and a mean for normal (P-n) and reversed (P-r) polarities and the overall mean (P-combined) were calculated (Table 3). These remagnetizations, when plotted on the APW path of Baltica, fall within the age range of 300–250 Ma. The comparison with the previously known primary pole Permian 1 from the Urals (Bazhenov et al. 2008) and secondary pole Permian 2 from Bornholm (Torsvik and Rehnström 2003) supports the late Palaeozoic age of the remagnetization found in the present studies (Fig. 5).

Table 3. Mean of Ordovician and Permian poles from Table 2 (revealed by studies in Papers I, III, IV).

Component	Polarity	*N*	*K*	A95	Plat (°)	Plong (°)
Ordovician	Normal	3	60.0	16.1	13.5	42.6
P-r	Reversed	5	35.1	11.5	48.3	159.2
P-n	Normal	6	41.1	12.1	45.7	151.1
P-combined	Mixed	11	39.3	7.4	47.2	155.4

N – number of sites; *K* – Fisher’s (1953) precision parameter of the mean pole; A95 – the radius of the circle of 95% confidence of the mean pole; Plat and Plong – latitude and longitude of the virtual geomagnetic poles.

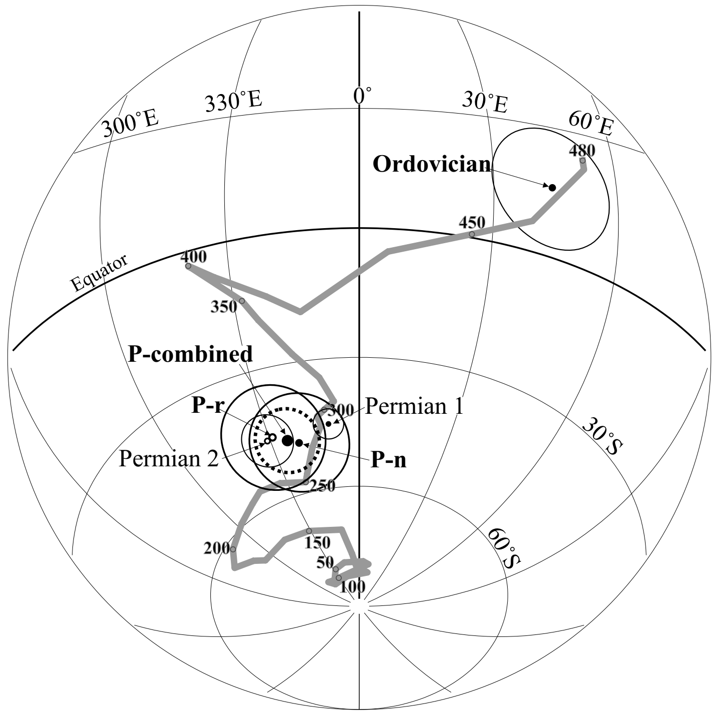

Fig. 5. APW path of Baltica with ages (Ma), redrawn after Torsvik and Cox (2005). Poles of the present study (P-r, P-n and P-combined) and previous studies (Permian 1 and Permian 2) are marked with circles with their A95 confidence cones. Closed (open) circles denote normal (reversed) polarities. See text for details.

Palaeomagnetic data allow reconstructing the relative motions of continents, but provide no information on their absolute position on the Earth's surface. Palaeolatitude can be derived, because it is a function of the inclination of the palaeomagnetic direction, but palaeolongitude remains indeterminate (Lanza and Meloni 2006). The palaeogeographic position of a continent can be created by rotating the pole together with the continent so that the palaeomagnetic pole is positioned on the geographic pole. The resulting map shows the palaeolatitude and the orientation of the continent at the time when the magnetic remanence was acquired. However, palaeogeographic reconstructions show not only the position of the continent itself, but when several continents are plotted, also the relation to each other. Here the mean Ordovician pole (Table 3 and Paper III) and the combined Permian pole (Table 3 and Papers I, III and IV) were used to find the position of Baltica (Fig. 6). In the Ordovician, Baltica plots to middle latitudes (Fig. 6A) and in the Permian to the latitude of 30–40˚N (Fig. 6B). The results match fairly well with the palaeogeographic maps for 460 Ma (Fig. 6C, Cox and Torsvik 2002) and 250 Ma (Fig. 6D, Torsvik and Cox 2004).

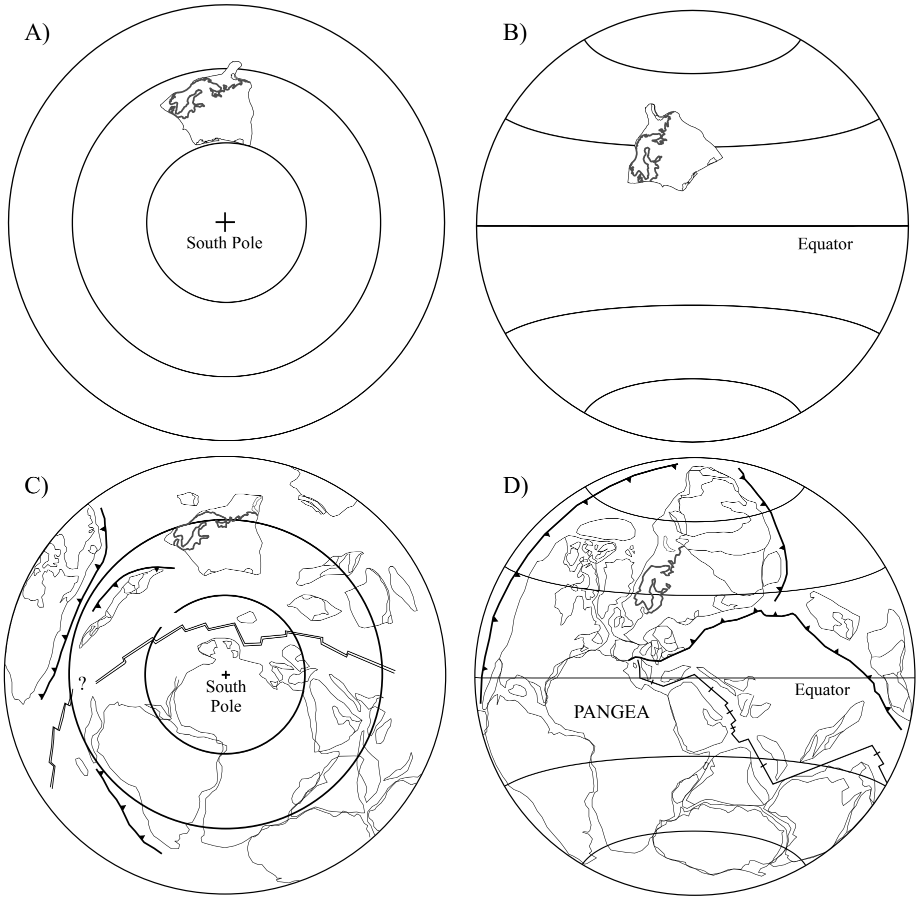

Fig. 6. Palaeogeographic reconstructions of Baltica during (A) Ordovician (~470 Ma) and (B) Permian (~265 Ma) according to the current thesis. Reconstruction of the whole world for (C) Middle Ordovician (460 Ma) (after Cox and Torsvik 2002) and for (D) late Permian (250 Ma) (after Torsvik and Cox 2004).

6. DISCUSSION

Lying in the central part of the Baltica plate, the study area has been tectonically relatively quiet since the Precambrian. However, several indications of tectonic processes around the plate margins have been observed (Fig. 7). Globally, these tectonic processes are related to the formation of the supercontinent Pangea. The collision of Baltica with Laurentia from late Silurian to Early Devonian produced the Scandinavian Caledonian orogenic belt at the western margin of the plate (Roberts and Gee 1985). In the succeeding Devonian and Carboniferous Periods the Hercynian orogeny was induced at the southern border of Baltica. The collision with Siberia in the latest Palaeozoic produced the Ural Mountains in the east. This completed the formation of Pangea.

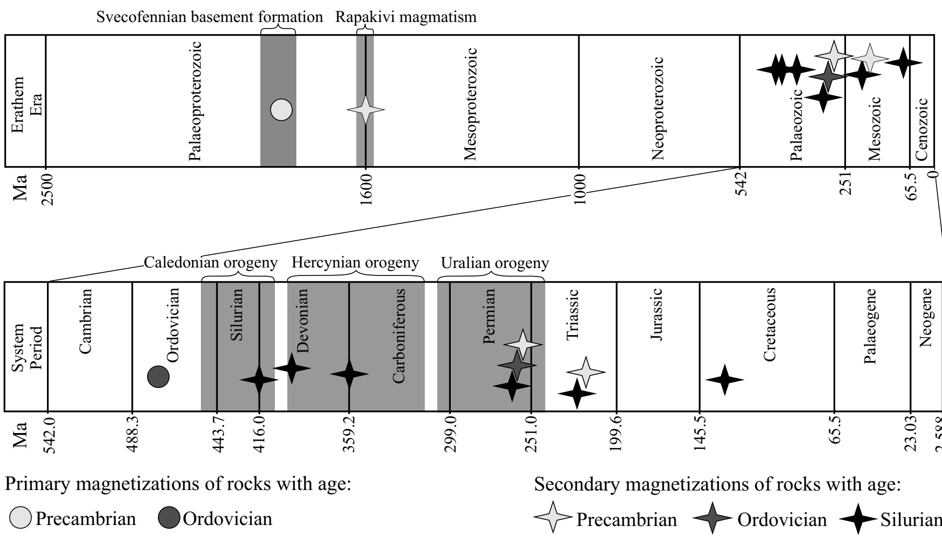

Fig. 7. Main magmatic and orogenic events (grey areas) in the region and observed primary (circles) and secondary (stars) magnetizations of the current study, marked on the stratigraphic chart (ISC 2009).

In Estonia, the Ediacaran to Devonian deposits are crosscut by fault and block structures, which are the far-field expression of the compression at the margins of the East European Craton (Puura et al. 1996, 1999; Sokman et al. 2008). Typical alteration products in Ordovician and Silurian carbonate rocks are shown as secondary dolomitization, leaching and karst processes, in places accompanied by secondary carbonate-sulphide mineralization (Pichugin et al. 1976). According to Puura et al. (1999), the abundant north-east–south-west trending tectonic deformation zones in Estonia are pre-Middle Devonian in age, but the north–south and west–east trending faults in the southern Baltic area, in southern and central Sweden and in the Gulf of Bothnia area are of late

Carboniferous–early Permian age (Puura et al. 1996). However, the exact age of the listed alteration processes is not known and this is where the palaeomagnetic method becomes a useful assistant. In southern Finland, geological and isotopic indications of Palaeozoic mineralization processes in Precambrian rocks have been found by Larson et al. (1999), Murrell (2003) and Alm et al. (2005). It gives more strength and evidence to the possibility that these (Precambrian) rocks have been altered by later secondary processes and the old fault structures of the basement may have been recurrently reactivated, giving rise to the formation of deep fluid circulation systems.

The results of Papers I–IV allow concluding that the studied rocks have been repeatedly remagnetized in different time periods (Fig. 7). However, the pervasiveness (or efficiency) of remagnetization, measured as the percentage of samples carrying a secondary magnetization signature, varies among localities. In some sites primary magnetization has survived until nowadays (Papers III and IV). In north-western part of Estonia the glauconitic limestones have still preserved the primary Ordovician magnetization acquired ~465 Ma ago. The carrier of this component is magnetite that has been formed in early diagenesis by chemical or biogenic processes in locally slightly reducing sub-bottom marine environment with an abundant supply of Fe and a low sedimentation rate (Paper III). Another primary component was revealed in shear and fault zone rocks of southern Finland (Paper IV). Its direction is similar to the remanence that is commonly observed in Svecofennian age (~1.9 Ga) rocks all over the Fennoscandian Shield. The component is carried by (titano)magnetite.

Separate secondary magnetizations that have been found during this research have different ages (Fig. 7). Their probable origins are discussed in the following papers: (i) 1.6 Ga remagnetization in Järvenpää (Paper IV), (ii) late Silurian–Early Devonian overprint in Kallasto, Kurevere and Anelema (Paper I), (iii) Late Devonian to Mississippian remagnetization in Rõstla (Paper II), (iv) Mesozoic secondary magnetizations in Kalana (Paper I), Rõstla (Paper II) and Kerava (Paper IV).

In addition, according to three studies (Papers I, III, IV), there exists a common secondary magnetization component hinting to processes that have activated during the Permian. The component was found in 11 localities, in Estonia and southern Finland (Tables 2 and 3). This Permian component has both normal and reversed polarities. Only normal polarity occurs in Finnish localities (Paper IV), while both normal and reversed polarities are recorded in Estonia. It is widely accepted that the Kiaman Long Reversed Polarity Superchron dominates the late Carboniferous and early Permian. This extended interval of reversed polarity may contain brief normal-polarity superchrons at the beginning of the Permian and in the early late Carboniferous (Ogg 1995; Molostovskii et al. 2007 and references therein), but the end of the Permian was already dominated by normal polarity (Fig. 8). On the basis of this knowledge we interpret that the remagnetization observed in the current studies was mainly acquired in the second half of the Permian.

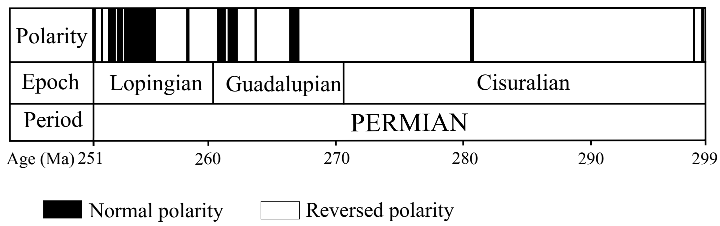

Fig. 8. Global magnetostratigraphic column for the Permian Period (after Gradstein et al. 2004).

6.1. Late Palaeozoic remagnetizations in the Baltic Plate

Carboniferous to Triassic remagnetizations have been reported from almost all studied lower Palaeozoic outcrops of Fennoscandia and north-eastern Russia (e.g. Perroud et al. 1992; Smethurst et al. 1998; Torsvik and Rehnström 2003). Different authors have attributed the component to different geological processes. Smethurst et al. (1998) showed hematite and goethite as carriers of the Triassic component in Ordovician limestones of the St. Petersburg area and suggested that the remanence represents chemical remanent magnetization due to breakdown of glauconite in the near-surface environment. Lubnina (2004) identified a Permian overprint while studying the same region and interpreted it as being related to the tectonic events in the Urals and Western Europe. The latest studies of basaltic and mafic intrusive rocks in the Lake Ladoga area in north-western Russia have also clearly indicated a late Palaeozoic remagnetization (Lubnina et al. 2009).

Earlier paleomagnetic studies performed in Finland, (Mertanen et al., 1989; Mertanen and Pesonen, 1995; Neuvonen et al., 1997) give different interpretations of the component with similar declination and inclination. For instance, in the Varpaisjärvi area in the western Karelian Province, the age of a pole corresponding to the current Permian pole was interpreted as ~2.15 Ga (Neuvonen et al. 1997; see discussion in Mertanen et al. 2008 and Paper IV). Another comparable Permian pole was found in the early Palaeoproterozoic rocks of the Kola Province (Mertanen et al. 1998), where it occurred also in one Palaeozoic dike, which questioned the Proterozoic origin of the remanence. Recent palaeomagnetic studies (Mertanen et al. 2008, Paper IV) state the possibility of a much wider late Palaeozoic remagnetization than previously thought.

Torsvik and Rehnström (2003) tied the Permian overprint in Komstad limestones of Bornholm with cooling/uplift after sedimentary burial (Hansen 1995). A significant stage in the formation and rejuvenation of faults occurred also in the Permian in western and southern Norway (Torsvik et al. 1992; Andersen et al. 1999). This activity is probably tied to the major Permo-Triassic rifting event (Oslo rift).

The Siljan meteorite impact structure in Sweden was formed during the Devonian, around 377 Ma ago (Reimold et al. 2004). Palaeomagnetic study by Elming and Bylund (1991) of the rocks, from inside and outside the impact structure, revealed that primary magnetizations were partly preserved within the impact area, although the directions of these original magnetizations were disturbed due to tectonic movements related to the impact. In addition, the impact affected older Ordovician carbonate rocks by producing cracks and fractures in them. A late Palaeozoic component of chemical remanent magnetization, carried by hematite, was revealed in the rocks, which was interpreted to be caused by oxidation caused due to circulating meteoric water in these cracks and fractures.

Palaeomagnetic studies of Middle and Upper Devonian sediments in south-eastern Estonia (Mootse 1986) have also revealed a corresponding late Palaeozoic overprint that shows both normal and reversed polarities. The carriers of remanence are hematite and iron hydroxides. However, the mechanism of remagnetization is neither discussed nor speculated.

6.2. Late Palaeozoic remagnetization worldwide

According to Zwing (2003), over 60% of all registered remagnetizations in the global palaeomagnetic database (GPMDB 2003, McElhinny and Lock, 1990) have given a Permian age. In this study more than 100 different indications of late Palaeozoic remagnetization worldwide were collected independently. The localities revealing such secondary magnetization were plotted on the present geographic world map (Fig. 9A). It can be seen that the localities are both (i) scattered on different continents and (ii) concentrated in some regions like Europe and North America. One reason for such kind of distribution can naturally be more intensive studies in these regions. However, when the continents are reconstructed in their late Palaeozoic configuration, the distribution of those localities that show the Permian magnetization is noticeable (see Fig. 9B).

The period from late Carboniferous to Early Triassic was the main formation time of the supercontinent Pangea with a peak in the late Permian, when the amalgamation of two megacontinents Gondwana and Laurussia produced a single landmass of 200 x 10^6 km^2 size (Trappe 2000). Looking at the locations of the late Palaeozoic remagnetizations in the 250 Ma palaeogeographic map, the concentration of points along the borders of colliding continents can be observed (Fig. 9B). In literature the events that have had a direct or oblique effect on the formation of a Permian remagnetization have been related to some local or regional orogenic or magmatic event. Most often the Alleghenian orogeny in North America and Africa (Beaubouef et al. 1990; Sun et al. 1993; Stamatakos et al. 1996; Lewchuk et al. 2003; Cederquist et al. 2006; Garner and Cioppa 2006), the Hunter-Bowen orogeny in Australia (Lackie and Schmidt 1993; Klootwijk 2003), extensional faulting within the Caledonides (Andersen et al. 1999) and Variscan synfolding and postorogenic events (Edel and Coulon 1984; Edel and Wickert 1991; Aifa 1993; Grabowski and Nawrocki 2001; Henry et al. 2004) are mentioned. Furthermore, the Uralian orogeny in Asia has had some influence on the rocks (Danukalov 1983; Davydov and Khramov 1991; Lubnina 2004) as has the magmatic activity in Siberia and China (Yianping et al. 1990; Nie et al. 1993; Gallet and Pavlov 1996; Kravchinsky et al. 2002). However, magnetic overprints have also been found in stable platform areas like the Russian platform (Jelenska et al. 2005; Gurevich et al. 2005).

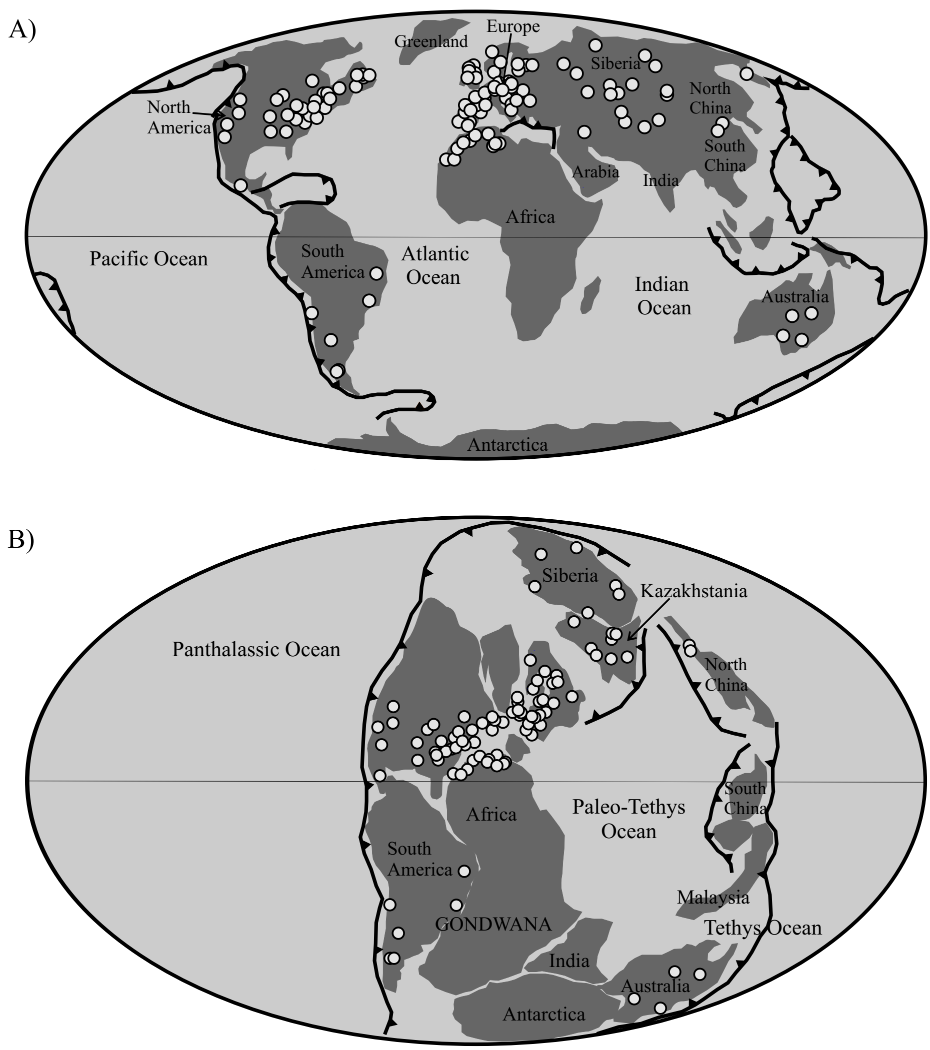

Fig. 9. Late Palaeozoic overprints found in different rocks and places in the world. (A) In the present configuration of continents and (B) in the ~250 Ma reconstruction, when the supercontinet Pangea was formed (maps redrawn after Scotese 2001).

The proposed mechanisms for remagnetization include the conversion of ferric sulphides to magnetic minerals due to oxidizing fluids (Perroud and Van der Voo 1984; McCabe and Elmore 1989; Suk et al. 1990; Hirt et al. 1993) and formation of magnetite as a by-product of conversion of smectite to illite (Katz et al. 1998). In addition, the formation of new magnetic minerals and alteration of primary minerals are linked to interaction between the rock and fluids or hydrocarbons (McCabe and Elmore 1989; Lewchuk and Symons 1995; Brothers et al. 1996; Banarjee et al. 1997) and to strain and stress related to the deformation (Hudson et al. 1989).

6.3. Possible reasons for late Palaeozoic remagnetizations in the studied rocks

Although the causes of widespread remagnetizations are currently not well understood, documenting the extent of remagnetization in terms of the lithologies and affected regions may lead to a better understanding of the mechanisms involved. Fluid interaction is a common mechanism invoked to explain many chemical remanent magnetizations (McCabe and Elmore 1989). Oliver (1986) was the first to link remagnetization events with large-scale fluid migration. In the presently studied rocks the importance of fluids is also confirmed by the location of alteration products along fluid pathways such as cracks, grain boundaries and interconnected voids, where they can either totally destroy the pre-existing remanence-carrying minerals or alter and form new magnetic minerals that are capable of carrying stable CRM.

In the studied rocks thermal influence on the magnetization is not probable. The high temperatures reached during thermal demagnetization (up to 680 ˚C for many samples) are due to the presence of hematite which can be formed at very low temperatures. Also, there is no geologic evidence that the rocks were heated to significantly high temperatures after their formation. The shallow burial and low diagenetic temperatures of the Estonian Palaeozoic complex are indicated by findings of unaltered organic and phosphatic remains in sedimentary beds (Nehring-Lefeld et al. 1997; Talyzina 1998). The maximum diagenetic temperatures suggested by Männik and Viira (1990) are from 50 to 80 ˚C. The thermoviscous or partial thermoremanent magnetization origin of secondary magnetizations is therefore not likely and the observed remagnetizations are interpreted as being of chemical origin.

Migration of orogenic fluids can be one mechanism for the late Palaeozoic secondary remanence in the studied rocks. This is one of the most common remagnetization mechanism for CRMs (e.g. Miller and Kent 1988; McCabe et al. 1989; Stamatakos et al. 1996; Davidson et al. 2000; Geissman and Harlan 2002). The activation of orogenic fluids in the late Palaeozoic could be triggered by post-folding processes of the Hercynian orogeny at the southern margin of Baltica and/or the effect of the collisional Uralian orogeny at the eastern margin of Baltica. Studies of fluid flow events in Scotland (Parnell et al. 2000; Elmore et al. 2002) have revealed that dormant faults or fault systems can be conduits for localized fluid flow events at different times. Since the majority of the CRMs in the study area are younger than the nearest Caledonian orogeny, they are not necessarily related to the major orogenic events (i.e. continent-continent collision; Oliver 1992) but can be connected with more localized igneous activity as well as with tectonic events, such as regional crustal extension. One such event could be the late Palaeozoic highly magmatic Oslo rifting event in southern Norway.

There exist highs in the proximity, and it has been speculated that dewatering of orogens occurs because of the formation of thrust sheets and development of topographic highs, which drive connate brines towards the craton (Oliver 1986). A similar mechanism could have been active also in the Fennoscandian region.

Even if the fluid movement mechanism due to different orogenic events is a compelling explanation for the secondary remanences, it has to be noted that the studied region has been a stable platform area, and therefore one possibility for the remanence acquisition mechanism can be environmental changes in the late Palaeozoic. Weathering can affect original ferromagnetic minerals and result in the formation of new ferromagnetic minerals with attendant CRM components. Because surface conditions are predominantly oxidizing, reactions that transform primary ferromagnetic minerals (such as magnetite) in to higher oxidation state minerals (such as hematite or goethite) are common. Although the usual concern for the occurrence of CRM is recent weathering, secondary CRM components may have resulted from ancient weathering as well (McElhinny and McFadden 2000).

In the early Palaeozoic the Fennoscandian Shield was buried under marine sediments and uncovered subsequently, giving rise to near-surface meteoric fluid circulation (Puura et al. 1999). Widespread Permian regression of the seas from old continental areas (see Zharkov and Chumakov 2001 and references therein) coupled with the presence of hematite and maghemite as the main carriers of the Permian overprint in the studied samples indicate that the base level of erosion lowered and the oxidizing fluids could have reached older rocks.

The Permian overprint found in Siljan impact rocks (Elming and Bylund 1991) and in Cambrian Royer dolomite in the Arbuckle Mountains (Nick and Elmore 1990) has been linked to the circulation of oxidizing meteoric fluids. New studies in France report palaeoweathering profiles of late Palaeozoic–Mesozoic age in igneous rocks of the Morvan massif (Ricordel et al. 2007; Parcerisa et al. 2009). The carrier of the overprint is hematite that formed due to the albitization of crystalline basement rock. The scale of the profiles (over 100 m depth) relates this alteration rather to a groundwater environment and therefore the authors favour a single, very specific alteration event (Thiry et al. 2009).

The late and post-Palaeozoic deposits are missing in the studied area and any direct sedimentary evidence for the last ~350 Ma is lacking. Thus, current palaeomagnetic studies give new knowledge and largely contribute to the detection of younger events that have affected the region. For the local geological history the Carboniferous–Neogene has been considered a relatively stable continental period. However, present studies have revealed several indications of younger remagnetizations, especially in the middle and late Permian, but also in the Mesozoic. Hematite has sporadically precipitated into the pore spaces of carbonates (Papers I and III) and crystalline rocks (Paper IV) and moreover, some iron oxides have formed due to alteration of original or secondary minerals like pyrite (Paper I), micas and epidote (Paper IV). As direct evidence for the mechanism of remagnetization remains elusive, geochemical studies are needed. At present, we support the possibility of multiple agents. Both, migration of orogenic and meteoric fluids could have been the reason for Permian remagnetization in the studied rocks. In an expanded view, all these processes might just be related to the formation of the Pangea supercontinent.

7. CONCLUSIONS

Palaeomagnetic, rock magnetic and mineralogical studies of rocks from Estonia and southern Finland show both primary and secondary magnetizations. Primary magnetizations were found in Ordovician sedimentary rocks of northern Estonia and in Palaeoproterozoic shear and fault zone rocks of southern Finland. Magnetite and titanomagnetite are the carriers of the primary remanence. Secondary magnetizations of different ages were detected, implying that the areas have experienced multiple reactivations. The processes and mechanisms responsible for secondary magnetizations are rather complex.

A common secondary overprint of late Palaeozoic age characterizes both the studied Ordovician–Silurian sedimentary rocks of Estonia and the Precambrian crystalline shear and fault zone rocks of southern Finland. The main carrier of this remanence is hematite, but the contribution of maghemite is observed as well. The remanence represents chemical remanent magnetization. The origin of this remagnetization is postulated to be associated with brines, possibly with meteoric waters, as well as with fluids derived from orogenic belts.

The late Palaeozoic overprint is quite widespread on several continents and has been observed in different types of rocks of different ages all over the world. Similarity of mineral carriers and parameters of remagnetization in Estonia and in the surrounding countries, for example in Finland, Sweden and Russia, support the influence of a wider fluid motion activity at the end of the Palaeozoic. For that reason we believe that the formation of Pangea has largely contributed to the formation of remagnetizations in the late Palaeozoic also in the studied region.

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SUMMARY IN ESTONIAN

Sekundaarsed magnetiseeritused Eesti settekivimites ja Lõuna-Soome kristalsete kivimite murranguvööndites

Käesolev doktoritöö kirjeldab paleomagnetiliste uuringute tulemusi Ordoviitsiumi ja Siluri vanusega sttekivimitest Eestis ja Paleoproterosoilise vanusega kristalsetest kivimitest Lõuna-Soomes. Uuringute peamiseks eesmärgiks oli piirkonna geoloogilise ajaloo täpsustamine.

Paleomagnetilised uuringud võimaldavad määrata Maa magnetvälja suunda hetkel kui kivim tekkis või seda mõjutati hilisemate geoloogiliste protsesside käigus juhul kui süsteemis sisaldusid ferromagnetiliste omadustega mineraalid.

Töö käigus koguti Ordoviitsiumi ja Siluri vanusega karbonaatsete kivimite proove kaheteistkümnest Eesti paljandist ja karjäärist ning viiest Paleoproterosoikumi vanusega kivimite paljandist Soomes. Soome materjal koguti eelistatult murranguvöönditest (Porkkala–Mäntsälä ja Vuosaari–Korso), mis on võrreldes ümbritsevaga olnud geoloogilistele protsessidele vastuvõtlikumad.

Laboratoorsete tööde käigus mõõdeti kivimproovide füüsikalised omadused (tihedus, magnetiline vastuvõtlikkus) ning jääkmagnetiseerituse väärtus ja suund. Lisaks identifitseeriti jääkmagnetiseeritust kandvad mineraalid, kasutades magnetmineraloogia ja optilise mineraloogia meetodeid.

Uuringute tulemused näitavad, et primaarne (kivimi tekkeaegne) magnetiseeritus on säilunud Alam- ja Kesk-Ordoviitsiumi karbonaatkivimites ning Paleoproterosoikumi graniitides ja gneissides. Primaarse magnetiseerituse kandjaks on magnetiit ja titanomagnetiit. Valdavalt esinevad aga kivimites sekundaarsed ferromagnetilised mineraalid: hematiit, maghemiit ja götiit. Nende mineraalide poolt kantud jääkmagnetiseeritused on moodustunud pärast kivimi enese tekkeaega. Magnetiseerituste suunad võimaldasid määrata hilisemate protsesside toimeaega ning täpsustada nende päritolu.

Uuritud kivimites leidub erineva vanusega sekundaarseid magnetiseeritusi, kuid valdavaks on keemilise päritoluga Permi vanusega komponent. Kivimi magnetiliste ja mineraloogiliste uuringute alusel on selle kandjaks hematiit ning kohati ka maghemiit. Magnetiseerituse tekkepõhjustena on välja pakutud mäestikutekkeliste fluidide levikut seoses Hertsüünia või Uuralite kurrutusega ning keskkonnatingimuste muutust. Samas on Hilis-Paleosoikumi vanusega sekundaarset magnetiseeritust avastatud kogu maailmas (rohkem kui sada viidet erinevates andmebaasides), mistõttu on käesolevas töös toodud paralleel Permi vanusega sekundaarse magnetiseerituse laialdase leviku ja Pangea superkontinendi tekke maksimumiga.

PAPERS I–IV

CURRICULUM VITAE

Ulla Preeden

Date of birth 29.04.1980
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Education

2004–	University of Tartu, PhD student, geology
2002–2004	University of Tartu, master studies, geology; MSc 2004
1998–2002	University of Tartu, bachelor's studies, geology; BSc 2002
1986–1998	Räpina Gymnasium

Career

2008–	Extraordinary Researcher, University of Tartu, Department of Geology
2005–2007	Analyst specialist, University of Tartu, Administrative and Support Structure

Research activity

Degree information
Ulla Preeden, Master's Degree, 2004, (supervisors) Juho Kirs, Väino Puura, Matrix grain size in Kärdla, Neugrund, Avike and Lumparn impact craters, University of Tartu, Faculty of Biology and Geography, Institute of Geology.

Field of research
Palaeomagnetism, rock magnetism, remagnetizations, mineralogy, sedimentary rocks, crystalline rocks, Baltica

Grants and Awards

2009	IAGA 2009 grant
2009	EGU Young Scientist Award
2009	DoRa programme (travel grant)
2009	Young scientist award at Geophysics days XXIV
2008	Certificate of excellence for outstanding student presentation, 11th Castle Meeting
2007	SA Archimedes (Kristjan Jaak programme)
2006	Doctoral school of Ecology and Environmental sciences
2004	National student research competition, III place
2004	CIMO scholarship

Current grants and projects

- Neoproterozoic and Palaeozoic geodynamic events on the Fennoscandian Shield in the light of the origin and ages of the magnetic remanence components – ETF6613
- Tectono-thermal development of the Baltic Palaeobasin: linking physical and chemical processes – SF0180069s08

Professional development

2008 NIR research course "Small Quaternary Craterforms – Geophysical and Ecological Aspects", organized by the University of Tartu, Estonia

2007 NIR research course "How impact cratering affects local geology, geochemistry and geophysics", organized by Stockholm University, Sweden

2006 "Quaternary paleomagnetism" organized by the University of Turku, Finland

2006 NIR research course "Signatures of an Impact – the K-T boundary in Denmark as an example", Geocenter Copenhagen, Denmark

2005 "Improving Generic and Professional Communication of Doctoral Graduates across Europe", Granada Doctoral School, Spain

2004 NorFa research course "A unique Paleoproterozoic rift: from the long history and complete record of environmental changes towards world-class deposits and environmental disaster", organized by the University of Oulu, in Pechenga, Russia

Important publications

Plado, J., **Preeden, U**., Pesonen, L., Mertanen, S., Puura, V., 2009. Magnetic history of early and middle Ordovician sedimentary sequence, northern Estonia. Geophysical Journal International (accepted).

Preeden, U., Mertanen, S., Elminen, T., Plado, J., 2009. Secondary magnetizations in shear and fault zones in southern Finland. Tectonophysics, doi:10.1016/j.tecto.2009.08.011 (in press).

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Puura, V., Huber, H., Kirs, J., Kärki, A., Suuroja, K., Kirsimäe, K., Kivisilla, J., Kleesment, A., Konsa, M., **Preeden, U.**, Suuroja, S., Koeberl, C., 2004. Geology, petrography, shock petrography, and geochemistry of impactites and target rocks from the Kärdla crater, Estonia. Meteoritics & Planetary Science, 39(3), 425–451.

CURRICULUM VITAE

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Haridus

2004–	Tartu Ülikool, doktorantuur geoloogia erialal
2002–2004	Tartu Ülikool, magistrantuur geoloogia ja mineraloogia erialal; MSc 2004
1998–2002	Tartu Ülikool, bakalaureuseõpe geoloogia erialal; BSc 2002
1986–1998	Räpina Gümnaasium

Teenistuskäik

2008–	Erakorraline teadur, Tartu Ülikool, Geoloogia osakond
2005–2007	Analüüsi spetsialist, Tartu Ülikool, Haldus- ja tugistruktuur

Teadustegevus

Teaduskraadi info
Ulla Preeden, magistrikraad (teaduskraad), 2004, (juhendajad) Juho Kirs, Väino Puura, Impaktbretšade peenfraktsiooni lõimis Kärdla, Neugrundi, Avike ja Lumparni kraatrites, Tartu Ülikool, Bioloogia-geograafiateaduskond, Geoloogia instituut

Teadustöö põhisuunad
Paleomagnetism, kivimite magnetilised omadused, sekundaarne jääkmagneti-seeritus, mineraloogia, settekivimid, kristalsed kivimid, Baltika kontinent

Saadud grandid ja tunnustused

2009	IAGA 2009 grant
2009	EGU noorteadlase auhind
2009	DoRa programm (noorteadlase osalemine rahvusvahelises teadmiste ringluses)
2009	Noorteadlase auhind Geofüüsika päevadel XXIV
2008	Tunnistus silmapaistva tudengi ettekande eest, 11th Castle Meeting
2007	SA Archimedes (Kristjan Jaagu programm)
2006	Ökoloogia ja keskkonnateaduste doktorikool
2004	Üliõpilaste teadustööde riiklik konkurs, III koht
2004	CIMO stipendium

Jooksvad projektid

- Balti kilbil toimunud Neoproterosoilised ja Paleosoilised geodünaamilised sündmused loodusliku jääkmagnetiseerituse tekke ja ea alusel – ETF6613
- Balti Paleobasseini tektonotermaalne areng: füüsikaliste ja keemiliste protsesside sidestus – SF0180069s08

Erialane enesetäiendus

2008 NIR kursus "Small Quaternary Craterforms – Geophysical and Ecological Aspects", organiseeritud Tartu Ülikooli poolt, Eestis

2007 NIR kursus "How impact cratering affects local geology, geochemistry and geophysics", organiseeritud Stockholmi Ülikooli poolt, Rootsis

2006 "Quaternary paleomagnetism" organiseeritud Turu ülikooli poolt, Soomes

2006 NIR kursus "Signatures of an Impact – the K-T boundary in Denmark as an example", Kopenhaageni Geotsentrum, Taanis

2005 "Improving Generic and Professional Communication of Doctoral Graduates across Europe", Granada Doktorikool, Hispaanias

2004 NorFa kursus "A unique Paleoproterozoic rift: from the long history and complete record of environmental changes towards world-class deposits and environmental disaster", organiseeritud Oulu ülikooli poolt, Pechengas, Venemaal

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