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New rock magnetic and paleomagnetic results for the 1.64 Ga Suomenniemi dyke swarm, SE Finland

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ABSTRACT

This study represents new petrophysical and paleomagnetic data obtained for the 1.64 Ga Suomenniemi diabase and quartz porphyry dyke swarm associated with Suomenniemi rapakivi granite. We also present petrophysical data for the coeval dykes of the Sipoo (1.63 Ga) and Häme (1.642 ± 0.002 Ga; 1.647 ± 0.014 Ga) swarms in order to address: (1) the discrepancy between the coeval Sipoo and Häme poles and (2) the proposed severe overprint in paleomagnetic data for rapakivi related dyke swarms in Fennoscandia.

Demagnetization of Suomenniemi dyke samples revealed dominantly normal polarity magnetization carried by magnetite. For the first time, a few samples from the few sites have shown a trace of a reversed magnetization. The combined normal (N) polarity direction from nine dykes (=sites) is at D = 031.2°, I = 07.2°, (with $\alpha 95$ = 10.6°, k = 21.8) yielding a paleomagnetic pole at Plat = 27.8°N; Plong = 171.7°E (with A95 = 7.9°, K = 38.4). The Suomenniemi pole fulfils four of the seven quality criteria for paleomagnetic poles (Van der Voo, 1990). The new pole for the Suomenniemi swarm is similar to the coeval Sipoo swarm pole, but distinctly different from the nearly coeval Häme swarm pole. The relative position of the poles compared to other well-defined paleomagnetic poles for Baltica indicates that the Suomenniemi and the Sipoo poles are slightly younger than the Häme pole.

We show here that the original magnetization in some of the 1.64 Ga dykes in Suomenniemi have been overprinted with a secondary magnetization component, but several dykes of the swarm lack this overprint. Moreover, the presumably primary Subjotnian remanence component for the Suomenniemi dykes can be clearly isolated due to its different coercivity and/or unblocking temperature from the overprinted component. The same applies to the Sipoo and Häme dyke swarms.

1. Introduction

Dyke swarms typically constitute hallmark representatives of mafic igneous activity associated with major continental rifting/plume events (e.g. Halls, 1987; Ernst and Buchan, 1997). Precambrian mafic dyke swarms are globally cutting Precambrian cratons, they are amenable to precise U-Pb dating, and they often preserve a stable record of ancient magnetic fields, making them valuable targets for reconstructing past continental configurations (e.g. Halls, 1987; Buchan and Halls, 1990). The dyke swarms associated with rapakivi granites have been widely used for providing data for supercontinent reconstructions as the temporal distribution of rapakivi magmatism worldwide at 2.8–2.6 Ga, 1.8–1.0 Ga, and 1.0–0.5 Ga could be coeval with supercontinent cycles (e.g. Rämö and Haapala, 1995; Condie, 1998; Åhäll et al., 2000; Haapala et al., 2005; Larin, 2009). Reconstructions of the supercontinents are crucial for understanding the evolution of the Earth (Reddy and Evans, 2009), since supercontinents have played a key role in the evolution of the Earth at least since Proterozoic times (Evans and Pisarevsky, 2008).

Paleomagnetic evidence and the amount of geological data for the reconstruction of the Mesoproterozoic supercontinent Nuna (a.k.a. Columbia, Hudsonland) have increased dramatically during the last decade (e.g., Baltica: Salminen et al., 2017 and references therein; Laurentia: Hamilton and Buchan, 2010 and references therein; Siberia: Evans et al., 2016; Congo-São Francisco: Salminen et al., 2016b; India: Pisarevsky et al., 2013; North China: Zhang et al., 2012; Xu et al., 2014;

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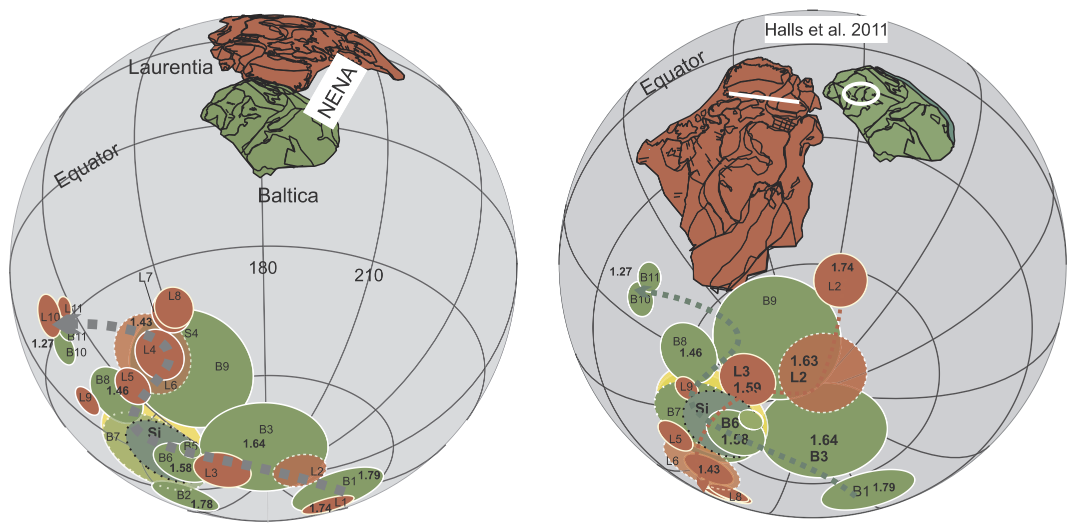

Fig. 1. Two alternative reconstructions for Baltica and Laurentia at 1.64 Ga. Left: the NENA fit, with supporting coeval 1.8–1.27 Ga paleomagnetic pole pairs from both continents. A common 1.8–1.27 Ga apparent polar wander path (APWP) can be formed (grey dashed line). Euler parameters (Elat, Elong, Erot): Laurentia to absolute (37.94°, −151.15°, −236.51° based on the 1.64 Ga Melville Bugt pole); Greenland to Laurentia (67.5°, 241.5°, −13.8°; Roest and Srivastava, 1989); Baltica to Laurentia (47.5°, 1.5°, 49°; Evans and Pisarevsky, 2008). Right: the proposed fit of Halls et al. (2011) where the Melville Bugt swarm approximately points towards the Scandinavian rapakivi granite province. Halls et al. (2011) did not provide Euler parameters, but they are provided here. Baltica to absolute: 39.0°, −107.1°, −108.4°. Laurentia to absolute: −0.70°, 168.0°, 269.72° (based on opposite polarity for the poles than in the NENA fit). This fit does not support a common APWP, but a separate APWP for both continents, indicating that there is no paleomagnetic support for the connection after 1.64 Ga. The poles used here are listed in Table 3. Transparent color with a dashed outline indicates a non-key pole. Full color with solid outline indicates a key pole. The yellow pole is the earlier Suomenniemi pole of Neuvonen (1986). The white line in Laurentia indicates the Melville Bugt swarm and the dashed circle in Baltica indicates the rapakivi granite province. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Australia cratons: Payne et al., 2009; Li and Evans, 2011; Pehrsson et al., 2016; Amazonia: Johansson, 2009; Bispo-Santos et al., 2012; D'Agrella-Filho et al., 2012, 2016). The original definition of the supercontinent Nuna was based on the assembly of Laurentia during the so-called Hudsonian orogeny at 1.9–1.8 Ga, and the recognition of coeval orogenies elsewhere around the world (Hoffman, 1989). Baltica and Laurentia are thought to form the core of Nuna in the geologically supported, long lasting ca. 1.8–1.27 Ga North Europe – North America (NENA) connection (Gower et al., 1990), where northern Norway and the Kola Peninsula of Baltica and North-eastern Greenland of Laurentia are connected (Fig. 1). This was confirmed paleomagnetically to the first order by Buchan et al. (2000), and quantitative Euler parameters with only slight variations were given by Salminen and Pesonen (2007), Evans and Pisarevsky (2008), Salminen et al. (2009), and Pisarevsky and Bylund (2010). Additional paleomagnetic support for the NENA connection was recently provided by well-defined poles from the rapakivi related 1.57 Ga Åland and Satakunta, and the 1.64 Ga Häme dyke swarm, exposed in southern Finland (Salminen et al., 2014, 2016b, 2017). The Häme dyke swarm, which is related to the Wiborg rapakivi granite batholith, has about the same age as the previously studied 1.633 Ga (Törnroos, 1984) Sipoo dyke swarm, which is related to the small Onas rapakivi granite intrusion in southern Finland (Mertanen and Pesonen, 1995; Fig. 2). Despite the close ages of the Sipoo and Häme dyke swarms, the paleomagnetic data from these dyke swarms differ (Fig. 1).

One aim of this study is to find the reason for the discrepancy in paleomagnetic data between the Sipoo and Häme dyke swarms. For this we studied a third dyke swarm, the Mesoproterozoic Suomenniemi dyke swarms, which is associated with the Suomenniemi rapakivi intrusion. Suomenniemi rapakivi intrusion is a satellite body of the Wiborg rapakivi batholith (Rämö, 1991) (Fig. 2). By detailed rock magnetic and petrophysical studies with additional optical studies on all three nearly coeval dyke swarms (Suomenniemi, Sipoo and Häme) we further try to find the reason for the differences in the paleomagnetic data between the formations.

The well-dated Suomenniemi dyke swarm provides an excellent target for obtaining additional Mesoproterozoic paleomagnetic data for Baltica (Fennoscandia). Like the Sipoo dyke swarm, the Suomenniemi dyke swarm comprises both quartz porphyry (1.635 ± 0.002 Ga; 1.638 ± 0.032 Ga; 1.639 ± 0.009 Ga; Vaasjoki et al., 1991) and diabase dykes (1.643 ± 0.005 Ga, Siivola, 1987). Paleomagnetic studies on the quartz porphyry dykes – "the SE quartz porphyry dykes" – of the Suomenniemi swarm have been done earlier by Neuvonen (1986). However, the statistics of the calculated pole is poor. Only four quartz porphyry dykes were studied and the magnetic measurements were conducted using a less sensitive spinner magnetometer. Moreover, the samples carry a strong present Earth field (PEF) – like component (Neuvonen, 1986). This study aims to obtain a higher quality for the pole of the Suomenniemi dyke swarm. This is done by a more extensive sampling, which also includes diabase dykes, and by using a sensitive SQUID magnetometer.

Recently Halls et al. (2011) made the assumption that the pole for the Sipoo dyke swarm (Mertanen and Pesonen, 1995) is partly overprinted by a younger PEF-like magnetization direction and further argued that this is the case for several rapakivi related dyke swarms in Fennoscandia. Halls et al. (2011) proposed that the NE-directed component of the Sipoo dyke swarm may have originally had a steeper upward pointing (negative) inclination, but because of difficulties in removing the strong steep (positive) PEF-like component the direction is now shallower. In the Northern Hemisphere, the convention is to refer to downward north-seeking magnetization directions as normal polarity and upward south-seeking directions as reversed polarity, despite the unknown absolute polarity sense owing to incompleteness of APWPs backward from Phanerozoic into Precambrian time. We follow that convention here. Halls et al. (2011) compared the paleomagnetic results from the Sipoo dykes with results from the coeval Melville Bugt

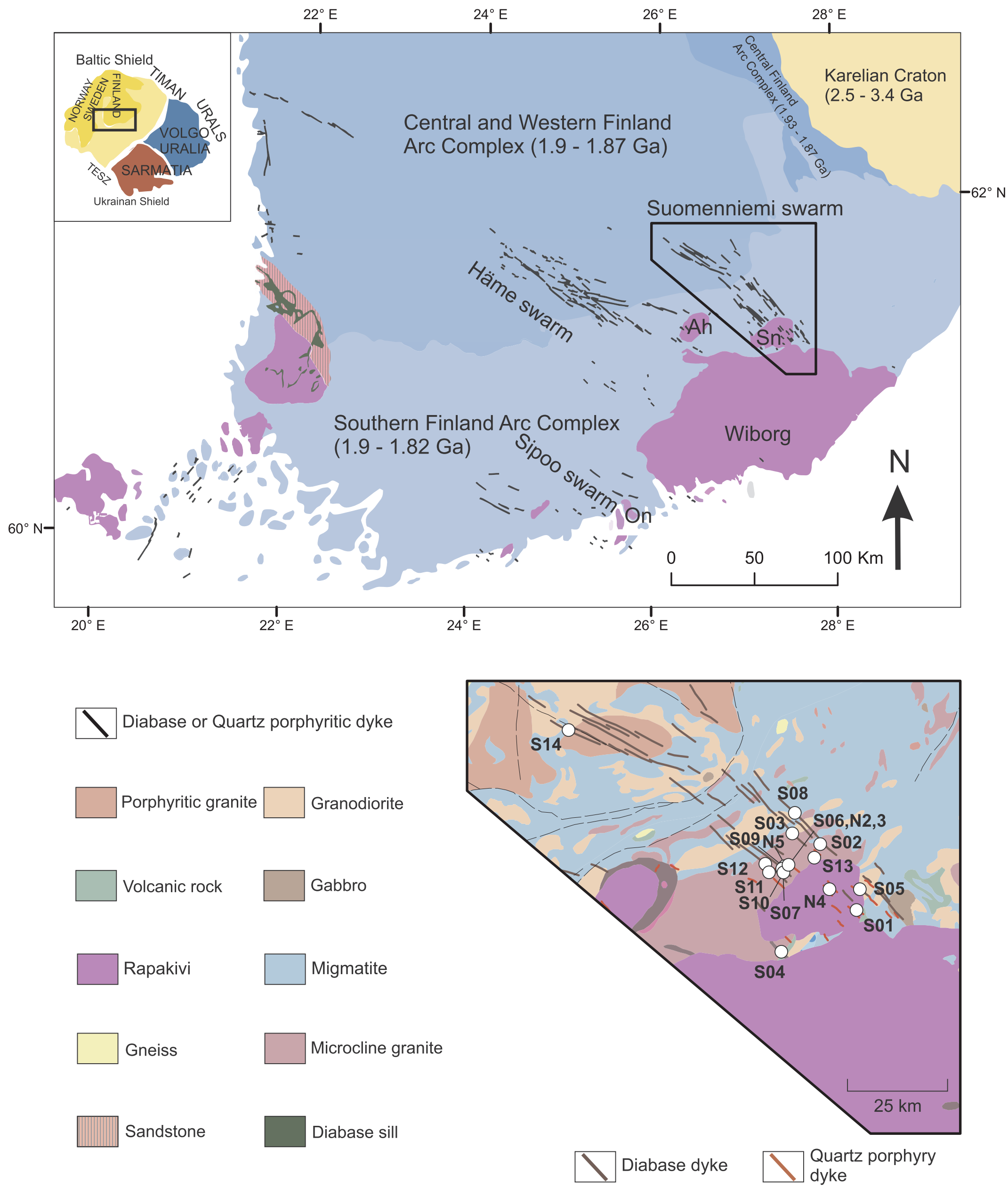

Fig. 2. Upper: Simplified geological map of Southern Finland. Lower: Suomenniemi study area. Sn – Suomenniemi; Ah – Ahvenisto, On – Onas.

dykes of Laurentia (Greenland) (Fig. 1). They proposed that, like in the Sipoo dykes, the NE-directed component (normal polarity) of the Melville Bugt dykes may originally have had a steeper negative inclination, which is now shallower due to difficulty in removing the secondary PEF-like component. However, they negated this assumption since the Melville Bugt dyke swarm has several dykes that lack PEF overprint. For reconstructing the paleogeography of Laurentia and Baltica at 1.63 Ga Halls et al. (2011) used an artificial Sipoo pole for Baltica assuming magnetization with a steeper upward pointing direction than the obtained direction of Mertanen and Pesonen (1995) and using opposite polarity for the same poles that were used for the NENA reconstruction (e.g. Salminen and Pesonen, 2007). This results in a reconstruction where the paleoposition of Laurentia is close to the present-day orientation, with the tip of Greenland pointing northward and the present-day north of Baltica is pointing northward. In the reconstruction of Halls et al. (2011) Melville Bugt swarm approximately points towards the Scandinavian rapakivi granite province (Fig. 1). The reconstruction is very different from the geologically permissible NENA model (Fig. 1). One of our aims in this paper is to address the question of the severe overprint in paleomagnetic data for rapakivi related dyke swarms in Fennoscandia by comparing the data from the Suomenniemi, Sipoo and Häme dyke swarms.

2. Geological background

The rapakivi related ca. 1.64 Ga dyke swarms of Häme, Sipoo and Suomenniemi are exposed in the Svecofennian domain of the Fennoscandian Shield in SE Finland (Fig. 2). The Svecofennian domain was formed between 1.9 and 1.8 Ga as a result of accretion of several island-arcs and microcontinents from the SW against the Archean craton in the NE (e.g. Korja et al., 2006; Lahtinen et al., 2008; Bogdanova et al., 2015). After post collisional uplift and exhumation between 1.815 and 1.80 Ga (Väisänen et. al., 2000), the Svecofennian domain was stable for about 200 million years. Then started a long period of crustal extension, development of rift basins and anorogenic magmatism, including intrusion of several mafic dyke swarms and sills. These magmatic units have been traditionally divided into three main groups based on their age relationship with the rift-filling ('Jotnian') sandstones: Subjotnian (c. 1.65–1.54 Ga), Jotnian (c. 1.4–1.3 Ga) and Postjotnian (c. 1.25 Ga). We will use the term 'Subjotnian' later in this paper when we refer to the Early Mesoproterozoic units in Finland.

The total age range from U-Pb dating for the Fennoscandian rapakivi province is ca. 1.65–1.5 Ga (e.g. Rämö, 1991). The older ca. 1.64 Ga rapakivi batholiths occur in the southeastern part of Finland, whereas the ca. 1.58 Ga rapakivi units (e.g. Åland, Vehmaa, and Laitila) are exposed in the SW part of Finland. The lower part of the rapakivi age range is represented by the intrusions in central Sweden. The largest batholith in SE Finland is the Wiborg batholith with two smaller prominent satellite intrusions, Suomenniemi and Ahvenisto. Several other smaller rapakivi batholiths such as Onas, Bodom and Obbnäs (Rämö, 1991) occur in southern Finland. The rapakivi granites are associated with diabase and quartz porphyry dykes, which radiate from the rapakivi granites (Fig. 2). Based on cross cutting relations, most diabase dykes around the rapakivi areas are considered coeval or slightly older than the rapakivi granite (Rämö, 1991; Haapala and Rämö, 1992). The quartz porphyry dykes are exposed along the border zone of the rapakivi granite batholiths and intrusions so that some of them cut the batholiths, indicating that quartz porphyry dykes are younger than rapakivi and diabase dykes. Most of the quartz porphyry dykes occur around the Suomenniemi, Ahvenisto and the smaller intrusions (such as the Onas rapakivi intrusion in the case of the Sipoo dyke swarm).

The most extensive of these three dyke swarms is the Häme dyke swarm, which extends ca. 150 km NW from the Wiborg and Ahvenisto rapakivi granites (Laitakari, 1987). The swarm comprises mostly diabase dykes. Recently Häme dykes have been dated at 1.642 ± 0.002 Ga (Virmaila dyke) and 1.647 ± 0.014 Ga (Torittu dyke) (Salminen et al., 2017). A previously obtained U-Pb zircon age for one of the Häme diabase dykes is 1.646 ± 0.006 Ga (Laitakari, 1987). Hence, the age range for the Häme dyke swarm is 1.661–1.633 Ga.

The narrower Sipoo dyke swarm is associated with the smaller Onas rapakivi granite intrusion (Fig. 2). The width of the swarm is about 80 km and it extends over more than 20 km in distance (Mertanen and Pesonen, 1995). The U-Pb zircon age determination from only two zircon fractions of one of the Sipoo quartz porphyry dykes yields a model age of 1.633 Ga, being coeval with the model age of 1.630 ± 0.01 Ga of the Onas batholith (Törnroos, 1984). The exposed diabase dykes of the Sipoo swarm are too fine grained for U-Pb geochronology work.

The Suomenniemi dyke swarm is associated with the Suomenniemi rapakivi intrusion (Fig. 2), which forms a prominent satellite body of the Wiborg rapakivi batholith (Rämö, 1991). Geochronology of the Suomenniemi rapakivi granite complex has been analysed using various isotopic methods, which indicate crystallization in the 1.644–1.640 Ga range, with a preferred age at 1.644 ± 0.004 Ga for the batholith (Rämö and Mänttäri, 2015). The Suomenniemi dyke swarm extends about 100 km to the northwest (Fig. 2). The Suomenniemi dykes are NW trending and vertically dipping. Diabase dykes and quartz porphyry dykes typically occur separately, but occasionally the magmas have intruded the same fractures, producing mixed and mingled compositions (Rämö, 1991). About 40 quartz porphyry dykes have been discovered in the Suomenniemi complex (Rämö, 1991). The quartz porphyry dykes cut both the Suomenniemi rapakivi granite batholith and the Svecofennian country rock (e.g. Rämö, 1991). Only three diabase dykes have been found to cut the batholith, while the majority (ca. 40 diabase dykes) cut the Svecofennian country rock northwest of the Suomenniemi batholith (Fig. 2). The width of diabase and quartz porphyry dykes range from a few centimetres to 50 m, but are commonly 5–20 m wide (Rämö, 1991). In addition to the dykes, there is also a large (over 5 km long and nearly 800 m wide; Siivola, 1987) diabase sheet like intrusion in Lovasjärvi (site S04, Fig. 2).

Various ages have been reported for the Suomenniemi dyke swarm (Siivola, 1987; Rämö, 1991; Vaasjoki et al., 1991; Table 2). The most reliable ages are the 1.635 ± 0.002 Ga (U-Pb, zircon) for the Nikkari quartz porphyritic dyke (Vaasjoki et al., 1991; S01 in Fig. 2) and 1.643 ± 0.005 Ga (U-Pb, zircon) for the Lovasjärvi diabase (Siivola, 1987; S04 in Fig. 2). Sm-Nd isotope ages of 1.64–1.635 Ga were obtained from eight Suomenniemi diabase dykes (Rämö, 1991), and a Sm-Nd age of 1.636 ± 0.017 Ga was obtained from the quartz porphyry part of the Kuusenhako mingled dyke (Rämö, 1991).

The Suomenniemi quartz porphyry dykes often have dark and aphanitic margins, while the central parts are composed of alkali feldspar (rounded or angular), quartz, and plagioclase phenocrysts in a fine- to medium-grained granitic groundmass. Occasionally a mafic phenocryst phase is present, consisting of fine-grained aggregates of green amphibole, biotite, and chlorite (Rämö, 1991). The diabase dykes contain plagioclase, olivine (not always present), clinopyroxene, and Fe-Ti oxides as primary magmatic minerals (Rämö, 1991).

3. Sampling and methods

3.1. Sampling

Standard 2.5 cm diameter cores were collected for paleomagnetic measurements from the Suomenniemi swarm with a portable field drill. Four quartz porphyry dykes, eight diabase dykes, one mingled dyke (consisting of both diabase and quartz porphyry), and a large, over 5 km long and nearly 800 m wide (Siivola, 1987), diabase intrusion were sampled (Fig. 1). Host rocks were sampled for baked contact tests (Everitt and Clegg, 1962) at three of the dyke sites. Cored samples were oriented using solar and/or magnetic compasses. Sampling of the Häme and Sipoo dyke swarms is described in Salminen et al. (2017) and in Mertanen and Pesonen (1995), respectively.

3.2. Laboratory methods

Density, rock magnetic and paleomagnetic measurements were carried out at the Solid Earth Geophysics Laboratory of the University of Helsinki (UH), Finland.

The density of specimens was defined by means of Archimedes' principle. Magnetic susceptibility was measured with an Agico KLY-3S-CS3 Kappabridge system, and the intensity of natural remanent magnetization (NRM) was measured with a cryogenic 2G (now WSGI) DC SQUID magnetometer. From these two magnetic parameters, the Koenigsberger (Q) ratio was calculated as follows:

$$Q = \frac{J_R}{J_I} = \frac{\mu_0 \times NRM}{\chi H}$$

where J_R and J_I are remanent and induced magnetization, respectively, μ_0 is the permeability of free space ($4\pi 10^{-7}$ H/A), NRM is natural remanent magnetization (mA/m), χ is magnetic susceptibility (10^{-6} SI), and H is magnetic field intensity (50 μT for Finland).

Table 1
Petrophysical and thermomagnetic results for the Suomenniemi diabase and the quartz porphyry dyke and for selected dykes from the coeval Sipoo (Mertanen and Pesonen, 1995) and Häme swarms.

Site	Site name	Density (kg/m^3)	Susceptibility (10^{-6} SI)	NRM (mA/m)	Q	T_c (°)	H	Magnetic minerals
Suomenniemi								
DIABASE								
S02	Syväjärvi	2937 ± 26	33,429 ± 9519	1348 ± 685	1.0 ± 0.6	582	ho	m
S03	Kirkkovuori	2937 ± 19	43,643 ± 11,131	3540 ± 3970	2.0 ± 2.3	582	ho	m
S04	Lovasjärvi	2999 ± 83	1316 ± 346	27 ± 14	0.5 ± 0.3	576		m
S08	Pellosniemi	2941 ± 24	7365 ± 10,655	437 ± 864	1.5 ± 3.7	585	ho	m
S09	Viiru	2998 ± 7	80,181 ± 7003	2611 ± 494	0.8 ± 0.2	585	ho	m
S10	Korpijärvi	2892 ± 13	7528 ± 5199	328 ± 245	1.1 ± 1.1	580	ho	m
S11	Lehtojärvi	2858 ± 144	20,494 ± 22,093	789 ± 676	1.0 ± 1.3	580	ho	tm, m
S12	Riippa	2887 ± 7	5782 ± 2690	132 ± 62	0.6 ± 0.4	340, 585	ho	tm, m
S13	Hujala	2878 ± 43	38,470 ± 7697	1673 ± 560	1.1 ± 0.4	585	ho	m
QUARTZ PORPHYRY								
S01	Nikkari	2701 ± 2	1044 ± 735	506 ± 610	12.2 ± 17.0	592		m/mg
S05	Kuusenhako	2623 ± 15	285 ± 95	38 ± 58	3.3 ± 5.2	594		mg
S06	Mentula	2635 ± 11	2901 ± 7559	2 ± 0.7	0.01 ± 0.04	592		m/mg
S07	Viiru	2640 ± 13	94 ± 8	2 ± 0.3	0.4 ± 0.1	588		m/mg
S10	Korpijärvi	2674 ± 62	419 ± 140	12 ± 7	0.7 ± 0.5	552, 590		tm, m/mg
Sipoo *from* Mertanen and Pesonen (1995)								
DIABASE								
SD	Kalkstrand	2787 ± 56[a]	487 ± 207[a]	15 ± 10[a]	0.8 ± 0.6[a]	580		m
SG	Sipoo, Paipis	3024 ± 17[a]	55,467 ± 27,347[a]	6611 ± 8199[a]	3.0 ± 4.0[a]	585	ho	m
SF	Sipoo railway	3016 ± 20[a]	1187 ± 23[a]	8 ± 1[a]	0.2 ± 0.03[a]	560		m/mg
QUARTZ PORPHYRY								
SA	Itä-Hakkila	2726 ± 12[a]	4805 ± 8210[a]	209 ± 344[a]	1.1 ± 2.6[a]	380, 585	ho	tm, m
PV	Spjutsund	2694 ± 2[a]	705 ± 441[a]	12 ± 5[a]	0.4 ± 0.3[a]	580		m
Häme								
DIABASE								
H1	Orivesi	2950 ± 72	54,670 ± 3988	2255 ± 705	1 ± 1	582[b]	ho	m
H12	Hirtniemi C	2943 ± 113	20,153 ± 873	629 ± 105	0.8 ± 0.8	582	ho	m
H13	Hirtniemi E	2831 ± 200	29,957 ± 14,494	6034 ± 6895	5.1 ± 5.1	430, 574	ho	tm, m
H15	Harmoistenkaivo	2929 ± 48	3387 ± 1154	138 ± 86	1 ± 1	572	ho	m
H17	Torittu	2975 ± 16	20,627 ± 6054	461 ± 111	0.6 ± 0.6	580	ho	m
H18	Tuomasvuori	2918 ± 140	29,098 ± 11,818	1304 ± 727	1.1 ± 1.1			
H20	Koukkujärvi	2961 ± 10	30,855 ± 3811	478 ± 95	0.4 ± 0.4	368, 580	ho	tm, m
H23	Partakorpi	3054 ± 34	11,572 ± 495	483 ± 69	1 ± 1	580	ho	m
H24	Romo	3010 ± 41	10,503 ± 2087	365 ± 289	0.9 ± 0.9	576	ho	m
H25	Muorinkallio	2920 ± 37	6650 ± 150	698 ± 128	2.6 ± 2.6			
A2	Iso Niinilammi	2984 ± 9	45,870 ± 5545	1057 ± 276	0.6 ± 0.6	388,585	ho	tm, m
A4	Kurjeniemi	2986 ± 17	33,391 ± 1111	859 ± 416	0.6 ± 0.6	574	ho	m
A5	Heinola	3172 ± 23	7247 ± 314	149 ± 14	0.5 ± 0.5	575	ho	m
VR	Virmaila	2951 ± 75	15,683 ± 2620	656 ± 329	1.1 ± 1.1	340[b], 578[b]	ho	tm, m

Mean value ± average deviation. T_c – Curie temperatures analysed with the cureval8.0-program (http://www.agico.com). H – Hopkinson's peak (ho in column indicates that the peak was obtained). Magnetic minerals – magnetic minerals based on thermomagnetic curves. m – magnetite, mg – maghemite – tm – titanomagnetite.

[a] Petrophysical results from Mertanen and Pesonen (1995).

[b] Thermomagnetic results from Salminen et al. (2017).

Magnetic mineralogy of the Suomenniemi dykes was investigated by thermomagnetic analysis of selected powdered samples using an Agico KLY-3S Kappabridge system, which measures the bulk susceptibility (k) of the samples during heating from room temperature to 700 °C and cooling back to room temperature (in Argon gas). Curie temperatures were determined using the Cureval 8.0 program (http://www.agico.com). The same procedure was also done for a selected set of samples of the Sipoo and Häme dyke swarms in order to compare their magnetic mineralogy with that of the Suomenniemi dykes. To further analyse the magnetic mineralogy of the studied dykes, optical studies were carried out using a Jeol JSM-5900LV scanning electron microscope at the Geological Survey of Finland.

To isolate the characteristic remanent magnetization (ChRM), component stepwise alternating field (AF) demagnetizations were done using a three-axis demagnetizer with a maximum field up to 160 mT, coupled with a cryogenic 2G DC SQUID magnetometer. Sister specimens were thermally demagnetized using an argon-atmosphere ASC Scientific model TD-48SC furnace, and remanent magnetization was measured with the SQUID magnetometer. Vector components were visually identified using stereographic and orthogonal projections (Zijderveld, 1967) and the directions were calculated by a least squares method (Kirschvink, 1980), accepting components with a maximum angular deviation (MAD) smaller than 9°. In the case of the dated Mentula dyke (site S06) a higher MAD (up to 25°) for two specimens was accepted. The Mentula dyke is important, since it was dated with the U-Pb method. However, most probably the large grain size hampers the separation of PEF magnetization from a ChRM direction, which results in more scattered directions. Mean remanence directions for each component were calculated according to Fisher (1953). Corresponding virtual geomagnetic poles (VGP) were calculated according to Irving (1964). Paleomagnetic poles were plotted using the GPlates program (Boyden et al., 2011; Gurnis et al., 2012; Williams et al., 2012).

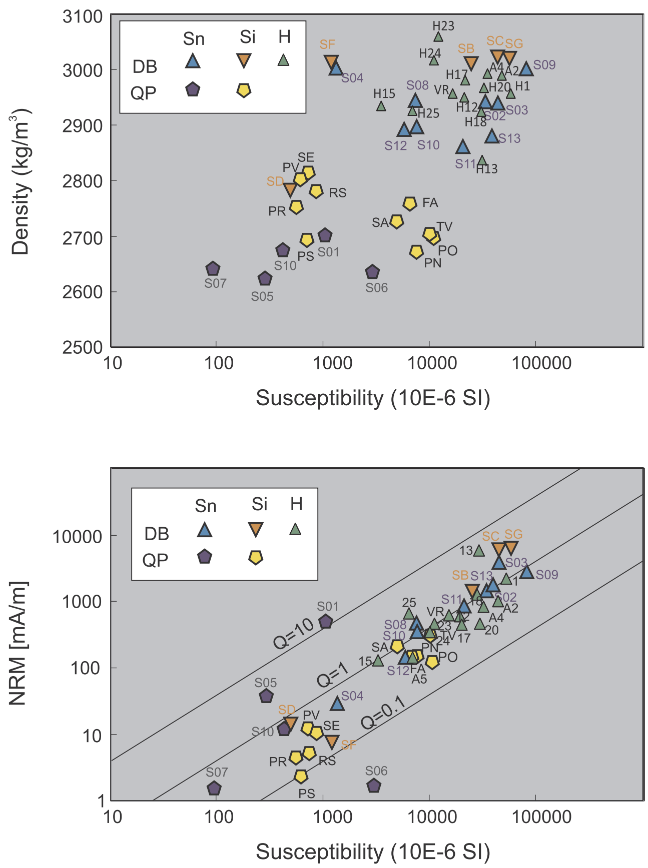

Fig. 3. Density and magnetic properties of the Suomenniemi (Sn), Sipoo (Si) and Häme dykes. Data for Sipoo from Mertanen and Pesonen (1995). Upper: Low field volume susceptibility vs. bulk density. Lower: Low field volume susceptibility vs. NRM, with Koenigsberger (Q) ratio shown as diagonal lines (top). Codes indicate dykes (listed in Table 1). In the lower figure the H in the code for the Häme dyke samples is left out for the sake of clarity. DB (QP) indicates diabase (quartz porphyry).

4. Results

4.1. Petrophysical results

Density and magnetic properties (susceptibility, NRM intensity and Q-ratio) for the Suomenniemi dykes are summarized in Table 1. The bivariate diagrams of density versus susceptibility, and NRM versus susceptibility, are shown in Fig. 3. The distribution of Q-ratios are expressed by lines in Fig. 3 The densities of the diabase dykes are in the range 2860–3000 kg/m^3 and the density of the quartz porphyry dykes are in the range 2620–2700 kg/m^3. Magnetic remanence and susceptibility of the Suomenniemi diabase dykes are higher than the ones for quartz porphyry dykes. The Lovasjärvi sheet like diabase intrusion (S04) has lower susceptibility and NRM values than other dykes. The range of susceptibility (5800–80,200 $\times 10^{-6}$ SI) and NRM (130–2620 mA/m) values are wide for diabase samples. The Q-ratios of diabase dykes are in the range 0.6–2.0, being mainly close to one (1). Susceptibility values for the quartz porphyry dykes are in the range 95–2900 $\times 10^{-6}$ SI. The NRM values for quartz porphyry are mainly below 40 mA/m, with one exception (S01) showing a value of 506 mA/m. The range of Q-ratios for quartz porphyry dykes is large: 0.01–12.2. The outlier S01 shows the highest Q-ratio for quartz porphyry dykes.

In general, the petrophysical properties of the Suomenniemi, Sipoo and Häme diabase dykes are similar. Densities and Q-values of the Sipoo dykes are slightly higher compared with the Suomenniemi and Häme dykes but do not differ significantly. Susceptibilities and remanence intensities (NRM) of the quartz porphyry dykes of the Suomenniemi swarm are similar with the Sipoo quartz porphyry dykes (Mertanen and Pesonen, 1995).

4.2. Magnetic mineralogy

4.2.1. Thermomagnetic analyses

Representative thermomagnetic data for the studied Suomenniemi, Sipoo, and Häme dykes are shown in Fig. 4 and listed in Table 1.

The majority of the studied diabase dykes show a Hopkinson peak in the heating curve, and the Curie temperatures range between 580 °C and 585 °C, indicating single-domain/pseudo-single-domain magnetite (Dunlop and Özdemir, 1997). A few of the diabase dykes show a lower temperature phase during the heating, which is interpreted as being due to titanomagnetite.

The heating curves for Suomenniemi and Sipoo quartz porphyry dyke samples indicate the presence of magnetite (Fig. 4). Susceptibility values for a few dykes form a prominent hump between 450 °C and 600 °C, which may indicate maghemite. In the case of a few magnetically weaker samples, e.g. S04 (Fig. 4), the susceptibility values decrease between room temperature and 400 °C. This kind of decrease is indicative of paramagnetic behavior, and in some cases it has been obtained for monoclinic pyrrhotite.

4.2.2. Optical results from scanning electron microscopy

Representative examples of magnetic minerals obtained with the scanning electron microscope (SEM) are shown in Fig. 5. SEM studies of diabase and quartz porphyry samples established the presence of nearly pure magnetite grains (Fig. 5d–f), many unaltered titanomagnetite grains (up to a few hundreds of a micrometre (Fig. 5b, c), altered magnetite (maghemite; Fig. 5a) grains, as well as some pyrrhotite and pyrite (Fig. 5). These confirm the thermomagnetic results.

4.3. Paleomagnetic results

The paleomagnetic results for the Suomenniemi dykes are listed in Table 2, and representative demagnetization behaviours are illustrated in Fig. 6. We also listed the earlier published results of Neuvonen (1986) for the Suomenniemi dykes. Alternating field (AF) treatment was more successful than thermal (TH) treatment in separating the magnetization components for the majority of the dykes. In general, both diabase and quartz porphyry dyke samples show two components: (1) a soft viscous component showing the Present Earth's geomagnetic Field (PEF) direction at the sampling site (D = 10°, I = 74°); (2) a shallow NNE- or SSW-pointing component, and/or (3) a component with a steep downward pointing inclination and NNE-NE declination. All three component were rarely obtained from one sample. The shallow NNE/SSW pointing component is regarded as the typical Subjotnian direction (e.g. Salminen et al., 2014, 2016b, 2017) and is interpreted to represent the primary magnetization. The component with NNE-NE declination is interpreted to represent a secondary remagnetization and is similar to the one obtained previously in several other Fennoscandian formations (for discussion, see e.g. Bylund, 1985; Bylund and Elming, 1992; Mertanen and Pesonen, 1995; Mertanen, 2008; Preeden et al., 2009; Salminen et al. 2014, 2016a,b, 2017).

4.3.1. The characteristic remanent magnetization

4.3.1.1. Diabase dykes of the Suomenniemi swarm. The dated 1.643 ± 0.005 Ga (U-Pb, Siivola, 1987) Lovasjärvi intrusion (S04) is stable against AF treatment (Fig. 6a) carrying a characteristic remanent

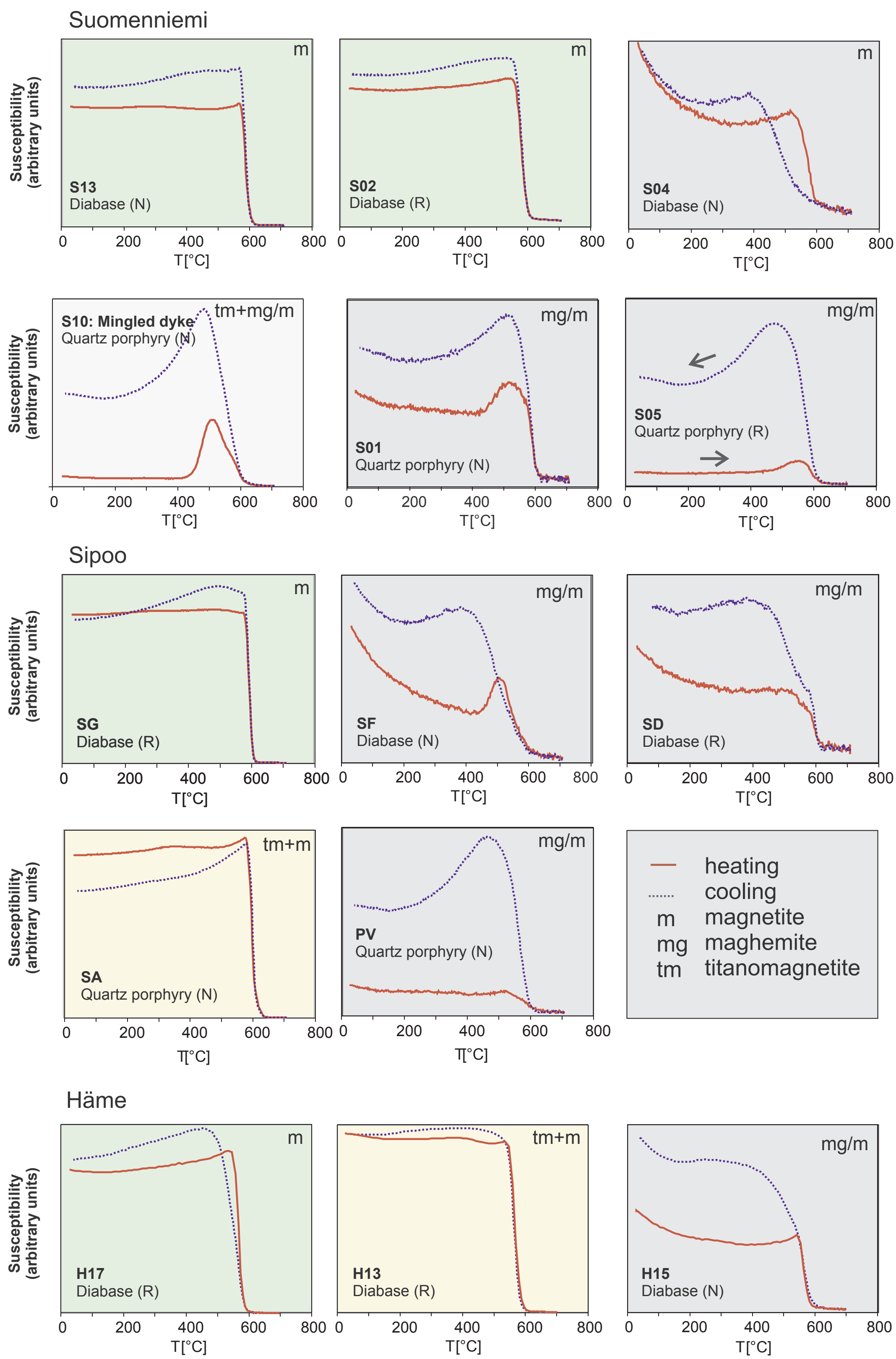

Fig. 4. Thermomagnetic analyses (susceptibility vs. temperature) for selected dyke samples of the Suomenniemi, Sipoo, and Häme swarms. Background color indicates similar thermomagnetic behavior. N (R) indicates normal (reversed) polarity obtained during paleomagnetic studies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

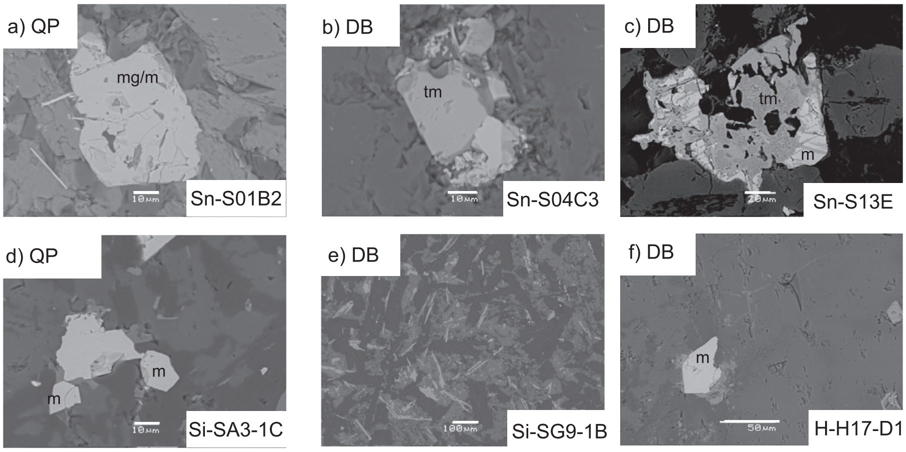

Fig. 5. Scanning Electron Microscope figures of magnetic minerals (JEOLJSM-5900LV). (a) Altered magnetite (maghemite) of Suomenniemi quartz porphyry sample S01B2 (scale: 10 µm), (b) titanomagnetite of Suomenniemi diabase samples S04C3 (scale: 10 µm), (c) magnetite/titanomagnetite of Suomenniemi diabase samples S13E (scale: 10 µm), (d) magnetite of Sipoo quartz porphyry samples SA3-1C (scale: 10 µm), (e) magnetite of Sipoo diabase SG9-1B (scale: 100 µm), (f) magnetite of Häme diabase H17-D1 (scale: 50 µm). QP – Quartz porphyry; DB – Diabase; Sn – Suomenniemi, Si – Sipoo, H – Häme.

magnetization component (ChRM) with shallow inclination and NNE declination. The component was isolated by AF demagnetization with fields between 25 and 80 mT. A high coercivity secondary component with a steep PEF-like direction, possibly carried by secondary minerals, was obtained at higher AF fields above 80 mT. The Median Destructive Fields (MDF; Dunlop and Özdemir, 1997) for S04 are ca. 30 mT, reflecting a fairly hard remanence. No stable ChRM could be isolated from S04 during thermal demagnetization. Four samples of the diabase part of the mingled dyke S10 show a ChRM with shallow down- and upward pointing inclinations and NE declinations decaying to the origin (Fig. 6b). The ChRM was identified using both AF and TH demagnetization techniques. Two samples from dyke S11 carry a ChRM with shallow upward pointing inclination and NNW declinations during AF (MDF: 5 mT) treatment. Diabase dyke S13 was stable against both AF and TH treatments carrying a ChRM with a shallow downward pointing inclination and NE declination, with trajectories decaying to the origin for two samples.

Two diabase dykes of the Suomenniemi swarm show a hint of a reversed polarity Subjotnian magnetization direction. One sample from diabase dyke S02 and two samples from dyke S08 (Fig. 6c) show a ChRM with downward pointing inclination and SSW declination. Samples were stable against AF treatment although the magnetization of S02 is soft (MDF: 5 mT), whereas it is harder for dyke S08 (MDF: 15 mT; Fig. 6). For dyke S08 there is a secondary hard coercivity component left after the removal of ChRM. TH treatment revealed only overprint directions.

4.3.1.2. Quartz porphyry dykes of the Suomenniemi swarm. Four out of the five sampled Suomenniemi quartz porphyry dykes show normal polarity Subjotnian remanent magnetization directions and one shows a hint of a reversed polarity direction. Three samples from the dated (1.635 ± 0.002 Ga, Vaasjoki et al., 1991) Nikkari quartz porphyry dyke S01 show a ChRM with an upward pointing shallow inclination and NNE declination (Fig. 6d). Both AF and TH treatments separated the magnetization components adequately. Three quartz porphyry dykes – S07 (five samples; Fig. 6e), S06 (five samples), and the quartz porphyry part of the mingled dyke S10 (one sample) – show a N-NNE pointing direction with shallow up- and/or downward inclinations. The dyke at site S06 is the dated Mentula dyke for which Vaasjoki et al. (1991) reported a U-Pb (zircon) age of 1.638 ± 0.032 Ga. Samples from all of these three dykes were stable against AF demagnetization, but only an overprint direction could be separated during TH demagnetization. MDFs for samples of dyke S07 (Fig. 6) range from 15 to over 160 mT, and MDF for S10 (quartz porphyry part of the mingled dyke) is higher than 160 mT, indicating very hard magnetization. Despite the hard remanence, the trajectories of S10 decay to the origin, unlike the samples of dyke S07. MDF's for samples of dyke S06 range between 15 and 20 mT and the trajectories decay to the origin.

Thermal demagnetization of one sample of the dated (Sm-Nd 1.635 Ga; Rämö, 1991) Suomenniemi quartz porphyry dyke S05 revealed a hint of a reversed polarity Subjotnian magnetization component of shallow upward pointing inclination and SWW declination (Fig. 6f) with an unblocking temperature of 560 °C. AF demagnetization was not sufficient to separate the Subjotnian component.

4.3.1.3. Mean remanent magnetization directions for the Suomenniemi swarm. Site mean data for Suomenniemi are listed in Table 2 and plotted in Fig. 8. The normal polarity and hints of the reversed polarity Subjotnian magnetization directions were obtained. Earlier results from three normal polarity quartz porphyry dykes of Suomenniemi (Neuvonen, 1986) were included for mean calculations (Table 2). Two of these dykes were dated using U-Pb on zircon: Mentula (1.638 ± 0.032 Ga; Vaasjoki et al., 1991) and Kiesilä (1.639 ± 0.009 Ga; Vaasjoki et al., 1991). The directions for these quartz porphyry dykes were obtained at an AF range of 30–70 mT, while no stable remanence direction could be isolated during TH treatment (Neuvonen, 1986), being consistent with our results.

The obtained magnetization directions for the quartz porphyry part of dyke S10 and for diabase dyke S11 are not included in the mean calculation. For the dyke S10 there is only one sample showing ChRM, so giving only hints of similar ChRM to other accepted dykes. For the dyke S11 the mean destructive field during the AF demagnetization is 5 mT, which indicates soft magnetization most probably carried by larger magnetite grains. These larger grains tend to remagnetize more easily that the smaller ones. The means were calculated for Suomenniemi (Sn): normal polarity diabase dykes (SnDB-N), normal polarity quartz porphyry dykes (SnQP-N), and combined normal polarity quartz porphyry + diabase dykes (SnC-N). There are hints of the reversed polarity magnetization, but due to the low number of samples it is not meaningful to discuss the mean of the reversed polarity. The components are shown in Table 2 and illustrated in Fig. 9.

The new Suomenniemi results for normal polarity dykes were combined with the earlier results of Neuvonen (1986). The Mentula dyke was sampled at two sites by Neuvonen (N2 and N3 in Table 2), and we sampled it at one site (S06). For statistics, two Mentula sites of Neuvonen (1986) were combined into one, but our new site for Mentula was kept as a separate additional site, since this is a separate study done

Table 2
New paleomagnetic results for Suomenniemi diabase dykes combined with previous published data and with coeval earlier published paleomagnetic data for the Sipoo and Häme dyke swarms in SE Finland.

Site	Rock type	U-Pb Age (Ma)	pol	str (°)	width (m)	Lat (°N)	Lon (°E)	(B/)N/n	D (°)	I (°)	a95 (°)	k	Plat (°N)	Plon (°E)	A95 (°)	K	Code/ Coer	MDF (mT)	Tub (°C)	Ref
Subjotnian magnetization Suomenniemi (Sn)																				
Normal polarity																				
S04	DB	1643 ± 5[1]	N	300	800	61.15562	027.14392	4*/7	026.7	−04.9	10.6	40.9	23.0	177.9				30	×	
S10	DB		N	310	> 20	61.33423	027.18958	3*/3	050.9	03.2	14.2	76.2	19.1	152.0				20	580	
S11**	DB		N	300	> 20	61.33242	027.12690	2*/2	329.5	−17.2			16.0	238.3				5	×	
S13	DB		N		20	61.35692	027.34140	2*/2	032.4	23.0			35.4	167.5				7.5	560	
S01	QP	1635 ± 2[2]	N	315	20	61.23117	027.51402	3*/5	039.6	−06.9	21.2	10.9	18.3	165.7				5–20	520–540	
S06	QP	1638 ± 32[2]	N	300	40	61.34602	027.22036	5*/5*	028.7	22.9	23.0	12.0	37.5	170.2				15–20	×	
S07	QP		N	310	3	61.33421	027.18965	5*/5	036.4	13.6	3.8	401.8	29.2	164.7				15–16-0	×	
S10**	QP	1636 ± 17[2]	N	310	> 20	61.33423	027.18958	1/1	358.4	08.5			32.9	209.1				15–16-0	×	
N2[a]	QP	1638 ± 32[2]	N	300	20–40	61.35	027.22	3[a]	025.6	12.2			31.6	176.9				30–70	×	6
N3 [a]	QP	1638 ± 32[2]	N	300	20–40	61.35	027.52	2[a]	039.8	11.0			26.8	162.0				30–70	×	6
N4	QP	1639 ± 9[2]	N			61.23	027.51	2	015.5	14.3			34.8	188.7				30–70	×	6
N5	QP		N			61.34	027.19	3	015.0	−18.5	34.4	12.9	18.2	191.6				30–70	×	6
Mean	**DB + - QP**	1635 ± 2[2]; 1638 ± 32[2]; 1639 ± 9[2]; 1643 ± 5[1]	**N**			**61.3074**	**027.2798**	**9*/32/37**	**031.2**	**07.2**	**10.6**	**21.8**	**27.8**	**171.7**	**007.9**	**038.4**	**SnC-N**			
Reversed polarity																				
S02	DB		R	300	10	61.38741	027.37468	1/1	216.8	28.4			08.1	171.6				5	×	
S08	DB		R	315	3	61.46265	027.26889	2*/2	224.5	29.7			05.0	164.7				15	×	
S05	QP	1635[3] Sm-Nd	R			61.27821	027.53886	1/1	239.6	−08.0			17.7	143.0				×	560	
Mean Sn	DB	1643 ± 5[1]	N					3*/9/12	036.7	07.2	29.8	18.1	26.3	165.6	022.6	030.9	SnDB-N			
Mean Sn	QP	1635 ± 2[2]; 1638 ± 32[2];	N					6*/23/25	028.8	07.1	13.4	21.1	28.4	174.3	009.6	040.2	SnQP-N			
Sipoo (Si)																				
Mean Si	DB		N					1/3*/3	015.5	09.9	52.9	6.5	33.4	186.8			SiDB-N			5
Mean Si	QP		N					5*/34/65	022.2	−01.8	13.3	34.1	26.4	180.4	007.4	107.0	SiQP-N			5
Mean Si	DB + - QP		N					6*/37/68	021.1	00.1	11.3	35.9	27.6	181.5	006.5	106.1	SiC-N			5
Mean Si	DB		R					4*/18/28	198.0	−06.5	40.1	6.2	31.6	183.5	030.7	009.9	SiDB-R			5
MEAN Si	**DB + - QP**	**1633[4]**	**N + R**					**10*/55/96**	**019.9**	**02.5**	**13.3**	**14.1**	**28.2**	**184.3**	**009.8**	**025.3**	**SiC**			
Häme																				
Mean Häme	DB		N					5*/20/20	015.8	−09.2	24.3	10.8	22.4	187.9	020.6	014.8	H-N			7
Mean Häme	DB	1642 ± 2[7]; 1647 ± 14[7]	R					6*/25/25	159.3	08.1	16.7	17.0	22.3	227.4	011.7	033.5	H-R			7
Mean Häme	**DB**		**N + R**					**11*/46/45**	**355.6**	**−09.1**	**16.6**	**8.6**	**23.6**	**209.8**	**014.7**	**010.6**	**H-C**			7
Overprint component for Suomenniemi sites of this study																				
S02	DB			300	10	61.38741	027.37468	8*/8	049.1	57.1	14.9	14.8	54.1	131.3			lo + hi	5	540	
S03	DB			300	15	61.4179	027.24749	4*/4	034.9	75.0	37.9	6.8	78.8	087.7			hi	5	580	
S04	DB			300	800	61.15562	027.14392	5*/5	009.2	74.1	7.9	95.2	85.9	120.8			lo	10	500	
S08	DB			315	3	61.46265	027.26889	2*/2	024.5	63.3			72.6	128.3			lo	10	360	
S09	DB			300	5	61.34045	027.18698	8*/13	044.3	63.1	12.3	12.3	61.9	130.3			hi	5	520	

(continued on next page)

Table 2 (*continued*)

Site	Rock type	U-Pb Age (Ma)	pol	str (°)	width (m)	Lat (°N)	Lon (°E)	(B)/N/n	D (°)	I (°)	a95 (°)	k	Plat (°N)	Plon (°E)	A95 (°)	K	Code/ Coer	MDF (mT)	Tub (°C)	Ref
S10	DB			310	> 20	61.33423	027.18958	4*/5	032.6	63.5	13.9	31.4	66.7	142.9			lo + hi	5/20	580	
S11	DB			300	> 20	61.33242	027.12690	4*/4	060.1	80.1	39.1	6.5	70.4	051.1			lo + hi	5/20	580	
S12	DB			270	0.2	61.35487	027.11097	4*/4	039.9	56.4	17.5	28.6	55.3	141.1			hi	20	×	
S13	DB				20	61.35692	027.34140	4*/4	045.4	47.7	38.2	6.7	46.6	139.9			lo + hi	5/15	580	
S14	DB							3*/3	013.9	72.6	16.8	55.0	81.8	129.8			lo	5	×	
S01	QP			315	20	61.23117	027.51402	2*/2	135.9	55.5			13.7	062.0			lo + hi	5/20	400/ 520–540	
S05	QP					61.27821	027.53886	5*/5	031.3	62.2	25.2	10.2	69.1	141.9			lo + hi	10/ 140	560	
S06	QP			300	40	61.34602	027.22036	4*/4	061.4	65.2			53.2	111.0			lo + hi	20	560	
S07	QP			310	3	61.33421	027.18965	6*/6	068.0	68.9	8.5	62.5	53.7	097.6			lo + hi	10/ 160	500	
S10	QP			310	> 20	61.33423	027.18958	7*/8	041.5	68.2	18.5	9.9	69.8	121.5			lo + hi	> 160	520	

pol., polarity of the isolated direction; N(R), normal (reversed) polarity; str, trend of the dyke; Lat/Lon, Latitude and Longitude of sampling site; (B)/N/n, number of (sites)/samples/specimens; * denotes the number used to calculate mean value; D, declination; I, inclination; a95, the radius of the 95% confidence cone in Fisher (1953) statistics. k, Fisher (1953) precision parameter; Plat/Plong, latitude/longitude of the pole. A95, radius of the 95% confidence cone of the pole; K, Fisher (1953) precision parameter of pole; Coer, obtained coercivity of the component; Code, code of pole in Fig. 9; hi, high; lo, low; MDF, median destructive field; Tub, unblocking temperature; **, excluded from mean calculation; a, same site of Neuvonen (1986). References: 1. Siivola (1987); 2. Vaasjoki et al. (1991); 3. Rämö (1991); 4. Törnroos (1984); 5. Mertanen and Pesonen (1995); 6. Neuvonen (1986); 7. Salminen et al. (2017).

in a different laboratory with more modern instruments. The mean normal polarity direction for these nine dykes (SnC-N) is: D = 31.2°, I = 07.2°, with α95 = 10.6°, k = 21.8 (Fig. 8). The corresponding paleomagnetic pole derived from nine virtual geomagnetic poles (VGP) is at Plat = 27.8°N, Plon = 171.7°E, with A95 = 7.9° and K = 38.4 (Fig. 9).

This is the first time that a hint of a reversed polarity direction was obtained from the Suomenniemi dyke swarm. In the earlier study by Neuvonen (1986), only normal polarity results were obtained. A positive outcome of a baked contact (Everitt and Clegg, 1962) test is crucial for proving a primary origin of a remanent magnetization of igneous rocks. The baked contact test was attempted at four dyke sites S03, S08, S09, and S11, but was inconclusive due to the unstable nature of the baked and unbaked host rocks. The host rock at site S03 is granitic migmatite and at the three other sites it is granite.

4.3.2. The secondary remanent magnetization

Results of the secondary magnetization component analyses are listed in Table 2 and illustrated in Figs. 7 and 8. Most measured samples show secondary magnetization components. A steep viscous component with a downward pointing inclination and northerly declinations was removed with AF fields below 2.5–5 mT. It resembles the PEF direction at the sampling site (D: 10°, I: 74°). Both AF and TH treatments revealed a component with a steep downward pointing inclination and NNE-NE-E declinations. This is a component which has been isolated in several other Fennoscandian intrusions and is interpreted to represent a wide spread remagnetization on the shield during early Mesozoic (e.g. Bylund, 1985; Bylund and Elming, 1992; Mertanen and Pesonen, 1995; Mertanen, 2008; Preeden et al., 2009; Salminen et al. 2014; 2017). Hereafter it is called component B, following Mertanen (1995). In Table 2 we list coercivities, MDFs, and the unblocking temperatures (T_{ub}) for the dykes showing overprinted PEF and/or component B. Remagnetization was identified in all the dykes and intrusion (S01, S02, S04, S05, S06, S07, S08, S10, and S13) carrying the primary Subjotnian remanent magnetization direction. It was also obtained from dyke S11, which was excluded from the mean calculation for Subjotnian remanence. Some of the samples of these dykes show component B as a low coercivity (< 10 mT) and low unblocking temperature component. However, some of the samples of these dykes were completely overprinted by this component, in which case it showed higher coercivities and unblocking temperatures; up to 20 mT and 580 °C for diabase, and up to 160 mT (dyke S05 as an example in Fig. 7) and 560 °C for some quartz porphyry dykes. For the diabase dykes (S03, S09, S12 and S14) that did not retain Subjotnian magnetization directions the MDFs were 5 mT, being very low and indicating soft magnetization. The diabase dyke S12 is completely overprinted and has a high MDF of 20 mT (Fig. 7). The unblocking temperatures of this component range between 520 °C and 580 °C for diabase dykes, indicating that it is carried by magnetite.

5. Discussion

5.1. Petrophysical properties and the secondary magnetization component of the Suomenniemi dyke swarm

Salminen et al. (2017) recently published paleomagnetic results for Häme diabase dykes, but the petrophysical properties for these same dykes are shown here for the first time. In the case of Häme, we only show petrophysical properties for the dykes that showed a primary Subjotnian magnetization direction. The Suomenniemi, Sipoo and Häme dyke swarms show similar petrophysical properties (Fig. 3, Table 2). In all diabase dyke swarms the increase of susceptibility correlates with the increase of remanence intensity, reflecting the amount of magnetite in the samples. The Q-values are around 1 in all the diabase dykes. The petrophysical results from the quartz porphyry dykes, both in Suomenniemi and Sipoo, are more scattered and reflect

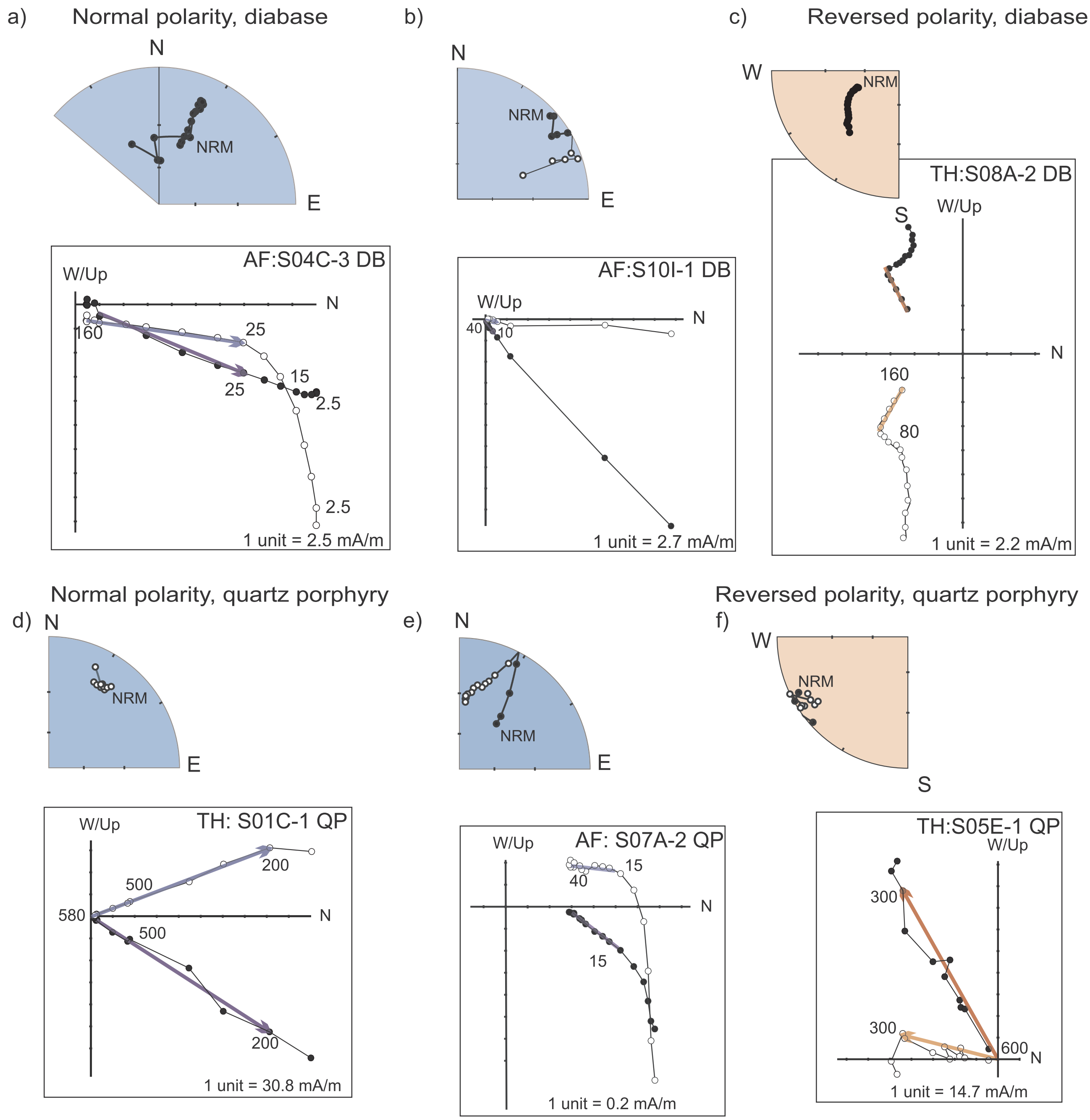

Fig. 6. Examples of demagnetization behavior for diabase (DB) and quartz porphyry (QP) samples showing Subjotnian remanent magnetization directions. In stereonets, filled (open) symbols represents downward (upward) directions. In orthogonal projections, filled (open) symbols represent horizontal (vertical) plane. TH – thermal (numbers indicate temperature in °C); AF – alternating field (numbers indicate the applied AF field in mT).

both the varying grain sizes of magnetite and the amount of magnetite, as well as the amount of feldspar and quartz phenocrysts in the dykes. For instance, the Sipoo quartz porphyry dykes form two distinct groups, each with different magnetic properties. In addition to the compositional differences, part of the differences in petrophysical properties can be explained by the degree of weathering and alteration, which is also shown in the variation of existence of the PEF and/or B component.

It is evident that the dykes have been partially overprinted with a magnetization represented by the B-component. The presumably primary Subjotnian remanence component can still be isolated due to its different coercivity and/or unblocking temperatures. The component B is a component, which has been isolated in several other Fennoscandian intrusions (e.g. Bylund, 1985; Bylund and Elming, 1992; Mertanen and Pesonen, 1995; Mertanen, 2008; Preeden et al., 2009; Salminen et al. 2014; 2017). It is interpreted to represent a wide spread remagnetization on the shield during early Mesozoic and could be related to early stages in the breakup of Pangea supercontinent (e.g. Mertanen, 2008; Preeden et al., 2009; Salminen et al. 2014; 2017). The meaning and origin of the component B is not further discussed here.

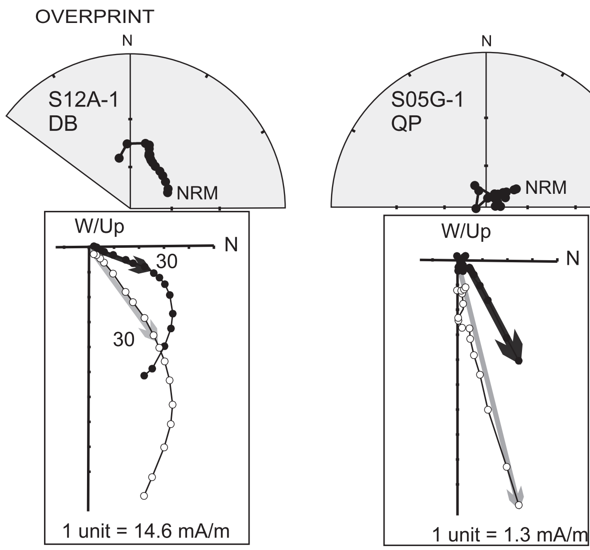

Fig. 7. Examples of demagnetization behavior for samples showing remagnetization component B/PEF. DB – diabase, QP – quartz porphyry. Symbols as in Fig. 6.

5.2. A new paleomagnetic pole from the Suomenniemi dyke swarm

In a previous study of the Suomenniemi swarm, Neuvonen (1986) obtained a presumably primary Subjotnian remanent magnetization direction with normal polarity in four different quartz porphyry dykes (in addition, the dyke at Mentula was sampled at two sites). In this study, a normal polarity direction was obtained for the majority of the analysed dykes. Additionally a hint of a reversed polarity Subjotnian magnetization direction was obtained for the Suomenniemi dyke swarm, although this direction was obtained from only one or two samples for each of the three dykes. The partial PEF/B overprint, which was obtained from several sites, does not affect the obtained Subjotnian ChRM and subsequently does not affect the paleomagnetic pole.

Paleomagnetic poles corresponding to different means are shown in Table 2 and illustrated in Fig. 9. The normal polarity pole for diabase dykes (SnDB-N) has a large A95 radius of the 95% confidence cone of the pole (22.6°). The pole obtained from normal polarity directions of quartz porphyry dykes (SnQP-N) has reasonable statistics with an A95 of 9.6°. The normal polarity poles for diabase (1.643 ± 0.005 Ga, Lovasjärvi intrusion, Siivola, 1987) and quartz porphyry (several dykes dated: 1.635 ± 0.002 Ga; 1.638 ± 0.032 Ga; 1.639 ± 0.009 Ga, Vaasjoki et al., 1991) are not distinct from each other, despite the differences in U-Pb ages for these units. The combined pole from these normal polarity units has an A95 of 7.9° (Figs. 8 and 9; Table 2).

The Suomenniemi normal pole fulfils four of the seven Van der Voo (1990) criteria. The Suomenniemi pole shows a well determined rock age (criterion 1). It has adequate statistics (K = 38.4, A95 = 7.9°, nine sites, 32 samples, (criterion 2) and magnetization directions were obtained using adequate demagnetization that includes vector subtraction (criterion 3). The pole does not include sites with a positive field stability test (criterion 4). The magnetization directions were obtained from an area that is tectonically coherent within Baltica, and the dykes are vertical indicating absence of tilting after the emplacement (criterion 5). It only shows a hint of reversed polarity direction therefore failing criterion 6. The pole resembles Phanerozoic paleopoles of Baltica (criterion 7). Since the new pole does not fulfil the critical fourth criterion, due to the unstable nature of the host rock, the pole cannot be considered to be a key pole (Buchan, 2013).

5.3. The Suomenniemi pole compared to other relevant Mesoproterozoic poles

5.3.1. The three coeval dyke swarms of Suomenniemi, Sipoo and Häme

For comparison, the paleomagnetic poles obtained for the coeval Suomenniemi and Sipoo (Mertanen and Pesonen, 1995), and the nearly coeval Häme (Salminen et al., 2017) swarm are plotted in Fig. 9. Different means for diabase and quartz porphyry dykes and combined means are shown for these three swarms (Table 2).

The normal polarity pole for quartz porphyry dykes (SiQP -N) of the Sipoo swarm is obtained from five dykes and it shows good statistics with A95 = 7.4°, and K = 107. One of the normal polarity quartz porphyry dykes of the Sipoo swarm yields a U-Pb age of 1.633 Ga (Törnroos, 1984). The geochronology result was defined from only two zircon fractions and a definition of the error was not possible. However, this age corresponds with the well-defined ages of the Suomenniemi quartz porphyry dykes. The normal polarity pole for diabase dykes (SiDB-N) of the Sipoo swarm is derived from only one dyke and it lacks

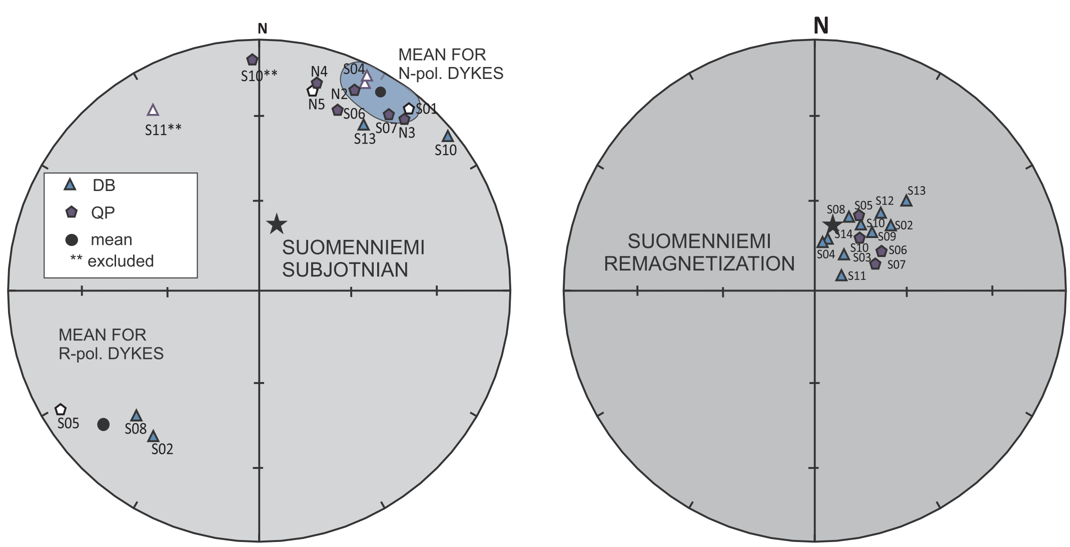

Fig. 8. Obtained paleomagnetic directions for Suomenniemi sites combined with the earlier results of Neuvonen (1986). Left: Site mean paleomagnetic directions for Suomenniemi dykes. Right: overprinted directions in Suomenniemi sites of this study. A closed (open) symbol denotes downward (upward) direction. ** – sites excluded from mean. A star indicates the present Earth field direction at the sampling site (D = 10°, I = 74°).

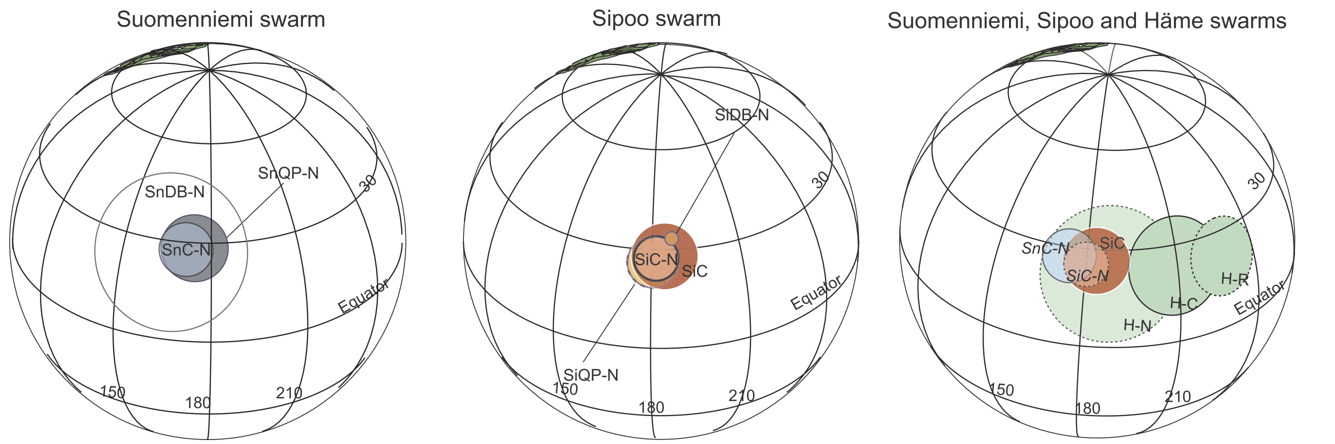

Fig. 9. Coeval ca. 1.64 Ga poles for diabase (DB) and quartz porphyritic (QP) dyke swarms in SE Finland. Left: Poles for Suomenniemi (Sn) DB and QP dykes from this study. Middle: Poles for Sipoo (Si) DB and QP dykes. Right: Poles for Häme DB dykes and mean poles for Suomenniemi and the Sipoo swarm. N – Normal polarity; R – Reversed polarity; C – combined N- and R – polarity poles. For example: SnDB-N – Suomenniemi normal polarity poles for diabase intrusions. See the discussion about the quality of the poles in the text.

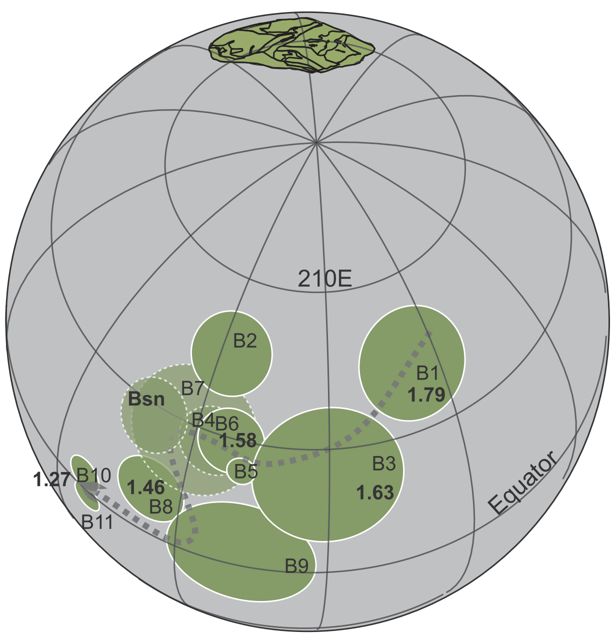

Fig. 10. Apparent polar wander path (APWP) for Baltica. Poles listed in Table 3. Transparent color with dashed outline indicate a non- key pole. Full color with solid outline indicates a key pole. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adequate statistics. For the Sipoo dyke swarm a traces of a reversed polarity direction was obtained from four of the diabase dykes, but not from the quartz porphyry dykes.

Poles from the Häme diabase dykes show a large scatter and normal (H-N) and the reversed (H-R) polarity poles are asymmetric (Salminen et al., 2017). The reversed polarity pole (H-R) for the Häme swarm occupies more northerly latitudes and easterly longitudes than normal polarity pole (H-N) and would shift the combined pole to the east. The reversed polarity dykes at Virmaila and Torittu have ages of 1.642 ± 0.002 Ga and 1.647 ± 0.014 Ga, respectively (Salminen et al., 2017). There is no age data for the normal polarity dykes of the Häme swarm. The Häme reversed polarity pole occupies the older side of the apparent polar wander path of Baltica (Figs. 9 and 10).

Both the combined (i.e., combined results for diabase and quartz porphyry dykes) normal polarity pole (SnC-N) of the Suomenniemi swarm, and the combined normal polarity pole (SiC-N) of the Sipoo swarm overlap, indicating a coeval magnetization age. These poles also overlap with the Häme normal polarity pole (Fig. 9). Normal polarity dykes for Suomenniemi and Sipoo swarms have been dated to be between 1.633 and 1.648 Ga, whereas the normal polarity dykes of the Häme swarm have not been dated. The grand mean poles for Suomenniemi and Sipoo overlap, but they do not overlap with the grand mean Häme pole (Fig. 10), indicating either that the age of magnetization for Suomenniemi and Sipoo is younger than for the Häme swarm or problems with the quality of the data.

5.3.2. *Other relevant Mesoproterozoic poles of Baltica*

The high quality 1.77–1.26 Ga poles for Baltica are plotted in Fig. 10 and are shown in Table 3. The new Suomenniemi pole is distinct from the coeval Häme pole and from the 1.58 Ga Satakunta and Åland poles (Salminen et al., 2014, 2016b), occupying the younger side of the apparent polar wander path (APWP) for Baltica. This could be explained with an age difference between the magnetization of the Häme, the Sipoo and the Suomenniemi dykes accompanied with slight continental drift. The Suomenniemi normal polarity pole overlaps slightly with the Sipoo pole, and with the 1.47 Ga pole from Bunkris-Glysjön-Öje dykes (Pisarevsky et al., 2014).

6. Conclusions

The studied Subjotnian quartz porphyry and diabase dykes, associated with the Suomenniemi rapakivi granite, show a paleomagnetic pole (Plat = 27.8°N; Plon = 171.7°E) with adequate statistics (A95 = 7.9°, K = 38.4). The pole fulfils four of the seven quality criteria for paleomagnetic poles (Van der Voo, 1990), in addition it has a hint of a reversed polarity magnetization direction. It is evident that the new pole for the Suomenniemi swarm is similar to the coeval Sipoo swarm pole, but distinct from the near-coeval Häme swarm pole. The relative position of the poles compared to other well-defined paleomagnetic poles for Baltica indicates that the Suomenniemi and the Sipoo poles are younger than the Häme pole.

We also showed that some of the rapakivi related 1.64 Ga dykes in Suomenniemi have been overprinted with a secondary magnetization component, but several dykes in the swarm lack this overprint. The presumably primary Subjotnian remanence component can still be isolated due to its different coercivities and/or unblocking temperatures. The same applies to the Sipoo and Häme dyke swarms. We can conclude that the overprint in paleomagnetic data for rapakivi related

Table 3
Selected 1.8–1.3 Ga paleomagnetic poles for Baltica and Laurentia.

Code	Rock unit	Age (Ma)	Age Ref	Plat (°N)	Plong (°)	A_{95} (°)	Q_{1-7}	Pmag Ref
Baltica								
B1	Hoting gabbro	1786 ± 3	Hellström and Larson (2003)	43.0	233.3	10.9	1111101 6	Elming et al. (2009)
B2	Småland intrusives	1780 ± 3, 1776 + 8/−7	Nilsson and Wikman (1997)	45.7	182.8	8.0	1111110 6	Pisarevsky and Bylund (2010)
B3	Häme DB dykes	1642 ± 2, 1647 ± 14	Salminen et al. (2016)	23.6	209.8	14.7	1011110 5	Salminen et al. (2017)
B4	Sipoo diabase and quartz porphyry dykes	1633	Törnroos (1984)	28.2	184.3	7.0	1110110 5	Mertanen and Pesonen (1995); recalculated in this work
BSn	Suomenniemi diabase and quartz porphyry dykes	1635 ± 2; 1638 ± 32; 1643 ± 5	Siivola (1987), Vaasjoki et al. (1991), Rämö (1991)	27.8	171.7	7.9	1110100 4	This work
B5	Åland diabase and quartz porphyry dykes	1575.9 ± 3	Salminen et al. (2016a,b)	23.7	191.4	2.8	1111111 7	Salminen et al. 2016
B6	Satakunta diabase dykes N-S & NE-SW	1575.9 ± 3	Salminen et al. (2016a,b)	29.3	188.1	6.6	1111110 6	Salminen et al. (2014)
B7	Bunkris-Glysjön-Öje dykes	1469 ± 9	Söderlund et al. 2005	28.3	179.8	13.2	1010101 4	Pisarevsky et al. (2014)
B8	Lake Ladoga mafic rocks	1452 ± 12, 1457 ± 2, 1459 ± 3	Lubnina et al. (2010), Rämö et al. (2001), Rämö et al. (2005)	11.8	173.3	7.4	1111110 6	Salminen and Pesonen (2007), Shcherbakova et al. (2008), Lubnina et al. (2010)
B9	Mashak suite	1386 ± 5	Bekker et al. (2006)	1.8	193.0	14.8	1011110 5	Lubnina (2009)
B10	Mean Post Jotnian intrusions	1265	Pesonen et al. (2003)	04.0	158.0	4.0	1111101 6	Pesonen et al. (2003)
B11	Mean Post Jotnian intrusions	1265	Pisarevsky et al. (2014)	−01.8	159.1	3.4	1111101 6	Pisarevsky et al. (2014)
Laurentia								
L1	Cleaver dykes	1740 + 5/−4	Irving et al. (2004)	19.4	276.7	6.1	1111101 6	Irving et al. (2004)
L2*	Melville Bugt dykes	1622 ± 3, 1635 ± 3	Halls et al. (2011)	02.7	261.6	9.0	1110111 6	Halls et al. (2011)
L3	Western Channel diabase dykes	1592 ± 3, 1590 ± 4	Hamilton and Buchan (2010)	09.0	245.0	7.0	1101101 5	Irving et al. (1972) Hamilton and Buchan (2010)
L4	St. Francois Mnt acidic rocks	1476 ± 16	Meert and Stuckey (2002)	−13.2	219.0	6.1	1111101 6	Meert and Stuckey (2002)
L5	Michikamau intrusion	1460 ± 5	Krogh and Davies (1973)	−01.5	217.5	4.7	1111011 6	Emslie et al. (1976)
L6	Mean Rocky Mnt intrusion	1430 ± 15	Elming and Pesonen (2010)	−11.9	217.4	9.7	1110011 5	Elming and Pesonen (2010)
L7	Purcell lava	1443 ± 7	Evans et al. (2000)	−23.6	215.6	4.8	1111101 6	Elston et al. (2002)
L8	Spokane Formation	1457	Evans et al. (2000)	−24.8	215.5	4.7	1111101 6	Elston et al. (2002)
L9*	Zig-Zag Dal intrusions	1382 ± 2	Upton et al. (2005)	13.3	209.3	3.8	1111111 7	Evans and Mitchell (2011)
L10	Mackenzie dykes	1267 ± 2	LeCheminant and Heaman (1989)	04.0	190.0	5.0	1111101 6	Buchan and Halls (1990), Buchan et al. (2000)
L11	Sudbury dykes	1235 + 7/−3,	Dudàs et al. (1994)	−02.5	192.8	2.5	1111101 6	Palmer et al. (1977)

Code corresponds with code in Figs. 1 and 10. Plat, Plong – pole latitude and longitude; A95 – 95% confidence circle of the pole; Q – Van der Voo (Van der Voo, 1990) reliability criteria. * Greenland rotated to the Laurentia reference frame using Euler parameters (67.5°, 241.5°, −013.8°) from Roest and Srivastava (1989).

dyke swarms in Fennoscandia does not affect the obtained Subjotnian magnetization directions.

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