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Palaeomagnetism and U-Pb geochronology of ca. 1570 Ma intrusives from Åland archipelago, SW Finland – implications for Nuna

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Abstract

We report new paleomagnetic and isotope age data of Early Mesoproterozoic (i.e. Subjotnian) intrusions from the Åland archipelago, SW Finland. The paleomagnetic results reveal dual polarity magnetizations with a pronounced reversal asymmetry occurring in dykes. We explain the asymmetry by an unremoved secondary component, which is affecting more N polarity dykes. Other explanations are discussed. The primary nature of magnetization in dykes for both normal (N) and reversed (R) groups is verified by positive baked contact tests. A dyke showing reversed polarity from Korsö is dated 1575.9 ± 3.0 Ma (U-Pb) in this study. This and previous U-Pb data of Suominen (1991) tightens the magmatic activity in Åland to 1580-1570 Ma. We combined new paleomagnetic data with those from earlier studies (Neuvonen & Grundström 1969; Neuvonen 1970; Johnson 1979; Pesonen & Neuvonen 1981) to provide a new key-paleomagnetic pole for Baltica. Our data positions Baltica on equatorial latitudes supporting the NENA (North Europe-North America) connection between Baltica and Laurentia at 1.59-1.58 Ga. Paleomagnetic data supports that NENA was valid at 1.75 Ga, 1.58 Ga, 1.46 Ga, and 1.26 Ga forming the core of Mesoproterozoic Nuna (a.k.a. Columbia) supercontinent

Introduction

Supercontinents are assemblies that contain a large proportion of the Earth's continental blocks (e.g. Rogers and Santosh 2004). They have played a key role in the evolution of the Earth's surface at least since Proterozoic times (Evans & Pisarevsky 2008), but possibly even as early as Archean times. A supercontinent cycle – amalgamation and subsequent break up of supercontinents – have had a major impact on geology and biology, such as the formation of orogenic belts, diversification of life forms on Earth, unique climatic conditions (glaciations and evaporations), global changes in ocean chemistry, long-lived mantle convection patterns giving rise to plumes and large igneous provinces, and variations in heat-flow across the core-mantle-boundary (e.g. Condie 2000; 2004; Karlstrom et al. 2001; Meert 2002; Rogers & Santosh 2002; 2004; Pesonen et al. 2003; Evans & Pisarevsky 2008; Li et al. 2008; Evans & Mitchell 2011). There is ample evidence of the existence of the youngest Phanerozoic supercontinent Pangea, but less indications on the Neoproterozoic supercontinent Rodinia (Li et al. 2008) and on the older Mesoproterozoic supercontinent Nuna (Columbia).

Most cratonic blocks show evidence of collisional events between 2.1 and 1.8 Ga, which has led many researchers to propose that a Mesoproterozoic supercontinent Nuna (also known as Columbia (Meert 2012) and Hudsonland (Williams et al. 1991)) existed in the Early Proterozoic (e.g. Meert 2002; Rogers & Santosh 2002; Zhang et al. 2012). There is common agreement that Baltica and Laurentia formed the core of Nuna, and two competing models based on paleomagnetic data have been proposed: 1) northern Norway and Kola Peninsula facing northeastern Greenland of Laurentia in the NENA (Northern Europe - North America) juxtaposition between ca. 1.75 Ga and ca. 1.27 Ga (e.g. Gower et al. 1990; Karlstrom et al 2001; Buchan et al. 2000; Pesonen et al. 2003; Zhao et al. 2006; Salminen & Pesonen 2007; Evans and Pisarevsky 2008; Salminen et al. 2009; Evans 2009) and maybe even up to 1.12 Ga (Salminen et al. 2009),, and 2) Western Baltica juxtaposed to the southeastern Greenland in Laurentia (Zhao et al. 2004; Hou et al. 2008; Johansson 2009; Halls et al. 2011). Recently, it was proposed that Siberia (Wingate et al. 2009; Evans & Mitchell 2011) and Amazonia + West Africa, forming the SAMBA fit with Baltica, (Bispo-Santos et al 2008; Johansson 2009) were also part of the core of Nuna. Nuna possibly also included other continents, such as the Australian cratons (e.g. Hoffman 1991, Karlstrom et al. 2001; Betts et al. 2008, Payne et al. 2009), North China Block (Halls et al. 2000; Kusky et al. 2007; Bispo-Santos et al 2008; Zhang et al. 2012) and India (Zhang et al. 2012). In a recent compilation Pisarevsky et al. (2013) suggested that supercontinent Nuna was assembled by at least ca. 1650-1580 Ma, and comprised West Nuna (Laurentia, Baltica and possibly India), and East Nuna (North, West and South Australia, Mawson

craton of Antarctica and North China), and possibly also Siberia and Congo/São Francisco which were combined as a third rigid continental entity colliding with Nuna at ca. 1500 Ma.

There are not enough high quality Mesoproterozoic paleomagnetic poles to construct adequate Apparent Polar Wander Paths (APWPs) for different cratons (Evans & Pisarevsky 2008; Pisarevsky & Bylund 2010), that could be used to test the Nuna assembly. It is therefore necessary to rely primarily on the “key pole” comparison (Buchan et al. 2000; Buchan 2013), which causes additional problems such as polarity ambiguity and longitudinal uncertainty. Although those problems can be partly resolved by comparison of coeval paleopoles from different continents (Cawood et al. 2006; Evans & Pisarevsky 2008), there are very few coeval key-pole pairs available. For Baltica-Laurentia there are pairs at 1740 – 1790 Ma, 1460 Ma, and 1265 Ma, supporting the NENA configuration (e.g. Salminen & Pesonen 2007). Furthermore, a new palaeopole from Baltica with an age of 1565 Ma (Salminen et al. 2013) was compared with the 1590 Ma pole (Hamilton & Buchan 2010; Irving et al. 1972) from Laurentia despite the fact that the data are not exactly coeval (Salminen et al. 2013). The data also supports the NENA configuration. To further test NENA, the Early Mesoproterozoic dykes (1577 ± 12 Ma, Suominen 1991) that are related to rapakivi granite magmatism (age of Åland rapakivi granite: 1568 ± 10 Ma, 1579 ± 13 Ma; Suominen 1991) in the Åland Archipelago in SW Finland can provide a more precise age match with the 1590 Ma data from Laurentia. However, as will be shown in this study, the old data (Pesonen & Neuvonen 1981 and references therein), and the ages from the Åland intrusions need to be re-evaluated.

Palaeomagnetism of dykes in Åland archipelago have previously been studied by Neuvonen & Grundström (1969), Neuvonen (1970), Johnson (1979), and Pesonen & Neuvonen (1981), and the authors gave key-pole status for the obtained poles. However, the key-pole data (especially positive baked contact tests) have not been published so far. The dykes in Åland show both normal and reversed magnetization directions (Neuvonen & Grundström 1969; Pesonen & Neuvonen 1981). It has been proposed that the units with reversed polarity are older than the ones showing normal polarity (Pesonen & Neuvonen 1981; Pesonen et al. 1985) based on published Rb-Sr ages from reversely magnetized units in Kumlinge (1599 ± 26 Ma) and Korsö (1600 ± 30 Ma; estimated from a preliminary whole-rock Rb-Sr isochron (a personal communications note of O. van Breemen mentioned by Suominen 1991)) versus U-Pb dated units with normal magnetization in Föglö 1577 ± 12 Ma (Suominen 1991). Unpublished (pers. comm. S. Fröjdö) data in a variety of whole-rock samples from the archipelago in SW Finland reveal that the Rb-Sr system is disturbed in the area and we therefore present new U-Pb age data from for the reversely magnetized Korsö dyke.

Moreover it is known that mineral alteration and metamorphic overprint greatly affect the Rb-Sr technique (Jourdan et al. 2009).

The motivation for this study is to obtain Early Mesoproterozoic key-palaeomagnetic data for Baltica, to obtain a preliminary pole for rapakivi granites in Åland, to refine the Early Mesoproterozoic APWP of Baltica, to obtain an additional precise U-Pb age from a reversely magnetized dyke in Åland (Korsö), and finally to test the proposed NENA connection within supercontinent Nuna (a.k.a Columbia, Hudsonland).

2. Geological setting

Most of the continental crust in southern Finland were formed during the Svecofennian (a.k.a. Svecokarelian) orogeny at ca. 1.9-1.8 Ga (Huhma 1986). This crustal formation is related to an oblique collision of a growing Svecofennian island arc system against the Archean craton and to the subsequent continental deformation, metamorphism and crust-forming magmatism (e.g., Korja et al. 2006; Lahtinen et al. 2008). The post-collisional uplift at ca. 1.8 Ga ended the Svecofennian orogeny. About 200 Ma later, the region entered into phases of a long period of crustal extension, development of rift basins, and anorogenic magmatism, including intrusion of several mafic dykes swarms and sills (e.g. Eklund & Shebanov 2005; Andersson et al. 2006). These magmatic units have been traditionally divided into three main groups based on their age relationship with the rift-filling (“Jotnian”) sandstones: Subjotnian (ca. 1.65-1.54 Ga), Jotnian (ca. 1.4 – 1.3 Ga), and Postjotnian (ca. 1.25 Ga). We will use the term “Subjotnian” later in this paper when we refer the Early Mesoproterozoic units in Finland. The Subjotnian units i.e., rapakivi granites and associated quartz porphyry and diabase dyke swarms, are exposed in the southern part of Finland (Figure 1a); the younger rapakivi units are exposed in the SW part of Finland (e.g. Åland, Vehmaa, and Laitila) and the older in the SE part of Finland (e.g. Wiborg, Suomenniemi, and Häme; Figure 1a). However, a detailed mineralogical study of ovoids from the Vehmaa rapakivi batholith in SW Finland (Figure 1a) (Shebanov et al. 2000) showed that the core of these ovoids has a U-Pb (zircon) age of 1630 Ma, while the matrix gives a U-Pb (zircon) age of 1573 Ma. These data indicate that in SW Finland there is a Subjotnian assemblage that gives the same age as the E-W dyke swarm (e.g. Häme swarm) and the rapakivi batholiths in SE Finland. Furthermore, both chemical and mineralogical compositions provide evidence that mixing and mingling occurred between the silicic quartz porphyry and basic diabase magmas as well as magma mixing between the rapakivi granite magmas and diabase magmas, indicating that the emplacements of Subjotnian rapakivi batholiths were coeval with the intrusion of the dykes (Rämö 1991; Lindberg & Eklund 1992; Eklund et al.

1994). At several rapakivi occurrences the diabase dykes do not cut the rapakivi granite intrusions, like in the small Onas and Bodom granites (Kosunen 2004) surrounded by the Sipoo dykes (Törnroos 1984; Mertanen & Pesonen 1995). The Vehmaa rapakivi granite intrusion is surrounded by quartz-porphyry dykes but diabase dykes do not occur in the vicinity of this intrusion (Karell et al. 2009). In the Suomenniemi rapakivi batholith only three diabase dykes have been found to cut the batholith while the majority (about 40) diabase dykes surround the batholith (Rämö 1991). Diabase dykes and quartz porphyry dykes associated with the Suomenniemi rapakivi batholith typically occur separately, but occasionally the magmas have intruded the same fractures, producing mixed compositions (Rämö 1991). In the Suomenniemi area the quartz porphyry dykes have a slightly younger age (1634 Ma) than the rapakivi granite (1635 Ma) suggesting that the quartz feldspar porphyry dykes may represent a slightly later event than that of the granites. Like in Suomenniemi, separate and composite dykes occur within the Sipoo dykes (Laitala 1984). It has been suggested that the fissures in the Sipoo area were first intruded by a diabase magma, and later, during rapakivi intrusion, the central part of the diabase dyke was intruded by granite porphyry (Laitala 1984; Törnroos, 1984).

In Åland, the Svecofennian crust consists of Paleoproterozoic granitoids, paragneisses and felsic and intermediate metavolcanic rocks. These are cut by several Subjotnian rapakivi granite intrusions and mafic dykes generally trending SSW-NNE. The dykes dip vertically or subvertically and widths vary from a few millimeters to over one hundred meters. Rapakivi granite intrusions are located in the SW part of the Åland archipelago. In general the diabase dykes do not cut the rapakivi granite, except at the SW part of the rapakivi granite intrusion (Eklund et al. 1994), where few crosscutting mafic dykes occur. They are differentiated compared to those forming the main dyke swarms (Eklund et al. 1994). Eklund et al. (1994) discuss a hybrid rapakivi variety consisting of 85% rapakivi granite magma and 15 % differentiated tholeiitic magma. Accordingly, at each rapakivi granite occurrence the dyke and rapakivi magmatism is bimodal mafic-felsicmagmatism, being different at each locality, and hence the timing of silicic and basic magmatism cannot be clearly separated. Based on petrography, ages of dykes, and field relations, it has been suggested that the dykes in Åland continue 300 km North up to the Satakunta region in western Finland (e.g. Pihlaja 1987; Lehtonen et al. 2003; Suominen et al. 2006). A recent paleomagnetic study of Subjotnian dykes in Satakunta further supports this (Salminen et al. 2013).

Several Subjotnian units in Åland have been dated before. The rapakivi granites yield U-Pb (zircon) ages of 1568 ± 10 Ma and 1579 ± 13 Ma (Suominen 1991), correlating with ages from Vehmaa

rapakivi granite in mainland Finland, NE from Åland (Figure 1b). However, the Åland and Vehmaa rapakivi granites are clearly separated from each other, based on the steep structures separating the Vehmaa rapakivi granite from the surrounding host rocks (Karell et al. 2009). Like the Åland rapakivi granite, the Vehmaa granite consists of several pulses separated by thin, chilled margins (Karell et al. 2009). Previous U-Pb (zircon) ages for diabase dykes in Åland are 1540 ± 12 Ma (Bergskär island), 1577 ± 12 Ma (Källsholm island), and an age obtained from a single zircon fraction falls between the 1577 ± 12 and 1540 ± 12 Ma (Västersten) discordia line (Suominen et al. 1991). Previous U-Pb (zircon) ages for quartz porphyry dykes are 1576 ± 13 Ma (Blåklobb island), 1576 ± 13 Ma (Åva), and 1571 ± 20 Ma (Jyddö island) (Suominen 1991). Previously it has been suggested that the diabase unit in Korsö, Brändö is 1600 ± 30 Ma, based on Rb-Sr whole-rock data (Suominen 1991). Other Rb-Sr ages from Åland are 1523 ± 34 Ma (Föglö), 1550 ± 35 Ma (Källholm), and 1599 ± 26 Ma (Kumglinge) (Suominen 1991). Although the Rb-Sr ages roughly overlap, within error limits, with U-Pb ages, they must be regarded as unreliable as discussed above.

3. Samples and methods

3.1 Sampling

Diabase and quartz porphyritic dykes, rapakivi granite as well as baked and unbaked host rock samples were collected for paleomagnetic studies during several sampling excursions: 2013 (A-coded sites in Figure 1b) by Salminen, Mertanen and Klein and several earlier sampling excursions by Pesonen (two letter codes for sites, for example KW in Figure 1b). Figure 1b shows the location of the sampled dykes and rapakivi sites that yield characteristic remanence directions regarded as primary. The majority of the samples have been taken in the region outside the rapakivi granite area (Figure 1), however, in the SW part of our sampling area the Subjotnian dykes cut the rapakivi granite. The samples of year 2013 were collected with a portable field drill and oriented using both sun and magnetic compasses. Samples taken before 2013 were collected as oriented blocks and cores with a portable field drill (magnetic and sun compasses).

One new sample for U-Pb geochronology was taken from the more than 100 m wide Korsö (Brändö) dyke, which is an elongated, coarse-grained, mafic magmatic body that strikes towards the NE and forms three bulbous swellings that are joined with thinner fine-grained necks. Its linear extent is over 1000 m and the width is about 200 m. The dyke is mainly exposed on the island of Korsö. The petrology of the dike was investigated by Branigan (1987) who recognized four main

rock types: (1) coarse-grained norite, (2) a micronoritic chilled margin, (3) quartz-monzonite, and (4) a transitional zone rock of jotunitic affinity (found in between the norite and the monzonite), but no attempt to date the intrusion was made in that study. The rock types are transitional and where contacts are observed they are sinuous, suggesting contemporaneity of the magmas. Branigan (1987) reports local alteration of mafic minerals, e.g the replacement of arfvedsonite amphibole by chlorite along fractures. Under the microscope, however, abundant zircon is clearly visible in the quartz-monzonitic rock and this unit was sampled for U-Pb zircon age determination.

3.2 Methods

3.2.1 Geochronological methods

Zircons for U-Pb dating were separated from a quartz-monzonitic Korsö sample at the Department of Geology and mineralogy, Åbo Akademi University, Finland. A ca. 3 kg whole-rock sample was crushed and milled to a grain-size of less than 0.3 mm. A heavy mineral concentrate was obtained using a Wilfley-table and a high-density liquid (di-iodomethane, $d \sim 3.3 \text{ g cm}^{-3}$). Nonmagnetic zircons were hand-picked after magnetic separation. Most crystals were long (length/width > 3) and showed well developed tetragonal prisms without overgrowths, but pyramidal faces were mostly lacking or only weakly developed. Almost all crystals were clear and brownish in color with no discernable older cores; however, small dark inclusions were noted in the larger fraction. Inclusion-free grains were selected and sieved on 75, 150 and 300 μm screens. Further preparation, chemical treatment and isotopic measurements were performed at the Isotope laboratory at the Geological Survey of Finland (GTK), Espoo. From the +75 and +150 μm fractions, zircons that were clearly fragments of larger crystals were selected for air-abrasion (Krogh, 1982). Multi grain zircon fractions (a minimum of a few tens of grains) were then decomposed by acid treatment and uranium and lead were extracted, generally following the methods of Krogh (1973). Thermal Ionization Mass Spectrometry (TIMS) analyses of ^{235}U - ^{208}Pb -spiked and unspiked isotopic ratios were performed on a VG Sector 54 mass-spectrometer. From repeated measurements on the SRM981 standard during the analytical sessions, a mass fractionation correction of $0.15 \pm 0.05\%$ per a.m.u. was estimated for Pb. Isotopic data reduction was performed with the PbDAT program (Ludwig 1991) and the U-Pb age calculations were performed using the Isoplot/Ex v. 4.15 add-in program (Ludwig 2003). All error ellipses are plotted at 2σ level in the concordia diagram (Figure 2). A long term estimate for the errors in the Pb/U ratios of 0.6% (2σ) is used in the age calculation while decay constant errors are ignored.

3.2.2 Paleomagnetic measurements

Paleomagnetic measurements were carried out at the Solid Earth Geophysics Laboratory of the University of Helsinki (UH), Finland (2013 samples) and at the Paleomagnetic laboratory of the Geological Survey of Finland (GTK), Espoo (all pre-2013 samples). For the 2013 samples, stepwise alternating field (AF) demagnetizations were done using a three-axis demagnetizer with a maximum field of up to 160 mT, coupled with a 2G–DC SQUID magnetometer (UH). For pre-2013 samples AF demagnetizations were carried out using a Schonstedt SD-1 demagnetizer up to 100 mT (GTK). Stepwise thermal demagnetizations were performed using a Schonstedt TSD-1 furnace (GTK) and a ASC Model TD48-SC controlled atmosphere (Ar) furnace (UH). Remanent magnetizations were measured with a 2G–DC cryogenic magnetometer (2013 samples, UH) and a GTK-built spinner magnetometer (pre-2013 samples, GTK). Both alternating-field (AF) and thermal demagnetization procedures were carried out on at least two sub-samples from the same sample. Both AF and thermal demagnetization give equal results. Vector components were isolated using principal component analysis (Kirschvink 1980; Leino 1991) and analyzed with Fisher (1953) statistics giving a unit weight to each sample (each specimen has a unit weight within a sample) to compute a site mean. The paleogeographical reconstructions were plotted with the GMAP program (Torsvik & Smethurst 1999).

Magnetic carriers were studied by thermomagnetic analysis of selected specimens using an Agico CS3-KLY-3S Kappabridge system (UH), which measures the bulk susceptibility (k) of the samples during heating from -192°C to 700°C and cooling back to room temperature (in Argon gas). Curie temperatures were determined using the Cureval 8.0 – program (www.agico.com).

4. Results

4.1 U-Pb geochronology results

The analytical results for the zircon fractions are presented in Table 1. Uranium and lead concentrations are fairly similar in all fractions, except for the un-abraded +300 and +150 μm fractions that show the highest uranium concentrations. The same fractions also show low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios. When plotting all fractions in a concordia-diagram (Figure 2) they roughly form a discordia with intercepts at 275 ± 72 Ma and 1569 ± 10 Ma (MSWD=36; $n=6$). The high MSWD suggests other causes of scatter than an underestimation of the analytical error. The two fractions of large un-abraded zircons are the most discordant. There are no older cores or overgrowths observed. This is consistent with them being richest in uranium (Table 1), as lead is readily lost from parts of the crystal lattice damaged by radioactive decay, preferably from the outer parts of the grains.

Disregarding these gives a solution on four points with a lower intercept of 342 ± 80 Ma, and an upper intercept of 1575.9 ± 3.0 Ma (MSWD = 1.16; $n = 4$; $\text{Pb/U} \pm 0.6\%$). The lower intercept lack geological significance and 1575.9 ± 3.0 Ma is thus taken to represent the crystallization of the quartz-monzonite, and, by association, the age of the mafic intrusion.

4.2 Paleomagnetic results

Paleomagnetic results are listed in Table 2, and representative demagnetization behaviour is illustrated in Figures 3, and 4. In Table 2 we also tabulated already published results of Neuvonen & Grundstrom (1969), Johnson (1979), Neuvonen (1970), and Pesonen & Neuvonen (1981). We accepted the data from a dyke where at least two samples showed similar directions. In some cases we accepted the result even if only one sample gave the characteristic (Subjotnian) direction if there were other dykes sampled from the same island giving similar results (e.g. Keistiö island). Components with Mean Angular Deviation (MAD) values less than 6° (in a few exceptional cases, a higher MAD was accepted) are included in the overall mean calculations. In general, samples show three components: a steep inclination viscous magnetization that was cleaned in the beginning of demagnetization (resembling the Present Earth's field at sampling site: $D: 7^\circ$, $I: 73^\circ$); a component with intermediate to steep inclinations and easterly declinations; and a shallow northerly or southerly pointing component being the characteristic remanence component (ChRM). In the Northern Hemisphere, the convention is to refer to downward north-seeking directions as “normal” polarity and upward south-seeking directions as “reversed” polarity, despite the unknown absolute polarity sense due to incompleteness of APW paths backward from Phanerozoic into Precambrian time. We follow that convention here. The mean direction for ChRM from normal polarity sites of this study (21 sites) is $D=12.5^\circ$, $I=13.1^\circ$, $k=28.9$, $a95=6.0^\circ$ (Table 2, Figure 5). The corresponding pole derived from the mean of the 21 VGPs is at 35.9°N , 185.1°E , $K=51.2$, $A95=4.5^\circ$ (Figure 7a). For 36 reversed sites from this study the ChRM mean is $D=183.6^\circ$, $I=21.1^\circ$, $k=39.6$, $a95=3.8^\circ$ (Figure 5), and the paleomagnetic pole derived from VGPs is at 18.2°N , 197.0°E , $K=46.6$, $A95=3.5^\circ$ (Figure 7a). The normally or reversely magnetized dykes do not occur on the same island or islet, but the polarity is constant in all dykes within a single island (Figure 1).

We also report preliminary rapakivi (1568 ± 10 Ma and 1579 ± 13 Ma; Suominen 1991) data from Åland archipelago. Results from rapakivi sites were mostly scattered, therefore baked host rock samples were included as they provided stable results. The results reveal a nearly symmetric dual polarity direction (Table 2) of $D=9.6^\circ$, $I=-16.4^\circ$, $k=19.4$, $a95=15.6^\circ$ and the corresponding pole derived from the mean of the six VGPs is at 20.8°N , 190.3°E , $K=54.1$, $A95=9.2^\circ$.

Most of the samples show a secondary component. In many cases the secondary component had a clear viscous origin, since it was removed with fields $\leq 5\text{mT}$ and it resembled the Present Earth's Field (PEF) direction at the sampling site ($D=7^\circ$, and $I=73^\circ$). Some samples also show the other secondary component, with an easterly declination and an intermediate to steep downward inclination, that was removed with a field of $\leq 20\text{ mT}$ (Figure 5). The latter secondary component is similar to the one obtained in several other Fennoscandian intrusions. Most recently it was obtained and discussed from western Finland from Subjotnian Satakunta dykes (Salminen et al. 2013).

4.2.1 Baked contact test

The basic requirement in paleomagnetic work is to verify that the observed magnetization direction is original, i.e. a primary ambient field direction obtained during emplacement of the rock formation and not during later events. Since we deal with remanent magnetization of thermal origin in this study, it can be tested by the baked contact test (Everitt and Clegg 1962). The concept of the test is that an igneous body heats (or bakes) the contact zone of the host rock to near or above the Curie temperature of the magnetic minerals. These minerals gain the direction of the Earth's magnetic field at the time of cooling. This direction is not likely to be greatly different from the remanence direction observed from the formation itself. Due to the temperature decrease the remanence directions of the baked zone gradually change. A complete test requires: (1) an agreement in demonstrated stable remanence direction between an igneous rock and adjacent baked country rock and (2) a difference between this direction and the remanence direction of the unbaked host rocks. Otherwise there is a possibility that both intrusion and the baked contact were remagnetized later (e.g. Irving 1964; Buchan 2013).

Baked-contact tests were performed at several sites. A normal polarity site FT (Föglö island, big dyke) and a reversed polarity site RM/RK (Rosmunklobb island, Table 2, Figure 3) provide full positive baked contact tests. The dyke and the baked host rock have similar shallow northerly (normal polarity) or shallow southerly (reversed polarity) pointing magnetization directions, while the unbaked Svecofennian aged host rock shows a typical Svecofennian direction. For the site FT dyke samples show a mean direction of $D = 9.7^\circ$ and $I = 15.0^\circ$ with $\alpha_{95} = 3.3^\circ$ and $k = 114.6$ (17 samples, 46 sub-samples). The baked host for this site shows a mean direction of $D = 13.9^\circ$ and $I = 16.2^\circ$ (two samples; 6 sub-samples). Unbaked host rock for this site shows $D = 350.6^\circ$ and $I = 41.3^\circ$ (one sample, two sub-samples). For reversed site the dyke mean is $D = 187.8^\circ$ and $I = 27.1^\circ$ with

$\alpha_{95} = 9.4^\circ$ and $k = 27.6$, (10 samples, 18 sub-sample). The baked host for this site shows a mean direction of $D = 199.1^\circ$ and $I = 8.1^\circ$ (one sample, two sub-samples). Unbaked host rock shows a Svecofennian direction $D = 333.3^\circ$ and $I = 49.4^\circ$ (one sample, two sub-samples). Furthermore, baked host rock samples at nine normal polarity sites and at five reversed polarity sites show a similar direction to the dyke (Table 2, Figure 5). Based on two full positive baked contact tests we consider these sites as additional proof for the primary origin of both normally and reversed magnetizations. Moreover, primary remanence in Åland is also supported by the two positive baked contact tests for the only marginally younger Satakunta dykes (1565 Ma) 300 km to the north which give similar paleomagnetic directions than Åland dykes (Salminen et al. 2013). Based on positive baked contact tests we interpret the dual-polarity shallow component as the primary characteristic remanent magnetization and the steep to intermediate component as a secondary magnetization. This is further supported by the fact that the secondary component was often obtained from the interior of the dykes where samples were coarser grained and more vulnerable for remagnetization.

4.2.2 Magnetic mineralogy

Both thermal (unblocking temperatures 500-590°C) and AF (coercivities < 50 mT) demagnetization indicate that the magnetic carrier is magnetite. To further confirm this, we conducted thermomagnetic measurements for both normally and reversely magnetized diabase and quartz porphyritic dyke samples and for some baked host rocks from several different islands covering the sampling area (A1: Enklänge (diabase); A3: Korsö (diabase); A19: Torsholma (diabase); A23: Åva (quartz porphyry); FM: Sälögren (diabase); FT: Föglö (wide diabase dyke and narrow cross-cutting diabase, see Figure 3); NB: Norra Betesön (diabase)). All heating and cooling curves for the dyke samples are irreversible, only baked granite samples show reversible curves (Figure 6). Irreversible heating and cooling curves indicate that dyke intrusions have not been re-heated above the Curie point of magnetite, whereas reversed curves for the baked host sample indicate that the sample was re-heated beyond the Curie point of magnetite. Curves reveal the presence of a single magnetic phase with a Curie temperature between 560 and 582°C. This is consistent with magnetite and/or low-Ti titanomagnetite as the magnetic carrier. We obtained peaks associated with the Verwey transition (Verwey 1939) between -146 and -156°C for samples from sites A3, A19; FM, and FT, indicating that in these samples magnetite is nearly stoichiometric. Magnetite was also observed in earlier thin section studies (e.g. Suominen 1991; Neuvonen & Grundström 1969).

5. Discussion

5.1 Geochronology

Based on paleomagnetic studies it has been proposed that the mafic units showing reversed polarity magnetization are older than the ones showing normal polarity (Pesonen & Neuvonen 1981) or vice versa, based on published Rb-Sr ages from reversely magnetized units in Kumlinge (1599 ± 26 Ma) and Korsö (1600 ± 30 Ma) (Pesonen et al. 1985; Suominen 1991). These Rb-Sr data are from whole rock analyses, which should be interpreted with caution, since there are cumulates and minerals in mafic rocks that are not in isotopic equilibrium, meaning that the whole rock isotopic method does not always work. Moreover a detailed mineralogical study of ovoids from the Vehmaa rapakivi (SW Finland; Fig. 1) batholith by Shebanov et al. (2000) showed that core zones of these ovoids give a U-Pb (zircon) age of 1630 Ma, and the matrix gives a U-Pb (zircon) age of 1573 Ma. These data indicate that there is a Subjotnian assemblage in SW Finland that gives the same age as the E-W dyke swarm and the SE Finnish rapakivi batholiths, suggesting a continuous Subjotnian magmatic province (Shebanov et al. 2000). Furthermore, both chemical and mineralogical compositions provide evidence for mixing of rapakivi and mafic magmas, indicating that the emplacement of Subjotnian rapakivi batholiths were coeval with the intrusion of the dykes (Lindberg and Eklund, 1992; Eklund et al., 1994). This study provides a new U-Pb (zr) age of 1575.9 ± 3.0 Ma for a mafic dyke in Korsö. Combined with earlier studies, U-Pb geochronology shows that Subjotnian units in SW Finland are very close to each other in age (within the error limits) (Suominen 1991). We favour the 1570-1580 Ma age range for dykes, since (1) most of the U-Pb ages fall in this age range; (2) the younger age (1540 Ma, Suominen 1991) was suggested from only from one sample in Föglö and evidence was found for subsequent disturbance during tectonic movements along a fracture line west of the sampling site. Suominen (1991) noted that there are older zircons in the sample and a second sample from the nearby Källsholm island yielded an age of 1577 ± 12 Ma; and (3) structurally mingled and mixed diabases and rapakivis at the outskirts of the main Åland rapakivi area supports coeval magmatism (Lindberg & Eklund 1992; Eklund 1993; Eklund et al. 1994) while the almost complete absence of cross-cutting dykes within the rapakivi indicates a low probability of late magmatism.

5.2 Combining results with earlier paleomagnetic studies at Åland Archipelago

Paleomagnetic studies of Åland Archipelago already started in the sixties (Neuvonen & Grundström 1969; Neuvonen 1970; Johnson 1979; Pesonen & Neuvonen 1981). These studies yielded dual polarity magnetization from different units (Table 2). Two of the dykes that show normal polarity were dated at 1540 ± 12 Ma (U-Pb, Suominen 1991) and 1577 ± 12 Ma (U-Pb, Suominen 1991).

The authors indicate that the dykes from Föglö island provide a positive baked contact test, but the baked data have not been presented. Two of the dykes that show reversed polarity have previously been dated with U-Pb method. The other one gives a coherent age of 1576 ± 13 Ma, whereas the other shows a vague age range of 1540-1577 Ma and is not dated by a discordia since there were too few zircons (Suominen 1991). Our new precise age of 1575.9 ± 3.0 Ma adds new data to R polarity dykes.

Previous data for Åland rapakivi granite (1568 ± 10 Ma, 1579 ± 13 Ma) data come from an unpublished MSc thesis (Johnson 1979) and included only few samples. It was assigned to show normal polarity. Our study shows, however, that both normal and reversed polarities occur. Figure 1 shows that normally or reversely magnetized dykes do not occur on the same island or islet, but the polarity is constant in all dykes within a single island (Figure 1). We have combined our primary paleomagnetic data with previous data so that each dyke will get a unit weight in a grand mean pole calculation (Table 2). The mean from 31 sites of normal ChRM directions is $D=12.4^\circ$, $I=10.5^\circ$, $k=12.9$, $a95=6.9^\circ$ (Figure 5). The corresponding grand mean paleomagnetic pole is at 34.6°N , 185.5°E , $K=14.6$, $A95=6.5^\circ$ (Figure 7b). For 56 reversed sites the ChRM mean is $D=186.2^\circ$, $I=24.9^\circ$, $k=31.26$, $a95=3.5^\circ$ (Figure 5), and the grand mean paleomagnetic pole derived from 56 VGPs is at 16.2°N , 194.8°E , $K=15.6$, $A95=5.0^\circ$ (Figure 7b). The resulting means do not pass the reversal test of McFadden and McElhinny (1990) i.e. they are not antiparallel at a 95% confidence level.

5.3 Asymmetric magnetization of Åland dykes

Site mean magnetization values from dyke intrusions are plotted in Figure 5. For both polarities inclination values vary from ca. -30° to ca. 30° and declination values are ca. 40° . Non-antiparallel directions have already been obtained in earlier Subjotnian studies from Fennoscandia (e.g. Pesonen & Neuvonen 1981). Several explanations for the asymmetry can be offered: (1) an unremoved secondary component; (2) an age difference between R- and N-polarity intrusions with continental drift (change in latitude); (3) relative crustal tilting between R- and N-polarity "dominated" blocks; or (4) the magnetic field that was contaminated by a permanent non-dipole field (e.g., Pesonen & Neuvonen 1981; Veikkolainen et al. 2013; 2014).

Unremoved secondary component

Both polarity samples show the viscous component due to Present Earth Field (PEF) and/or the other secondary component (Figures 3 and 4) during the demagnetization. Unremoved secondary

component could explain the obtained difference between means of N – and R – polarity data. Even though the linear fits of the data points of the primary component are straight lines and decay to origin the components might be mixed. For Åland data inflection point between the PEF component from primary component is more subtle in N-polarity data. Figure 5 shows that the N-polarity data have a wider dispersion of inclinations than R-polarity data supporting unremoved secondary component. Additional support for component mixing comes from the secondary component distribution (Figure 5), which is streaked in part toward the N-polarity direction.

Age difference

Positive baked contact tests verify that a primary component was separated from both polarity dykes. Yet: (1) the errors in Suominen (1991) U-Pb ages are larger than in our new age (1575.9 ± 3.0 Ma), (2) one normal polarity dyke provided an age of 1540 ± 12 Ma (Suominen, 1991); and (3) Suominen (1991) favors an age of 1569 ± 3 Ma for the dykes, which could indicate that there is indeed an age difference between the dykes. Scatter may also arise from individual plate motion (perhaps Baltica alone, or perhaps within the Nuna supercontinent; Zhang et al. 2012) since similar asymmetry is also seen in Satakunta data (Salminen et al. 2013; Figure 7). However the nearly coeval Subjotnian units (e.g. Nordingrå in Sweden) do not reveal polarity asymmetry, the asymmetry in Åland is also seen in baked rocks, and the error bars of current U-Pb age data are overlapping. This indicates that asymmetry could be explained by a small but significant age difference between normal and reversed dykes, but the actual age span of the remanence acquisition in the normal and reversed dykes awaits further precise dating.

Relative crustal tilting

Relative tilting of blocks with N- and R-polarity dykes has explained asymmetry of the Matachewan dykes (Halls & Shaw 1988). In Åland the R- and N- polarity dykes form clear areas; the majority of the R-polarity dykes are obtained from the NE part of the sampling area (Figure 1), whereas the majority of the N-polarity dykes are obtained from the SSE part of the sampling area. This could indicate that the different polarity dykes occur on different blocks. However in Åland the majority of the dips of the dykes are vertical to subvertical and R- and N-polarity dykes show similar trends, negating the different tilting of the blocks.

Non-dipolar field contamination

In paleomagnetic studies we assume that the Earth's magnetic field can be described with the Geocentric Axial Model. Deviations from this model could cause asymmetries in paleomagnetic data. However, based on recent inclination and reversal asymmetry analyses of the Precambrian paleomagnetic data, it is proposed that the Geocentric Axial Model of the geomagnetic field is valid throughout the Precambrian (Veikkolainen et al. 2013, 2014). We can therefore conclude that asymmetry could be explained by age difference between N- and R-polarity data.

5.4 New Subjotnian paleomagnetic poles for Baltica

Both polarity poles fulfill five Van der Voo (1990) reliability criteria providing new key poles (e.g. Buchan & Halls 1990; Buchan et al. 2000) for Baltica. They have: (1) well-determined U-Pb ages that are also the age of magnetization; (2) a sufficient number of samples that were demagnetized; (3) adequate demagnetization methods used; (4) positive baked contact tests; and (5) structural control. Since the mean normal and reversed directions do not pass the reversal test (McFadden & McElhinny 1990) they are not antiparallel in 95% confidence level which indicates that the data are asymmetric. Consequently the criteria number six (antiparallel polarities are present) is not satisfied. The other criterion they do not satisfy is number (7) - a similarity to younger poles. The poles (are similar to the poles obtained from Carboniferous and Permian formations in Sweden and Norway (e.g. Torsvik et al. 1992). However, these areas are more than 500 km to the southwest of our sampling sites, and considering the positive baked contact tests for two dykes it is very unlikely that Carboniferous-Permian geological events generated the ChRM in Åland. Our new Åland data combined with recent results from the Satakunta region of western Finland (Salminen et al. 2013; Klein et al. 2013) adds three new or recent key-poles for Baltica's record and refines the Early Mesoproterozoic APW of Baltica.

We plotted each individual VGP from dykes in Figure 7a with other relevant data for Baltica (Table 3). At a few sites (FO, FT, RK/RM, and VS) younger Subjotnian dykes cross-cut older Subjotnian dykes. These dykes are indicated with the letter y in Figure 7a. VGPs of these younger dykes are not distinct from VGPs of older dykes, therefore data from them were combined for mean data. VGPs from quartz porphyritic dykes are comparable to VGPs of diabase dykes, indicating that their magnetization is of similar age, as is also supported by their coeval U-Pb ages (Figure 7a). The poles cannot be separated based on U-Pb ages (Figure 7a). Due to the previously described polarity asymmetry the normal polarity data of both dyke types (diabase and quartz porphyry) occupy slightly higher latitudes than reversed polarity data. Since the asymmetry is mainly in inclinations (declination share 180° symmetry within the error limits) the longitudinal spread of poles is similar.

Figure 7b reveals that data of Åland dykes is similar to Subjotnian NNE-SSW trending Satakunta dykes (300 km north of Åland) suggesting that they belong to the same dyke swarm converging on the western margin of Finland (western part of Baltica) (Figure 7b).

Rapakivi granites (1568 ± 10 Ma and 1579 ± 13 Ma; Suominen 1991) provide dual-polarity data with nearly symmetric pole of 23.1°N , 192.6°E , $K=38.6$ $A95=9.8^\circ$ which mean plots close to the reversed polarity dyke pole (Figure 7b). In this study normal polarity comes from rapakivi and reversed polarity from baked host rock. This could be explained by the heating and subsequent cooling in the host rock as rapakivi was emplaced in multiple magma pulses (e.g. Bergman, 1986) over a long period (20 – 60 Ma) (Vigneresse, 2005). Both normal and reversed polarity poles from Åland dykes fall within 95% confidence circle of rapakivi pole (Figure 7b).

5.5 Nuna reconstruction with emphasis on NENA configuration

Figure 8 shows the new normal and reversed polarity poles from the Åland dykes, together with well-dated Mesoproterozoic poles from other continents (Table 3). The reconstruction shows the relative positions of cratons in present North American coordinates and the Euler rotation parameters are shown in Table 4. In this reconstruction the normal polarity mean pole of Åland dykes (1570-1580 Ma; Suominen (1991) favored 1569 ± 3 Ma age) overlaps with the 1592 ± 3 Ma Western Channel Diabase (WCD) pole from Laurentia (Figure 8a) indicating that Laurentia and Baltica were joined at that time. Similarity of poles at 1.75 Ga, 1.46 Ga and 1.27 Ga (Figure 8a) further suggests that the two continents were connected during the whole time period between 1.75 and 1.27 Ga. The reversed polarity pole from Åland dykes does not overlap with similar aged Laurentian poles, as the normal polarity pole does. Similarity in geology, e.g. the 2.1 – 1.8 Ga collisional events on several cratons, led many researchers to propose that a Mesoproterozoic supercontinent, such as Nuna, existed in the Early Proterozoic (e.g. Hoffman 1997; Meert 2002; Rogers & Santosh 2002).

Earlier reconstructions of this supercontinent were based on geology and therefore were non-unique. The number of good quality paleomagnetic data has increased in recent years enabling more reliable global reconstructions based on paleomagnetic data (e.g. Evans & Mitchell 2011; Zhang et al. 2012). Zhang et al. (2012) provided a reconstruction that encompasses almost all major continents. In that reconstruction all selected high-quality poles for the time interval of 1.8–1.4 Ga fall on a common APWP, whereas poles of >1.8 Ga from different continents or cratons diverge with increasing ages. These data suggest that Nuna was likely assembled by ca. 1.75 Ga.

In several recent reconstructions of Nuna, Baltica and Laurentia form its core in the geologically valid NENA configuration (e.g. Gower et al. 1990; Karlstrom et al. 2001; Buchan et al. 2000; Pesonen et al. 2003; Zhao et al. 2006; Salminen & Pesonen 2007; Evans & Pisarevsky 2008; Salminen et al. 2009; Evans 2009). We favor the NENA configuration over the one where western Baltica is adjacent to SE Greenland (Halls et al., 2011) since NENA is also supported by the 1775-1270 Ma paleomagnetic data from both Laurentia and Baltica. Recently it was proposed that Siberia also formed part of the core of Nuna together with NENA between 1.8-1.4 Ga (Wingate et al. 2009; Evans & Mitchell 2011). The latest paleomagnetic data from Nova Guarita mafic intrusions (Bispo-Santos et al. 2012) suggests that Nuna also included the Amazonia and West Africa cratons in the so called SAMBA connection (Johansson 2009) during 1.8 and 1.4 Ga. Laurentia, Baltica and Amazonia cratons formed the other margin of Nuna where the Andian-type, subduction-related accretionary mobile belts such as the Yavapai-Mazatzal-Labradorian (1.8-1.4 Ga) belts in Laurentia, the Trans-Scandinavian Igneous belt (1.8-1.7 Ga) and the Gothian (1.66 – 1.52 Ga) belts in Baltica and the Ventuari-Tapajós (1.95-1.8 Ga) and Rio Negro-Juruena (1.85-1.55 Ga) belts in the Amazonian craton were formed during the Paleo- to Mesoproterozoic. Other cratons are shown (Figure 8a) as in a recent Nuna configuration of Zhang et al (2012).

At 1.59 Ga the core of Nuna (Baltica, Laurentia, Siberia and Amazonia) occupied equatorial to low latitudes. Paleomagnetic data appear to support a coherent Nuna until ca. 1.40 Ga (Figure 8a), but poles younger than ca. 1.3-1.2 Ga diverge from each other indicating that Nuna had been broken-up by that time. Zhang et al. (2012) pointed out that the long break-up time of Nuna is similar to Rodinia in length: it started at 1.6-1.4 Ga as manifested by large igneous provinces and reached its final stage at 1.28-1.26 Ga.

6. Conclusions

In this paper we report a new U-Pb (zircon) age of 1575.9 ± 3.0 Ma for the reversed polarity Korsö dyke, from Åland Archipelago, Finland. The new age with analyses of previous data tightens the occurrence of magmatism in Åland in between 1570-1580 Ma.

The paleomagnetic results reveal dual polarity magnetizations in all rock types with a pronounced reversal asymmetry occurring in dykes. This is probably due to an unremoved secondary component, which is affecting more the N – polarity data than R – polarity data. We obtained two new key-poles (1570-1580 Ma), which include new and earlier published data (Neuvonen &

Grundström 1969; Jonhson 1979; Pesonen & Neuvonen 1981) for Baltica: a normal polarity pole (1570-1580 Ma; Suominen (1991) favored 1569 ± 3 Ma age) at $\text{Plat}=34.6^\circ\text{N}$ and $\text{Plon}=185.5^\circ\text{E}$ with $K=14.6$ and $A95=6.5^\circ$ (31 sites) and a reversed polarity pole (1570-1580 Ma; 1575.9 ± 3.0 Ma) at $\text{Plat}=16.2^\circ\text{N}$ and $\text{Plon}=194.8^\circ\text{E}$ with $K=15.6$ and $A95=5.0^\circ$ (56 sites). The paleomagnetic data from the Åland dykes are similar to the data from the Satakunta dykes (Salminen et al. 2013), supporting the existence of a 300 km long dyke swarm along the west coast of Finland. Furthermore, we obtained a preliminary dual-polarity pole for rapakivi (1568 ± 10 Ma and 1579 ± 13 Ma; Suominen 1991) in Åland at $\text{Plat} = 20.6^\circ\text{N}$ and $\text{Plon} = 191.2^\circ\text{E}$ with $K=62.1$, and $A95=7.7^\circ$. The number of Early Mesoproterozoic paleomagnetic poles for Baltica is large, but only two poles fulfilled the key-pole criteria before this study. The Åland data adds two new key-poles, increasing the number to four.

This study added a new Baltica-Laurentia key-pole pair (1.57-1.59 Ga) to test the geologically supported NENA configuration. As the normal polarity pole supports the NENA fit, there are now four key-pole pairs; at 1.75 Ga, 1.58 Ga, 1.46 Ga, and 1.26 Ga that give evidence for the NENA configuration. At 1.59 Ga the majority of continents occupied low latitudes. Paleomagnetic data appear to support a coherent Nuna until ca. 1.40 Ga (Figure 8), but poles younger than ca. 1.3-1.2 Ga diverge from each other indicating that Nuna had been broken-up by that time.

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FIGURE CAPTIONS

Figure 1. (a) Simplified geological map of Southern Fennoscandian shield (modified after Rämö, 1991), (b) Geological map of the study area with the location of sampling sites of this study and earlier studies (Neuvonen & Grundström 1969; Johnson, 1979; Neuvonen 1970; Pesonen & Neuvonen 1981). Blue (red) – reversed (normal) polarity magnetization. Orientation of the line indicated strike of the dyke (not available for all). This information was available for only some of the dykes sampled before 2013. TESZ – Trans European Suture Zone.

Figure 2. Concordia diagram of zircon TIMS analyses from the Korsö dyke, Åland, SW Finland. Information on the numbered zircon fractions is found in Table 1.

Figure 3. Positive baked contact test for site FT (Föglö) where a 247 m wide diabase dyke is cut with a 0.3 m wide diabase dyke. Data are plotted as orthogonal projection diagrams, equal-area stereoplots, and normalized intensity. Location of samples are indicated in the lower part of the figure on the site sketch (not in scale).

Figure 4. Representative demagnetization data for both normal and reversed directions from dykes and baked host rocks, plotted as orthogonal projection diagrams, equal-area stereoplots, and normalized intensity.

Figure 5. Site mean directions for primary magnetization for both Åland dykes and rapakivi as well as for their host rocks (Table 2) of this study. Secondary magnetization directions are also shown. Upper left: Site (dyke) mean directions for primary component. Mean for reversed polarity is inverted. Upper right: Site mean directions for rapakivi sites of this study. Low: Site mean for obtained secondary component.

Figure 6. Typical low-field thermomagnetic curves measured from $-192\text{ }^{\circ}\text{C}$ to $700\text{ }^{\circ}\text{C}$ (from room temperature to $700\text{ }^{\circ}\text{C}$ in argon) for selected Åland dykes. Susceptibility values were corrected with empty furnace values. A3: Korsö; A23: Åva; FT: Föglö; and FM: Sälgören (diabase). Left plot shows low and right plot shows high temperature curve (note the change in scale between these two figures).

Figure 7. Poles from this study with Precambrian key-poles for Baltica. (a) Normal and reversed polarity virtual geomagnetic poles (data by each dyke and rapakivi site) from this study (Table 2).

(b) Mean poles from this study with recent Subjotnian mean poles by polarity. AD - Åland dykes (this work): AD-N (Plat: 35°N, Plong: 186°E, A95: 7°); AD-R (Plat: 16°N, Plong: 195°E, A95: 5°); . ARK - Åland Rapakivi (this work): ARK-N (Plat: 23°N, Plong: 190°E, A95: 13°); ARK-R (Plat: 17°N, Plong: 191°E, A95: -). SK2- Satakunta dykes trending E-W (Salminen et al. 2013): SK2-N (Plat: 30°N, Plong: 225°E, A95: 30°); SK2-R (Plat: 33°N, Plong: 200°E, A95: 15°). SK2- Satakunta dykes trending E-W (Salminen et al. 2013): SK1-N (Plat: 32°N, Plong: 183°E, A95: 7°); SK1-R (Plat: 23°N, Plong: 206°E, A95: 16°). SS-Satakunta sandstone (Klein et al. 2013): SS-N (Plat: 28°N, Plong: 175°E, A95: 8°); SS-R (Plat: 31°N, Plong: 208°E, A95: 17°). New Åland poles from dykes fulfill key criteria, but preliminary pole from Rapakivi does not. N/R- normal/reversed; Plat – pole latitude; Plong – pole longitude; A95 - radius of the 95% confidence cone of the pole.

Figure 8. Reconstructing Nuna supercontinent. New data combined with data from Zhang et al. (2012) (a) Selected paleomagnetic poles for the reconstruction of Nuna (in present North American coordinates) according to Euler rotation parameters given in Table 4 (after Zhang et al. 2012). Cratons and their poles are matched in color, and ages following pole abbreviations are in Ma. For more details see Table 3. Recent work of Zhang et al. (2012) showed that poles between ca. 1.78 Ga and ca. 1.60 Ga from Australian cratons, Laurentia, Baltica and North China (NC) define a common APWP of Nuna (light yellow curve). Paleomagnetic poles of NC, Siberia, Laurentia, Baltica and Amazonia against the common APWP indicate common motion at >1.75 Ga to ca. 1.38 Ga. Moreover paleomagnetic data support NENA configuration at least between 1.8 -1.26 Ga. (b) Configuration and paleogeographic position of Baltica, Laurentia, Amazonia and Siberia at ca. 1.59 Ga. Paleomagnetic pole from Laurentia (WC1590 Table 3) was used to plot the paleolatitude of the core of the supercontinent.

Sample information			ISOTOPIC RATIOS*								APPARENT AGES / Ma (±2SE)				
Analysed mineral/fraction	weight / mg	U ppm	Pb ppm	²⁰⁶ Pb/ ²⁰⁴ Pb measured	²⁰⁸ Pb/ ²⁰⁶ Pb radiogenic	²⁰⁶ Pb/ ²³⁸ U	2SE%	²⁰⁷ Pb/ ²³⁵ U	2SE%	²⁰⁷ Pb/ ²⁰⁶ Pb	2SE%	Rho**	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb
A1589 Korsö; zircon l:w>3, black inclusions															
1) +300µm	0.66	1034	260	838	0.34	0.19300	0.40	2.4951	0.42	0.09377	0.13	0.95	1138	1271	1503.4±2.5
2) +150µm	0.48	862	246	1287	0.33	0.22374	0.43	2.9311	0.44	0.09501	0.10	0.98	1302	1390	1528.4±1.8
3) +150µm abraded (5h) broken crystals	0.49	721	241	2350	0.37	0.25967	0.39	3.4561	0.50	0.09653	0.32	0.78	1488	1517	1558.2±5.9
4) +150µm abraded (7h) broken crystals	0.63	815	267	1888	0.35	0.25553	0.39	3.3954	0.40	0.09637	0.08	0.98	1467	1503	1555±1.4
5) +75µm	0.55	785	230	1684	0.35	0.22881	0.39	2.9959	0.40	0.09496	0.08	0.98	1328	1407	1527.3±1.5
6) +75µm abraded (7h) broken crystals	0.65	698	242	2768	0.38	0.26789	0.40	3.5864	0.40	0.09710	0.06	0.99	1530	1547	1569.1±1.2

****)** Error correlation for $^{207}\text{Pb}/^{235}\text{U}$ vs. $^{206}\text{Pb}/^{238}\text{U}$ ratios.

Table 2. Palaeomagnetic results from Åland Subjotnian diabase and quartz porphyritic dykes, rapakivi granites, and their host rocks combined with previous published data.

Site	Island	Lat (°N)	Lon (°E)	width (m)	Str (°)	pol	Age: U-Pb (Ma)	D (°)	I (°)	a95 (°)	k	plat (°N)	plon (°E)	A95 (°)	K	(B)/N/n	Ref
NORMAL POLARITY																	
DIABASE DYKES																	
A01	Enklinge	60.33	20.74	3	45	N	1577 ±12; 1569±3	11.1	22.0	25.2	25.0	40.6	185.9	21.9	32.8	3*/3	
A09	Keistiö	60.37	21.33	0.12	20	N		352.2	6.2			32.4	210.6			1/1	
A11	Keistiö	60.37	21.29	0.35	35	N		7.9	10.0			34.3	191.7			1/1	
A13	Keistiö	60.37	21.29	5	25	N		15.0	-3.9	11.5	45.1	26.6	184.5	7.3	111.3	5*/5	
FG	Lill Broskär	60.11	19.81	20	320	N		15.8	28.2			43.4	178.6			2*/2	
FO	Föglö	60.41	20.99		30	N		12.2	-8.1			24.8	187.7			2*/2	
FT	Föglö/Källsholm	60.05	20.65	243	30	N		9.7	15.0	3.3	114.6	37.2	188.6	2.3	242.1	17*/46	
FT	Föglö/Källsholm	60.05	20.65	0.3	40	N		5.5	6.8	17.2	16.1	33.1	194.0	12.0	32.3	6*/11	
JC	Stor Broskär	60.09	19.8		75	N		13.5	4.5	6.8	58.3	31.3	184.0	5.6	86.2	9*/26	
NB	Norra Betesön	60.07	20.6	1	35	N		24.3	26.0	14.7	71.4	40.4	169.1	12.3	102.0	3*/5	
	Mean diabase dykes					N		10.5	10.8	8.8	31.1	34.8	187.7	6.4	58.4	10*/49/102	this work
QUARTZ PORPHYRY DYKES																	
A23	Åva	60.45	21.07		240	N	1576±13	12.4	38.0	5.6	273.0	50.0	182.8	4.6	396.3	4*/4	
JC	Stor Broskär	60.09	19.8			N		7.2	15.4	13.3	33.9	37.6	190.6	10.7	52.4	5*/13	
JD	Jyddö	60.1	20.53			N	1571 ±20	23.6	-5.5	8.9	107.0	24.5	174.4	6.8	181.6	3*/4	
RC	Next to Pepparn	60.09	19.82			N		5.3	6.4	10.1	83.0	33.0	193.5	7.8	138.8	4*/7	
	Mean quartz porphyry					N		12.2	13.6	23.3	16.4	36.4	185.2	14.7	40.2	4*/16/28	this work
BAKED HOST																	
A01	Enklinge	60.33	20.74			N		11.3	22.8			40.9	185.9			2*/2	
A9-13	Keistiö	60.37	21.29			N		357.8	11.3			35.3	204.0			1/1	
FG	Lill Broskär	60.11	19.81			N		35.4	11.4			29.4	158.4			1/1	
FT	Föglö/Källsholm	60.05	20.65			N		13.9	29.2			44.4	181.7			2*/6	
FT	Föglö/Källsholm	60.05	20.65			N		13.6	16.2	6.1	97.7	37.3	183.6	4.2	210.1	7*/17	

JC	Stor Broskär	60.09	19.8		N		20.1	0.3			38.7	177.9			2*/10	
NB	Norra Betesön	60.07	20.6		N		16.5	20.4	3.7	333.3	39.0	179.7	3.0	49.2	6*/22	
	Mean baked host				N		15.6	16.2	10.8	31.9	37.0	181.1	9.4	42.0	7*/21/59	this work
	UNBAKED HOST ROCK															
FT	Föglö	60.05	20.65		SVF		350.6	41.3			50.7	223.8			1/2*	
Earlier normal polarity data (refs. 1-4 below)																
	Bergskär	60.6	20.6		N	1540 ± 12; 1569 ± 3	8.0	8.0			33.7	191.0			1*/2*	1
	Bergskär	60.03	20.62		N	1540 ± 12; 1569 ± 3	14.0	19.0	9.9		38.7	182.8			1/7*	3
	Föglö/Källsholm	60.05	20.63		N		14.0	11.0	1.0		34.5	183.6			1/7*	3
	Kråkskärsharun	60.06	20.63		N		14.0	-6.0	5.7		26.0	185.0			1/7*	3
	Vestrafjärdsharun	59.95	20.56		N		13.0	10.0			34.2	184.8			1/7*	3
	Vidkobb	59.93	20.53		N		19.0	11.0			33.7	177.6			1/7*	3
	Vidskär, N	59.94	20.52		N		2.0	12.0			36.1	198.1			1/7*	3
	Vidskär, S	59.93	20.53		N		13.0	5.0			31.7	185.2			1/7*	3
	Tvidolskär	60	20.6		N		6.0	-31.0			13.1	194.7			1/7*	3
	Föglö and Sottunga dykes	60	20.6		N	1540±12; 1569±3; 1577±12	11.2	-2.8	12.7	29.0	27.8	187.5	6.4	12.7	6*/25	4 this work
AD-N	GRAND MEAN NORMAL POLARITY DATA					1570-1580; 1569±3	12.4	10.5	6.9	12.9	34.6	185.5	6.5	14.6	36*/150/272	
REVERSED POLARITY																
	DIABASE DYKES															
A02	Korsö	60.41	20.99	> 100	350	R	1575.9 ± 3.0	177.8	19.3	16.4	22.8	19.6	203.3	13.5	33.2	5*/5
A03	Korsö	60.42	20.99	> 100	350	R	1575.9 ± 3.0	176.9	10.8	10.6	28.5	24.1	204.4	8.1	47.5	8*/8
A04	Brändö-S-tip	60.4	21.04	0.2	45	R		186.4	21.7	24.9	14.6	18.2	194.5	25.9	13.6	4*/4
A05	Brändö-S-tip	60.4	21.04	0.3	45	R		165.6	28.1			13.8	215.4			2*/2
A06	Brändö-S-tip	60.4	21.04	0.1	45	R		172.2	19.7	30.0	17.9	19.2	209.2	31.0	16.9	3*/3
A07	Brändö-S-tip	60.4	21.04	0.15	45	R		178.4	19.6	7.5	271.2	19.5	202.7	7.2	291.9	3*/3
A08	Brändö-S-tip	60.42	20.99	0.3	45	R		182.9	28.9	2.1	34.7	14.1	198.1	1.4	81.4	3*/3
A22	Brändö-S-tip	60.42	20.99	> 5	45	R		194.4	18.9			18.9	186.0			1/1
A14	Torsholma-Barkholm	60.35	21.06	1.5	40	R		179.8	25.0	7.6	64.8	16.5	201.2	6.2	96.0	7*/7

A15	Torsholma-Barkholm	60.35	21.06	0.8	40	R		173.9	17.3	3.8	251.0	20.6	207.5	3.6	286.6	7*/7	
A16	Torsholma-Barkholm	60.35	21.06	0.5	40	R		175.1	21.8	7.7	63.1	18.2	206.2	7.4	67.1	7*/7	
A17	Torsholma-Barkholm	60.35	21.06	1.5	25	R		175.0	18.3	6.2	118.1	20.1	206.3	5.6	142.6	6*/6	
A18	Torsholma-Barkholm	60.35	21.06	1	40	R		175.4	22.5	6.1	97.4	17.9	205.8	5.9	106.9	7*/7	
A19	Torsholma-Barkholm	60.35	21.06	1.5	30	R		171.7	18.6			19.8	209.8			2*/2	
A20	Torsholma-Barkholm	60.35	21.06	1.5	25	R		180.7	21.5	8.1	56.2	18.5	200.4	8.1	56.6	7*/7	
A21	Torsholma-Barkholm	60.35	21.06	1.5	35	R		176.7	33.2	9.1	71.1	11.5	204.3	9.7	63.0	5*/5	
CG	Långnäs	60.14	19.83			R		200.4	25.1			14.9	179.3			2*/3	
DE	Degerbrok	60.26	20.99	8	40	R		186.0	24.7	9.0	46.1	16.6	194.9	8.9	46.7	7*/10	
EK	Alöklubbsören	60.38	20.82	9	60	R		187.1	30.5			72.2	157.4			2*/5	
FM	Sälgören	60.23	20.82	2	50	R		202.8	18.7	4.7	118.6	17.8	177.1	4.3	145.3	9*/30	
KB	Kungsholm	60.11	20.05		110	R		183.3	5.6	22.5	12.5	27.0	196.4	12.4	39.1	3*/5	
KW	Kungsholm	60.11	20.05		110	R		183.6	11.0	4.7	166.3	24.3	196.1	3.3	330.0	7*/13	
LU	Ljungskär	60.27	20.96	1.8	40	R		190.5	19.6	9.4	67.5	19.2	190.0	9.4	67.5	5*/11	
RK, RM	Rosmunklobb	60.3	20.85	8	40	R		187.8	27.1	9.4	27.6	15.1	193.1	7.8	39.4	10*/18	
RK, RM	Rosmunklobb	60.3	20.85	4	30	R		190.5	22.2	3.2	92.1	17.7	190.0	3.0	104.5	23*/54	
VS	Västersten	60.13	19.65	2	275	R		188.8	16.9	19.4	41.6	20.9	190.3	16.0	60.5	3*/12	
VS	Västersten	60.13	19.65	1	360	R	1569±3	192.0	6.9	8.2	55.1	25.7	186.3	7.5	65.9	7*/26	
VT	Västra Sundskär	59.92	20.05	0.5	10	R		186.7	38.3			67.5	163.6			2*/5	
	Mean diabase dykes							182.9	21.4	3.7	55.0	18.5	197.7	3.5	69.1	28*/157/269	this work
QUARTZ PORPHYRY DYKE																	
CG	Björkudden	60.14	19.83			R		201.2	24.4			15.1	178.4			1/5/5	
BAKED HOST																	
A04	Brändö-S-tip	60.4	21.04			R		153.5	7.6			22.5	229.8			2*/2	
FM	Sälgören	60.23	20.82			R		184.5	29.5			13.9	196.4			1/1	
KB	Kungsholm	60.11	20.05			R, N		177.0	17.9	19.8	8.8	20.7	203.3	15.8	13.3	8*/8	
KW	Kungsholm	60.11	20.05			R		209.6	13.8			18.9	168.8			2*/4	
RK, RM	Rosmunklobb	60.3	20.85			R		199.1	8.1			23.9	180.0			1/2*	
VS	Västersten	60.13	19.65			R		176.8	24.5			76.8	193.8			1/1	

	Mean baked host		R		183.6	19.5	14.9	17.4	19.5	196.7	14.0	19.5	6*/15/18	this work
	UNBAKED HOST ROCK													
RK, RM	Rosmunklobb		SVF		333.3	49.4			50.5	-37.6			1/2*	
	Mean (DB, QP and baked rocks)		R	1570-1580	183.6	21.1	3.8	39.6	18.2	197.0	3.5	46.6	36*/178/293	this work
	Earlier reversed polarity data (refs. 1-4 below)													
	Kumlinge	60.3	20.8	R	192.0	43.0			4.1	189.9			1/2*	1
	Brändö	60.3	20.7	R	192.8	25.4	17.3	29.0	15.6	187.7	10.0	18.6	4*/8	1
	Korsö	60.4	21	R	1575.9 ± 3.0	188.0	24.0		16.7	192.8			2*/2	2
	Korsö	60.4	21	R	1575.9 ± 3.0	182.0	28.0		14.7	199.0			1/2*	1
	NE of Slätskär	60.3	20.83	R	195.0	15.0	2.5		21.0	184.9			1/7*	3
	E of Slätskär	60.3	20.83	R	190.0	31.0	8.8		12.6	191.0			1/6*	3
	E of Slätskär	60.29	20.8	R	189.0	42.0	-		5.2	192.6			1/2*	3
	SW of Slätskär	60.29	20.78	R	151.0	50.0	13.6		-4.1	225.5			1/3*	3
	Kumlinge, NE	60.29	20.78	R	143.0	49.0	8.5		-5.2	232.4			1/6*	3
	Kumlinge-Brändö	60.3	20.8	R	198.6	30.2	7.9	60.0	12.2	182.0	5.0	9.0	7*/25	4
AD-R	GRAND MEAN REVERSED			R	186.2	24.9	3.5	31.1	16.2	194.8	5.0	15.6	56*/216/331	This work
AD-R+N	GRAND MEAN N+R	60	20	N,R	006	8.6	4.0	13.7	23.7	191.4	2.8		92*/366/603	
	RAPAKIVI REVERSED POLARITY													
FH	Flisö/Färnsholm	60.03	20.04	R	181.4	13.9			22.9	198.5			2*/5	
SC	Skräckskär	59.92	20.09	R	196.8	34.2	24.7	25.9	9.9	184.2	25.7	24.1	3*/3	
ARK-R	Mean rapakivi reversed polarity			R	1568 ± 10; 1579 ± 13	188.5	24.3		16.6	191.0			2*/5/8	this work
	BAKED HOST FOR RAPAKIVI, NORMAL POLARITY													
IC	Flisö	60.01	20.35	N	9.9	15.5			37.3	187.9			2*/4	
HC	Gripö	60.5	22.4	N	13.2	-13.2	4.6	112.0	22.0	187.2	2.7	324.7	3*/10	
KJ	Blekörarna	60.14	20.53	N	14.2	-29.4	3.6	43.7	13.1	186.7	3.3	50.8	9*/38	
GC	Rödsjärshällen	59.95	20.18	N	3.1	-21.7			18.7	196.9			1/1	
ARK-N	Mean baked host by rapakivi, normal polarity			N	10.1	-12.4	23.4	16.3	22.9	190.0	12.8	52.3	4*/15/53	this

ARK mean	Mean Rapakivi			R, N		9.6	-16.4	15.6	19.4	20.8	190.3	9.2	54.1	6*/20/61	work this work	
	Earlier rapakivi data (refs. 1-4 below)															
	Åland Rapakivi	60.5	22.3	N		5.8	-18.8	18.8	14.0	19.5	194.4	15.0	18.0	18/1/7*	1	
	GRAND MEAN RAPAKIVI AND BAKED ROCKS				R, N	1568 ± 10; 1579 ± 13	9.0	-16.8	12.8	23.1	20.6	191.2	7.7	62.1	7*/21/68	this work

lat/long - sampling latitude and longitude. str – structural orientation (strike) of dykes. pol - polarity of the isolated direction: N(R) - normal (reversed) polarity. D - declination. I - inclination. α_{95} - the radius of the 95% confidence cone in Fisher (1953) statistics. k – Fisher (1953) precision parameter. Plat/Plong – pole's latitude/longitude of the pole. A95 - radius of the 95% confidence cone of the pole. K - Fisher (1953) precision parameter of pole. (B)/N/n - number of analyzed (sites)/samples/specimens. * - denotes the number used to calculate mean value. SVF – Svecofennian. References: 1: Johnson, 1979; 2: Neuvonen, 1970; 3: Neuvonen & Grundstrom, 1969, 4: Pesonen & Neuvonen, 1981

Table 3. Selected palaeomagnetic poles for Nuna reconstruction at 1.6-1.4 Ga.

Code	Rock unit	Plat (°N)	Plong (°E)	A ₉₅ (°)	Age (Ma)	References
BALTICA-FENNOSCANDIA						
SVF1	Mean Svecofennian 1	41	233	5	1881	Pesonen et al. 2003
SVF2	Mean Svecofennian 2	48	225	3	1840	Pesonen et al. 2003
HG	Hoting gabbro	43	233	11	1786 ± 10	Elming et al. 2009
SI	Småland intrusives ^a	46	183	8	1780 ± 3; 1776 +8/-7	Pisarevsky & Bylund 2010
SQ	SE quartz porphyry dykes	30	175	9	1617 ± 2, 1639 ± 9, 1638 ± 53	Neuvonen 1986
AD-N	Åland dykes N-polarity	34.6	185.5	6.5	1570-1580; 1569±3	this study
AD-R	Åland dykes R -polarity	16.2	194.8	5.0	1570-1580; 1575.9 ± 3.0	this study
SK1	Satakunta N-S & NE-SW dykes	29	188	7	1565	Salminen et al. 2013
LA	Lake Ladoga mafic rocks ^c	15	177	6	1452 ± 12	Lubnina et al. 2010
PJ	Mean post-Jotnian intrusions ^c	4	158	4	1265	Pesonen et al. 2003
LAURENTIA						
MB	Melville Bugt dyke swarm	5	274	9	1622 ± 3, 1635 ± 3	Halls et al. 2011
WCD	Western Channel diabase ^c	9	245	7	1592 ± 3 1590 ± 4	Irving et al. 1972 Hamilton & Buchan 2010
MK	Michikamau intrusion ^c	-2	218	5	1460±5	Emslie et al. 1976
ST	St. Francois Mnt acidic rocks ^c	-13	219	6	1476±16	Meert & Stuckey 2002
Mean	Mean of MK and ST	-7	218	6	1468	Salminen & Pesonen 2007
ZG	Zig-Zag Dal intrusions	11	221	3	1382±2	Evans & Mitchell 2011
MC	Mackenzie dykes grand mean ^c	4	190	5	1267+7/-3	Buchan & Halls 1990
SIBERIA						
CD	Chieress dyke	4	258	9/5	1384±2	Ernst & Buchan 2000
OL	Olenëk mafic intrusion in Sololi Group	33.6	253.1	10.4	1473±24	Wingate et al. 2009

AMAZONIA						
NG	Nova Guarita mafic intrusions	-47.9	245.9	7.0	1418.5±3.5	Bispo-Santos et al. 2012
NORTH CHINA BLOCK (NCB)						
TL	Tieling formation	11.6	187.1	8.1/4.9	1437±21	Wu 2005
YZ	Yangzhuang formation	17.3	214.5	8.0/4.1	1560-1440	Wu et al 2005
NORTH AUSTRALIA						
BDU	Balbirini dolomite (upper),	-52	176.1	7.5	1589±3	Idnurm, 2000
BDL	Balbirini dolomite (lower)	-66.1	177.5	5.7	1613±4	Idnurm 2000
ED	Emmerugga dolomite	-79.1	202.6	6.1	1645	Idnurm et al. 1995
TS	Tooganinie formation	-61	187	6	1650±3	Idnurm et al. 1995

Code – code in Figure 7; Plat – pole latitude; Plong – pole longitude; A_{95} – 95% confidence circle of the pole. ^a – Used rotation of Evans and Pisarevsky, 2008 for Baltica to Laurentian reference frame; ^b - Used rotation of Roest & Sirvastava, 1989 for Greenland to Laurentian reference frame. ^c Primary magnetization demonstrated by baked or inversed baked contact test from the dated rock units.

Table 4. Euler rotation poles (Elat, Elong, Erot) for Nuna reconstruction (Zhang et al. 2012).

Baltica to Laurentia: (47.5, 1.5, 49), after Evans & Pisarevsky (2008)

Amazonia to Laurentia: (53, 293, 127), based on SAMBA geology (Johansson 2009)

India to Laurentia: (56.0, 75.4, 123), after Zhang et al. 2012

NCB to Laurentia: (45.7, 330.8, 33.4), after Zhang et al. 2012

North Australia to Laurentia:

(31.5, 098, 102.5) after Evans & Mitchell (2011) and Payne et al. (2009)

Mawson block to North Australia:

South Australia to North Australia (-18, 134, 51), after Payne et al. (2009)

West Australia to North Australia (-20, 135, 40), after Li & Evans (2011)

Mawson block, E Antarctica to present Australia (-2, 38.9, 31.5), after Powell & Li (1994)

Siberia to Laurentia:

Anabar block to Laurentia (78, 099, 147), after Evans & Mitchell (2011)

Aldan to Anabar before Devonian (60, 115, 25), after Evans (2009)

W Africa to Laurentia: (30, 266, 70.7), based on SAMBA geology (Johansson 2009)

Laurentia absolute rotation (for use in Figure 8b only): For 1.59 Ga reconstruction (0, 155, 81)

FIGURE 1

FIGURE 2

FIGURE 3

NORMAL POLARITY

REVERSED POLARITY

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 8