

Palaeomagnetic Evidence for the Drift of the Fennoscandian Shield

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(Received: February 1996; Accepted: August 1996)

Abstract

The basic requirements of reliable palaeomagnetic data for calculation of continental drift and past plate reconstructions are that the Natural Remanent Magnetization is primary, separated from younger overprints by multicomponent analysis and that it is statistically well defined. The age of the remanence is established by using rock units dated predominantly by the U-Pb method on zircon or baddeleyite. By using these criteria, the palaeomagnetists of Scandinavia have recently defined nine key palaeopoles ranging in age from 2446 Ma to 930 Ma.

The oldest key pole was obtained from the 2446 Ma old gabbro-diorite dykes in Russian Karelia. A pole of the age of 1930 Ma isolated in the gabbro-diorite intrusion in Tsuomasvarri, in northern Finland. An 1880 Ma pole represents four separate syn- to late orogenic gabbro intrusions at the Svecofennian orogen in Finland and Sweden. A younger pole of 1840 Ma was obtained from the post-orogenic Haukivesi lamprophyre dykes in central Finland. Two Subjotnian palaeopoles with mean ages of 1630 and 1560 Ma were obtained from dyke rocks in SE and SW Finland, respectively. A Jotnian palaeopole with a mean age of 1266 Ma represents the diabase dykes and sills in SW Finland. The youngest palaeopole with a U-Pb age of 930 Ma, is the mean from two Sveconorwegian mafic intrusions in southern Norway. A palaeopole from the Laanila dykes in northern Finland, with a mean Sm-Nd age of 1030 Ma is the only key pole to fill the gap between 1266 and 930 Ma.

Calculations of the past continental drift of the Fennoscandian Shield show that at 2450 Ma the Fennoscandian Shield was located at a latitude of 30°S and was rotated about 90° clockwise with respect to its present orientation. At 1930-1840 Ma the Fennoscandian Shield was located at a latitude of about 15°N and drifted to the Equator by 1630-1560 Ma. At 1270 Ma Fennoscandia was located at about 20°S and drifted further south by 1030 Ma. The highest southern latitude of ca. 70°S was attained 930 Ma ago.

Key words: palaeomagnetism, Fennoscandia, Precambrian, continental drift, palaeolatitude

1. Introduction

One of the most important tasks of palaeomagnetic studies in Fennoscandia has been to calculate the drift history of the shield and to try to detect intracontinental movements within the shield. Recently, the existence of supercontinents in the Precambrian has been suggested by correlation of coeval geological features in different

continents (see e.g. *Hoffman*, 1991; *Dalziel*, 1991; *Park*, 1994 and references therein). Also, recent palaeomagnetic studies have provided direct evidence for a supercontinent called Rodinia (see e.g. *Meert et al.*, 1995) in the Precambrian. In previous palaeomagnetic reconstructions for Early Precambrian time (e.g. *Piper*, 1980; 1987; *Poorter*, 1981; *Stearn and Piper*, 1984), there was a lack of precise isotopic dating and hence, an uncertainty in the magnetization ages used in reconstructions. Today, precise U-Pb dating has provided the means to determine the magnetization ages of rock units more accurately. However, before we can reconstruct the Fennoscandian Shield with other shield areas, reliable and coeval palaeomagnetic data from each shields are needed.

The main aim of this paper is to present the most reliable palaeomagnetic data from the Fennoscandian Shield. In Fennoscandia, palaeomagnetic data are updated by the Scandinavian palaeomagnetists every fourth year (see *Pesonen et al.*, 1991; *Pesonen and Van der Voo*, 1991; *Elming et al.*, 1993), and in that connection the criteria for reliable data are also set. The purpose of the latest evaluation in 1994 (*Mertanen and Pesonen*, 1995b; *Pesonen*, 1995) was to establish common reliability criteria for the data from Fennoscandia and Canada in order to facilitate reconstructions of the Fennoscandian Shield and Laurentia. These criteria and the data are discussed here. The drift history of the Fennoscandian Shield based on the key poles, is also shown. Results of the Fennoscandian/Laurentian reconstructions will be published elsewhere (*Buchan et al.*, 1997).

2. *Criteria for reliable palaeomagnetic data*

The Precambrian Fennoscandian palaeomagnetic database (*Pesonen et al.*, 1991; *Elming et al.*, 1997) consists of about 500 palaeopoles ranging in age from 2850 Ma to 650 Ma. However, only a few palaeopoles are sufficiently well-dated to be used for drift calculations (e.g. *Roy* 1983; *Buchan and Halls*, 1990). The principal requirements for the most reliable data for Precambrian rocks in Fennoscandia are following:

1) *Natural Remanent Magnetization (NRM) is a primary thermoremanent magnetization, acquired during original cooling of the rock.*

The most reliable data have been obtained mainly from igneous intrusions, preferentially from dyke rocks, where the remanence has been acquired as the rocks have cooled below the Curie temperature of the remanence-carrying minerals, typically magnetite (580°C). Important factors in searching for primary remanence of a rock are composition, fine grain size of the remanence carriers, minimal metamorphism and deformation. Unfortunately, in old reworked shield areas like Fennoscandia and Laurentia, the rocks are typically metamorphosed and deformed. Therefore, as in many studies it has not been possible to unravel the whole tectono-metamorphic history of the rocks, the amount of useful data has diminished significantly.

2) *Rocks are dated by U-Pb method on zircon or baddeleyite.*

The palaeomagnetic database of Fennoscandia consists of only a small number of formations which have U-Pb zircon or baddeleyite ages. Most isotope ages are based on K-Ar or Rb-Sr methods which are imprecise and may reflect metamorphic events. More often, the age of the rock is known only on geological grounds (cross cutting relations, references to corresponding dated rocks, etc.). The true magnetization age cannot be defined accurately from rocks dated by these methods, although data from those rocks can lend support to data from precisely dated rocks. For drift history calculations, only the data with U-Pb zircon or baddeleyite ages have been used.

3) *Different remanence components are isolated accurately*

Most Fennoscandian rocks carry at least two remanence components of different ages. The components can be separated if their blocking temperatures and/or coercivity spectra are distinct. Typically, the primary remanence component, acquired during the emplacement and cooling of the rock, is overprinted by the present Earth's magnetic field. In addition, rocks older than Mesoproterozoic, are often partly remagnetized in metamorphic events (see e.g. *Elming, 1994; Mertanen, 1995*). Conventional magnetic cleaning methods (alternating field and/or thermal demagnetization) which have been used in almost all studies are generally sufficient for separating the characteristic remanence component. However, modern multicomponent analysing methods which are used to separate different remanence components more accurately, were not used in Fennoscandia until at middle 80's. Multicomponent analysis has improved the accuracy of data significantly and has allowed separation of secondary components which are important in studies of geological evolution of the Fennoscandian Shield (see e.g. *Mertanen, 1995*).

4) *Primary nature of the remanence is verified by field tests.*

Multicomponent analysis can separate different components, but cannot determine their relative ages. Therefore, other methods (see e.g. *Buchan and Halls, 1990*), described below, are required to establish the sequence of the magnetizations.

a) The most rigorous field test, the baked contact test (*Everitt and Clegg, 1962*), is positive for the primary magnetization when both the igneous formation and the baked host rock carry similar remanence directions, while the remanence direction of the unbaked host rock differs. In the case of secondary magnetization, all rocks would carry a similar direction. In Fennoscandia, the primary nature of remanence has been verified by baked contact tests for only a few formations (mainly dykes). In many cases a positive baked contact test has not been obtained due to lack of host rocks which carry stable remanences. In many other studies, baked contact tests have not been carried out.

b) The secular variation test is applicable to dyke swarms. It is positive if the remanence direction is constant along a single dyke, but deviates between dykes. This is due to emplacement of dykes at slightly different times. Thus, each dyke records a spot reading of the magnetic field (see e.g. *Halls*, 1986).

c) In fold tests, the remanence is verified to be primary, if the remanence directions from samples taken at different parts of the fold are highly scattered, but become more coherent after restoring the fold into its original attitudes.

5) *Remanence is statistically well defined.*

Palaeomagnetic sampling must average out secular variation of the Earth's magnetic field. Therefore several samples are collected from each of a number of sites. In the latest compilation, for a well defined remanence direction, the minimum values were ≥ 3 sites with ≥ 15 samples with α_{95} values $\leq 15^\circ$ and $\leq 7^\circ$, respectively and Fisher $k \geq 30$ (*Fisher*, 1953).

3. *Fennoscandian palaeomagnetic data*

Nine key Proterozoic palaeopoles are regarded as sufficiently reliable to be used in drift history calculations. Most of the key poles represent mean poles from coeval formations. An Apparent Polar Wander Path (APWP) is not drawn through the poles, because there are large time gaps (even hundreds of million years) with no reliable data. Archaean data was not used in drift calculations, because they did not pass the criteria. The data are briefly discussed below.

Source areas for the data are presented in Figure 1. The nine key poles are plotted in Figure 2 and listed in Table 1, together with the individual poles used for calculating the means.

3.1 *Archaean (2800-2500 Ma)*

Palaeomagnetic data from Archaean rocks in Fennoscandia are quite scarce which is due mainly to the inability of felsic basement rocks to carry stable remanent magnetizations. However, stable remanences have been obtained in some areas where the basement rocks are more mafic or where Archaean dry, granulite-grade metamorphism has prevailed. One such area is the Jonsa block in the Varpaisjärvi area where the basement enderbite has a U-Pb zircon age of 2682 ± 6 Ma (*Paavola*, 1986) and the age of the granulite-grade metamorphism, on the basis of U-Pb dating, is 2630 Ma (*Hölttä et al.*, 1996). The remanence direction is steep down (*Neuvonen et al.*, 1981; *Neuvonen*, 1992; *Pesonen and Mertanen*, 1996; *Neuvonen et al.*, 1997, this volume) and the pole is statistically well defined. However, because the Jonsa block probably rotated (*Hölttä et al.*, 1992; see also *Pesonen and Mertanen*, 1996) after this presumably Archaean remanence was blocked, the pole cannot be used for drift calculations. Another area, where Archaean remanence directions may have been

Table 1. Palaeomagnetic poles for Fennoscandia.

Number	Rock unit	B/N/n	D_{ref}, I_{ref} (°)	Plat, Plong (°N, °E)	A95 (°)	Pol	Age (Ma)	References
I	1 Russian Karelian dykes	*3/3/17	100.3, 46.4	-20.4, 276.1	13.5	R	2446±5/4	Mertanen, 1995, Vuollo et al., 1995
II	2 <i>Tsuomasvari gabbro-diorite</i>	1/*8/28	329.0, 34.4	40.2, 247.3	6.8	N	1931±2	Mertanen & Pesonen, 1994, Forsberg-Heikkilä, 1990
3	Vittangi gabbro	1/*8/28	344.5, 32.8	42.6, 227.9	4.9	N	1886±14	Elming, 1982, 1985, 1994, Skiöld, 1988
4	Kiuruvesi gabbro diorites	*3/3/35	341.9, 30.5	40.7, 230.9	4.1	N	1886±5	Neuvonen et al., 1981, Marttila, 1981
5	Pohjanmaa gabbro-diorites	*5/5/45	334.8, 28.1	37.9, 239.1	11.0	N	1879±5	Pesonen & Stigzelius, 1972, Ekdahl, 1993
6	Jalokoski gabbro	1/*5/22	340.0, 34.8	43.1, 233.9	7.1	N	1871±4	Mertanen & Pesonen, 1992, Hiltunen, 1983
III	Mean <i>syn-late Svecofennian gabbros (3-6)</i>	*4/10/21/130	340.3, 31.7	41.2, 233.0	4.9	N	1880	
IV	7 <i>Haukivesi lamprophyres</i>	12/12/25	347.5, 40.2	48.0, 225.0	2.9	N	1837-1840	Neuvonen et al., 1981, Huhma, 1981
8	SE quartz porphyry dykes	*9/9/21	28.2, 14.9	30.0, 175.0	9.4	N	1617-1638	Neuvonen, 1986
9	Sipoo quartz porphyry dykes	3/*5/34	24.3, 6.0	26.4, 180.4	7.4	N	1630	Mertanen & Pesonen, 1995a, Tönroos, 1984
V	Mean <i>Subjotnian quartz porphyry dykes (8-9)</i>	*2/12/14/55	26.3, 10.4	28.2, 177.7	-	N	1630	
10	Kumlinge-Brändö dykes	*7/7/25	25.6, -21.6	12.2, 182.0	6.7	R	1550-1601	Pesonen & Neuvonen, 1981, Neuvonen, 1987
11	Föglö-Soittunga dykes	*6/6/25	17.8, 6.7	27.9, 187.5	8.8	N	1540 ± 12	Pesonen & Neuvonen, 1981, Neuvonen, 1991
VI	Mean <i>Subjotnian diabase dykes (10-11)</i>	*2/15/15/50	21.7, -7.8	20.1, 184.6	-	M	1560	
12	Vasa dolerite dykes	*15/15/15	44.5, -22.6	7.0, 164.0	4.2	N	1268 ± 13	Neuvonen, 1966, Suominen, 1991
13	Satakunta dolerite dykes	*18/18/18	51.9, -27.4	2.0, 158.0	3.9	N	1264 ± 12	Neuvonen, 1965, Suominen, 1991
14	Märket dolerites	*8/8/8	67.1, -31.7	-5.9, 145.5	8.9	N	1265 ± 6	Neuvonen & Grunström, 1969, Suominen, 1991
VII	Mean <i>Jotnian dykes (12-14)</i>	*3/4/14/41	54.2, -27.8	1.0, 156.0	17.3	N	1266	
VIII	Mean <i>Laanila-Ristijärvi dykes</i>	*3/7/54	354.9, -46.7	-2.1, 212.2	13.8	N	^b 1042±50, 1013±32	Mertanen et al., 1996
16	Åna-Sira massif	1/* 11/65	22.7, -80.4	-46.3, 197.4	12.5	N	930±4	Stearm & Piper, 1984, Duchesne et al., 1993
17	Egersund farsundite	1/*7/35	27.1, -78.5	-43.3, 194.0	9.5	N	920-940	Murthy & Deutsch, 1975, Pasteels et al., 1979
IX	Mean <i>Svecofennian formations (16-17)</i>	*2/2/18/100	25.0, -79.4	-44.8, 195.7	-	N	930	

Note: The Roman numbers refer to the key poles used in drift calculations, the other numbers refer to individual poles used in the mean pole calculations. B/N/n = number of formations/sites/samples. * denotes the statistical level used in mean calculations. D_{ref}, I_{ref} are the palaeomagnetic directions calculated for the reference city of Kajana (Lat = 64.1°, Long = 27.7°) where the R polarity directions have been inverted by 180°. Plat, Plong are the latitude and longitude of the pole, respectively. A95 is the radius of the circle of 95% confidence of the mean pole. Polarity (Pol.) is normal (N) when the north-seeking palaeomagnetic direction yields a pole in the Pacific, otherwise reversed (R) and M denotes that N and R data have been averaged together (see *Pesonen and Neuvonen, 1981*). Age (Ma) is established by U-Pb dating on zircon or baddeleyite, except ^bSm-Nd

preserved, is the Middle Archaean Vodlozero block east of Lake Onega in SW Russia. Vodlozero block is also a high grade metamorphic terrain where, on the basis of U-Pb datings of zircon, repeated metamorphism has taken place at 3100, 2850 and 2700-2650 Ma ago (*Sergeyev et al.*, 1990). *Krasnova and Go'oskova* (1990) have obtained a shallow southward remanence direction from the Archaean basement and they interpret it to date from the latest Archaean metamorphism at 2700-2650 Ma. Hence, palaeopoles from the Varpaisjärvi and Vodlozero blocks differ significantly, although the ages of the rocks are in close agreement. This may indicate ⁱ) regional tectonism within the blocks, ⁱⁱ) separate movements of the blocks during Archaean and hence different APW paths or ⁱⁱⁱ) considerable drift of a single continent between the time of metamorphism of the blocks. These models are testable with palaeomagnetism, but it requires more studies on coeval Archaean rocks elsewhere in the Fennoscandian Shield.

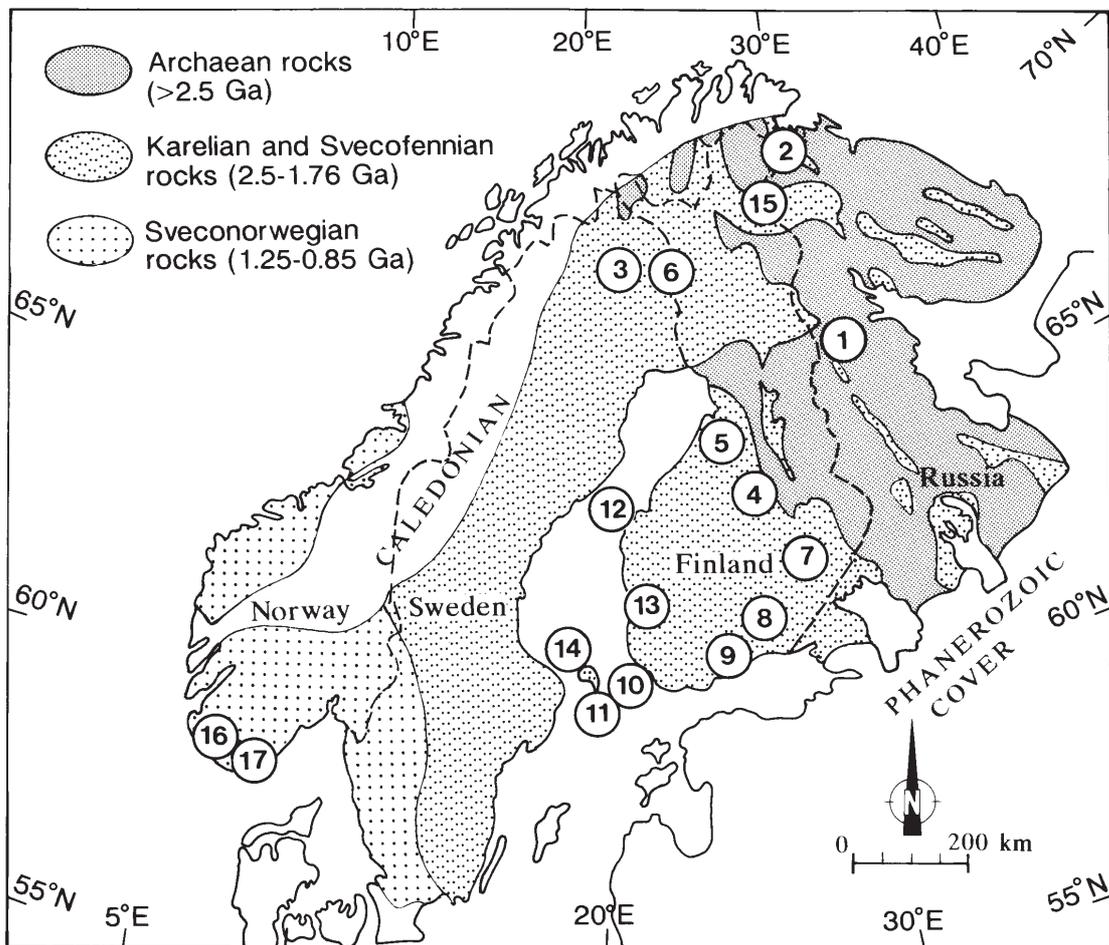


Fig. 1. Source areas of the Fennoscandian poles used in drift calculations. Numbers as in Table 1.

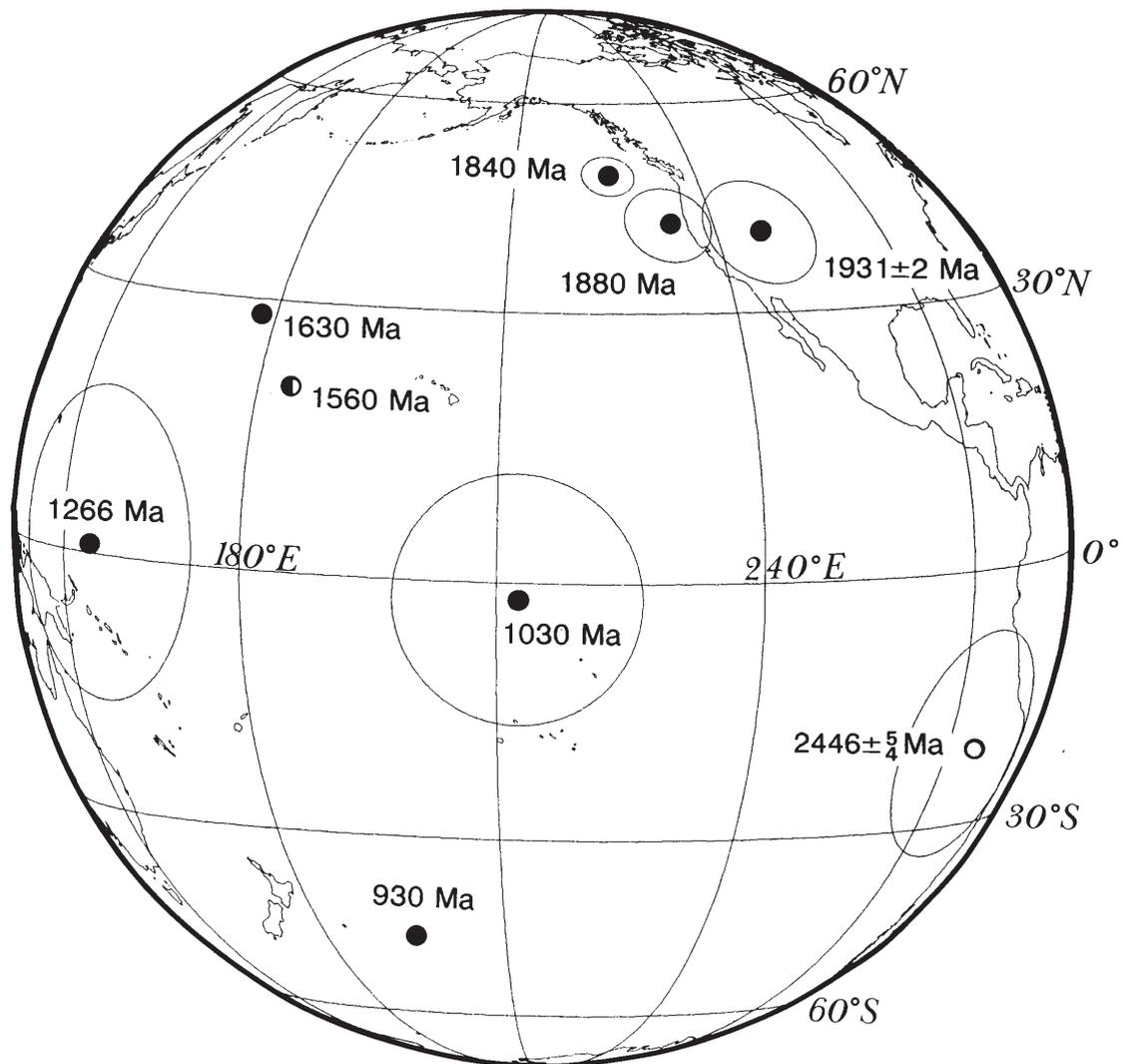


Fig. 2. Nine key palaeomagnetic poles for Fennoscandia (see Table 1). Ages of the poles are established on the basis of U-Pb dating of zircon or baddeleyite, except pole at 1030 Ma which is based on Sm-Nd dating. Closed (open) symbols denote normal (reversed) polarity and half open symbol mixed polarity.

3.2 Early Palaeoproterozoic (2450-2000 Ma)

The oldest pole used in drift calculations (Fig. 3) has been obtained from gabbro-dykes in Russian Karelia (Mertanen, 1995). The dykes are subvertical, undeformed and only slightly altered. The age of the dykes is 2446 ± 5 Ma on the basis of U-Pb dating of baddeleyite (Vuollo *et al.*, 1995). The primary nature of the pole has not yet been verified by field tests. Support for a primary origin comes from 2435 Ma old Koillismaa layered intrusions (Mertanen *et al.*, 1989) and from dyke rocks related to the 2449 ± 1 Ma old (Amelin *et al.*, 1995) Burakovskaja layered intrusion which carry a similar remanence direction (Krasnova and Go'oskova, 1990).

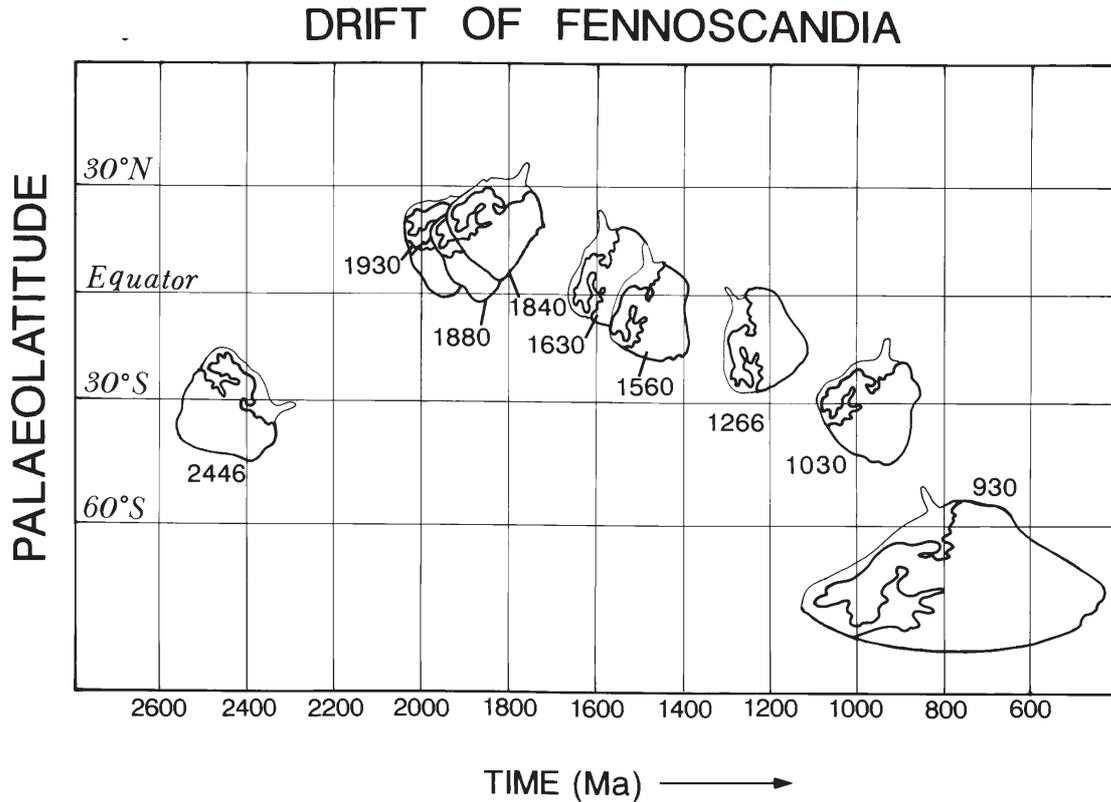


Fig. 3. Drift history of the Fennoscandian Shield at 2446 - 930 Ma calculated from the nine key poles (Table 1, Fig. 2). Vertical axis shows the palaeolatitude and horizontal axis shows time. Orientation of the shield at different times is with respect to its present orientation. The map has been compiled by using GMAP (Torsvik *et al.*, 1990) and MapDraw (M. Leino, GSF).

So far the palaeomagnetic database lacks reliable palaeopoles of Jatulian age (ca. 2200-2000 Ma). The main reason why Jatulian remanences have not been isolated, is probably the strong Svecofennian overprint at 1900-1800 Ma, which in most formations has totally remagnetized the rocks. The Jatulian Varpaisjärvi diabase dykes carry a remanence direction which might be Jatulian in age (Neuvonen *et al.* 1981; Neuvonen, 1992 Neuvonen *et al.*, 1997, this volume), but there are contradicting results from other Jatulian formations (Torsvik and Meert, 1995).

3.3 Svecofennian (1900-1800 Ma)

Three key palaeopoles (Fig. 3, Table 1) reflect the continental movement at successive stages of the Svecofennian orogeny, when new juvenile crust was formed in an accretion of oceanic island arcs to the Archaean craton. The poles range in age from 1930 to 1840 Ma.

The first pole is obtained from the Tsuomasvarri gabbro-diorite intrusion with an age of 1931 ± 2 Ma (Mertanen and Pesonen, 1994). The intrusion is located in the Archaean Sörvaranger terrain, north of the Lapland granulite belt. Due to collisional tectonism related to the Lapland granulite belt at about 1900 Ma, it is, however, still uncertain if the pole represents the whole Fennoscandian Shield.

The second pole with an age of 1880-1840 Ma represents a mean of four palaeopoles from gabbroic intrusions emplaced at the syn- or late orogenic stages of the Svecofennian orogeny (see Table 1). The U-Pb ages of the different intrusions vary from 1880 to 1870 Ma, but the magnetization ages cannot be properly established for several reasons. First, (unlike dyke rocks) the intrusions represent slowly cooled plutons and therefore the magnetization age is slightly younger than the U-Pb age. Second, the remanence directions may reflect remagnetizations during Svecofennian post-emplacment metamorphism. No baked contact tests are available for any of these intrusions to show that the remanence direction differs from the direction of the surrounding host rocks (which in all cases are also Svecofennian in age). Third, the intrusions may have been deformed, tilted or rotated in the later stages of the orogeny and, hence, the remanence directions may have changed from that at the time of emplacement. Due to these reasons, the magnetization age for the mean of these intrusions is estimated to be between 1880 Ma, the maximum age based on U-Pb datings, and 1840 Ma, the minimum based on the age of post-orogenic formations (see below).

The third pole represents a remanence direction obtained from the Haukivesi lamprophyre dykes in central Finland (*Neuvonen et al.*, 1981). The lamprophyres are clearly younger than the surrounding Svecofennian basement which they cut. The age is defined by U-Pb method to be 1837-1840 Ma.

3.4 Subjotnian (1.65-1.3 Ga)

Subjotnian palaeopoles have been obtained from dyke swarms related to rapakivi intrusions in southeastern and southwestern Finland. The older palaeopole with an age of 1630 Ma, represents a mean from two NW-SE trending quartz porphyry dyke swarms in southeastern Finland. The U-Pb zircon age of the SE quartz porphyry dykes, related to the Wiborg rapakivi massif, is 1617-1638 Ma (*Neuvonen*, 1986). No field tests are reported, but based on the similarity with other Subjotnian palaeopoles, the remanence is regarded as primary. The Sipoo dykes, related to the Onas rapakivi body, are 1630 Ma in age (U-Pb, zircon) and the primary nature of the remanence was verified by a secular variation test (*Mertanen and Pesonen*, 1995a). In both areas, support for the primary nature of remanence comes from coeval dykes which carry remanent magnetization of reversed polarity. However, the remanence directions of these reversely magnetized dykes are much more scattered.

The younger palaeopole with a mean age of 1560 Ma is obtained from two NE-SW trending diabase dyke sets related to the Ahvenanmaa rapakivi granite (*Pesonen and Neuvonen*, 1981). The U-Pb zircon age of the reversed polarity Kumlinge-Brändö dykes is 1550-1601 Ma and of the normal polarity Föglö-Sottunga dykes 1540±12 Ma. Cross cutting relations show that at least some of the reversed polarity dykes are slightly older than the normal polarity dykes (*Pesonen et al.*, 1985). The primary nature of remanence was verified by positive baked contact tests for both dyke sets.

3.5 Jotnian (1300-1200 Ma)

The mean Jotnian palaeopole has been calculated from three coeval dyke swarms and sills in western Finland. The remanence direction of the NNE-SSW trending 1268 ± 13 Ma old (U-Pb, zircon) Vaasa dolerite sheets and dykes (*Neuvonen, 1966*) is in close agreement with the direction from nearly N-S trending Satakunta dykes (*Neuvonen, 1965*). The age of the Satakunta dykes is 1264 ± 12 Ma (U-Pb, zircon) and positive baked contact tests (*Pesonen et al., 1992*) indicate that the remanence is primary. Remanence direction of the 1265 ± 6 Ma old (U-Pb, zircon) Märket olivine dolerite dykes and sills (*Neuvonen and Grundström, 1969*) is close to the direction of the Satakunta dykes, supporting the primary origin of the remanence.

Other Jotnian dolerites that have well-defined poles include the Väster-Norrland dolerites (*Piper, 1979*), Ulvö dolerites (*Larson and Magnusson, 1976*), Särna dolerites (*Piper and Smith, 1980*) and Älvdalsåsen dolerite sill (*Bylund, 1985*). Unfortunately, the ages of the formations are poorly constrained by K-Ar or Rb-Sr methods. Therefore, although the poles are in agreement with the precisely dated poles, data from these formations was not used in drift calculations.

3.6 Sveconorwegian (1200-850 Ma)

The palaeomagnetic database includes about 90 Sveconorwegian poles from the Southwest Scandinavian Domain in southern Norway and Sweden. However, most of the poles have isotope dates obtained by Rb-Sr and K-Ar methods, and they are therefore not used here. When dated by the U-Pb method, the ages of part of the formations reflect the uplift and cooling following the granulite facies metamorphism during the Sveconorwegian orogeny.

Because there is a large gap from 1270 Ma to 930 Ma with no precisely dated poles, the pole from the Laanila-Ristijärvi dykes, which cut sharply across the Palaeoproterozoic Lapland Granulite belt in northern Finland, has been used here. The ca. 1030 Ma (Table 1), Sm-Nd age of the dykes is thought to represent the time of emplacement (*Mertanen et al., 1996*). The remanence also reflects the primary cooling of the dykes on the basis of positive baked contact tests. Roughly similar poles have been obtained from the Bamble intrusions (*Stearn and Piper, 1984*) in southern Norway, where, on the basis of Sm-Nd dates from granulite grade rocks, high-grade metamorphism ended at 1095 Ma (*Kullerud and Dahlgren, 1993*).

Sveconorwegian poles from Southwest Scandinavian Domain are obtained from the Rogaland igneous complex in southwestern Norway. The complex is a composite anorthosite massif consisting of basaltic and charnockitic series (*DemaiFFE et al., 1986*). A pole is available from the basaltic Åna-Sira massif (*Stearn and Piper, 1984*) which has a U-Pb zircon age of 930 ± 4 Ma (*Duchesne et al., 1993*). A pole is also available from the charnockitic Egersund Farsundite (*Murthy and Deutsch, 1975*) with a U-Pb zircon age of 940-920 Ma (*Pasteels et al., 1979*). Several other statistically well defined poles obtained from the Rogaland complex may be affected by deformation and

were not used in drift calculations. Also, new U-Pb datings on titanite giving ages of 940 Ma (Johansson, 1993) from palaeomagnetically well defined poles in Scania dolerites and syenites in SW Sweden (Bylund, 1981) record the Sveconorwegian reworking. The poles might be useful in constructing the drift history of the Shield, but, for consistency, they are not used in the present paper.

4. Drift history of the Fennoscandian Shield

The drift history of the Fennoscandian shield (Fig. 3) was calculated from the nine key palaeopoles of Table 1. Drift velocity of the shield has been divided into latitudinal drift velocity and rotational velocity (Fig. 4) (see also Pesonen *et al.*, 1989). Because the palaeolongitude of the shield cannot be defined palaeomagnetically and because of the large time gaps between most of the poles, the velocity values are only minimum estimates of the true velocity.

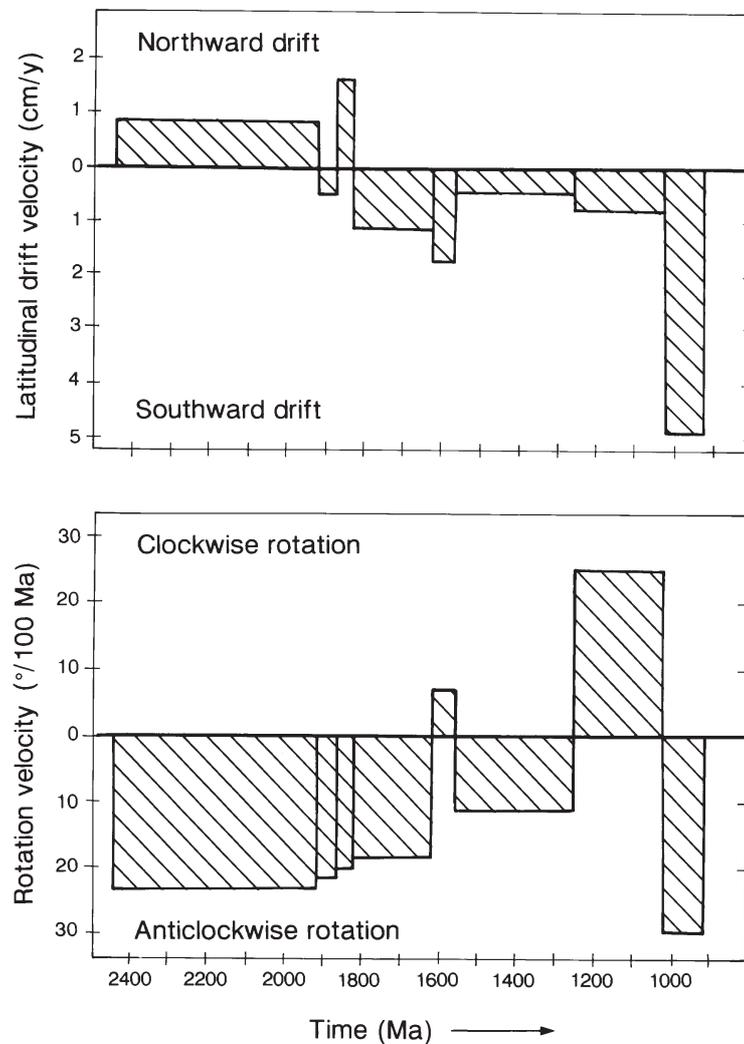


Fig. 4. a) Latitudinal drift velocity (cm/year) for the Fennoscandian Shield separated into northward and southward movements. b) Angular rotation velocity ($^{\circ}/100$ Ma) separated into clockwise and anticlockwise rotations. Reference location for Fennoscandia is the city of Kajaani: Lat = 64.1° N, Long = 27.7° E.

Based on the pole position from the Russian Karelian dykes, the Fennoscandian Shield was located at the latitude of about 30°S at 2450 Ma and had rotated about 90° clockwise with respect to its present orientation. Between 2450 and 1930 Ma there is a large time gap with no reliable palaeomagnetic data. Before the onset of Svecofennian orogeny, the Fennoscandian Shield drifted towards shallower northern latitudes of about 15°N. The position of the Shield does not change significantly between different stages of the orogeny. The age of magnetization from 1880 Ma old intrusions in Fennoscandia could not be accurately defined, but because the poles from the 1930-1840 Ma time period form a small track, it is most probable that at 1880 Ma the Fennoscandian Shield maintained a position somewhere between the 1930 and 1840 Ma positions (see Fig. 3). At Subjotnian time, 1630-1560 Ma, the Fennoscandian Shield had drifted to the Equator and continued to move southwards. At 1270 Ma Fennoscandia was located at about 20°S and at 1030 Ma drifted further south to a latitude of about 30°. At about 930 Ma, in the later stages of the Sveconorwegian orogeny, the Shield had drifted to the latitude of about 70°S.

The minimum latitudinal drift velocity from 2450 to 930 Ma has been quite constant, about 1-2 cm/year. An abrupt change of the latitudinal velocity to about 5 cm/year took place during Sveconorwegian orogeny (Fig. 4a). Angular rotation velocity (Fig. 4b) has varied within 0.1-0.3 °/Ma, being fastest during the Sveconorwegian orogeny.

5. *Conclusions*

Reliable primary palaeomagnetic data from rock units with precise U-Pb zircon or baddeleyite ages of 2450-930 Ma enable the movement of the Fennoscandian Shield to be determined more accurately than before. The palaeomagnetic data span most of the Precambrian, but there are still great time gaps with no reliable data. The main problems are a lack of precise U-Pb dating and a lack of field tests to demonstrate the primary nature of remanence. In the future, integrated studies, where careful palaeomagnetic sampling is conducted at the same sites as isotopic dating, are of vital importance.

Acknowledgements

We wish to thank Dr. Kenneth Buchan and Dr. Sten-Åke Elming for valuable discussions. Ms. Salme Nässling is acknowledged for drawing the figures.

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