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The magnetostratigraphy and a 1780 Ma palaeomagnetic pole from the red sandstones of the Vazhinka River section, Karelia, Russia

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SUMMARY

A palaeomagnetic study of the Vepsian sandstones of the upper part of the Shoksha Formation has revealed a stable remanence. Rock magnetic and mineralogical studies suggest diagenetic haematite as the main carrier of this remanence. Two magnetic polarities with a regular stratigraphic zonation have been found. The reversal test is positive. The tilt-corrected palaeomagnetic direction is: $N=36$, $D=354.3°$, $I=21.6°$, $k=22.3$, $\alpha_{95}=5.2°$. The corresponding palaeomagnetic pole of 39.7°N, 221.1°E ($D_\mathrm{p}=2.9°$, $D_\mathrm{m}=5.5°$) is proposed as a 'key pole' for 1790–1770 Ma for Fennoscandia.

Key words: Fennoscandia, magnetostratigraphy, palaeomagnetism, Palaeoproterozoic, sandstone.

1 INTRODUCTION

The late Svecofennian and post-Svecofennian rocks (*c.* 1850–1750 Ma) of Fennoscandia have undergone extensive palaeomagnetic study. Elming *et al.* (1993), for example, reported about 18 reliable palaeomagnetic results for these time intervals. However, the recent analysis of Buchan *et al.* (2000) did not reveal any 'key pole' for this time. Their requirements for a 'key pole' include good dating ($< \pm 20$ Ma) and the satisfaction of basic reliability criteria. A search of the Global Palaeomagnetic Database by McElhinny & Lock (1996) reveals 15 palaeopoles with $Q>2$ (Van der Voo 1990). These poles are shown in Table 1. Two features are interesting in this table. First, these data are almost exclusively of single polarity with positive inclination (we will refer to this polarity as 'normal'). There are only two exceptions—the result from Shoksha red sandstones in Karelia (Damm *et al.* 1997) and a few samples from Tavinunnanen gabbro in northern Sweden (Elming 1994).

Table 1 Late Svecofennian and post-Svecofennian palaeomagnetic data from Fennoscandia with $Q>2$.

Rockname	Age (Ma)	Decl. (°)	Incl. (°)	Plat (°)	Plong (°)	%R	Reference
Jokkmokk basic rocks	1731–1829	349	33	41	214	0	Piper 1980
Haukivesi Intrusives	1837–1840	348	39	49	225	0	Neuvonen *et al.* 1981
Kiuruvesi Intrusions	1881–1891	338	35	43	235	0	Neuvonen *et al.* 1981
Nilsia–Varpaisjarvi Dykes	1830–1860	349	38	47	224	0	Neuvonen *et al.* 1981
Tarendo Gabbro	1714–1800	339	42	45	230	0	Elming 1985
Svappavaara Gabbro	1860–1880	336	52	52	235	0	Elming 1985
Vittangi Gabbro	1707–1880	340	39	43	228	0	Elming 1985
Shoksha Formation	1770–1800	6	31	45	206	0	Damm *et al.* 1997
Shoksha Formation	1770–1800	161	−33	44	242	100	Damm *et al.* 1997
Ropruchey Sill	1758–1782	3	18	38	211	0	Damm *et al.* 1997
Ropruchey Sill	1758–1782	349	24	41	230	0	Fedotova *et al.* 1999
Ropruchey Sill	1758–1782	6	15	39	209	0	Fedotova *et al.* 1999
Ropruchey Sill	1758–1782	357	23	41	218	0	Fedotova *et al.* 1999
Post–Svecofennian Intrusions	1730–1830	5	39	48	201	MIX	Elming 1994
Post–Svecofennian Intrusions	1730–1830	20	51	53	171	0	Elming 1994

Decl, Incl = declination and inclination of remanence; Plat, Plong = latitude and longitude of palaeopole;
%R = percentage of "reversed" (with negative inclination) polarity.

Second, almost all these directions lie close to (but are significantly different from) the direction of the present-day magnetic field (PDF). The only exception is the palaeomagnetic direction for the Ropruchey Sill in Karelia (Damm *et al.* 1997; Fedotova *et al.* 1999). These two features beg the question—is there a strong predominance of 'normal' geomagnetic field during late Svecofennian and post-Svecofennian times, or, at least in some cases, are we dealing with incomplete isolation of the ancient magnetization? It is well known in palaeomagnetism that unipolar data can be slightly biased towards the PDF therefore new palaeomagnetic results with dual polarity would be useful in resolving this problem.

Katseblin (1968) reported three samples with 'reverse' magnetization in the upper part of Vepsian Pukhta Formation, which is the top part of Shoksha Formation according to the present stratigraphic scheme for Karelia (Sokolov *et al.* 1987). He used only primary measurements of the NRM. The 'reverse' polarity was also found in lower levels of the Shoksha Formation (Damm *et al.* 1997), see Table 1. Katseblin (1968) studied the Vazhinka River section, which is the biggest outcrop of the Shoksha Formation and the only one with exposed upper horizons. In order to obtain more information about 'reverse' magnetization in the Shoksha Formation using modern palaeomagnetic techniques we decided to study the Vazhinka section again, especially the upper layers not studied by Katseblin (1968). This section lies at some distance from the Ropruchey Sill, which has caused partial remagnetization of nearby Shoksha sediments (Damm *et al.* 1997).

2 GEOLOGY AND SAMPLING

According to Sokolov *et al.* (1987), the Vepsian Group is the top lithostratigraphic unit of the lower Proterozoic (Karelian) strata in Southern Karelia. The lower and upper time boundaries for the Vepsian are about 1850 and 1750 Ma (Heiskanen 1990). Heiskanen (1990) correlates the Vepsian Group with the Vakko sedimentary series of the Kiruna district and with the Vargfors series of the Skellefte district in northern Sweden. The Vakko sediments are postdated by the Lina Granite (1794 ± 24 Ma, U-Pb zircon), and the Vargfors sediments are postdated by the Revsund-type granites (1778 ± 16 Ma, U-Pb zircon) (Skiöld 1988).

The study area belongs to the Karelian crustal block of the Fennoscandian Shield (Fig. 1a). Vepsian sediments cover a wide region along the western coast of the Onega Lake (Fig. 1b). The Vepsian unit is divided into two formations. The lower Petrozavodsk Formation (300–450 m) consists mainly of grey quartz sandstones. There is one known K-Ar date (on glauconite) of 1800 Ma (Sokolov *et al.* 1987) for this formation. The upper Shoksha Formation (~1000 m) is made up of red and pink quartzites and quartz sandstones. It is divided into three subformations (Sokolov *et al.* 1987). The Shoksha sediments are intruded by the gabbro-dolerite Ropruchey Sill (Fig. 1b). The U–Pb (zircon) age of this sill, 1770 ± 12 Ma (Bibikova *et al.* 1990) marks the younger age limit for the Shoksha Formation. The Vepsian sediments form a gentle syncline (Fig. 1b). The time of folding probably corresponds to the time of the intrusion of the Ropruchey Sill (Simanovich 1966).

The Vazhinka section is the most exposed of the Shoksha Sandstone in Karelia and the only one where the uppermost part of the Shoksha Formation is exposed. It is situated on the western limb of the syncline, mainly in the E–W trending Genoi-Selga Gorge of the Vazhinka River. The uppermost part of the section was sampled outside the gorge, in the submeridional part of the river. The studied sandstones dip up to 10° NEE in the eastern part of outcrop (upper part of the sequence) and up to 20° in the western part.

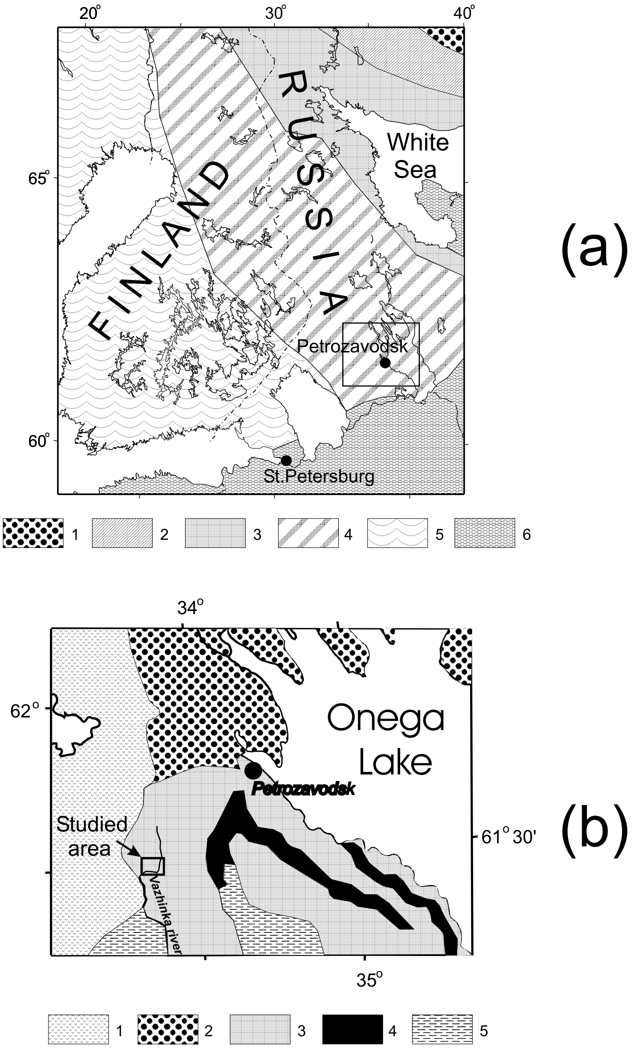

Figure 1. (a) Simplified tectonic map of the southeastern part of the Fennoscandian Shield. 1 = Murmansk block (Archaean); 2 = Kola block (Archaean); 3 = Belomorian Belt (Archaean); 4 = Karelian block (Archaean); 5 = Svecofennian block (Palaeoproterozoic); 6 = Phanerozoic cover. (b) Simplified geological map of Prionezhie area. 1 = Archaean granitoids; 2 = Jatulian (2.3–2.1 Ma), Ludikovian (2.1–1.95 Ma) and Kalevian (1.95–1.92 Ma) rocks; 3 = Vepsian (1.85–1.77 Ma) Petrozavodsk and Shoksha Formations; 4 = Roprychey mafic Sill (1.77 Ma); 5 = Vendian to Phanerozoic sediments.

The section studied is made up of red to pink quartz sandstones (Fig. 2). There is a 100 m layer of intraformational conglomerate at the bottom part of the section. The upper part of the section was studied in several river outcrops. The middle part is exposed in the gorge and consists mostly of talus with a number of outcrops. Unlike the upper part of the section, some blocks in this part have been slightly dislocated during recent neotectonic events. In our sampling we have avoided such outcrops.

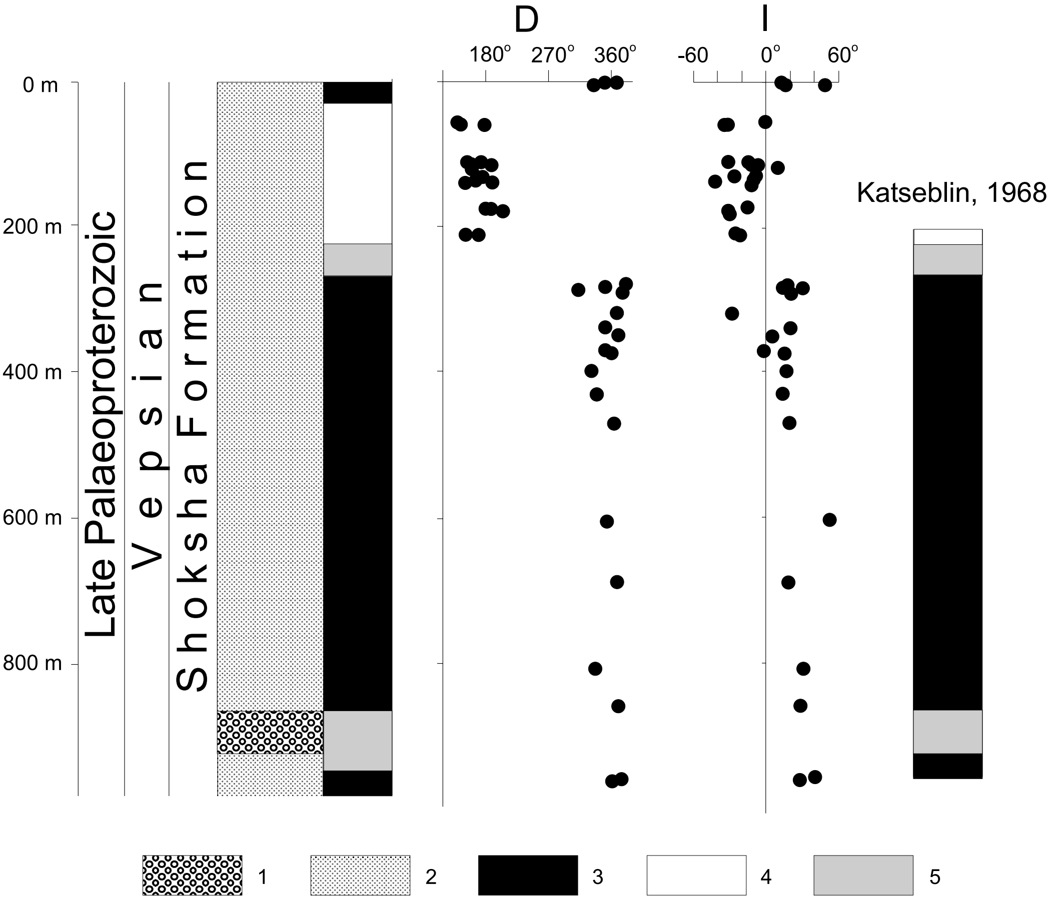

Figure 2. Simplified lithological column and magnetostratigraphy of the Vazhinka section. 1 = conglomerate; 2 = red quartz sandstone; 3 = "normal" polarity; 4 = "reversed" polarity; 5 = not sampled.

The section studied corresponds to the upper subformation of the Shoksha Formation, so according to the age constraints mentioned above an age of between 1790 and 1770 Ma can reasonably be assigned to these sediments. The age of folding is supposed to be about 1770 Ma (see above).

Katseblin (1968) studied the middle part of the section (Fig. 2). In order to trace the scope of the 'reverse' polarity zone we collected oriented samples both at the upper part, which has never been studied palaeomagnetically and at the middle part (Fig. 2). We did not find any undisturbed outcrop of the conglomerate unit near the bottom of the section (Fig. 2), so it was impossible to carry out a conglomerate test. Additionally, there were only few pebbles large enough to cut at least two specimens. However, we were able to collect four pebbles in two large boulders, taking two samples from each.

Altogether we collected 53 orientated samples—25 from the upper part of the section, 24 from the lower part and 4 from the conglomerate boulders. 2–10 cubic specimens with sides of 2 cm were trimmed from each orientated sample.

3 MEASURING TECHNIQUES

The palaeomagnetic study of the collection was carried out in the palaeomagnetic laboratory of VNIGRI (St. Petersburg, Russia) and in the palaeomagnetic laboratory of the Tectonics Special Research Centre at the University of Western Australia. Magnetic remanence was measured using a 2G755R cryogenic magnetometer and JR4 spinner magnetometer (Geofyzika, Brno, Czech Republic). All specimens were subjected to stepwise thermal demagnetization using MMTD2 furnaces manufactured by Magnetic Measurements and VNIGRI home-made screened furnace (~10 nT residual field). A few specimens were subjected to stepwise alternating field (AF) demagnetization using a 2G600 automated degaussing system, but this type of magnetic cleaning proved to be ineffective for the studied rocks. Magnetic susceptibility was measured after each heating step with a KLY-2 bridge (Geofyzika, Brno, Czech Republic). Isothermal remanent magnetization (IRM) experiments were carried out using a MMPM9 pulse magnetiser.

4 MAGNETIC MINERALS AND ROCK MAGNETISM

Petrographic and X-ray analyses show that haematite is mainly present in the form of fine-grained (0.1–1 μm) pigment in thin films over quartz grains. Detailed studies of these films led Simanovich (1966) to the conclusion that they were formed by the redistribution of colloid ferric oxides during diagenesis. Additionally there is some minor fine-grained clastic haematite and magnetite. Very small amounts of secondary haematite, martite and ferric hydroxides were also found.

The natural remanent magnetization (NRM) of the studied sandstones ranges from 0.3 to 70 mA m^{-1}, and their magnetic susceptibility from about 0 to 1.6×10^{-4} SI units. Rock magnetic studies confirm the dominance of haematite. IRM curves (Fig. 3) show that the saturation was not achieved even in magnetic fields of about 3 T.

Two specimens were used for the analysis of rock magnetic mineralogy following the method proposed by Lowrie (1990). Fields of 2900, 400 and 120 mT were applied successively along three orthogonal axes of each specimen. These specimens were then subjected to stepwise thermal demagnetization (Fig. 4). This procedure enables detection of the predominance of haematite with the wide range of the coercivity. The medium-coercivity fraction also shows a peculiarity near the Curie temperature of magnetite (~ 585 °C). All these features confirm the results of the petrographic and X-ray studies.

The dominance of single-domain (SD) diagenetic haematite and the presence of some fine clastic magnetite and haematite provide evidence in favour of a primary nature of the magnetization of the sandstones.

5 PALAEOMAGNETIC ANALYSIS

The characteristic components of NRM (ChRM) were isolated using a least-squares algorithm (Torsvik 1986), combined with analysis of stereograms. Fisher (1953) statistics were used for calculations.

Some typical examples of the thermal demagnetization are shown on Figs 5 and 6. All studied samples show very stable remanence. In most cases only one component is present (Fig. 5). This is a high-temperature component with unblocking temperatures above 600 °C. In some samples the low-temperature component is also present (Fig. 6). Its direction is close to that of the present-day field (PDF) (Fig. 7a).

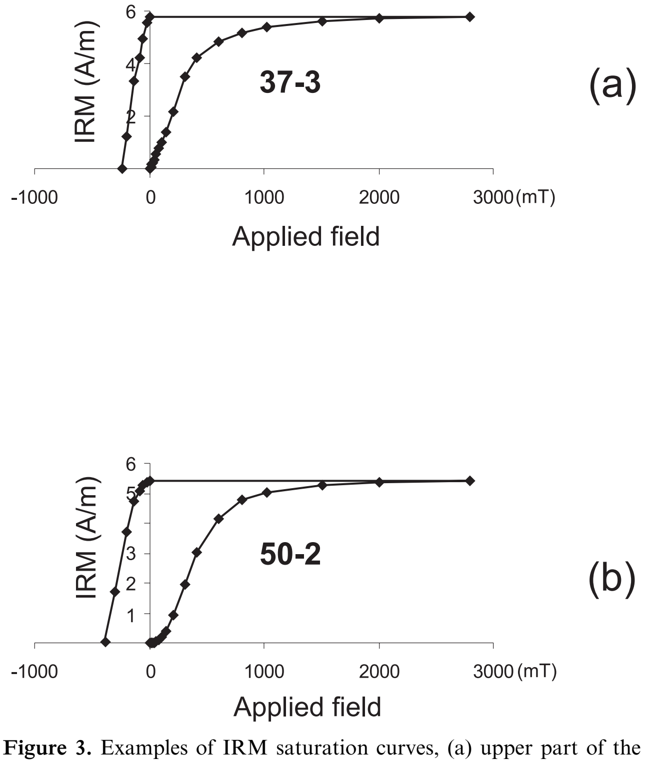

Figure 3. Examples of IRM saturation curves, (a) upper part of the section, (b) lower part of the section.

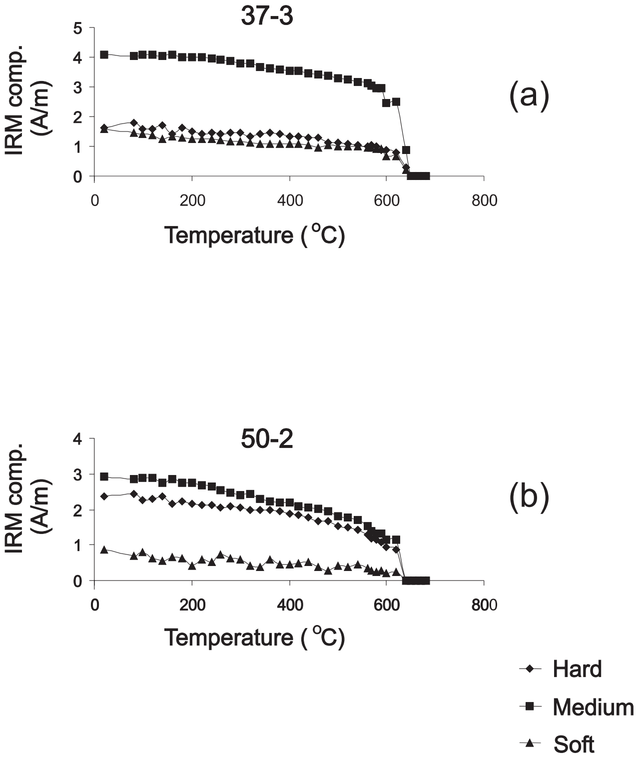

Figure 4. Three-axis IRS(T) curves (Lowrie 1990). The magnetization fields are 2.9 T (hard), 0.4 T (medium) and 0.12 T (soft).

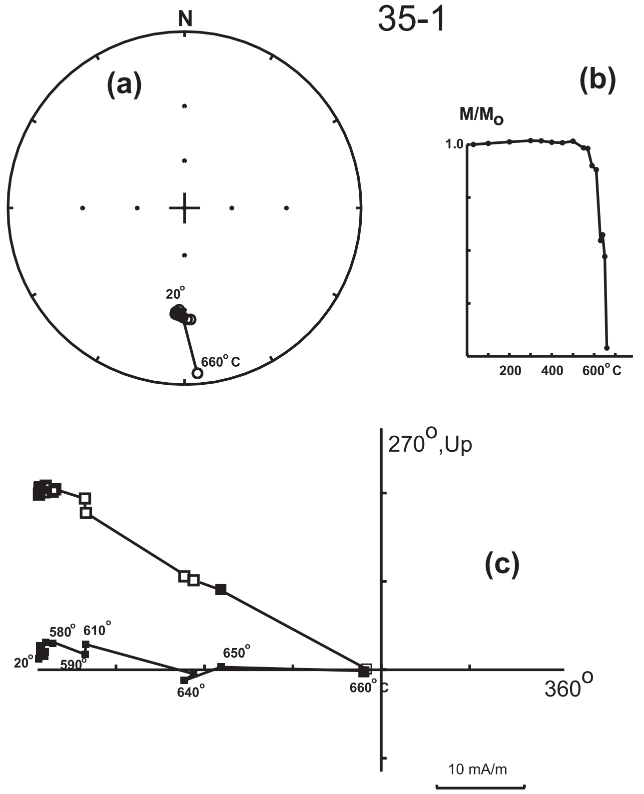

Figure 5. Example of thermal demagnetization for the ''reversed'' part of the section (equal-angle projection, normalized demagnetization curve and orthogonal plot). Solid and open symbols on the stereoprojection represent downward and upward directions, respectively; solid and open symbols on the Zijdelveld (1967) diagram denote horizontal and vertical projections, respectively.

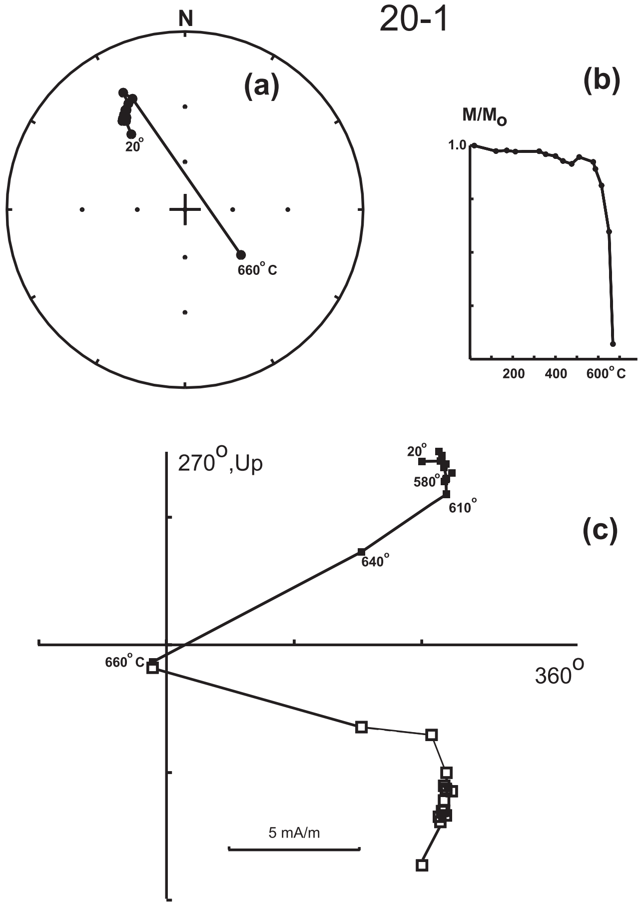

Figure 6. Example of thermal demagnetization for the "normal" part of the section (see notes to Fig. 5).

The high-temperature component is bipolar (Fig. 7b,c), and the reversal test of McFadden & McElhinny (1990) gives a positive result with classification C both for *in situ* and tilt corrected distributions.

All 'reverse' palaeomagnetic directions were only found in the upper part of the section (Fig. 2). This permits us to build a magnetostratigraphy column for the Vazhinka section. The top few metres combine a 'normal' zone, there is ~170 m thick 'reverse' zone below it, and the rest of the section is represented by a 'normal' zone (Fig. 2). Katseblin (1968) studied the part of Vazhinka section using NRM, without thermal demagnetization. However, our results show the high stability of remanence (Figs 5 and 6), so NRM directions can be used at least for the determination of magnetic polarity. We compare Katseblin's magnetostratigraphy column with ours in Fig. 2 and there is good agreement.

The mean palaeomagnetic directions for the high-temperature component are shown in Table 2. The directions before and after tilt correction are very close to each other and their statistics are practically the same. This is not surprising, because the bedding is almost uniform and the dips are quite shallow. However, the good stratigraphic zonation of the magnetic polarity intervals (Fig. 2) together with mineralogical evidence (see Section 3) suggest a primary nature for the high-temperature component. So, we prefer to use the palaeopole based on the tilt-corrected results.

Fig. 8 shows the differences between the directions of the high-temperature component in the pebbles of two conglomerate boulders. The between-pebbles difference obviously exceeds the within-pebble difference, but the number of samples is insufficient for a proper conglomerate test.

6 DISCUSSION

Buchan *et al.* (2000) proposed the use of 'key poles' rather than the apparent polar wander path (APWP) approach for the analysis of Precambrian plate tectonics. Their definition of a 'key pole' includes reliable dating ($<\pm 20$ Ma) and the satisfaction of basic reliability criteria. Their analysis of the available palaeomagnetic information from Fennoscandia revealed only two Proterozoic key poles with ages >1600 Ma. They are both from Subjotnian quartz porphyry dykes from Finland—30°N, 175°E (Neuvonen 1986) and 26°N, 180°E (Mertanen & Pesonen 1995; Törnroos 1984). These poles are shown on Fig. 9(a) as SE and SI respectively. Buchan *et al.* (2000) also used some non-key poles for their analysis. The closest in age to our pole is the one from the Haukivesi Lamprophyres (Neuvonen *et al.* 1981; Huhma 1981)—see Table 1 (entry 2). We have also shown this pole on Fig. 9(a) (HL pole).

We believe that our new palaeopole from Vazhinka section can be accepted as the 'key pole' for the time interval between 1790 and 1770 Ma. The Q factor (Van der Voo 1990) is equal to 6. Unfortunately (see previous sections) it is impossible to carry out a proper conglomerate test or a fold test for the Vazhinka section. However, good mineralogical and rock magnetic evidence of the primary (diagenetic) nature of the haematite and its remanence (see sections 3 and 4), and a regular behaviour of the magnetic polarity through the section (Fig. 2), lead to the reasonable suggestion about the primary nature of the

Table 2 Sample mean palaeomagnetic directions from the Shoksha Formation in Vazhinka River section, Karelia, Russia (61.3°N, 33.8°E).

Component of magnetisation	N/n	Decl. (°)	Incl. (°)	k	α_{95} (°)	Plat (°N)	Plong (°E)	Dp (°)	Dm (°)
1 High-T, tilt corr.	36/61	354.3	21.6	22.3	5.2	39.7	221.1	2.9	5.5
2 High-T, in situ	36/61	347.4	23.7	22.1	5.2	40.2	230.0	3.0	5.5

N/n = number of samples/specimens; Decl, Incl = sample mean declination, inclination; k = best estimate of the precision parameter of Fisher (1953); α_{95} = the semi-angle of the 95% cone of confidence; Plat, Plong = latitude, longitude of the palaeopole; D_p, D_m = the semi-axes of the cone of confidence about the pole at the 95% probability level.

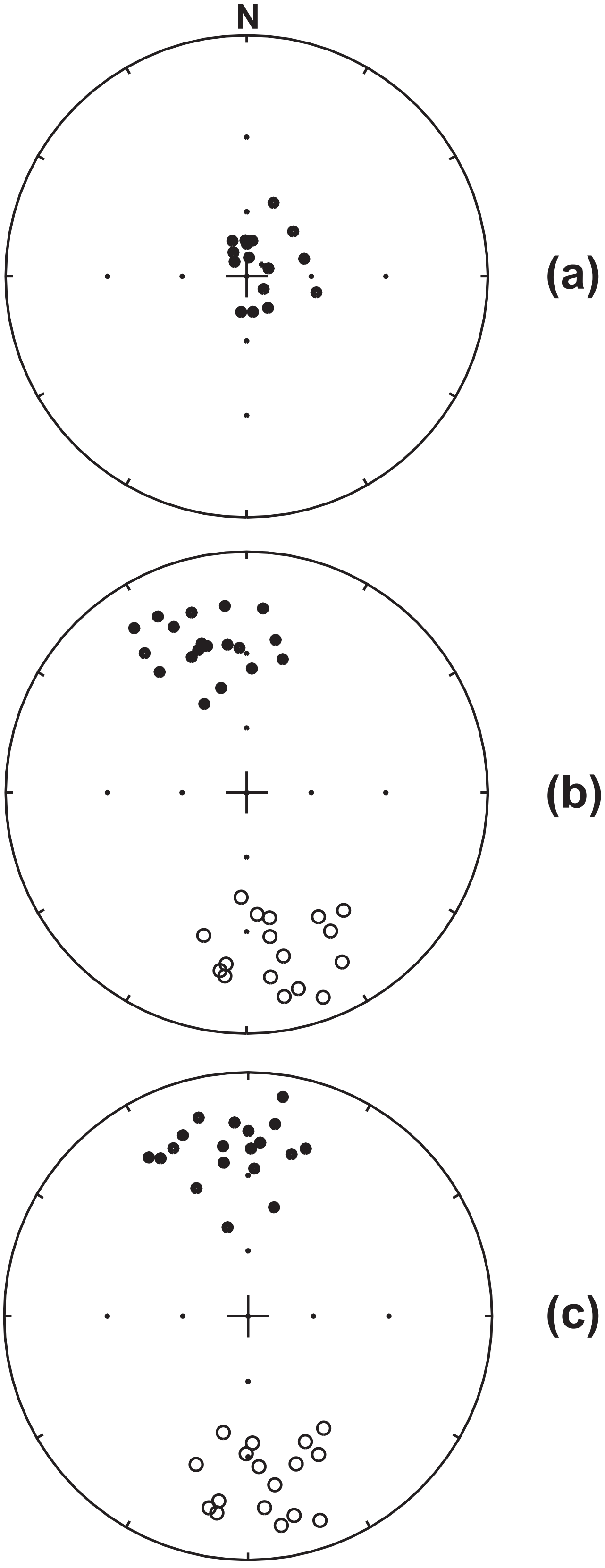

Figure 7. Stereoplots (equal-angle projection): (a) low-temperature component (PDF); (b) high-temperature component *in situ*; (c) high-temperature component after tilt correction.

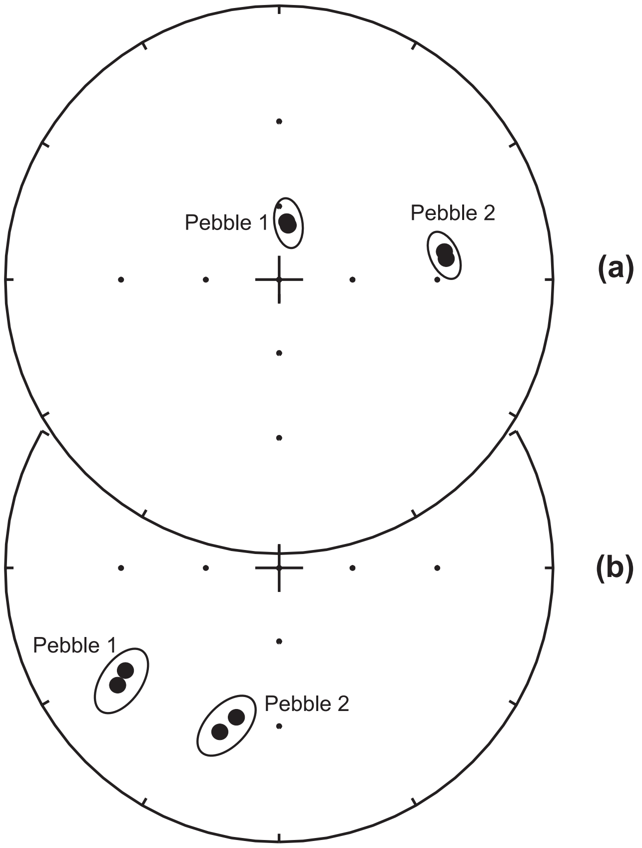

Figure 8. Remanence directions of the pebbles in two boulders of conglomerate: (a) and (b) correspondingly. Absolute direction is arbitrary.

remanence. In our view, the presence of both polarities provides a pole position that is more reliable, than most of studies presented in Table 1. Fig. 2 shows that there were at least two polarity reversals during the deposition of the studied sediments. Therefore, the time interval covered is enough to average the effect of palaeosecular variations.

The Vazhinka pole (VS) is shown on Fig. 9(a) (star). The dashed line shows the possible APWP for Fennoscandia between ~1840 Ma and ~1630 Ma. However, a time interval of about 150 Ma without any 'key poles' allows a more complex APWP. Fig. 9(b) shows the corresponding palaeopositions of Fennoscandia at three time slices.

7 CONCLUSIONS

First, a palaeomagnetic study of the upper part of the Shoksha Formation at Vazhinka River section has revealed a stable bipolar remanence. Mineralogical and rock magnetic studies suggest that diagenetic haematite is the main carrier of this remanence.

Second, regular magnetostratigraphic zonation in the section (Fig. 2) is evidence in favour of the primary nature of the remanence and finally the stratigraphic position of the studied section together with geochronological data from the Ropruchey Sill suggest that the age of the new palaeomagnetic pole lies between 1790 and 1770 Ma.

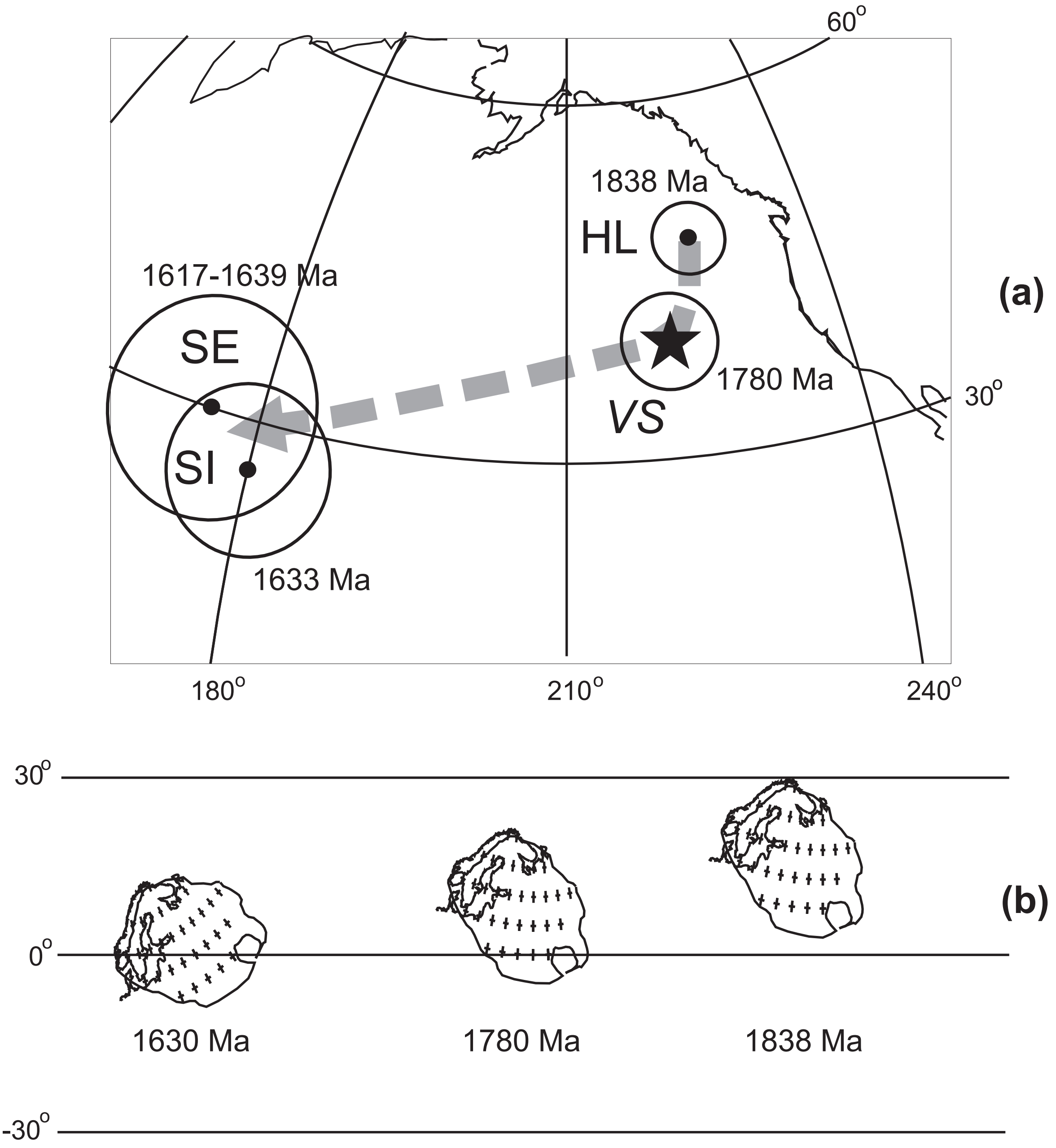

Figure 9. (a) Post-svecofennian palaeomagnetic poles for Fennoscandia: SE–SE quartz porphyry dykes (Neuvonen 1986); SI–Sipoo quartz porphyry dykes (Mertanen & Pesonen 1995), age after (Törnroos 1984); HL–Haukivesi lamprophyres (Neuvonen *et al.* 1981), age after (Huhma 1981); VS (star)–Vazhinka section (this study). SE and SI are "key poles" according to (Buchan *et al.* 2000). (b) Corresponding palaeopositions of Fennoscandia.

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