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Paleomagnetic studies of gabbronorites of the southern White Sea region, Karelia, Russia

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Abstract. The paper describes the paleomagnetic studies of gabbronorites of the southern White Sea region. It has been found that the major part of the rocks studied was remagnetized during the Svecofennian tectonomagmatic epoch and that the secondary magnetization is fairly stable. Its direction deduced from the intrusions on the Borshevets Island ($N = 27$, $D = 6.1°$, $I = 48.3°$, $k = 50.6$, $\alpha_{95} = 3.9$) corresponds to the coordinates of the pole (54.8°N, 206.8°E, $dp = 3.4°$, $dm = 5.1°$), which is in a good agreement with the "Svecofennian" fragment of the apparent polar wander path of Fennoscandia. This means that the age of this magnetization is about 1.8 Ga. The paleomagnetic pole deduced from the contact zone of the intrusion on the Emestrov Island lies close to the group of early Karelian poles. However, judging by its statistical characteristics, the hypothesis on the primary origin of the magnetization of this intrusion should be regarded only as tentative. The rocks of the central part of this intrusion and also of the intrusion located near the town of Belomorsk were remagnetized during the Svecofennian period as well. It is concluded that the narrow spectrum of unblocking temperatures suggests that the superimposed magnetization has a partial thermoremanent nature, and the temperatures of the secondary heating of the rocks under investigation are estimated.

1. Introduction

The research efforts aimed at construction of the apparent polar wander path (APWP) for the Fennoscandian Precambrian started more that 30 years ago [*Katseblin*, 1968; *Neuvonen*, 1965]. These and more recent works resulted in several versions of the APWP. To analyze the history of the Fennoscandian Shield drift in the Early Proterozoic, the most recent version of the APWP is typically used [*Elming et al.*, 1993]. Not all fragments of the Early Proterozoic track of this curve are well justified; for instance, the fragment be-

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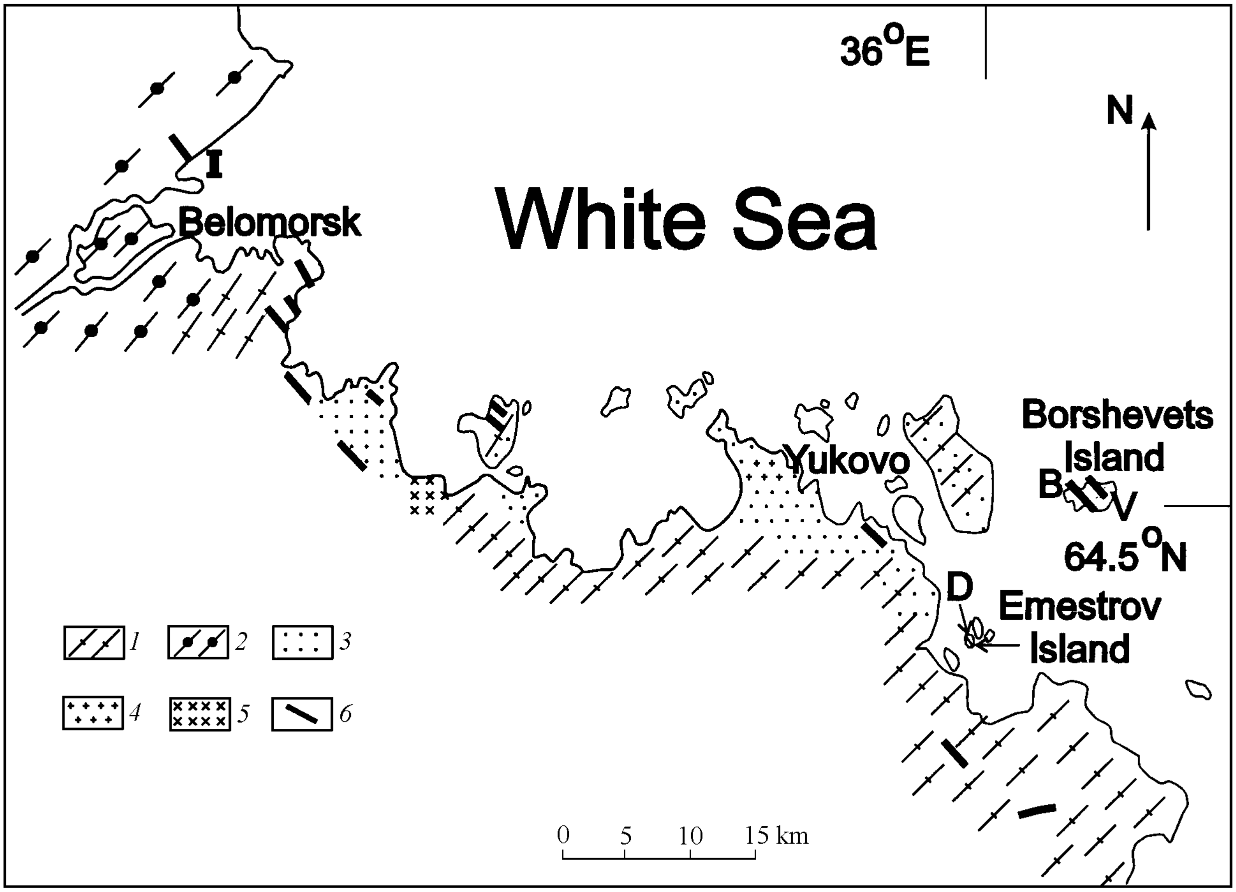

Figure 1. Geological sketch map of the southern White Sea region.

tween the "key" poles with the ages of 1.88 Ga and 1.76 Ga is built on the basis of a sufficiently large number of reliable paleomagnetic determinations. There is also a group of reliably dated poles with the ages of about 2.4 Ga. At the same time, the part of the curve between 2.4 Ga and 1.88 Ga is poorly justified.

In addition, greatly differing amounts of the paleomagnetic data are available for different parts of the shield. There are more than 200 paleomagnetic determinations for its western part (the territory of Finland and Sweden), while for the Karelian-Kola region, there are less than 40 determinations, and until recently, only 14 of them have been for the early Karelian (2.5–1.9 Ga). The latest paleomagnetic studies [*Damm et al.*, 1997; *Khramov et al.*, 1997] have improved the situation only a little. Specifically, the southern White Sea region still remains poorly studied from the paleomagnetic point of view. The goal of this paper is to fill the gap to some extent.

2. Geology and Sampling

The southern White Sea region is a part of the White-Sea mobile belt separating the Karelian granite-greenschist and Kola granulite-gneiss regions. The determining role in the structure of the southern White Sea region is played by the Archean complex of homogeneous rocks of the tonalite-plagiomicrocline granite composition which has experienced multiple structural and metamorphic transformations. A characteristic feature of the southern White Sea region distinguishing it from the western White Sea region is a small amount of mafic rocks. The studies of this region, including the structural-metamorphic analysis have revealed three groups of mafic rocks, the most ancient among which (2.8 Ga) are analogs of volcanic rocks of the Archean greenschist belts of Karelia. According to the isotope-geochemical data the remaining groups of mafic rocks (to which gabbronorite intrusions belong (Figure 1)) are considered to be of one age and formed in the interval 2.5–2.45 Ga [*Chekulaev et al.*, 1994].

The structural scheme of the region of the southern White Sea is completely determined by late Svecofennian deformations. Relicts of the earlier structures are present now only in some lens-like areas. A detailed mapping of these areas made it possible to reveal three long stages of the endogenic development: two Archean and one Proterozoic-Svecofennian.

All mafic rocks of the southern White Sea region have experienced the Svecofennian metamorphism under the conditions of epidote amphibolite–amphibolite facies of increased pressures ($T = 650^\circ - 550^\circ$C, $P = 7 - 8$ kbar) [*Kotova*, 1988]. As a result of intense transformations, the most ancient mafic rocks have been preserved mainly as relics, which makes the choice of oriented specimens for paleomagnetic studies difficult. For this reason the objects for our studies were chosen to be gabbronorites (taken from intrusions B and V on the Borshevets Island, intrusion D on the Emestrov Island, and intrusion I near Belomorsk) and granitoids of the Yukovo complex (Figure 1).

Oriented hand samples of gabbronorites were collected from (1) a 1-m-thin dike B sampled at the distance of 50 m (13 hand samples, including 4 samples of gneisses cut by the dike); (2) about 250-m-thick intrusion V (31 hand samples), (3) intrusion D with the visible thickness of 70 m and sampled length of 145 m (27 hand samples) (these rocks had different granularities (from small-grain rocks at the intrusion margins to large-grain and gigantic-grain rocks at its center)), and (4) intrusion I with the visible thickness of about 50 m (23 hand samples).

From the body of granitoids near the village of Yukovo, 18 samples were collected along the White Sea coast at a distance of about 1.5 km. In spite of metamorphic Svecofennian transformations, both mafic rocks and granites had regions of rocks with the well-preserved magmatic structures. The samples were oriented by a magnetic compass.

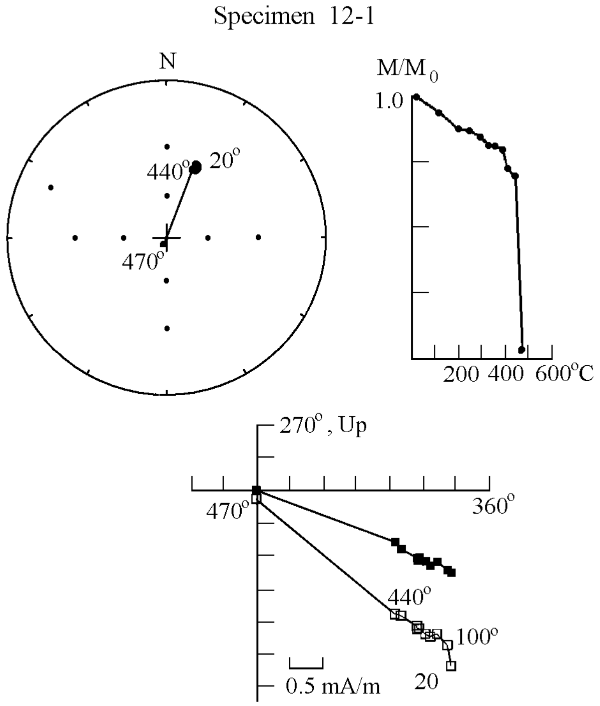

Figure 2. Example of thermal demagnetization of gabbronorites of dike B: Decay curve, stereographic plot, and Zijderveld diagram.

3. Instrumentation and Experimental Procedure

Oriented hand samples were cut into cubes with the rib of 2 cm. From each hand sample, from two to eight cubic specimens were prepared.

The remanent magnetization of the specimens was measured by JR4 “Geophysica” spinner magnetometers (Brno, Czech Republic) at the paleomagnetic laboratory of the All-Russian Petroleum Research Geological Exploration Institute at St. Petersburg. A stepwise thermal demagnetization was performed by a setup developed at the same Institute. The local geomagnetic field was screened in the setup by a three-layer μ metal screen. A part of the specimens (intrusion D) was studied at the Laboratory of Magnetic Properties of the Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation at St. Petersburg. The experiments involving the stepwise demagnetization with an alternating magnetic field were carried out at the laboratories of the National Geological Institute and the Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation at St. Petersburg. The differential thermomagnetic analysis of the specimens was performed at Kazan State University.

The obtained data were statistically processed using a standard procedure [*Fisher*, 1953; *Kirschvink*, 1980; *Zijderveld*, 1967] by the IAPD computer program [*Torsvik*, 1986].

4. Paleomagnetic Analysis

The natural remanent magnetization (NRM) of gabbronorites of dike B (the Borshevets Island) was found to range from 0.06 to 1.3 mA m^{-1}, and the magnetic susceptibility (κ) was $(4.3 - 5.6) \times 10^{-4}$ SI units. The rocks of intrusion B (which outcrop on the same island) proved to be more magnetic: NRM was from 0.5 to 2.5 mA m^{-1}, and the magnetic susceptibility was $(4.5-6.5) \times 10^{-4}$ SI. The differential thermomagnetic analysis of the specimens from these bodies has shown that the main magnetic mineral in them is magnetite. Pyrrhotite is also present in some specimens. A stepwise thermal demagnetization of specimens from intrusions B and V (Figures 2 and 3, respectively) has revealed the presence of one stable component with the unblocking temperatures $T_{UB} = 450^\circ - 530^\circ$C. This component is also well isolated at demagnetization by an alternating magnetic field. The distribution of the component directions is shown in Figure 6a; the mean paleomagnetic direction and its statistical characteristics are listed in Table 1.

The magnetic properties of gabbronorites from intrusion D (the Emestrov Island) were as follows: NRM = $(1.5 - 9.6)$ mA m^{-1}, $\kappa = (1.8 - 5.0) \times 10^{-4}$. The example of demagnetization with an alternating magnetic field is given in Figure 4. It was found that the characteristic magnetization components have different directions in various parts of the intrusion. The rocks of the marginal (contact) part exhibit a stable magnetization whose direction distribution is shown in Figure 6c. Its mean direction and statistical

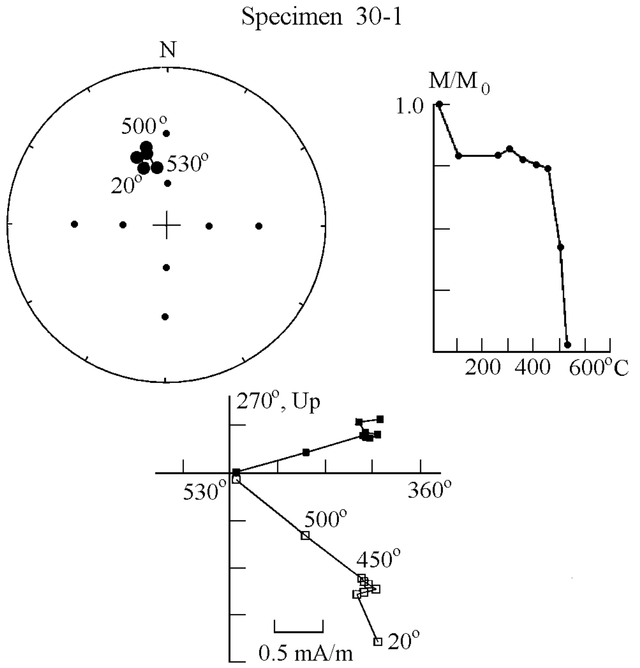

Figure 3. Example of thermal demagnetization of gabbronorites of dike *V*.

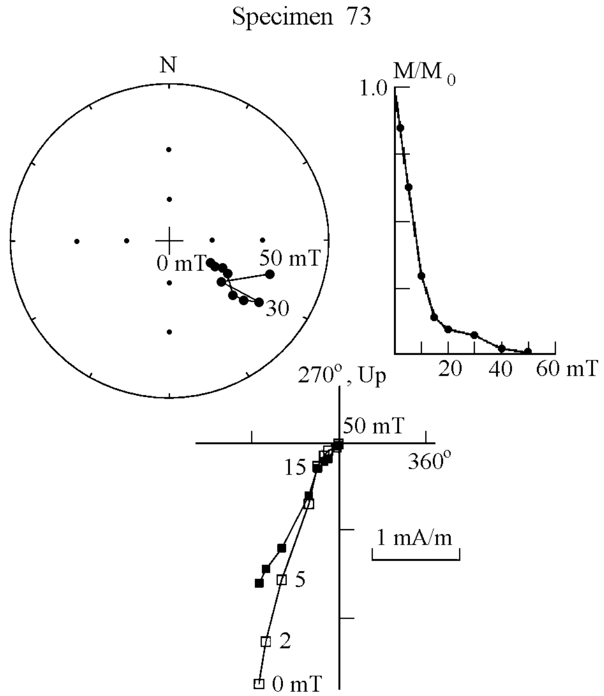

Figure 4. Example of AC demagnetization of gabbronorites of dike *D*.

characteristics are given in Table 1. The central part of the body is characterized by another direction (see Table 1 and Figure 6d).

The increase of Q values from the center ($Q = 1.7$) to the contact zone ($Q = 2.4$) manifests initially a magmatic origin of the minerals, which are a bearer of the magnetization. In the near-contact region these minerals might have saved the initial magnetization, whereas the less magnetically tough minerals of the central part of the intrusion had more chances to obtain a new magnetization in the Svecofennian activization period. Actually, the most ancient component is present exclusively in the endocontact zone, and the rocks of the central part of the intrusion keep the Svecofennian magnetization (Figures 6c and 6d).

The magnetization of the most metamorphosed parts of intrusion *I* (Belomorsk) proved to be rather low: NRM = (0.04–0.96) mA m^{-1}. However, several specimens from the weakly altered parts of the body were found to be strongly magnetic: NRM = (1.2–3.4) mA m^{-1}. The magnetic susceptibility of the rocks of intrusion *I* proved to be in approximately the same limits as that of other bodies studied: $\kappa = (4.5-5.5)\times 10^{-4}$. The thermal demagnetization of these rocks revealed a lower stability of the characteristic magnetization compared with those of intrusions *B* and *V*. It falls sharply even at the first temperature steps (Figure 5) and sometimes becomes comparable with the noise level after heating up to 300°–400°C. The reliable (statistically significant) directions are presented in Figure 6b. Of particular interest is the presence of two polarities (though one of them is indicated in Figure 6b by only one point). The mean direction of the characteristic magnetization of intrusion *I* is shown in Table 1.

A considerable part of the specimens studied was found to have a low-temperature component ($T_{UB} = 200° - 300°$C)

Table 1. Paleomagnetic Directions and Poles for Lower Proterozoic Gabbronorites of the Southern White Sea Region

Geological Unit	ϕ, deg	λ	N/n	D, deg	I, deg	k	α_{95}, deg	Φ, deg	Λ, deg	dp, deg	dm, deg	Polarity	Magnetization Age, Ga
Intrusions *B* and *V*	64.5	36.0	27/34	6.1	48.3	50.6	3.9	54.8	206.8	3.4	5.1	N	1.8
Intrusion *D*, central part	64.4	36.0	6/6	306.3	55.1	19.5	15.6	47.2	290.5	15.7	22.2	N	1.9?
Intrusion *D*, contact part	64.4	36.0	9/9	107.4	11.2	19.8	11.9	2.3	287.9	6.1	12.1	R	2.4
Intrusion *I*	64.6	34.8	10/14	320.8	27.5	13.8	13.5	33.3	261.8	8.0	14.7	N	1.9?

Here ϕ and λ are the geographic coordinates of the sampling site; N/n is the number of hand samples/specimens; D and I are the declination and inclination of the characteristic magnetization; k is the precision parameter [*Fisher*, 1953]; α_{95} is the confidence circle radius; Φ and Λ are the latitude and longitude of the paleomagnetic pole; dp and dm are the semiaxes of the confidence oval.

and a low-coercive component with greatly “scattered” directions (Figure 6e). The characteristic magnetization of granitoids of the Yukovo massif also proved to have greatly differing directions (Figure 6f). Because of the poor statistics of the directions, these magnetizations are not given in Table 1.

5. Discussion

The history of rock metamorphic transformations in this region manifests that the most probable epochs of remagnetization might have been metamorphism episodes with the age of 2.45, 1.9, and 1.8 milliard years.

Figure 7 shows paleomagnetic poles for gabbronorites of the southern White Sea region (Table 1) and also a fragment of the apparent polar wander path (APWP) for Fennoscandia [*Elming et al.,* 1993]. Note that the fragment of the APWP between the key poles at 1.88 Ga and 1.76 Ga (which corresponds to the Svecofennian epoch) is fairly reliable and is based on a large number of reliable paleomagnetic determinations. The key pole with the age of 2.45 Ga is also justified statistically fairly well. At the same time, the part of the curve between 2.45 Ga and 1.88 Ga is poorly justified. Moreover, as recent studies [*Pisarevsky and Sokolov,* 1999] have shown, there is reason to believe that it can be reconsidered.

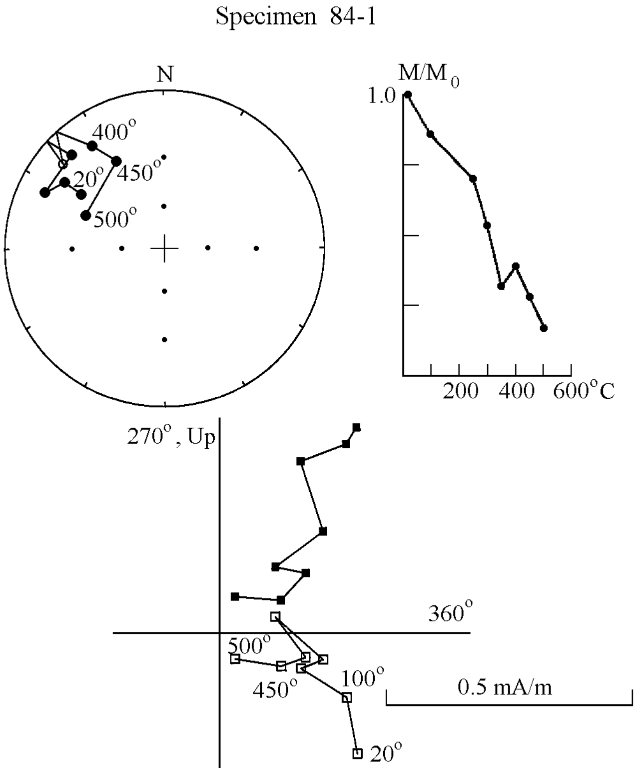

Figure 5. Example of thermal demagnetization of gabbronorites of dike *I*.

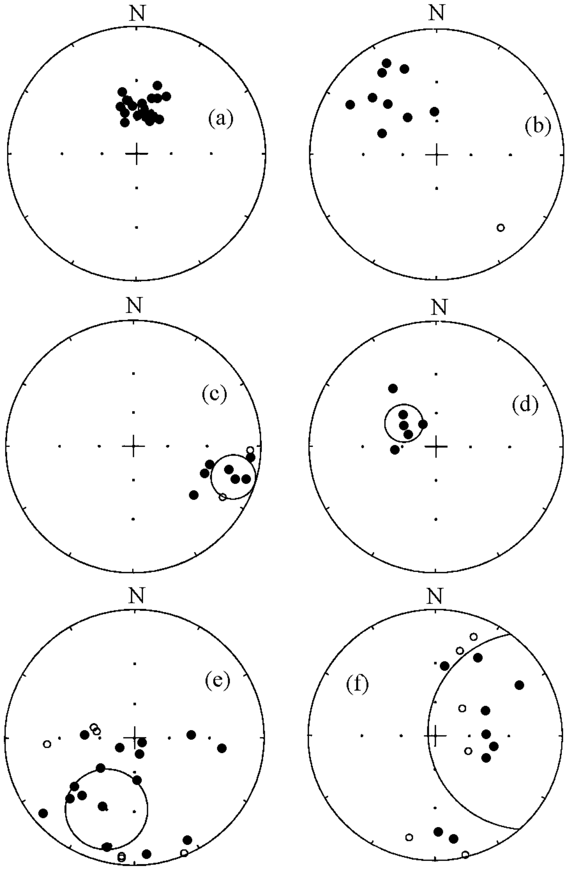

Figure 6. Stereoplots of the paleomagnetic directions: (a) dikes *B* and *V*, (b) dike *I*, (c) dike *D* (contact zone), (d) dike *D* (central part), (e) directions of the low-temperature components isolated for gabbronorites, and (f) the same for granitoids of the Yukovo massif.

As can be seen from Figure 7, the most reliably defined pole derived from intrusions *B* and *V* (pole 1, Figure 7) is in a good agreement with the Svecofennian fragment of the APWP. This leads to the conclusion that the gabbronorites of intrusions *B* and *V* were fully remagnetized in the Svecofennian epoch, to be more exact, about 1.8 Ga. This magnetization is characterized by a rather narrow interval of unblocking temperatures (450°–530°C). It can be supposed that the secondary heating, which caused remagnetization, was characterized by the temperatures not exceeding the above indicated one. Since the temperature of the Svecofennian metamorphism is evaluated by petrologists within the 650°–550°C interval, the age of this magnetization cannot be more than 1.8 milliard years. However, additional studies are needed to confirm this conclusion.

The paleomagnetic pole deduced from intrusion *I* (pole 4) and both poles determined from intrusion *D* are also consistent with the APWP. However, because of a lower quality of the determinations and the necessity to revise the 2.45–1.88 Ga fragment of the APWP, it is impossible to date exactly these magnetization components. Our tentative estimates of their ages are listed in Table 1. It is clear that

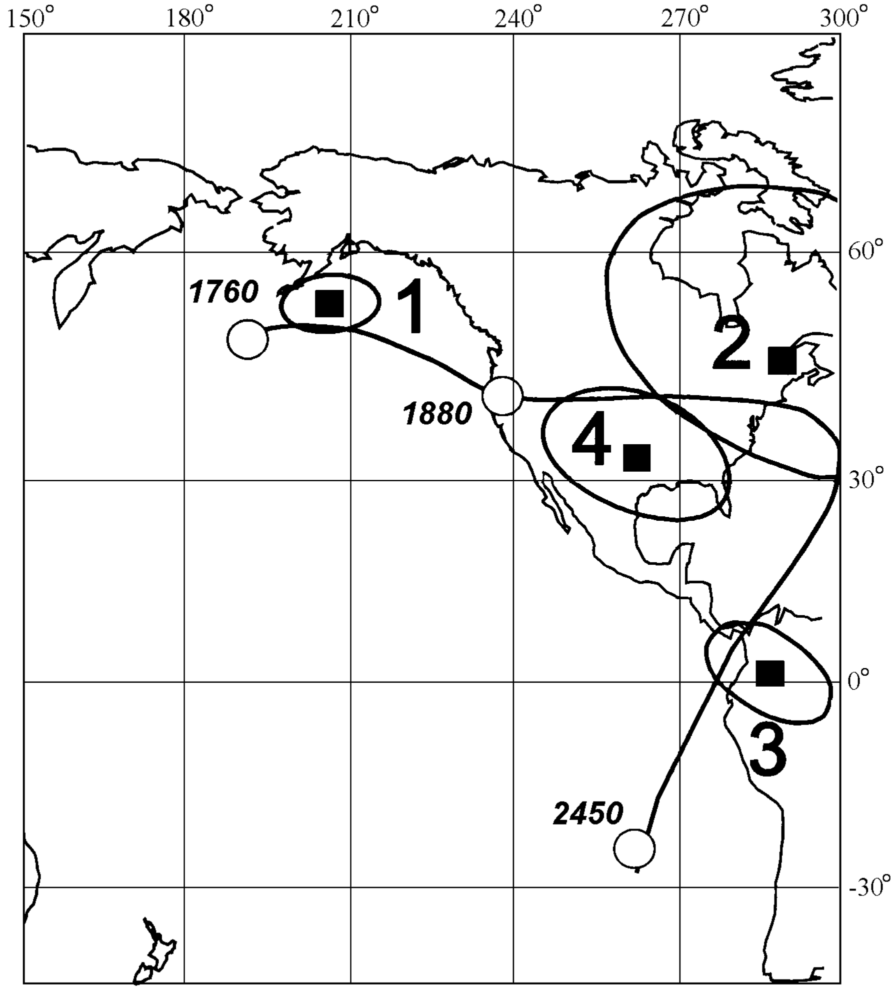

Figure 7. Paleomagnetic poles deduced from gabbronorites of the southern White Sea region (squares) and fragment of the apparent polar wander path [*Elming et al.,* 1993]. The circles show the "key" paleomagnetic poles (with their ages) [after *Elming et al.*, 1993].

only pole 3 can correspond to the rock formation time (2.5–2.45 Ga) because it is derived from the contact region of intrusion *D*. Intrusion *I* and the central part of intrusion *D* were also remagnetized in the Svecofennian. Because of the insufficient reliability of the 2.45–1.88 Ga fragment of the APWP, only the lower limit of the age of this remagnetization can be estimated (1.88 Ga).

6. Conclusions

The paleomagnetic studies of gabbronorites of the southern White Sea region have revealed that their major part was remagnetized in the Svecofennian epoch. The paleomagnetic pole inferred from intrusions *B* and *V* on the Borshevets Island has satisfactory statistical characteristics and is fairly reliable. By comparing it with the APWP for Fennoscandia, its age is estimated to be 1.8 Ga. The paleomagnetic age inferred from the contact part of intrusion *D* on the Emestrov Island probably corresponds to the rock formation time (2.5–2.45 Ga); however, it is poorly justified statistically and requires verification. Intrusion *I* (Belomorsk) and the central part of intrusion *D* were also remagnetized in the Svecofennian epoch; however, the age of this remagnetization is not less than 1.88 Ga.

The narrow spectrum of unblocking temperatures of the characteristic component of magnetization of intrusions *B* and *V* suggests that the temperatures of secondary heating, which led to remagnetization of rocks in the Svecofennian, were between 450°C and 530°C.

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