ISSN 0145-8752, Moscow University Geology Bulletin, 2018, Vol. 73, No. 6, pp. 473–483. © Allerton Press, Inc., 2018.
Original Russian Text © N.V. Lubnina, V.S. Zakharov, 2018, published in Vestnik Moskovskogo Universiteta, Seriya 4: Geologiya, 2018, No. 5, pp. 3–13.

Assessment of the Contribution of Secondary Metachronous Magnetization Components to the Precambrian Paleomagnetic Poles of the Karelian Craton

N. V. Lubnina[a, *] **and V. S. Zakharov**[a, **]
[a] *Department of Geology, Moscow State University, Moscow, 119991 Russia*
**e-mail: natalia.lubnina@gmail.com*
***e-mail: zakharov@geol.msu.ru*

Received October 30, 2017

Abstract—The secondary (metachronous) magnetization components identified in the Precambrian complexes of the Karelian Craton have been analyzed. The average directions of high-temperature components (deviations from the true direction) have been calculated based on the contribution of secondary magnetization components resulting from tectonomagmatic events of uneven ages. The Precambrian key poles often coincide with the vector sum of the Phanerozoic magnetization components of uneven ages. The conclusion on the primary/secondary origin of the Precambrian paleomagnetic poles should be made on the basis of the integrated petro- and paleomagnetic and isotope data and geological correlations, rather than based on only the paleomagnetic reliability tests.

Keywords: Precambrian paleomagnetic pole, Karelian Craton, paleomagnetism, remagnetization, key pole, and secondary magnetization components

DOI: 10.3103/S014587521806008X

INTRODUCTION

The paleomagnetic poles are traditionally used to make magnetotectonic reconstructions and to calculate the kinematic parameters of plate motion (the travel velocity and rotation on a sphere). The correct correlation of magnetotectonic reconstructions with geological data is considerably dependent on the quality of the paleomagnetic data. The reliability criteria of paleomagnetic poles were developed for the Phanerozoic (Van der Voo, 1990) and the Precambrian (Buchan et al., 2000). One of the significant criteria of these scales is to prove the time when the rocks acquired magnetization components with uneven ages. The paleomagnetic reliability tests were taken as a basic quality assessment of paleomagnetic poles. For magmatic complexes, they primarily include a contact test and a reversal test. For the sedimentary rocks, in addition to a reversal test, the fold and conglomerate tests are also applied. Positive contact and conglomerate tests are indicative of the fact that a high-temperature magnetization component was formed at the time of rock formation. Having determined the age of rocks on the basis of independent isotope data, we obtain reliable information on the time when the rocks acquired a magnetization component. A reliable or key paleomagnetic pole can be calculated by testing of a sufficient number (at least ten, according to the paleomagnetic reliability criteria) even-aged complexes (for example, dike bodies) (Buchan et al., 2000).

It is harder to determine the time when the rocks acquired a secondary metachronous magnetization component. The negative reversal test is indicative of incomplete subdivision of the magnetization components of uneven ages, i.e., of the impossibility of correct identification of a secondary, later, magnetization component. Even if the components are correctly separated during magnetic cleaning, the formation time of the secondary magnetization component is estimated by similarity to the paleomagnetic poles obtained earlier for the same tectonic block. As a result of this logical circular estimation, the magnetization age is "dated" by paleomagnetic poles. According to R. Van der Voo (1990) and K. Buchan, one of the first reliability criteria is to obtain a paleomagnetic pole for the rocks whose age is determined by isotope methods. For the Precambrian magmatic complexes, these primarily include U–Pb dating of magmatic zircons and baddeleyite, as well as Ar–Ar dating of stratified intrusions.

Recently, attempts have been made to estimate the time when the rocks acquired secondary magnetization components based on U–Pb dating of rutile and sphen, as well as with Rb–Sr and Ar–Ar rock dating (review in (Lubnina et al., 2015)), because the closing temperatures of the isotope systems of these minerals are lower than the Curie temperature of major magnetization-carrying minerals. Direct correlation between the closing time of any isotope system and formation of the secondary magnetization component has not been established yet.

Along with this, an equally important criterion of a reliable paleomagnetic pole is a disagreement with younger paleomagnetic poles for the same tectonic block. Such a restriction denies the presence of loops in the apparent pole migration paths (APMPs), because self-crossing of APMPs means the same position of poles of uneven ages and also, indirectly, the formation of stable configurations such as NENA (North Europe—North Atlantic) for the Precambrian and Euro-America (Laurussia) for the Phanerozoic. However, independent geological correlations without the use of paleomagnetic data suggest the opposite. Natural questions arise: what contribution to the primary Precambrian magnetization is made by the later tectonomagmatic events; is it possible to distinguish all of them correctly, or are some of them are obscured, and inevitably we have to deal only with their vector sum; is it possible that some events do not lead at least to a partial substantial rock remagnetization; how far does the influence of certain tectonomagmatic events spread within the craton, and what is the magnetization rate of the rocks under such changes?

ANALYSIS OF THE PRECAMBRIAN “RELIABLE” POLES OF THE KARELIAN CRATON AND THE PHANEROZOIC PALEOMAGNETIC POLES OF THE EAST EUROPEAN PLATFORM (Fig. 1)

At present, in the Global Paleomagnetic Database (Pisarevsky, 2005; Vekkolainen et al., 2014), 432 out of the Precambrian determinations were obtained for the East European (Karelian) Craton (EEC), of which 38 single determinations were obtained for the Ukrainian Shield, 2 for the Voronezh Massif, 56 for the Southern Urals and the Polar Urals, and the primary origin of the natural residual magnetization vector was confirmed by field tests of paleomagnetic reliability only for 7 of these determinations.

A revision of all paleomagnetic data accumulated by 2000 for the EEC and Laurentia allowed K. Buchan et al. to propose the concept of key poles (2000). In addition, the identified non-key, but reliable poles can also be used to make reconstructions when the key poles are not available in the interval exceeding 50 Ma.

The Phanerozoic Paleomagnetic Poles of the East European Platform

In the system of global paleotectonic reconstructions, the position of the East European Platform (EEP or Baltic Region) in the Vendian—Paleozoic is specified on the basis of single paleomagnetic poles obtained from sedimentary deposits whose age (and, accordingly, the time when the rocks acquired characteristic magnetization components) was determined stratigraphically (Smethurst et al., 1998). Most APMP segments were constructed on the basis of interpolation, while their geometry was largely determined by the set of used data and the averaging method (sliding window method, splines, or the most reliable poles, taking their weight or significance into account). According to the analysis of Paleozoic parts of the APMP of the EEP performed by S.V. Shipunov and others, regardless of the amount involved data and the APMP construction method, all paths cross each other at the nodal points, forming four clusters: 370—402, 330—350, 262—283, and 240—261 Ma (Shipunov et al., 2007). In this case, the age of paleomagnetic poles correlates in time with the tectonomagmatic events within the EEP and the major EEP rock remagnetization stages in the Phanerozoic (Bazhenov et al., 2016; Lubnina, 2009).

UNEVEN-AGED SECONDARY MAGNETIZATION COMPONENTS IDENTIFIED IN THE PRECAMBRIAN AND PHANEROZOIC COMPLEXES OF FENNOSCANDIA

The long-term paleomagnetic studies of the Precambrian and Phanerozoic complexes in one of the East European Craton segments, that is, Fennoscandia, made it possible to reveal at least one metachronous secondary magnetization component in addition to the recent viscous component (review in (Lubnina, 2009)). In most Precambrian and Phanerozoic deposits, this component can be identified in the middle- or high-temperature range. The secondary nature of metachronous components was determined on the basis of negative paleomagnetic reliability tests and/or based on coincidence with the younger EEP poles (Fig. 2). It is assumed that in the course of the remagnetization, the primary magnetization component is either completely destroyed or is present as an inseparable sum of magnetization components in the high-temperature range.

Thermoviscous and chemical rock remagnetization types are commonly distinguished. They depend on P–T combinations and the presence of fluids, leading to either partial or complete disintegration of a carrier mineral and/or to formation of a new mineral fraction. Within Fennoscandia, such remagnetization conditions are related either to fluid migration under the postorogenic collapse or to the mantle superplume effect (Lubnina, 2009).

Remagnetization Related to the Mantle Superplume Effect

The manifestation of the mantle superplume on the surface is currently reconstructed on the basis of

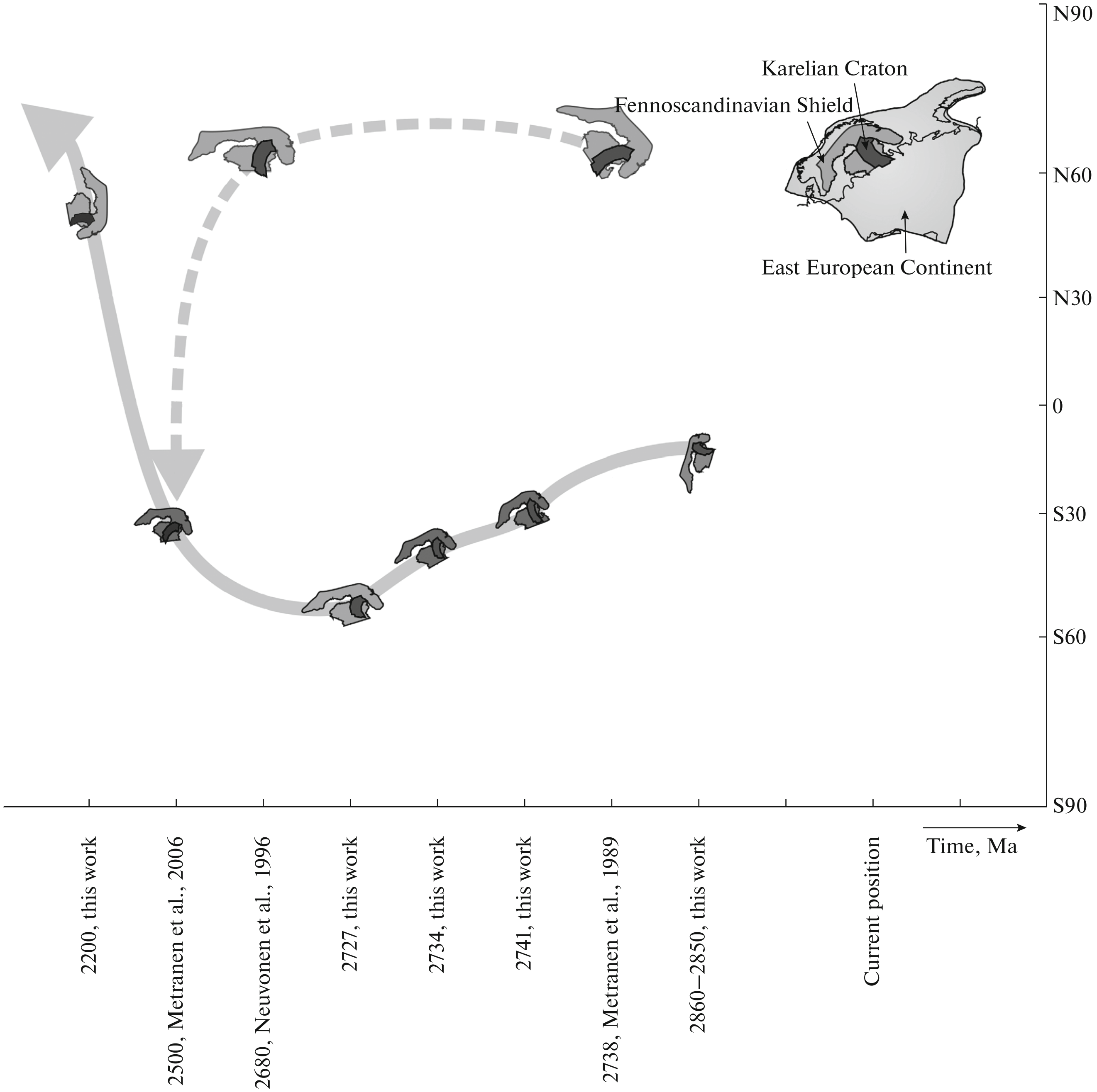

Fig. 1. The paleolatitudinal position of the Karelian Craton at different stages of its Neoarchean–Neoproterozoic history. Digits indicate the age of the Precambrian key poles. Letter designations of the key poles are given in Table 1.

radial, mainly dolerite swarms of dike bodies (Ernst and Buchan, 1997). In general, the mantle superplume setting is characterized by high-temperature effects (which significantly exceed the Curie points of magnetic minerals) at low pressures, the presence of CO_2, CH_4 fluids, and the absence of H_2O. The monopolar magnetization component that arises at the same time has a thermoviscous nature and depending on the combination of effect duration and temperature it can be both medium- and high-temperature.

The characteristic superplume magmatism ages within the EEP are as follows: 2.50–2.45 and 1.27–1.20 Ga and 380–360 and 250–245 Ga (Figs. 3, 4). The mantle superplume effect on the rock magnetization in Fennoscandia is considered below.

The 2.50–2.45 Ga period. Remagnetization of the rocks of this age is relatively common in Fennoscandia (Fig. 3) and is the most characteristic for the Archean complexes of the Vodlozero block of the Karelian Craton, where it is most often expressed as a low–medium temperature magnetization component (Fedotova

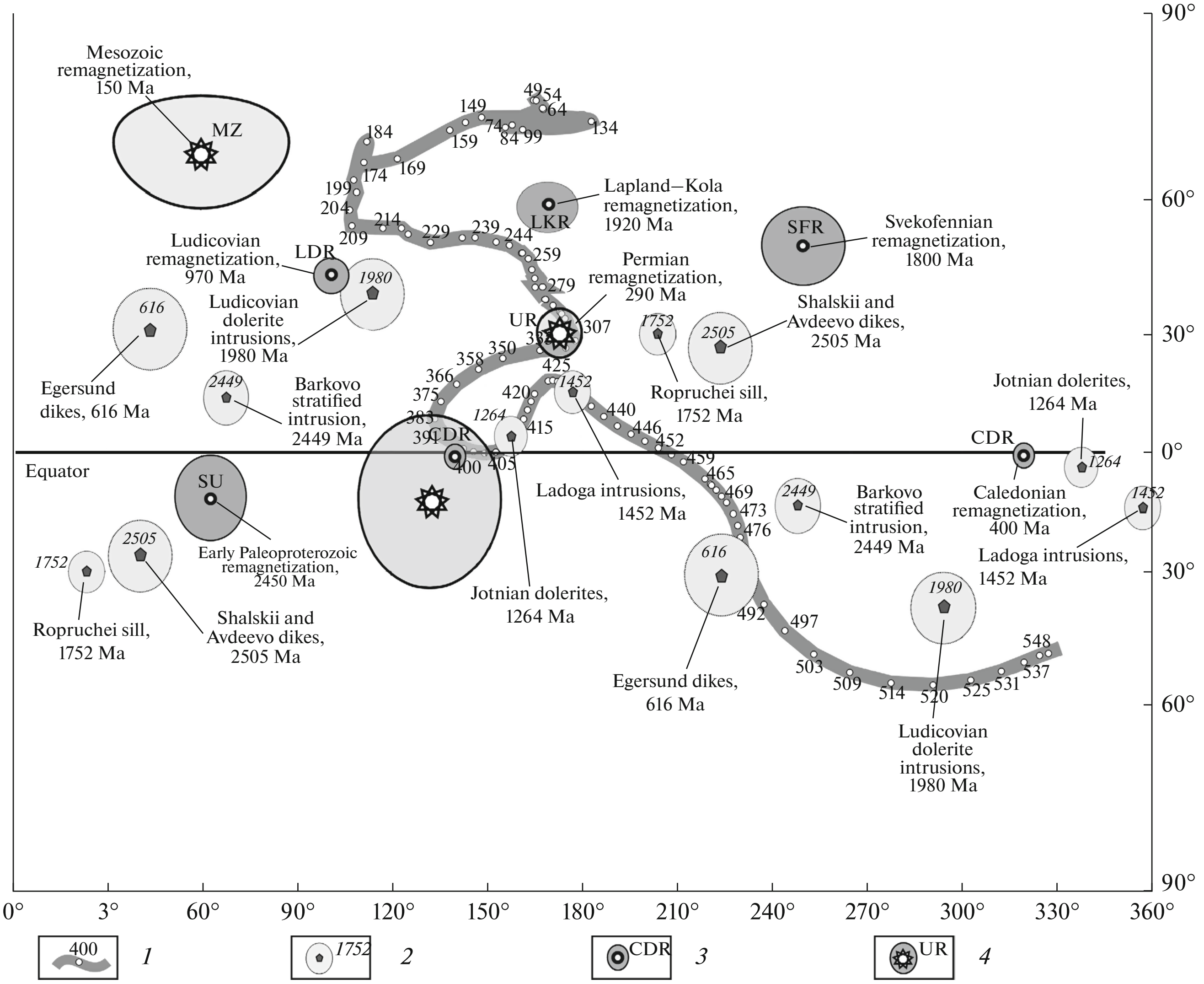

Fig. 2. Comparison of the Precambrian key poles of the Karelian Craton and the Paleoproterozoic–Phanerozoic remagnetization poles with the reference Phanerozoic apparent pole migration path of the East European Craton, according to (Smethurst et al., 1998): (*1*) Phanerozoic apparent pole migration path of the East European Craton, according to (Smethurst et al., 1998); (*2*) Precambrian key poles of the Karelian Craton; (*3*) paleomagnetic poles recalculated from the Paleoproterozoic–Paleozoic secondary magnetization components of the Karelian Craton; (*4*) paleomagnetic poles of the global Phanerozoic rock remagnetization of the East European craton. Digits in circles indicate the age of paleomagnetic poles. Letter designations of key poles for the Karelian Craton are given in Table 1; letter designations of secondary components and global remagnetization are given in Tables 2 and 3, respectively.

et al., 1999; Mertanen et al., 2006). The secondary component in the studied rocks is monopolar and has a southeast declination and a moderately positive inclination (Fig. 4). The indication of a possible secondary remagnetization in the range of 2.5–2.4 Ga is confirmed by ^{40}Ar/^{39}Ar dating data that suggest metamorphism of the host Archean gneisses in the Burakovo intrusion of the Karelian Craton estimated at approximately 2.4 Ga (Mertanen et al., 2006).

The 1.27–1.25 Ga period. A component with a northeastern declination and a moderately negative inclination is commonly identified only in the Precambrian complexes in the Fennoscandinavian segment of the East European Craton (Arestova et al., 2007; Fedotova et al., 1999; Lubnina, 2009). The monopolar component is destroyed at medium temperatures and variable fields during magnetic cleaning. Paleomagnetic poles recalculated from directions of these components lie on the trend of the EEC Precambrian poles and differ in longitude by ~30° (Fig. 2). The formation time of this magnetization component in the Precambrian complexes of Fennoscandia correlates with the manifestation of the MacKenzie mantle superplume of 1.27–1.25 Ga (Ernst and Buchan, 1997) and is estimated by the EEC key poles obtained

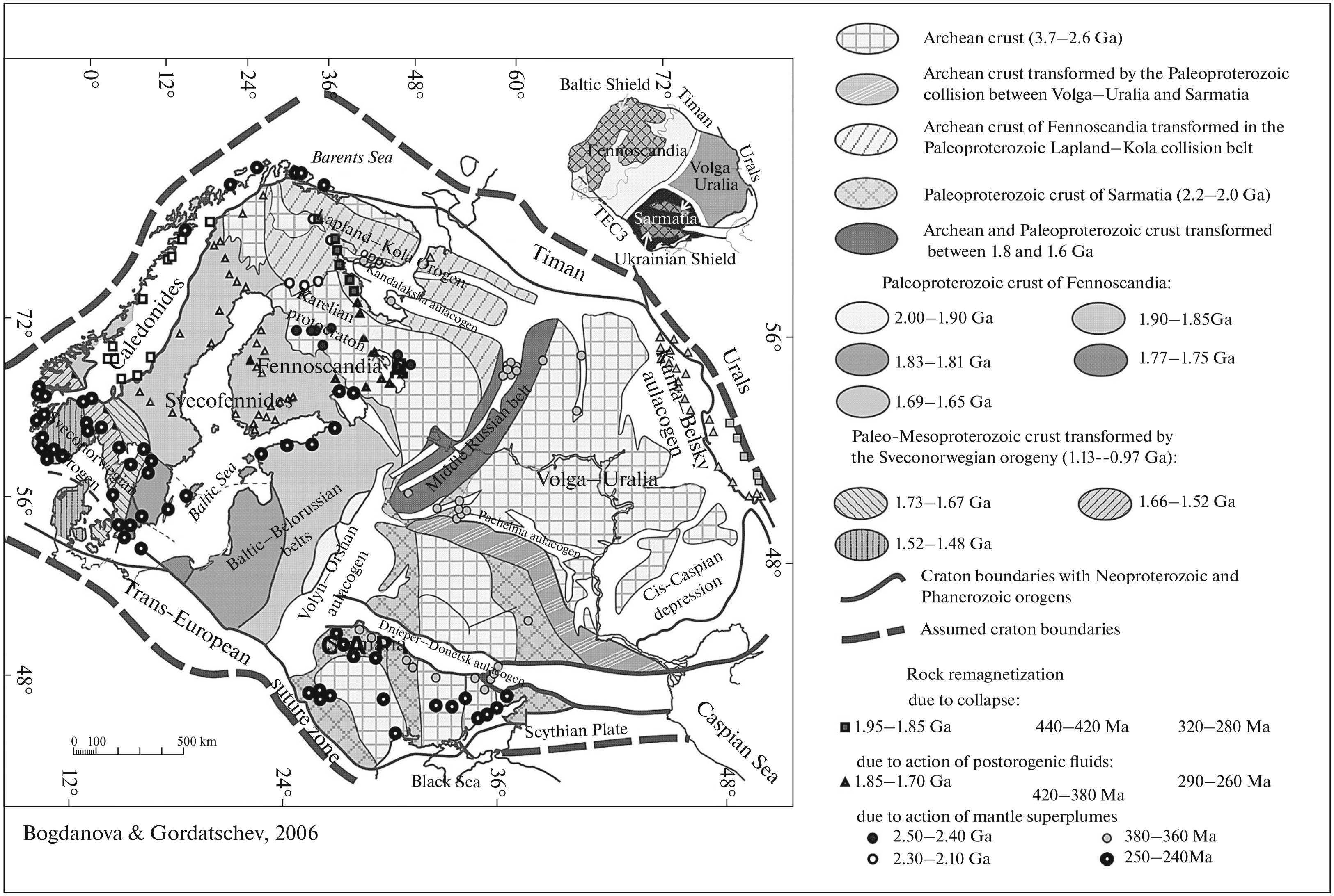

Fig. 3. Basic rock remagnetization areas of the Karelian Craton on the tectonic map, according to (Bogdanova et al., 2016) with additions.

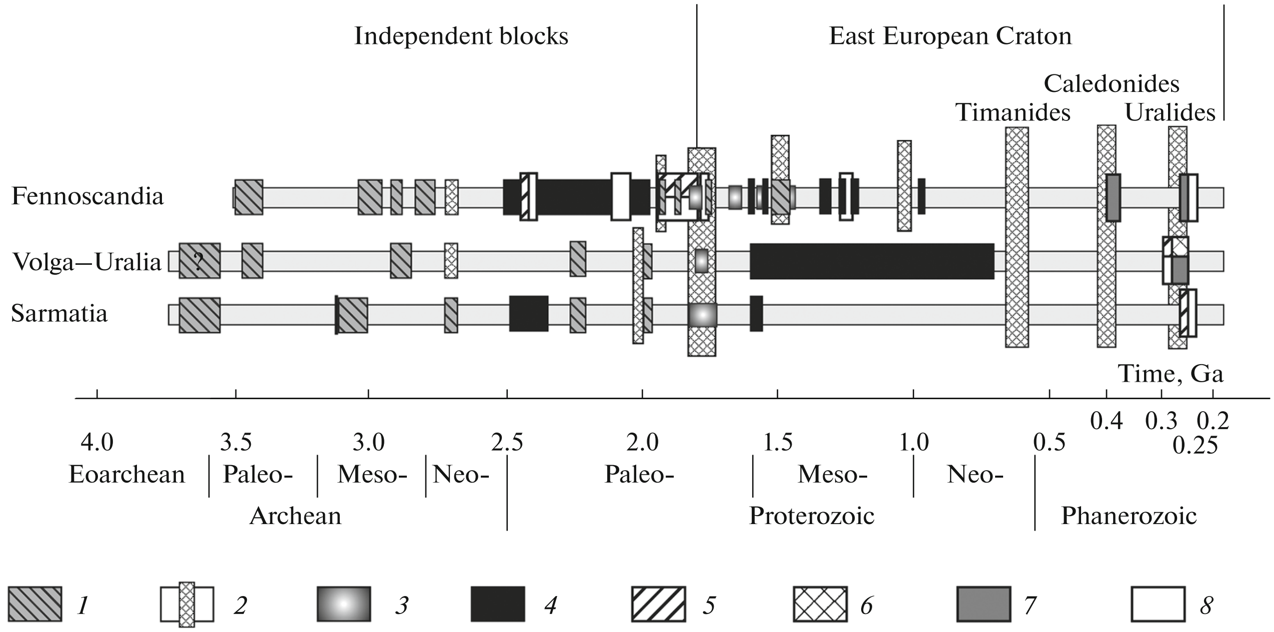

Fig. 4. The correlation of rock remagnetization time with major events of the tectonic evolution of the East European Craton, according to (Bogdanova et al., 2016) with additions: (*1–4*) tectonic events: (*1*) accretion and growth of the continental crust; (*2*) major collision events; (*3*) postcollision magmatism (AMCG, type A, bimodal); (*4*) major rift and plume events; (*5–8*) rock remagnetization: (*5*) complete remagnetization, one polarity; (*6*) complete remagnetization, two polarities; (*7*) partial remagnetization, two polarities; (*8*) partial remagnetization, one polarity.

in the study of dikes of the Central Scandinavian dolerite group (Buchan et al., 2000).

The 380–360 Ma period. A component with an east–northeastern declination and a low positive inclination was identified in the Devonian alkali dikes of the Kola Peninsula (Veselovskiy et al., 2013). In addition, a component with a similar direction was identified in the medium-temperature range in the study of the EEC Precambrian and Paleozoic complexes located mainly in the central part of the considered craton (Fig. 3). Its formation is related to the Devonian tectonomagmatic activation in the Dnieper–Donetsk, Central Russian, Pachelma and Kandalaksha aulacogens due to the action of the mantle superplume in the period of 380–360 Ma (Lubnina, 2009).

The 150–145 Ma period. A component with a northeastern declination and a steep positive inclination is widespread within EEP (Figs. 2, 3). It stands out in the medium-temperature range and is monopolar; it is present in almost all sedimentary sections of Leningrad oblast, Estonia, Podolia, magmatic complexes of the Northern Ladoga region, Mesoproterozoic dikes of Central Sweden, etc. (see review in (Lubnina et al., 2015)). Formation of this component is related to the development and destruction of the Pangea Supercontinent due to the impact of the mantle superplume (Fig. 4) ((Lubnina, 2009; Veselovskiy et al., 2013) and references in these works).

Remagnetization Resulting from the Postorogenic Collapse

The collapse of collision systems is caused by gravitational instability of the anomalously thick continental crust under the collision process. This process results in collapse under stretching at a dramatic decrease in pressure and temperature over a short period of time. The magnetization that arises under such conditions is thermoviscous in nature (a dramatic drop in temperature below the Curie point of the magnetization carrier minerals over a short time interval) and completely destroys the primary magnetization developed at the rock formation time. The newly formed secondary component is monopolar and most often unique in the component analysis, except for the viscous (recent) magnetization component. Within the East European Craton, the secondary magnetization component of such genesis was locally identified within the Belomorian mobile belt, along the front of the Caledonides and Uralides (Fig. 3).

In addition, the collapse is accompanied by abundant fluids, whose impact can last for tens of millions of years after the major collision stage. The impact of fluids with different compositions leads to the formation of new magnetization carrier minerals as a result of the oxidation of primary minerals and the acquisition of a secondary (metachronous) magnetization component by the rocks. The newly formed component can be both mono- and bipolar (Figs. 3, 4). In this case, the directions of the natural residual magnetization vectors corresponding to different carrier minerals almost coincide with each other. The secondary component can be formed before, during, and after folding. It should be emphasized that the acquisition time of the secondary (metachronous) magnetization component can be "delayed" by a few tens of millions of years compared with the major postorogenic collapse stage.

The secondary magnetization formation during the postorogenic collapse and the fluid effect was considered based on the example of the Belomorian mobile belt and the Ural fold belt (Fig. 3).

The 1.95–1.85 Ga period. Paleomagnetic determinations estimating the secondary magnetization age at 1.95–1.70 Ga form two clusters (Fig. 3). The first cluster includes determinations where the secondary component with a northwestern declination and a moderately positive inclination identified in the high-temperature range is the only one. This component is monopolar; its main carrier is magnetite. The mean directions of this component are grouped fairly well on the Precambrian APMPs of the Karelian Craton (Fig. 2).

In the medium-temperature interval, in addition to the high-temperature component, a component with a similar direction occurs, but is somewhat "smeared" on the trend of the Precambrian poles of the East European Craton (Fig. 2). Meanwhile, the mean direction for the Lapland–Kola Orogen differs from that for the Karelian Craton (Fedotova et al., 1999; Lubnina et al., 2015). Both trends for the Lapland–Kola Orogen and the Karelian Craton are also characterized by a regular shift of paleomagnetic poles from the northeast to the southwest (Lubnina et al., 2015).

Remagnetization of this age is related to migration of orogenic hydrothermal fluids during the collisional events of the major stage (Figs. 3, 4). It should also be noted that most Jatulian (2.3–2.1 Ga) rocks in Fennoscandia were completely remagnetized at this stage of the evolution of the Karelian Craton.

The 300–250 Ma period. The duration of the formation of the secondary component in the Precambrian rocks under collapse and subsequent fluid exposure was estimated based on the paleomagnetic results for complexes of uneven ages of the western slope of the Southern Urals (Bashkirian Anticlinorium) (Lubnina, 2009). It has been proven that the secondary high-temperature magnetization component was formed in the range of 300–250 Ma and the remagnetization front migrated from the southeast to the northwest (Shipunov et al., 2007).

COMPUTER MODELING

Special software was developed to estimate the contributions of different components to the resulting magnetization value and direction. This software makes it possible to determine the total (summary) magnetization vector from given values of a few magnetization components (component length (J), declination (D), and inclination (I)).

The following approach is applied to determine the resulting magnetization. Since the magnetization is a vector, the total value is obtained by vector summation of individual components (Shipunov, 2000). For this purpose, the following should be done.

(1) Transfer from the representation of all magnetization components in the local spherical coordinate system (J, D, I) to the Cartesian rectangular system (X, Y, Z):

$$X_i = J_i \cos I_i \cos D_i,$$
$$Y_i = J_i \cos I_i \cos D_i,$$
$$Z_i = J_i \sin I_i,$$

where $i = 1, 2, \ldots, N$ gives the numbers of summed components;

(2) Summing of the components. The sum vector $R_S = (x_S, y_S, z_S)$ will have a length which is calculated by the following formula:

$$R_S^2 = x_S^2 + y_S^2 + z_S^2,$$

where

$$x_S = \sum_{i=1}^{N} X_i,\ y_S = \sum_{i=1}^{N} Y_i,\ z_S = \sum_{i=1}^{N} Z_i,$$

is the Cartesian coordinates of the vector sum; it is also necessary to identify the direction based on a resulting declination (D_S) and inclination (I_S):

$$D_S = \arctan\frac{y_S}{x_S},\ I_S = \arcsin\frac{z_S}{R_S}.$$

The software makes it possible to vary the contribution of the absolute value of each component (at a fixed value of declination and inclination) and thus to visually identify the effect of these variations on the resulting magnetization vector.

In order to estimate the contribution of secondary magnetization components of uneven ages, the most widespread in the Precambrian and Phanerozoic EEC complexes, to the resulting magnetization (Tables 1, 2, 3), we tested their mutual influence from 0 to 100% with a 5% step in all possible combinations. In addition, in order to estimate the effects of secondary Phanerozoic magnetization components of uneven ages on primary key directions of the Precambrian age, we attempted to determine possible combinations (sum of components) by a simple brute force method: it was assumed that the primary magnetization component (the average directions are taken from Table 1) overlapped by one of the secondary Phanerozoic magnetization components (the average directions are taken from Table 3) could be partially preserved as a result of the secondary processes.

The sums of the most characteristic secondary magnetization components of uneven ages depending on contribution of each component are given in Fig. 5.

Table 1. "Key" paleomagnetic poles obtained from the Neoarchean rocks of the Karelian Craton

No.	Body	Site	Sampling coordinates		Paleomagnetic direction					Paleomagnetic pole				Age, Ma	Reference
			φ, deg.	λ, deg.	N	Dec, deg.	Inc, deg.	K	α_{95}, deg.	Plat, °N	Plong, °E	d_p, deg.	d_m, deg.		
Key paleomagnetic poles															
1	Shalskii and Avdeevo Neoarchean dikes	SHN	61.8	35.9	8	174.6	3.6	64.2	7.0	–26.2	41.9	3.5	7.0	2504	1
2	Burakovo stratified intrusion	BU	61.9	36.1	8	139.1	56.5	54.9	7.5	14.3	68.5	7.9	10.9	2449 ± 1	2
3	Ludicovian dolerite intrusions	LI	61.8	36.9	3	77.3	58.6	216.4	8.4	39.8	114.7	9.3	12.5	1980	3
5	Ropruchei sill	RS	61.3	35.5	12	9.7	5.3	61.2	5.6	30.9	204.0	4.7	4.7	1752 ± 3	4
8	Ladoga intrusions	LA	61.7	30.5	278	32.5	–16.7	168.6	7.1	15.2	177.1	3.8	7.3	1452 ± 12	5
9	Jotnian dolerites	JD	64.4	27.5	41	51.0	–24.0	20.1	5.1	04.0	158.0	4.0	4.0	1264 ± 12	6
10	Egersund dikes	ED	58.0	6.0	82	120.0	69.0	28.0	10.0	31.4	44.1	14.5	17	616 ± 3	7

(*N*) Number of samples; (Dec°, Inc°) declination and inclination of average component directions in the geographic coordinate system; (*K*) vector clustering; (α_{95}) confidence circle radius at a 95% probability for average direction; paleomagnetic pole in terms of coordinates of sampling points: (Plat, Plong) latitude and longitude of paleomagnetic pole; (d_p, d_m) ratio of minimum and maximum axes of 95% confidence oval, respectively.

References: (1) (Scherbakova et al., 2017); (2) (Mertanen et al., 2006); (3) (Lubnina et al., 2017); (4) (Lubnina et al., 2016); (5) (Lubnina et al., 2010); (6) (Buchan, 2000); (7) (Walderhaug et al., 2007).

Table 2. Secondary magnetization components identified in the Precambrian complexes of the Karelian Craton

No.	Remagnetization	Letter symbol of secondary component	Paleomagnetic direction					Paleomagnetic pole				Age, Ma	Reference
			N	Dec, deg.	Inc, deg.	K	α_{95}, deg.	Plat, ° N	Plong, ° E	d_p, deg.	d_m, deg.		
Secondary components related to action of mantle superplumes													
1	Early Paleoproterozoic	SU	67	146.1	55.4	63.2	11.6	–12.3	243.5	11.8	16.5	2450	1, 2
2	Ludicovian	LDR	153	83.8	66.7	8.4	4.2	44.4	101.5	5.7	6.9	1970	3, 4
3	Mesoproterozoic (Jotnian)	MJR	41	51.0	–24.0	20.1	5.1	04.0	158.0	4.0	4.0	1270	5, 6
Secondary components formed during the postorogenic collapse													
4	Lapland–Kola	LKR	62	28.6	58.5	11.0	5.7	58.7	169.2	6.3	8.5	1900	7
5	Svekofennian	SFR	67	334.6	47.9	5.2	8.4	49.9	250.4	7.2	11.0	1800	7, 8
6	Caledonian	CDR	15	74.2	–29.3	163.4	3.2	–1.4	320.0	2.0	3.5	400	9

(*N*) Number of samples; (Dec°, Inc°) declination and inclination of average component directions in the geographic coordinate system; (*K*) vector clustering; (α_{95}) confidence circle radius at a 95% probability for average direction; paleomagnetic pole in terms of coordinates of sampling points: (Plat, Plong) latitude and longitude of paleomagnetic pole; (d_p, d_m) ratio of minimum and maximum axes of 95% confidence oval, respectively.

References: (1) (Scherbakova et al., 2017); (2) (Mertanen et al., 2006); (3) (Lubnina et al., 2017); (4) (Fedotova et al., 1999); (5) (Lubnina et al., 2009); (6) (Buchan, 2000); (7) (Lubnina et al., 2015); (8) (Mertanen, 1995); (9) (Smethurst et al., 1998).

RESULTS AND DISCUSSION

The secondary magnetization components of uneven ages form two clusters in the stereogram (Fig. 5): the first cluster includes directions "spread" in the first and fourth quadrants (declination 300°–80°) that have a positive inclination of 20°–70°, while the second cluster includes directions of S–SE declination (80°–200°) and moderate positive inclination.

The first cluster includes the directions obtained by summing of the Devonian (D), Ural (UR), Mesozoic (MZ) and/or recent (Q) remagnetization. If only the Devonian remagnetization is preserved in the rocks,

Table 3. Phanerozoic paleomagnetic poles used to calculate a contribution of secondary magnetization components

No.	Component	Letter symbol	Paleomagnetic direction					Paleomagnetic pole			φ_m, deg.	Magnetization age, Ma	Reference
			N	Dec, deg.	Inc, deg.	*K*	α_{95}, deg.	Plat, deg.	Plong, deg.	A95			
1	Recent	Q	–	12.6	74.5	–	–	–	–	–	–	0	(Thébault et al., 2015)*
2	Mesozoic	MZ	297	72.6	84.8	26.1	5.2	68.8	60.9	10.0	79.7	150	(Veselovskiy et al., 2013)
3	Permian (*Ural remagnetization*)	UR	31	229.1	–20.0	82.9	5.1	30.0	173.0	6.0	30.0	290	(Lubnina et al., 2014)
4	Devonian	D	64	76.4	15.8	12.3	19.8	12.5	132.3	22.8	8.1	380	(Veselovskiy et al., 2013)

(*N*) Number of samples; (Dec°, Inc°) declination and inclination of average component directions in the geographic coordinate system; (*K*) vector clustering; (α_{95}) confidence circle radius at a 95% probability for average direction; paleomagnetic pole in terms of coordinates of sampling points: (Plat, Plong) latitude and longitude of paleomagnetic pole; (d_p, d_m) ratio of minimum and maximum axes of 95% confidence oval, respectively. (A95) 95% confidence circle radius; (φ_m) paleolatitude; (*) recent magnetic field direction in the investigation area in terms of 61° N, 35° E.

the resulting NRM vector has an E–NE direction with a low positive inclination (Fig. 5). If, in addition to the Devonian, the rocks are also characterized by the Ural remagnetization, the resulting vector shifts northwestward along the great circle arc (Fig. 5). If the direction of the Mesozoic and/or recent remagnetization is added to the indivisible sum of the Devonian and Ural remagnetization, the inclination of the resulting vector increases.

Along with this, the first cluster includes directions obtained by summing of primary magnetization components in the Ropruchei sill, Ladoga intrusions, and Jotnian dolerites (components RS, LA, and JD in Table 1, respectively), as well as Svekofennian remagnetization components (SFR in Table 2), and the Phanerozoic secondary directions from Table 3.

In addition, this cluster also includes the Precambrian secondary components that occurred during the postorogenic collapse at 1.80 and 1.90 Ma in the Precambrian complexes of the Belomorian mobile belt and the Lapland–Kola Orogen (SFR and LKR poles in Table 2, respectively) (Fedotova et al., 1999; Lubnina et al., 2015) and the Paleozoic secondary medium-temperature components identified in the Paleozoic complexes of the Leningrad oblast, Estonia (see review in (Lubnina, 2009)), and Kola Peninsula (Veselovskiy et al., 2013).

The second cluster is formed by summing of Caledonian (CDR), Ural (UR), Devonian (D), Mesozoic (MZ) and/or recent (Q) magnetization directions (Fig. 5). The main variations are observed when summing the Caledonian and Devonian remagnetization: the resulting direction varies from E–SE (with the prevalence of the Devonian remagnetization) to S–SW (with the Caledonian remagnetization of more than 70%). If the Ural remagnetization direction is added to the indivisible sum of the Caledonian and Devonian remagnetization, the resulting vector inclination changes

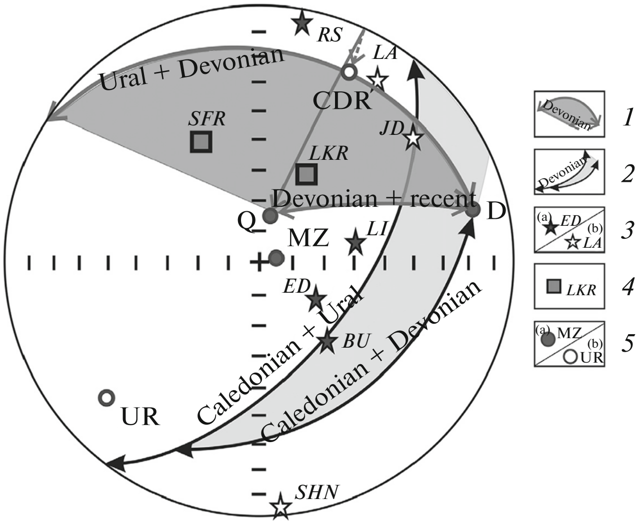

Fig. 5. Remagnetization clusters formed at different contributions of secondary magnetization components of uneven ages: (*1*) cluster formed by summing of Ural, Devonian, and recent remagnetization directions; (*2*) cluster formed by summing of Caledonian, Ural, Devonian, and Mesozoic remagnetization; (3) primary directions identified in the Neoarchean–Neoproterozoic complexes of the Karelian Craton and key poles with (a) positive and (b) negative inclination used in the calculations; (*4*) secondary magnetization components identified in the Precambrian complexes of the Karelian Craton; (*5*) Phanerozoic remagnetization directions with (a) positive and (b) negative inclination. Letter designations of paleomagnetic directions are given in Tables 1–3.

from +30° (with the UR contribution of 80%) to +65° (with the UR contribution of less than 20%).

This cluster also includes the key Sumian (2.45 Ga) and Ludicovian (1.98 Ga) poles of the Karelian Craton (BU and LI in Table 1, Fig. 5), the Neoarchean pole obtained from Shalskii and Avdeevo dikes of the Karelian Craton, as well as the primary Ordovician pole obtained from sedimentary rocks of Sweden, Leningrad oblast, and Estonia (Lubnina, 2009; Smethurst et al., 1998).

According to these results, the declination "smearing" of the ancient Precambrian magnetization, in both the first and the second clusters, is due to undercounting of the contribution from either the Devonian (an increase in a declination) or the Permian (respectively, a decrease in a declination) secondary magnetization components (Fig. 5). The difference in inclinations in both cases is due to incorrect identification of either the Mesozoic (MZ) or recent (Q) magnetization components. The greater the contribution of MZ and Q components is to the total magnetization, the steeper the inclination is in the rocks; occurrence in clusters 1 and 2 suggests a 55–70% contribution of secondary magnetization components (Fig. 5).

CONCLUSIONS

(1) Regular variations in directions of the Precambrian magnetization components depending on the contribution of the Phanerozoic secondary components are considered. Variations in declination are due to the impossibility of identifying or undercounting the contribution of the Devonian and Permian secondary components, while variations in inclination are caused by failure to take the Mesozoic and recent secondary components into account.

(2) The obtained correlations enable a more reasonable identification of the primary magnetization component in the crustal structures with a complex tectonic evolution and in the tectonomagmatic activation areas.

(3) Only the comprehensive use of paleomagnetic poles, isotope data, and geological correlations of complexes with even ages makes it possible to correctly distinguish magnetization components of uneven ages.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 17-05-01270) and was performed using the equipment purchased under the Development Program of the Moscow State University.

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Translated by E. Maslennikova