УДК 550.384 DOI: https://doi.org/10.24028/gj.v45i4.286283

New palaeomagnetic data for Palaeoproterozoic AMCG complexes of the Ukrainian Shield

V.G. Bakhmutov*[1]*, O.V. Mytrokhyn*[2]*, I.B. Poliachenko*[1]*, S.I. Cherkes*[1]*, 2023

[1]S.I. Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine

[2]Institute of Geology, Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

Received 15 April 2023

A palaeomagnetic study of rocks for two Palaeoproterozoic anorthosite-mangerite-charnockite-granite (AMCG) complexes in the Ukrainian Shield was done to put additional constraints on the interpretation of palaeogeography of Fennoscandia and Volgo-Sarmatia in the Palaeoproterozoic. With this study, 5 sites of Korsun-Novomyrhorod and 3 sites of Korosten AMCG complexes in central and north-western parts of the shield, respectively, were chosen for palaeomagnetic sampling given the geological, modern geochronological and previous palaeomagnetic data. Primary remanent magnetization was isolated on samples of anorthosites, Gabbro, and monzonites within a narrow time interval of U-Pb geochronology dataset of 1.76—1.75 Ga. The palaeomagnetic poles calculated for Korosten and Korsun-Novomyrhorod complexes are almost identical, which indicates that the Volyn and Ingul Domains developed within a single structure of the Ukrainian Shield since at least 1.75 Ga. The new palaeomagnetic pole calculated for all 8 sites (P_{lat}=22.7 °N, P_{lon}=167.4 °E, A_{95}=3.3°) agrees well with previous studies by Elming et al. [2001, 2010]. The selection of the most reliable palaeomagnetic poles for Fennoscandia and Volgo-Sarmatia of this time indicates that the present position of the Ukrainian Shield relative to Fennoscandia is not the same as for about 1.75 Ga, when Fennoscandia occupied a subequatorial position within palaeolatitudes of 5—20 °N, and Volgo-Sarmatia was located close to the equator and rotated relative to Fennoscandia counterclockwise by about 40° compared to its present position.

Key words: Ukrainian Shield, Proterozoic, palaeomagnetism, AMCG complexes, tectonic reconstruction.

Introduction. The Ukrainian Shield comprises the exposed crust of the large Palaeoproterozoic protocraton and consists of metamorphic and magmatic rocks. Volgo-Sarmatia together with the Fennoscandian crustal segment constitutes the East European Craton (EEC hereafter, or Palaeoproterozoic Baltica).

From the north and northeast the Ukrainian shield is bounded by the Palaeozoic Pripyat-Dnieper-Donets Aulacogen (PDDA) which separates the Ukrainian Shield from the partly exposed Precambrian Voronezh Massif in northeastern Sarmatia. The Precambrian crustal structures, Archaean and Palaeoproterozoic terranes can be traced across the PDDA between the Ukrainian Shield to the south and the Voronezh Massif to the north PDDA [Shchipansky, Bogdanova, 1996; Shchipansky et al., 2007].

The tectonic fabric of the crust in the Ukrainian Shield was developed through persistent strike-slip faulting and deformation during several tectonic phases [Gintov, 2005; Gintov, Mychak, 2014]. The earliest and best

Citation: *Bakhmutov, V.G., Mytrokhyn, O.V., Poliachenko, I.B., & Cherkes, S.I.* (2023). New palaeomagnetic data for Palaeoproterozoic AMCG complexes of the Ukrainian Shield. *Geofizicheskiy Zhurnal*, *45*(4), 3—19. https://doi.org/10.24028/gj.v45i4.286283.

expressed was the formation of N-S suture zones. They were caused by oblique collision of the Sarmatian and Volgo-Uralian terranes between ca. 2.1 and 2.0 Ga when the mega-continent Volgo-Sarmatia was built [Bogdanova et al., 2006, 2008, 2013]. The postcollisional tectonics is characterized by numerous S-type granitoid intrusions and migmatites of 2.08—2.04 Ga age and multiphase monzonitic Gabbro-granitic intrusions of 2.04—2.03 Ga age [Shcherbak et al., 2008].

Due to collision of the Fennoscandian terranes with Volgo-Sarmatia at c. 1.83—1.81 Ga, postcollisional disturbance and melting of the upper lithosphere, the large intrusions of anorthosite-mangerite-charnockite-granite (AMCG) complexes were embedded between 1.80 and 1.74 Ga. There are multiphase Korosten complex in the Volyn Domain and the Korsun-Novomyrhorod complex in the Ingul Domain. In the north-western part of the Ingul Domain, on the NW border with the Ros-Tikich Domain, the AMCG complex elongated in the N-S direction with a total area of about 5 500 km^2. The rocks of the Korosten complex, which occupies an area of about 10 400 km^2 and has a near-isometric shape, lie in the north-eastern part of the Volyn Domain and form one of the largest and typical AMCG complex in the world. The different domains of Ukrainian Shield, separated by suture zones with intense shearing, are treated as a single unit since 1.77 Ga [Bogdanova et al., 2013, and references herein].

For the last decade, due to extensive U-Pb and Hf isotope investigations of the two Palaeoproterozoic AMCG complexes located in the Ukrainian Shield and reviews of existing geochronological and geochemical data, there has been made significant progress in understanding the secular relationships between the main rocks of these complexes and their origins. The basic rocks of AMCG have proven to be excellent palaeomagnetic recorders, which is supported by preliminary results from Ukraine (e.g. [Elming et al., 2001]).

Palaeomagnetism, coupled with precise age determinations, is the only method that provides direct estimate of the orientations and palaeolatitudes of continents. Precambrian palaeomagnetic data are crucial for various tectonic and geophysical applications, in particular for the reconstructions of fusion and fission of supercontinents. Due to many objective reasons, there is less confidence in the Precambrian data in comparison to Phanerozoic results. The rather common refusal to consider the resemblance between Precambrian and younger poles from Fennoscandia, Ukraine and the Uralian margin of Baltica and compare them with Phanerozoic apparent polar wander path for this craton cannot but be alarming [Bazhenov et al., 2016].

In this article, we present new palaeomagnetic data for AMCG rocks for a narrow time range in order to test the hypothesis of the coherent unity of two domain of the Ukrainian Shield and to put additional constraints on the interpretation of palaeogeography of Fennoscandia and Volgo-Sarmatia in the Palaeoproterozoic.

Geological setting. ***Ingul Domain and Korsun-Novomyrhorod AMCG complex.*** Ingul Domain is located in the central part of the Ukrainian Shield (Fig. 1), separated from the neighboring Ros-Tikych and Dniester-Bug Domains by the Golovanivsk shear zone and from the Middle Dnieper Domain by the Ingulets-Kryvyi Rih shear zone. Palaeoproterozoic amphibolite facies supracrustal rocks of the Ingul-Ingulets series represent ancient basement of the Ingul Domain. Gneisses and schistes of the Ingul-Ingulets series are the initial substrate for anatectic melting that derived 2.06—1.97 Ga granites and migmatites of the Kirovograd complex. The latter predominate on the area of the Ingul Domain. Porphyritic granites and monzonites with U-Pb isotopic ages of 2.04—2.00 Ga formed the huge Novoukrainka massive in the central part of the Ingul Domain [Shcherbak et al., 2008]. All of the above Precambrian formations are the framework of the Korsun-Novomyrhorod AMCG complex.

Korsun-Novomyrhorod AMCG complex (KNC) lies in north-western part of Ingul Domain near the border with Ros-Tikych Domain and covers an area of 5 500 km^2. In the north, east and partly west KNC is framed by granites and migmatites of the Kirovograd com-

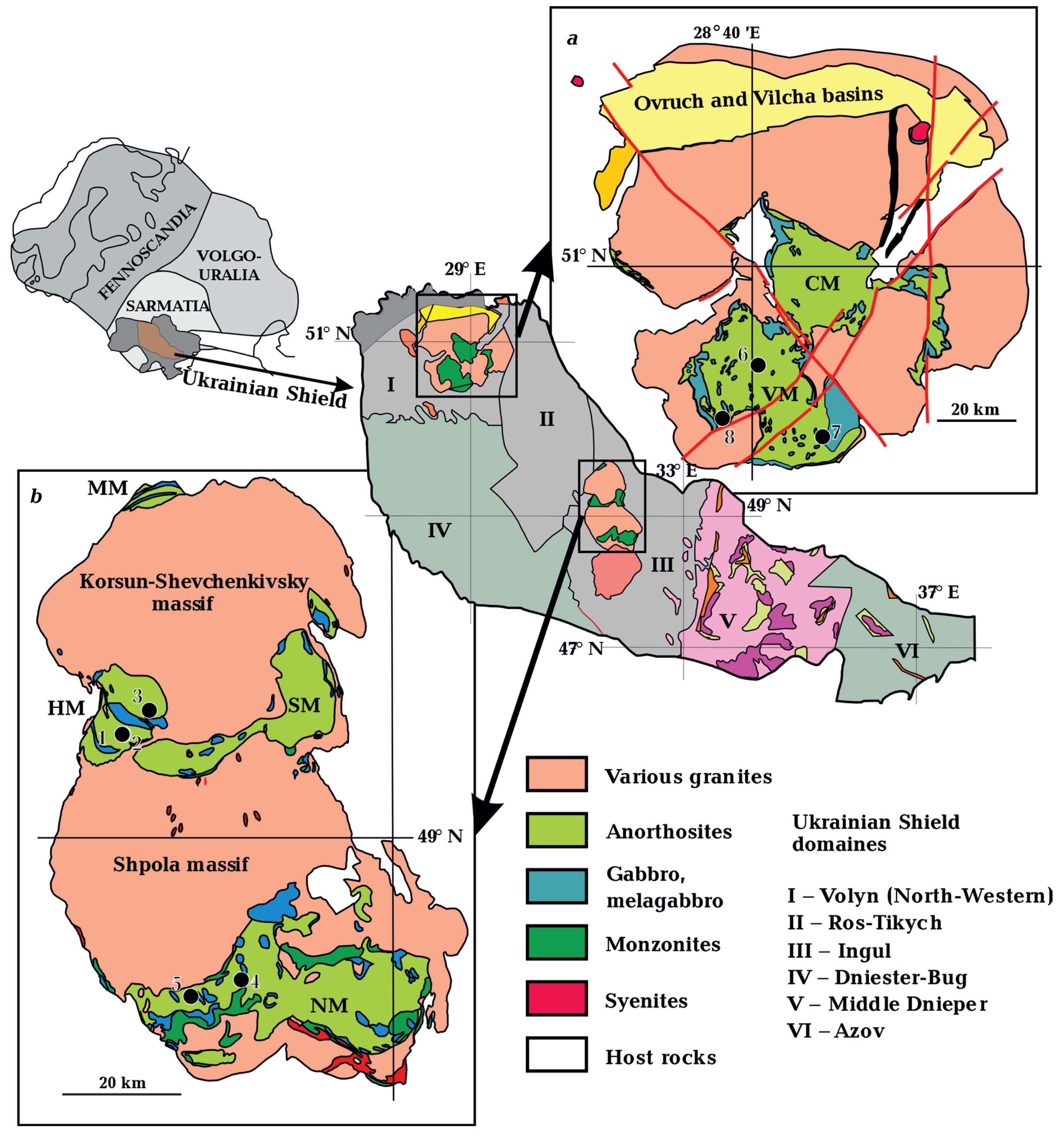

Fig. 1. Sketch maps of the Ukrainian Shield, Korosten AMCG complex (*a*) and Korsun-Novomyrhorod AMCG complex (*b*). Massifs: MM — Mezhyrichy massif, HM — Horodyshche massif, SM — Smila massif, NM — Novomyrhorod massif, CM — Chopovychi massif, VM — Volynsky massif. The location of sampling sites are given by black circles, numbers the same as in the Table 1. The sketch maps were adopted from [Shumlyanskyy et al., 2017].

plex as well as supracrustal rocks of the Ingul-Ingulets series. Only in the southern part the contact with the porphyritic granites of the Novoukrainka massif is traced.

Up to 76 % of the total area of KNC is represented by rapakivi granites, which form two large massifs, namely the northern Korsun-Shevchenkivsky and the southern Shpola (Fig. 1, *b*). Coarse-grained biotite-amphibole rapakivi granites of the wiborgitic type are predominated in both massifs. Hypabyssal varieties of the rapakivi and their volcanic counterparts are absent here. Ub-Pb zircon dating revealed a surprising consistency in the ages of the KNC rapakivi, namely 1.75 Ga [Shumlyanskyy et al., 2017].

Basic rocks make up no more than 21 % of the KNC total area. They form four separate large massifs (Novomyrhorod, Smila, Horodyshche, and Mezhyrichy) and a number of smaller bodies (see Fig. 1, *b*). Anorthosite and leucocratic Gabbro-norites predominate in the area of the massifs. Monzonites and monzodiorites are common, but mesocratic norites, Gabbro-norites, and Gabbro are minor rock varieties. Intermediate monzonites and monzodiorites are much more common here than in the Korosten complex. Field geological observations indicate that basic rocks of the KNC are a multiphase intrusion, but the accuracy of modern isotope geochronology is still insufficient for this confirmation. U-Pb isotope dating of the zircon from various massifs of basic rocks gives the ages 1.76—1.75 Ga [Shumlyanskyy et al., 2017].

One of the characteristic features of the Ingul Domain is the significant development of basite dykes [Bogdanova et al., 2013]. Numerous fan-like dyke swarms are known south- and east-ward of the KNC. Sparse geochronological data available for the dykes indicate the age of c. 1.8 Ga when the Ingul Domain underwent activation, which is associated with the formation of numerous fault zones. The processes of dyke's emplacement were discussed by Shumlyanskyy et al. [2016a,b].

Volyn (North-Western) Domain and Korosten AMCG complex. The Volyn Domain is located in the north-western part of the Ukrainian Shield (see Fig. 1). The ancient basement of the Domain is Paleoproterozoic supracrustal rocks of the amphibolite facies of the Teteriv series. The Sm-Nd dating at 2.35—2.29 Ga [Shcherbak et al., 2008] determines the lower age limit for the Teteriv series. Granites and migmatites of the Zhytomyr complex formed as a result of anatectic melting of the Teteriv series. They are widely distributed in the southern and western parts of the Volyn Domain. U-Pb isotope dating of zircon gives Palaeoproterozoic age of 2.08—1.96 Ga for the granitoids of the Zhytomyr complex [Shcherbak et al., 2008]. Calc-alkaline metavolcanites of the Klesiv Series and Gabbro-diorite-granite intrusions of the Osnitsk complex form a long igneous belt on the north-west of the Volyn Domain with the U-Pb zircon dating ages of 1.99—1.97 Ga. Gabbro-monzonite-granite intrusions of the Buky complex were formed in the same age interval.

The Korosten AMCG complex (KC) covers an area of 10 400 km^2 and occurs in the north-eastern part of the Volyn Domain, in proximity to its margin with the Ros-Tikych Domain. Granitoids of the Zhytomyr complex and supracrustal rocks of the Teteriv series form the framework of the KC on its western and southern borders. Rapakivi and rapakivi-like granites occupy about 75 % of the total area (see Fig. 1, *a*). They form four vaguely separated massifs differing in age of formation [Shumlyanskyy et al., 2017, 2021].

Basic rocks occupy no more than 23 % of the KC total area. They form three large massifs and many small bodies. The largest Volodarsk-Volyn massive with an area of 1250 km^2 consists predominantly of anorthosites and leucocratic Gabbro-norites. U-Pb isotope dating of their zircons and baddeleyites yields the age of 1.76—1.75 Ga [Amelin et al., 1994; Verkhogliad, 1995; Shumlyanskyy et al., 2017]. Multi-phase intrusions of this largest massive were proved by field geological data [Mitrokhin, 2001]. Numerous bodies of the mesocratic Gabbros and Gabbro-norites intruding anorthositic rocks were found. However, their U-Pb dates are indistinguishable from the anorthosite and leucocratic Gabbroids. The same U-Pb isotope ages represent minor monzonites and monzodiorites on the contacts of the Gabbroids with the rapakivi. Nevertheless, there are some older basic rocks in the neighboring massifs. Thus, U-Pb isotope ages of 1.78 and 1.77 Ga were obtained for zircons from xenoliths of the so-called «ancient» anorthosites and host leucocratic Gabbroids of the easternmost Fedorivka massive [Verkhogliad, 1995; Shumlyanskyy et al., 2017]. Xenoliths of the «ancient» anorthosites in the Gabbroids of the Chopovychi massive contained zircons with the age of 1.79 Ga. And finally, the oldest U-Pb isotope dating of 1.80 Ga was obtained for anorthosites in the small Pugachivka massive on the western side of the KC [Verkhogliad, 1995].

A large number of mantle-derived mafic

dykes and several layered Gabbroic intrusions are known in the vicinity of the KC. The available geochronological data indicate they were emplaced at 1.8—1.76 Ga [Verkhogliad, 1995; Shumlyanskyy et al., 2016a].

Previous palaeomagnetic investigations. The first papers about magnetic properties of the Ukrainian Shield rocks date back to the 1960-s [Khramov, 2001; Orlyuk, Orlova, 2013, and references herein]. After an early publication [Mikhailova, Glevaskaya, 1965] about the magnetization of basic and ultrabasic rocks of the Ukrainian Shield, the first attempt to evaluate the drift pattern of the Ukrainian Shield versus the Fennoscandian Shield by palaeomagnetic data was performed by Mikhailova and Kravchenko [1987]. The most complete results of the work of Ukrainian scientists were presented in the monograph by Mikhailova et al. [1994]. Unfortunately, the Ukrainian palaeomagnetic data were too sparse and the ages of magnetizations were often not well constrained due to lack of trustworthy data. Subsequently, Elming et al. [1993] presented a more comprehensive attempt of Precambrian reconstructions of Fennoscandia and Ukraine based on databases that were compiled for the two shields.

At the beginning of the XXI century, the studies of the Ukrainian Shield for the purpose of palaeotectonic reconstructions were continued, and the most informative findings of palaeomagnetic investigation confirmed the rocks of the Gabbro-anorthosite complex [Elming et al., 2001] and basic dykes [Elming et al., 2010]. These rocks seem to be most preferable due to the following reasons:

– their stratigraphic positions are established reliably and correspond to the conventional stratigraphy schemes on the territory of the East European Craton (see, e.g. [Shcherbak et al., 2008]);

– there is a set of consistent U-Pb zircon and baddeleyite data determining the ages distribution of rocks in different stage of formation of KNC and KC complexes (see, e.g. [Shumlyanskyy et al., 2017]);

– the characteristic component of natural remanent magnetization (ChRM) of these rocks with high unblocking temperatures (500—570 °C) is stable and demonstrated primary origin (see, e.g. [Elming et al., 2001, 2010]).

Over the last 20 years on the bases of geological, geochronological, and directional palaeomagnetic data, many publications have been devoted to the connection between Baltica and Laurentia in different relative configurations as a part of both supercontinents Nuna and Rodinia (e.g. [Salminen et al., 2023] and references herein). To test the palaeogeography models of Fennoscandia and Volgo-Sarmatia in the Palaeoproterozoic, the directions of ChRM component of remanent magnetization were employed as reliable results (e.g. [Elming et al., 2001, 2010; Lubnina et al., 2009; Pisarevsky, Bylund, 2010]). However, no palaeointensity determinations have been made from Palaeoproterozoic AMCG complexes in the Ukrainian Shield.

Sampling and laboratory techniques. The sampling was generally encompassed to previous geochronology (U-Pb) dated rocks. Taking into account the results of previous palaeomagnetic studies of the Ukrainian Shield (see previous chapter), the anorthosites, monzonites, Gabbro-anorthosites and Gabbroids were chosen as the most attractive units for palaeomagnetic experiments.

The samples were collected using a portable drill and oriented with magnetic and sun compasses. The magnetic and solar directions (where available) agree well with each other, so the magnetization of the rocks is too small to affect the compass needle. The drilled cores were sliced into standard cylindrical specimens (2.2 cm high and 2.5 cm in diameter, 2—4 specimens from each core).

The palaeomagnetic measurements were carried out inside the MMLFC magnetically shielded space (a low-field cage, Magnetic Measurements, UK). Conventional stepwise thermal (TD) and alternating field (AF) demagnetization procedures were applied, and the magnetic susceptibility (MS) after each heating step was measured to track mineralogical changes during thermal treatment. The TD procedure was performed in steps of 50—10 °C up to 600—670 °C using the MMTD80 furnace (Magnetic Measurements, residual field <10 nT). For some of duplicate specimens, the AF demagnetization procedure was done in steps of 10—20 mT up to 100 mT with an LDA-3A demagnetizer. After comparing the results, we preferred the TD method to isolate the magnetization components.

The natural remanent magnetization (NRM) of specimens and the MS were measured using a JR-6 (AGICO) spinner magnetometer and kappabridge MFK1-B (AGICO). Demagnetization results were processed by a multicomponent analysis of the demagnetization path [Kirschvink, 1980] using Remasoft 3.0 software [Chadima, Hrouda, 2006]. The vectors of characteristic remanent magnetization (ChRM) were isolated by the TD method; the maximum angular deviation (MAD) is generally smaller than 5°.

Results. The studied palaeomagnetic sites within Volyn and Ingul Domains are shown in Fig. 1, *a* and Fig. 1, *b* respectively. The palaeomagnetic directions of the high-temperature ChRM component of magnetization for sites with the statistical parameters are presented in Table 1. A short description of locations, radiometrically dated rocks, and palaeomagnetic results for each site is given below.

Ingul Domain, Horodyshche massif. The Horodyshche Gabbro-anorthosite massif in the western part with the Smila massif in the central-western part of the KNC divides the granitoids of the Korsun-Shevchenkivsky massif from the Shpola massif (see Fig. 1).

Site Vyazivok. On the left bank of the Vilshanka River near the Vyazivok village in a flooded quarry, the dykes of quartz monzonites and monzodiorites cut the anorthosite of the Horodyshche massif. The sampling was carried out on the NW and SE parts of the quarry from host anorthosites and subvertical 3 m-thick monzonite dyke cutting the host rock. Dovbush et al. [2009] reported the U-Pb zircon ages of Gabbro-monzonites from the Horodyshche massif 1752.8±6.5 Ma. The same ages (1753±7 Ma) are reported by Shumlyanskyy et al. [2017, Table 1, sample KN-15-1] for an olivine-amphibole monzonite dyke in Vyazivok village. According to Shestopalova [2017], the U-Pb zircon ages of anorthosites from Vyazivok fall within the 1750—1740 Ma interval with the weighted average value of 1744.5±6.5 Ma.

The mean values of the NRM and MS of dyke specimens are 0.34 A/m and 0.01 SI, respectively, while for anorthosite specimens the NRM is almost the same but MS is much lower (0.003 SI). The ChRM component is isolated in the temperature range of 520—540—600 °C, the mean directions for specimens from the dike (D=41.5°; I=–6.1°, α_{95}=8.0°) and host anorthosites (D=41.6°; I=–16.4°, α_{95}=7.1°) is coincides within the α_{95} confidence intervals, but differ 10° in inclination. The typical examples of thermal demagnetization of specimens from the dyke (Fig. 2, *a*) and anorthosite (Fig. 2, *b*) are presented by orthogonal projections of the demagnetization paths (Zijderveld diagrams) and stereographic projections of remanent magnetization directions for each demagnetization steps. In the range of 120—480 °C, the low temperature component (LTC) was isolated in the several specimens with mean direction of D=18.6°, I=52.9°, α_{95}=17.5°, which is close to the direction of present Earth's magnetic field (PEMF) at the sampling location.

Site Khlystunivka. The anorthosite samples were taken along the perimeter of an old flooded quarry to the west of Khlystunivka village near the left bank of the Vilshanka River. There are a few U-Pb ages of rocks taken from the same massif in the Khlystunivka village area: norite (1749±0.5 Ma) and leuconorite (1739±3 Ma) by [Shestopalova et al., 2013; Shestopalova, 2017], quartz monzonite (1746±9 Ma) and quartz syenite (1748±7 Ma) by [Shumlyanskyy et al., 2017]. This data are close to the age of Vyazivok quarry and the age of troctolite from quarry of Voronovka village in the same Horodyshche massif (1750±1.2 Ma) [Shestopalova et al., 2013, 2014].

The mean values of the NRM and MS are 0.068 A/m and 0.0018 SI, respectively, which is lower than in the anorthosites from Vyazivok site. The ChRM-component was isolated on one third of the specimens in the blocking temperature range of 500—560—590 °C (Fig. 2, *c*) with the mean direction of D=43.8°, I= –14.8°, α_{95}=13.5°. The LTC in the tempe-

Table 1. Magnetic parameters and site-mean palaeomagnetic directions and poles

Number	Lithology	NRM, A/m	MS, SI unit	Component	*n*(S)/N	*D*, deg	*I*, deg	*k*	α_{95}, deg	P_{lat}, deg	P_{lon}, deg	$dp/dm(A_{95})$, deg
Ingul Domain, Korsun-Novomyrhorod AMCG complex Horodyshche massif												
Vyazivok (49°10.565'N, 31°22.072'E)												
1	monzonites (dyke)	0.054—0.76 0.34	0.0003—0.02 0.01	HTC	12/29	41.5	–6.1	31	8	26.7	163.6	4.0/8.0
2	anorthosites (host)	0.047—0.45 0.24	0.0003—0.011 0.003	HTC	13/29	41.6	–16.4	35	7.1	21.9	166.3	3.8/7.3
2`				LTC	15/29	18.6	52.9	12.5	17.5	—	—	—
Khlystunivka (49°12.840'N, 31°26.405'E)												
3	anorthosites	0.001—0.28 0.068	0.00013—0.011 0.0018	HTC	11/33	43.8	–14.8	12	13.5	21.6	163.9	7.1/13.8
3`				LTC	23/33	21.3	58.4	11	9.7	—	—	—
Ingul Domain, Korsun-Novomyrhorod AMCG complex Novomyrhorod massif												
Kamyanka (48°47.716'N, 31°42.891'E)												
4	anorthosites	0.035—0.343 0.14	0.0006—0.011 0.002	HTC	9/11	218.2	26.6	8	19.8	18.6	172.4	11.7/21.5
Likareve (48°44.867'N, 31°32.676'E)												
5	anorthosites	0.02—0.09 0.055	0.0002—0.0015 0.0005	HTC	12/13	217.8	19.9	6	19.1	22.3	170.9	10.5/20.0
Mean KNC*					**(5)**	**40.6**	**–16.8**	**106**	**7.5**	**22.3**	**167.5**	**(4.5)**
Volyn Domain, Korosten AMCG complex Volynsky massif												
Syniy Kamin (50°43.1'N, 28°40'E)												
6	anorthosites, gabbro	0.023—0.24 0.093	0.0004—0.003 0.0014	HTC	17/28	217.9	14.5	110	3.4	23.3	167.1	1.8/3.5
Horbuliv (50°31.305'N, 28°56.44'E)												
7	anorthosites	0.1—0.66 0.3	0.0005—0.005 0.002	HTC	30/35	212.2	11.8	15	7	27.1	172.4	3.6/7.1
7`				LTC	13/35	54.5	63.8	11	13.1	—	—	—
Paromivka (50°34'N, 28°30.54'E)												
8	anorthosites	0.17—1.25 0.5	0.0013—0.052 0.007	HTC	26/38	43.1	–18.1	18	6.9	19.5	162.9	3.7/7.2
8`				LTC	17/38	17.5	66.5	7.8	13.6	—	—	—
Mean KC*					**(3)**	**37.7**	**–14.8**	**174**	**9.4**	**23.3**	**167.4**	**(8.9)**

Notes: NRM — diapason (under lined) and mean initial remanent magnetization; MS — diapason (under lined) and mean magnetic susceptibility; n(S)/N — number of individual directions (sampling sites) used in statistical calculation to the total number of treated samples; Component: LTC, HTC — low temperature and high temperature components; *D*, *I* — mean declination and inclination, respectively (in degrees); α_{95} — radius of 95 % confidence cone around mean direction (in degrees); *k* — estimate of precision parameter; P_{lat}, P_{lon} — latitude and longitude of the palaeomagnetic pole; dp/dm (A_{95}) — 95 % confidence ellipse (circle) of the pole. *Mean values for the studied domains are shown in bold, paleomagnetic poles are calculated using virtual geomagnetic poles.

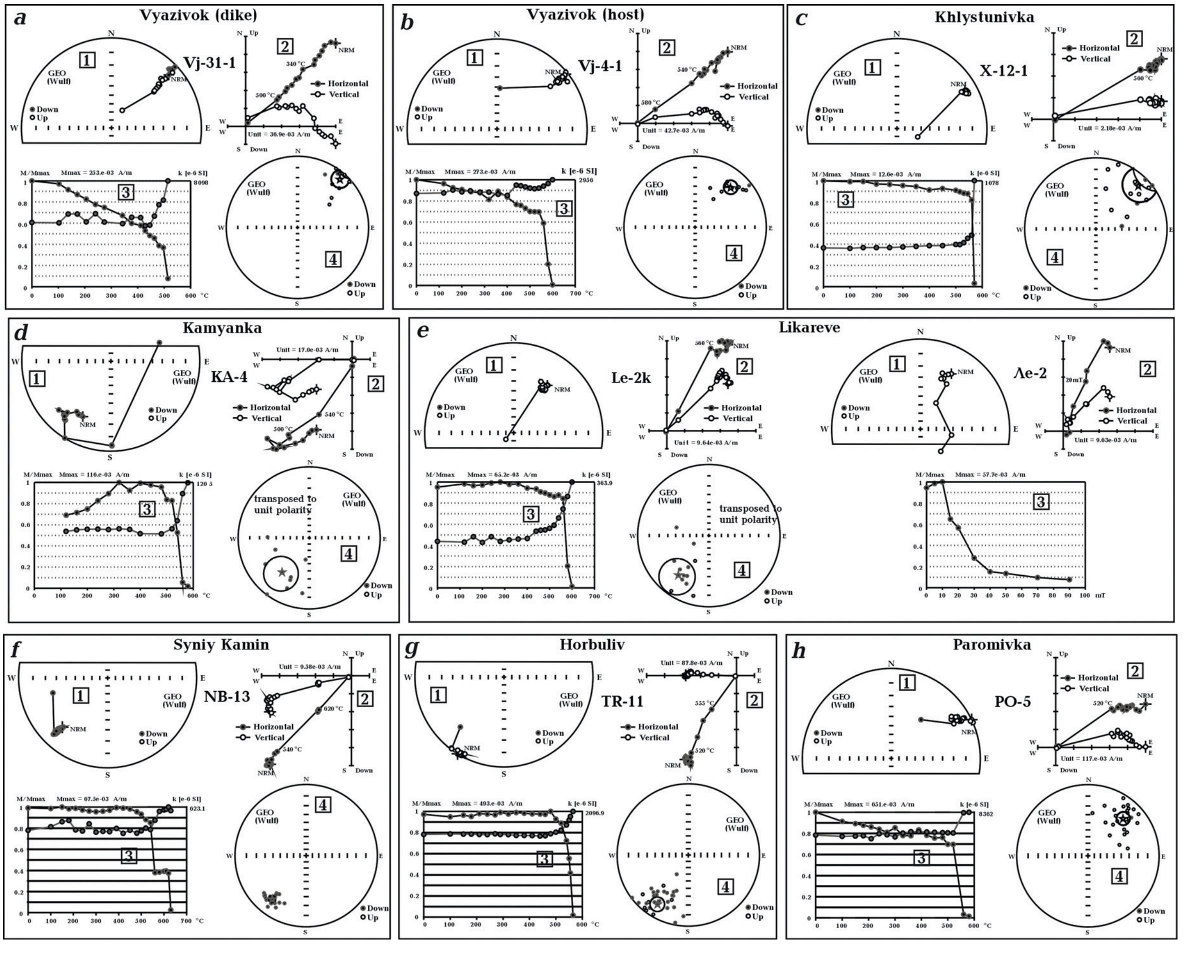

Fig. 2. Examples of stepwise demagnetization of AMCG specimens from the Ingul (*a*—*e*) and Volyn (*f*—*h*) Domain: *1* — stereographic projections of NRM demagnetization directions (full and open circles represent projections in the lower and upper hemispheres, respectively), *2* — orthogonal projections of NRM demagnetization paths (Zijderveld diagrams) on horizontal and vertical planes, *3* — NRM intensity and MS curves (M/Mmax and k, respectively) of demagnetization treatment, *4* — stereographic projections of ChRM directions of specimens (circles) with the site mean direction (star) with radius of the 95 % confidence cone, open symbols denote upward- and solid denote downward-pointing inclinations.

rature range of 150—450 °C was isolated on most of the specimens with the mean value (D=21.3°; I=58.4°; α_{95}=9.7°) close to the PEMF.

Ingul Domain, Novomyrhorod massif. The Novomyrhorod Gabbro-anorthosite massif is located in the southern part of the Ingul Domain and elongated in the sublatitudinal direction (see Fig. 1, *b*). It includes several smaller separate massifs of basic rocks with a complex configuration. Anorthosites and Gabbro-anorthosites make up about 72 % of the area of the Novomyrhorod massif mainly in its central part. Norites and Gabbro-norites occupy 14 % of the area and are represented by elongate narrow bodies which occur in small individual outcrops. Gabbro-monzonites frame the massif from the north and south. They form a series of elongated bodies and occupy about 10 % of the area while quartz monzonites occupy about 4 %.

Site Kamyanka. This site is located in the Novomyrhorod massif and exposed below the dam along the right and left banks of the Velika Vis River to the west from Kamyanka village. The U-Pb zircon age of anorthosite of the main phase from this site is 1750.2±0.9 Ma [Dovbush et al., 2009; Shumlyanskyy et al., 2017]. The ages of zircons in the xenoliths of white (altered) anorthosite that was found within anorthosite of the main phase vary from 1744 to 1806 Ma [Shestopalova et al., 2014]. Shumlyanskyy et al. [2017] presented the U-Pb age of early anorthosite xenoliths as 1801±10 Ma. Thus, the age of about 1750 Ma can be attributed to the sampled anorthosites.

The mean values of the NRM and MS are 0.14 A/m and 0.002 SI, respectively, close to the values for Horodyshche anorthosites. The high temperature ChRM component is isolated in most specimens in the temperature range of 500—600 °C and showed the dual polarity: 7 specimens are grouping in the third quadrant (conventionally normal polarity), while 2 specimens with negative inclination — in the first quadrant (conventionally reverse polarity). The mean ChRM direction (reduced to one polarity, Fig. 2, *d*) is D=218.2°; I=26.6°; α_{95}=19.8°.

Site Likareve. In the other part of the Novomyrhorod massif, the anorthosites were sampled in the southwestern area of a flooded quarry near the Likareve village. The age of the rocks is the same as in Kamyanka (about 1750 Ma). The magnetic parameters of the specimens vary widely, but the mean values of the NRM and MS are 0.055 A/m and 0.0005 SI, respectively, which are one order less than in specimens from Kamyanka. The ChRM component is confidently isolated in the temperature range 500—540—600 °C (Fig. 2, *e*) and characterized by the dual polarity as well as in Kamyanka. The mean ChRM direction (reduced to one polarity) is D=217.8°; I=19.9°; α_{95}=19.1°. The results of AF demagnetization of duplicate specimens are confirmed the thermal demagnetization data (see Fig. 2, *e*).

Volyn Domain, Korosten AMCG complex. The Korosten AMCG complex occurs in the eastern part of the Volyn Domain. We focused on sampling from three sites of the Volyn massif in the southern part of the Korosten pluton (see Fig. 1, *a*) which belong to the main anorthosite series (A_2) with the precise U-Pb zircon age data of crystallization between c. 1761 Ma and 1758 Ma [Shumlyanskyy et al., 2017].

Site Syniy Kamin. Anorthosites were sampled within a flooded quarry about 0.5 km southeast of Turchynka village. The U-Pb zircon ages of these rocks are 1758.0±1.8 Ma by Verkhogliad [1995] and 1756±4 Ma (for pegmatite) by Shumlyanskyy et al. [2017]. The mean values of the NRM and MS are 0.093 A/m and 0.0014 SI, respectively. The directions of the LTC are isolated up to 500 °C, but the directions are rather chaotic and their contribution to the NRM is usually no more than 30 %. The directions of HTC lie in the range of 500—580 °C, directed toward the origin of the orthogonal plot and have the mean direction of D=217.9°, I=14.5°, α_{95}=3.4° (Fig. 2, *f*). Some of the samples demonstrated a negligible component in the range of 570—630 °C with directions close to ChRM component.

Site Horbuliv. Anorthosites were sampled within a quarry located about 1 km northwest of the border of Torchyn village near the left bank of the Verkholuzhzhya River. The U-Pb age of the host rocks (for pegmatite) is estimated at 1754±4 Ma [Shumlyanskyy et al., 2017]. The mean NRM and MS values are 0.3 A/m and 0.002 SI, respectively, which is higher than that of Syniy Kamin anorthosites. Up to 440—500 °C, the remanent magnetization is stable and contribution of this LTC to the initial NRM does not exceed 10 %. The mean direction of this component lies in the first quadrant of the stereogram (D=54.5°, I=63.8°, α_{95}=13.1°) not far from the PEMF. The ChRM component is distinguished in almost of all samples in the range of 440—580 °C (Fig. 2, *g*) with the mean direction of D=212.2°, I=11.8°, α_{95}=7.0° and unit polarity.

Site Paromivka. The sampling on this site was carried out within a flooded quarry about 1 km south of Paromivka village. A U-Pb age of pegmatites of this quarry is estimated at 1757±3 Ma [Shumlyanskyy et al., 2017]. The mean NRM and MS values of rocks are 0.3 A/m and 0.007 SI, respectively, which are higher than in the other anorthosites. In most samples, two components with overlapping spectra were isolated by thermal demagnetization. The LTC is isolated up to 540 °C and shows the mean direction (D=17.5°, I=66.5°, α_{95}=13.6°) that corresponds to the PEMF. Its contribution can reach 50—70 %, but generally does not exceed 30 % of the initial NRM. The ChRM components are isolated for two-thirds of the specimens in the range of 500—580 °C with low negative inclinations (*D*=43.1°, *I*= −18.1°, α_{95}=6.9°), they are located in the first quadrant of stereoprojection (Fig. 2, *h*).

Discussion. ***Palaeomagnetic directions.*** The studied rocks of the AMCG complexes of the Ingul and Volyn Domains carry a stable remanence, which unblocks in a narrow temperature range at c. 540—580 °C (see Fig. 2 and Table 1). From the previously published petrographic studies and the thermomagnetic analyses of these rocks, we can summarize that the carrier of remanent magnetization is thin isolated needle-like and lamellar ferromagnetics in plagioclases and pyroxenes. This is probably the result of high temperature exsolution of plagioclase and pyroxene at a late magmatic stage of rock formation [Mikhailova et al., 1994; Elming et al., 2001], in connection with which the systems of fine-oriented lamellar inclusions are formed in these minerals. The unblocking temperatures suggest that the carrier of the ChRM component is fine-grained magnetite, sometimes with a small amount of Ti.

The palaeodirectional data of the particular NRM components are given in Table 1 and on the stereographic projections in Fig. 3. The direction of the less stable LTC was not reliably allocated for all sites (Fig. 3, *a*). Confidence cones (95 %) around mean directions of three sites (Vyazivok, Khlystunivka and Paromivka) intersect with the direction of PEMF, so it seems like a present-day viscous magnetization. The LTC mean direction of the Horbuliv site is located a little further from PEMF. This fairly stable but probably viscous remanence is isolated in some specimens up to 500 °C, but the direction is not so far from PEMF as to interpret it as a separate component.

The ChRM site mean directions fall into the first and third quadrants of the stereographic projection (Fig. 3, *b*) and can be divided into two bipolar groups. This allows us to perform a reversal test [McFadden, McElhinny, 1990] to estimate the stability of magnetization for 4 direct (mean is *D*=216.5°, *I*=18.2°, *k*=131, α_{95}=8.1°) and 4 reversed (mean is *D*=42.5°, *I*=–13.9°, *k*=221, α_{95}=6.2°) site mean directions; the obtained values γ=7.2° and γ_c=8.8° (class B) yield positive results. New directions are very similar to the data represented by Elming et al. [2001] for anorthosite samples from the Korosten and Korsun-Novomyrhorod plutons. The bipolarity and great value of confidence cone (α_{95}) of mean ChRM directions from Kamyanka and Likareve sites we can explain by a longterm cooling of the plutonic rocks during changes in the geomagnetic field. We cannot determine the acquisition time of thermoremanence magnetization in rocks during cooling (it can differ signifi-

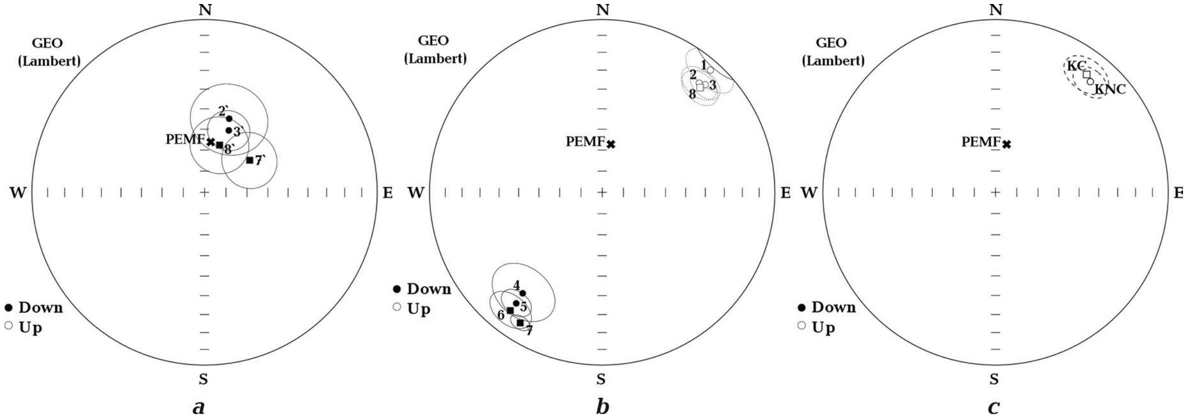

Fig. 3. Stereographic projections of the site mean directions of LTC (*a*) and ChRM HTC (*b*), and mean palaeomagnetic directions (*c*) for KNC and KC. Open symbols denote upward- and solid denote downward-pointing inclinations, the circles around these symbols represent the radius of the 95 % confidence cones. Palaeomagnetic directions for KNC (KC) are shown by circles (squares). The position of the PEMF is shown with a cross. The numbers correspond to the site numbers in Table 1.

cantly in the central and marginal parts of the large pluton).

The KNC and KC were formed 150—200 Myr after the last orogenic event. Geological and geochemical data indicate a within-plate tectonic setting of the AMCG magmatism in the Ukrainian Shield which took place in several phases [Shumlyanskyy et al., 2017].

As was mention above, the large anorthosite bodies of the main anorthosite (A_2) series of Volynsky massif crystallized between ca. 1761 and 1758 Ma, while residual melts, represented by pegmatitic pods, crystallized at ca. 1758 Ma. The combined weighted average $^{207}Pb/^{206}Pb$ age for all results obtained for the three different sites (Syniy Kamin, Horbuliv, and Paromivka quarries), is 1758±4 Ma, and this age was accepted as the time of crystallization of the pegmatites in the Volynsky Gabbro-anorthosite massif [Shumlyanskyy et al., 2017]. It corresponds to the previously obtained age of their host anorthosites of 1758±2 Ma [Verkhogliad, 1995]. According to [Shumlyanskyy et al., 2017], the majority of the KC rocks that crop out at the surface formed between ca. 1768 and 1755 Ma, and the latest stages are expressed by the formation of the minor intrusion about 1752—1743 Ma.

In contrast to the KC, most of the basic and silicic rocks of the KNC emplaced simultaneously between ca. 1757 and 1750 Ma. The U-Pb zircon ages of studied sites from Horodyshche and Novomyrhorod massifs are 1750—1740 Ma. The latest phases of the complex are represented by monzonites and syenites that were formed between 1748 and 1744 Ma. The emplacement of the KNC slightly postdates the main intrusive phase of the KC, whereas the majority of silicic and basic rocks intruded within a similar time interval of 10 Myr [Shumlyanskyy et al., 2017].

Based on the statistical paleomagnetic directions, the corresponding poles were calculated for collections of eight sampling sites (see Table 1), where three sites belong to the Korosten pluton, and five to the Korsun-Novomyrhorod pluton. The mean directions lie rather closely, are characterized by bipolar N-E and S-W declinations with low inclinations and almost coincide with each other (Fig. 3, *c*).

We have the following reason to claim that the isolated high-temperature ChRM component is primary: 1) dual polarity magnetization both in different sites (passed the reversal test with class B) and even within individual sites; 2) the carrier of remanent magnetiza-

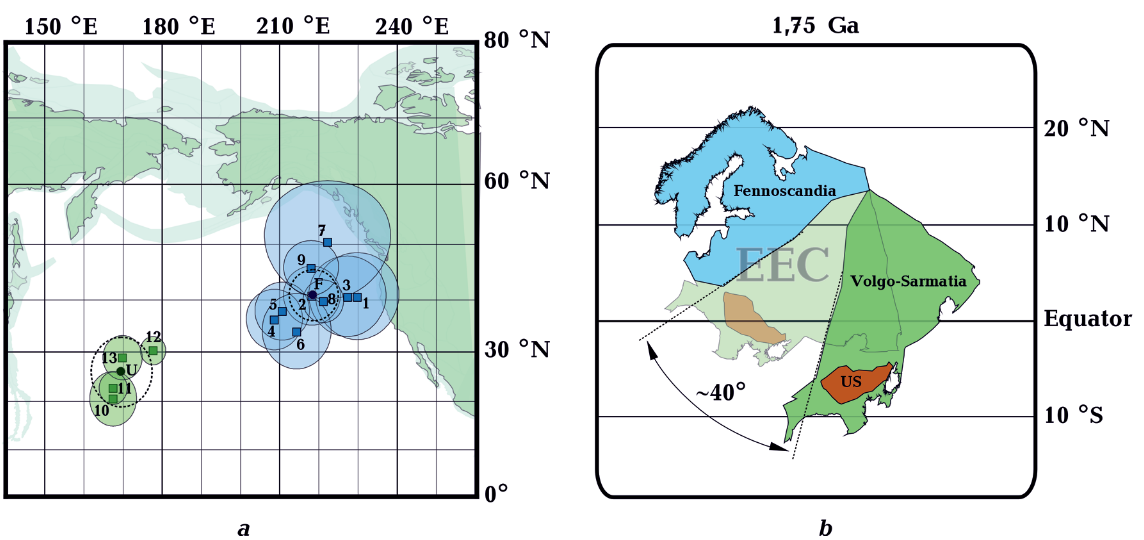

Fig. 4. Selected palaeomagnetic poles for EEC (*a*) and palaeotectonic model of the EEC's segments for 1.75 Ga (*b*). In Fig. 4, *a*: the green (blue) symbols denote the position of the poles for the Ukrainian Shield (Fennoscandia), and the circles around them denote the corresponding A_{95}, numbers of poles correspond to Table 2, mean poles for the Ukrainian Shield (*U*) and Fennoscandia (*F*) are shown as filled circles with a dotted A_{95} intervals.

tion is thin isolated needle-like and lamellar ferromagnetics (stable fine-grain magnetite, sometimes with minor titanium impurities) in plagioclase which formed at high temperatures during the cooling of magma; 3) overlap the data from different AMCG massifs with similar ages; 4) consistency of the data with the other palaeomagnetic results of AMCG complexes in the Ukrainian Shield [Elming et al., 2001].

Palaeotectonic reconstruction. The new paleomagnetic data for the KNC and KC (see Table 1 and Fig. 3) agree well with each other, suggesting a fixed relative position of the Volyn and Ingul Domain within a unified structure of Ukrainian Shield since at least 1.75 Ga. The new paleomagnetic determination also corresponds well to the data of previous palaeomagnetic studies on the Ukrainian Shield [Elming et al., 2001, 2010].

As there are no signs of remagnetization of AMCG rocks and the differences between the positions of two domains within the Ukrainian Shield, the palaeomagnetic pole calculated from the 8 sites is P_{lat}=22.7 °N, P_{lon}=167.4 °E, A_{95}=3.3°. Following the Q reliability criteria by Van der Voo [1990], we evaluate our result by criteria 6.

Taking into account the delay of magnetization blocking (less than the Curie temperature of 580 °C for magnetite) in the sampled anorthosites, which is not equivalent to the geochronological age (the U-Pb system closure temperature in zircon/baddeleyite in excess of 850 °C), the age of thermal remanent magnetisation acquisition could be tens of million years later than the emplacement age of the anorthosites [Kravchenko, 2005].

The consistent positions of paleomagnetic poles in time serve to quantify the horizontal movements of the plates, and ultimately for paleotectonic reconstructions. Based on the palaeomagnetic determination for the Ukrainian Shield, the apparent polar wander path shows that the sequence of poles from 2.0 to 1.72 Ga does not coincide with the data of similar ages from the Fennoscandia, and the position of the Ukrainian Shield in that time interval was different from the present position relative to Fennoscandia [Elming et al., 2001]. The palaeomagnetic data suggested that the final accretion of Fennoscandia to the Ukrainian Shield as a part of Sarmatia took place sometimes after ca. 1.8 Ga, and Fennoscandia and Sarmatia then may have formed a part of the supercontinent Nuna (Columbia) assembled in the Mesoproterozoic.

We assign the age of palaeomagnetic pole for AMCG rocks for 1.75 Ga. The selection of the most reliable paleomagnetic determinations for Fennoscandian and Volgo-Sarmatian segments of EEC is presented in Table 2 and Fig. 4, *a*. Our new paleomagnetic data (№ 11 in Table 2 and Fig. 4, *a*) agree well with the data in the age range of 1.77—1.74 Ga obtained earlier for rocks of the Volyn Domaine by other authors (№ 10, 12, and 13). The mean paleomagnetic pole for Volgo-Sarmatia (P_{lat}=25.6 °N, P_{lon}=170.4 °E, A_{95}=7.2°) is significantly different from that for Fennoscandia (P_{lat}=40.8 °N, P_{lon}=218.7 °E, A_{95}=4.7°) which confirms the earlier results by [Elming et al., 2001, 2010].

Based on the new data (see Table 1) and the selection of the most reliable poles (see Table 2), the model of the relative position of the EEC segments is presented in Fig. 4, *b*. About 1.77—1.75 Ga, Fennoscandia occupied a subequatorial position within paleolatitudes of 5—20 °N, and Volgo-Sarmatia was located near the equator at paleolatitudes of 10 °S to 10 °N. At the same time, Volgo-Sarmatia was rotated relative to Fennoscandia counterclockwise by about 40° compared to its present position within the EEC.

Conclusions. In this paper we presented new palaeomagnetic results for the AMCG complexes of the Ukraine Shield, the Korosten and the Korsun-Novomyrhorod plutonic rocks, which are provided the additional target U-Pb dating and lead to the following conclusions.

The isolated high-temperature ChRM component is stable and demonstrated primary origin: 1) antipodal bipolar ChRM was isolated for different sites (and even within individual sites) and passed the reversal test with class B; 2) carrier of remanent magnetization is lamellar fine-grain oriented magne-

Table 2. Selected palaeomagnetic poles for EEC

Number	P_{lat}, °N	P_{lon}, °E	A_{95}, deg	Age, Ma	Q	Pole reference
Fennoscandia						
1	40.5	229.8	8.1	1751	4	Fedotova et al., 1999
2	40.7	218.2	5.5	1751	4	Fedotova et al., 1999
3	40.5	227.3	7.5	1751	4	Khramov et al., 1997
4	36.2	208.6	5.8	1751	4	Fedotova et al., 1999
5	37.8	210.6	5.5	1751	4	Damm et al., 1997
6	33.9	214.3	7.3	1751	4	Khramov et al., 1997
7	50.4	222.2	10.2	1767	4	Veselovskiy et al., 2013
8	39.7	221.1	4	~1775	6	Pisarevsky, Sokolov, 2001
9	45.8	218.0	4.9	~1775	4	Damm et al., 1997
F	***40.8***	***218.7***	***4.7***	***1775—1751***		***Mean pole***
Ukrainian Shield (Volgo-Sarmatia)						
10	20.5	167.4	5.6	1740	6	Elming et al., 2001
11	22.7	167.4	3.3	1760—1750	6	This paper
12	30.2	177.6	2.8	1760	6	Kravchenko, 2005
13	28.8	169.8	4.4	1770—1760	7	Elming et al., 2010
U	***25.6***	***170.4***	***7.2***	***1770—1740***		***Mean pole***

Notes: Number — number refers to numbers used in Fig. 4, *a*; P_{lat}, P_{lon} — pole latitude and longitude; A_{95} — the radius of the 95 % confidence circle of the pole; Q — Van der Voo [1990] reliability criteria.

tite in an exsolution structure of plagioclase which was formed at high temperatures during the cooling of the magma; 3) coincidence of results from different sites of AMCG rocks of similar ages; 4) consistency of the data with the previous palaeomagnetic studies of the same domains of the Ukrainian Shield. The results confirm the previous thesis that the most informative rocks of the AMCG complex for palaeomagnetic studies are anorthosites.

With this study of basic AMCG rocks from Ingul and Volyn Domains, the palaeomagnetic data for the Ukrainian Shield were extended and a new reliable pole for 1.75 Ga (geochronology age) was determined. Five sites (mostly anorthosite) of the KNC and three sites of the KC with the similar (within 10 Myr) ages show that the mean site directions of ChRM components lie rather closely. The mean palaeomagnetic poles for the KNC and KC agree well with each other and suggest a fixed relative position of the Volyn and Ingul Domains within a unified structure of Ukrainian Shield since at least 1.75 Ga.

The selection of the most reliable palaeomagnetic poles for Fennoscandia (1.775—1.751 Ga) and Volgo-Sarmatia (1.77—1.74 Ga) with new data for 1.75 Ga indicates that the present position of the Ukrainian Shield relative Fennoscandia is not the same as it was about 1.75 Ga. In that time, Fennoscandia occupied a subequatorial position within paleolatitudes of 5—20 °N, Volgo-Sarmatia was located close to the equator at paleolatitudes of 10 °S to 10 °N and rotated relative to Fennoscandia counterclockwise by about 40° compared to its present position within the EEC.

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Нові палеомагнітні дані щодо палеопротерозойського АМЧГ комплекса Українського щита

В.Г. Бахмутов[1], О.В. Митрохин[2], Є.Б. Поляченко[1], С.І. Черкес[1], 2023

[1]Інститут геофізики ім. С.І. Субботіна НАН України, Київ, Україна
[2]ННІ «Інститут геології» Київського національного університету імені Тараса Шевченка, Київ, Україна

Проведено палеомагнітне дослідження порід двох палеопротерозойських анортозит-мангерит-чарнокіт-гранітних (АМЧГ, або AMCG) комплексів Українського щита з метою визначення додаткових обмежень при інтерпретації палеогеографії Фенноскандії та Волго-Сарматії в палеопротерозої за палеомагнітними даними. З урахуванням геологічних, сучасних геохронологічних та отриманих раніше палеомагнітних даних вибрано та досліджено п'ять сайтів Корсунь-Новомиргородського та три сайти Коростенського АМЧГ комплексів у північно-західній та центральній частинах Українського щита. На зразках анортозитів, габро та монцонітів вікового діапазону 1,76—1,75 млрд років було виділено первинну залишкову намагніченість. Розраховані палеомагнітні полюси для Коростенського (1,76 млрд років) та Корсунь-Новомиргородського комплексу (1,75 млрд років) майже ідентичні, що вказує на приналежність Волинського та Інгульського мегаблоків до однієї структури Українського щита принаймні починаючи з 1,75 млрд років тому. Новий палеомагнітний полюс, розрахований для всіх восьми сайтів (P_{lat}=22,7 °N, P_{lon}=167,4 °E, A_{95}=3,3°), добре узгоджується з результатами попередніх досліджень [Elming et al., 2001, 2010]. Аналіз найнадійніших палеомагнітних полюсів для Фенноскандії та Волго-Сарматії у досліджуваному часовому діапазоні показав, що сучасне положення Українського щита відносно Фенноскандії відрізняється від його положення близько 1,75 млрд років тому, коли Фенноскандія займала субекваторіальне положення в межах палеоширот 5—20 °N, а Волго-Сарматія була розташована близько до екватора і повернута відносно Фенноскандії проти годинникової стрілки приблизно на 40° порівняно з її сучасним положенням.

Ключові слова: Український щит, протерозой, палеомагнетизм, АМЧГ комплекси, тектонічна реконструкція.