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Palaeomagnetism of the Vendian traps of Volyn, southwestern margin of the East European Platform, P. 2: magnetostratigraphy

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We present new results of palaeomagnetic studies of the Vendian (Ediacaran) rocks of the Volyn Basalt Province revealed by six boreholes on the NW Ukraine. This is a continuation of previous studies of upper part of the Volyn series described by Bakhmutov et al. [2021]. In the recent works [Shcherbakova et al., 2020; Thallner et al., 2022], the results of palaeointensity determinations of the Volyn series basalts showed the ultra-low dipole moment of Earth's magnetic field which coincident with other palaeomagnetic data for Ediacaran indicating an extremely weak geomagnetic field. Clear stratification and correlation of the basalt and tuff layers by magnetic parameters allow us to determine the magnetic field reversals throughout the stratigraphic succession of the Volyn series of about 400 m thick. In basalts, tuffs and baked contact rocks, a high-temperature characteristic component of remanent magnetization (ChRM) with all signs of primary magnetization have been isolated. For the directions of inclination of ChRM-components at least six magnetic polarity reversals were revealed. The geochronological ages of rocks is in the range of 580—545 Ma, but the errors in the age estimation are too large for separation of individual formations within the pulses of activity or differentiation of individual eruptions. Therefore the formation time of the entire stratum remains uncertain, and the key issue for interpretation of the magnetic polarity reversal frequency is the duration of accumulation of traps. Two possible interpretations of palaeomagnetic results are considered. In the first, which takes into account different stages of magmatic activity, the time interval of accumulation can be about 10 million years. Then the average frequency of geomagnetic inversions is close to mean for the Phanerozoic. We prefer the other interpretation when the formations of the Large Igneous Provinces have been occurred over a short time interval (e.g. 0.5 Myr). Taking into account the results of palaeointensity estimations for the same samples, which shown the extremely weak geomagnetic field, the hypothesis of the «hyperactivity» of the field with a frequency of at least 12 reversals per one million years on the end of the Ediacaran gain the additional confirmation.

Key words: palaeomagnetism, Ediacaran magnetic field, Volyn traps.

Introduction. In the first part of the article regarding the palaeomagnetism of the Ediacaran traps of Volyn [Bakhmutov et al., 2021] we presented the results of study the basalts and tuffs of the Volyn series with an age of about 560—580 Ma. Attention to this topic was aroused by a series of publications concerning the extremely irregular behavior of the geomagnetic field in the Ediacaran one order of magnitude weaker than the present-day field (see references in [Shcherbakova et al., 2020; Bakhmutov et al., 2021]).

The importance of accounting for the geometry and intensity of the geomagnetic field is obvious when considering the reasons that can cause different modes of geodynamo. The basalts of the Volyn series are a favorable object for palaeomagnetic studies. These rocks are most complete in the territory of Ukraine in Volyn and Rivne regions where they protrude onto the pre-Cretaceous surface and are exposed in the quarries northern of Rivne city. Palaeomagnetic studies of Volyn traps were carried out by different research groups [Glevasskaya et al., 2000; Iosifidi et al., 2000; Nawrocki et al., 2004; Elming et al., 2007; Shcherbakova et al., 2020; Bakhmutov et al., 2021]. But only the upper part of the trap formation is outcropped by quarries. The much thicker lowermost part of the Volyn section is revealed only by boreholes [Glevasskaya et al., 2006]. The effusive beds of the Volyn series consisting of Zabolottya, Babyne, Luchichiv and Ratne suites are well correlated in boreholes and can be traced over tens of kilometers. The formation of these suites occurred cyclically and eruptions of basaltic lava were preceded by significant ejections of pyroclastic material. They form areas of traps of the plateau-basalt type at different stratigraphic levels which are distributed over fairly large areas. Basalts of the Volyn series and their equivalents are traced in the western part of the East European Platform (EEP) and occupy an area approximately of 200,000 km^2 [Gozhik, 2013].

New palaeomagnetic data on extremely low values of palaeointensity by Volyn basalts [Shcherbakova et al., 2020] and their palaeomagnetic directions [Bakhmutov et al., 2021] led us to further studies of the Volyn series traps with the aim to get more information about Ediacaran geomagnetic field. We continued these studies for the boreholes cores. The boreholes uncover the Volyn traps succession about 400 m thickness represented by an alternation of basalt flows with lava breccias and tuffs. In this paper, we are presented detailed information about palaeomagnetic study and magnetostratigraphy of the sequence in addition to palaeointensity determination presented in [Thallner et al., 2022]. This sequence stratigraphycally lies below the sections described in [Bakhmutov et al., 2021].

Geology and age of rocks. The geological description of the Volyn traps, age of rocks and stratigraphy are given in [Bakhmutov et al., 2021, and references therein]. Here we briefly describe the continental Ediacaran trap formation of the Volyn series explored by boreholes, Fig. 1. The effusive rocks of the Volyn series were formed during a few individual volcanic cycles separated by interruptions during the volcanic activity. The volcanogenic sequence of the Volyn series unconformable overlies the terrigenous deposits of the Polissya series and forms a large igneous province covering western Ukraine, eastern Poland, southwestern Belarus, also known as the Volyn Large Igneous Province (Volyn Basalt Province — VBP) or Volyn continental flood basalt province, Fig. 1, *a* [Velikanov, Korenchuk, 1997; Shumlyanskyy et al., 2007; Melnychuk, 2010]. In upper part, the Volyn series is overlain by volcanogenic sediments of the Mogyliv-Podilsky series.

The structure of the trap formation of the Volyn-Podillya Plate on the territory of Ukraine is known mainly from exploration boreholes for copper. Since the drilling usually stopped on the top of Babyne suite tuffs, the Ratne suite has been studied in the most detail. The lower horizons of the Volyn series (Zabolottya and Gorbashy suites) are described only by boreholes on the northwest.

We studied the basalts and tuffs uncovered by boreholes on the area of a small ledge of the Archean gneisses well seen on the geological map of pre-Mesozoic deposits (Fig. 1, *b*). The cores from six boreholes represent complete stratigraphic secession of the Volyn series in the Zabolottya, Babyne, Luchichiv and Ratne Suites (Fig. 1, *c*).The cores stratigraphically overlapped and correlated with each other as shown on the logging of the boreholes magnetic susceptibility measurements (Fig. 2).

The most preserved core sections for sampling were from the borehole CK3 chosen as a reference borehole and CK2 as a backup. In these boreholes the Babyne and Ratne suites are well exposed. However, the Luchichiv suite in CK3 is reduced and represented by only a thin layer of breccia. It is possible that the underlying basalt flow in CK3 also belongs to the Luchichiv suite, but we accept its complete reduction. The samples from other cores were taken only from basalt flows

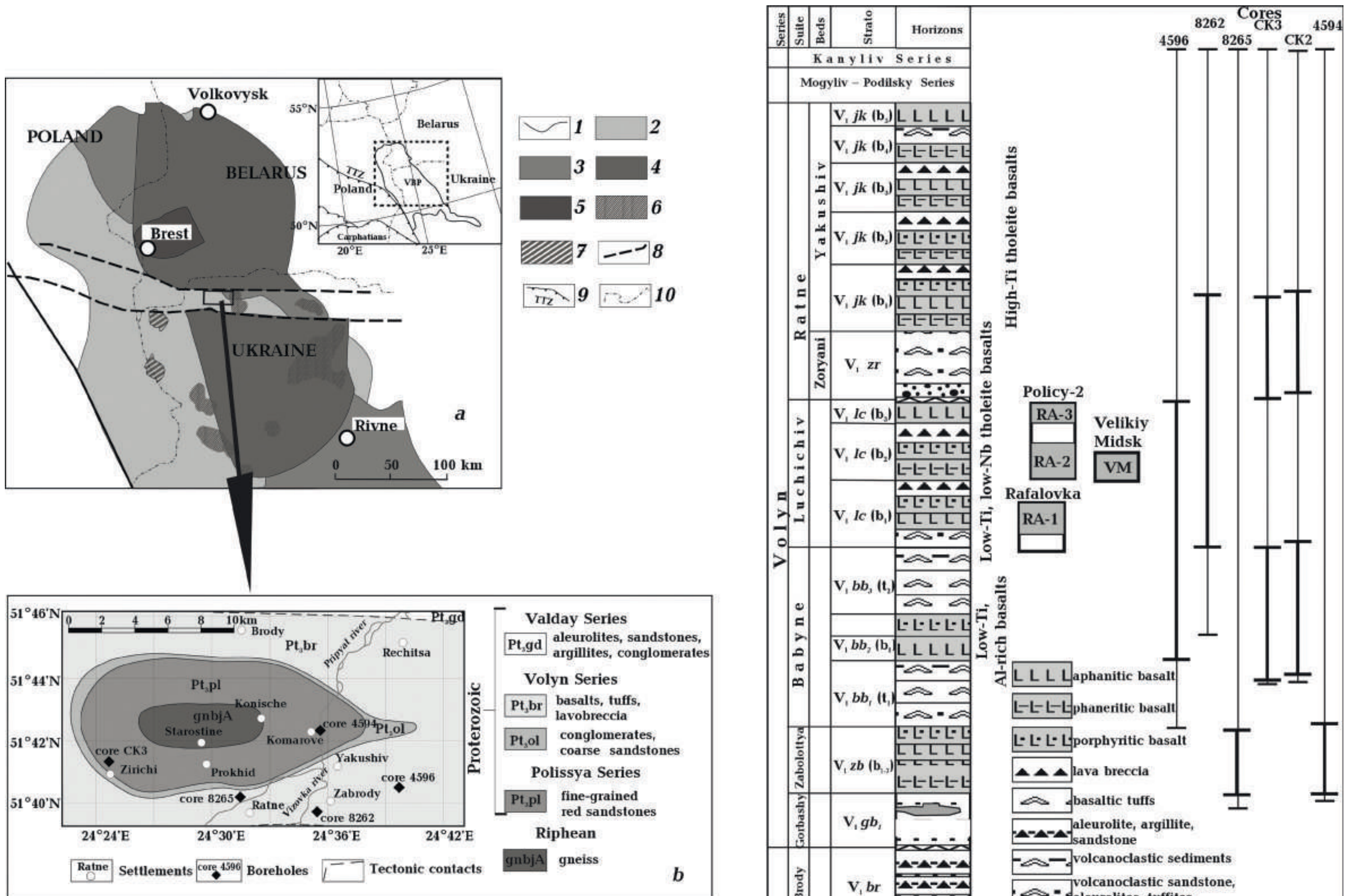


Fig. 1. Schematic map of the Volyn Basalt Province (*a*): *1* — Lava and tuff facies, *2—4* — Basalts and tuffs (*2, 3* — olivine basalts of the lower sequence (low-Ti (*2*), moderate-Ti (*3*)), *4* — high-Ti tholeiitic basalts of the upper sequence); *5* — felsic and intermediate rocks; *6, 7* — dolerite sills; *8* — faults; *9* — Trans-European Suture Zone; *10* — state boundaries. Adopted from [Nosova et al., 2005; 2008]. Geological map (Volyn-Podillya part, M-35-I) of Pre-Mesozoic rocks and locations of boreholes (*b*); Summary stratigraphic scheme of the lower Vendian of the Brest-Volyn structural-facial zone according to [Gozhik, 2013] (*c*); the stratigraphic positions of boreholes are displayed on the right. The thin (thick) line are represented the whole depth (sampling interval) of each borehole core. The stratigraphic position of studied quarries in [Bakhmutov et al., 2021] is presented on the center. The scale on this diagram is arbitrary.

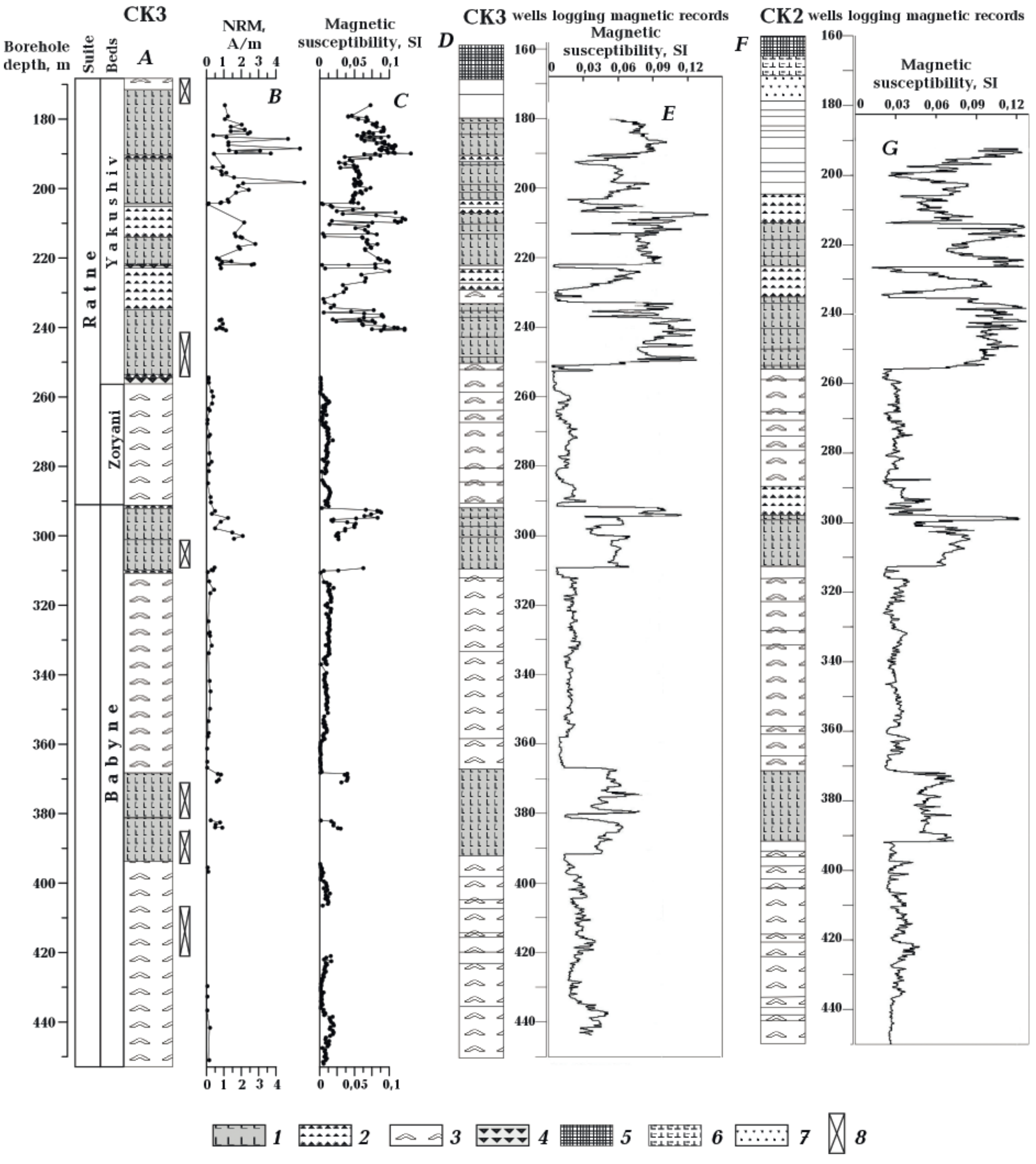


Fig. 2. Stratigraphic subdivision of cores adopted from: core description (*a*) and initial specification (*d*, *f*); NRM intensity (*b*); magnetic susceptibility measured by KT-6 kappameter (*c*); wells logging magnetic susceptibility records along the cores CK3 (*e*) and CK2 (*g*): *1* — basalt, *2* — lavabreccia, *3* — tuff, *4* — baked contact, *5* — Cretaceous sediments, *6* — marls, *7* — sandstones, *8* — no samples.

including Zabolottya and Luchichiv suites which are not presented in CK3. The Zabolottya suite about 60 m thick is represented by the cores 8265 and 4596. The Luchichiv suite in boreholes 8262 and 4596 has thicknesses of 55 and 63 m respectively. The core sections of borehole 8262 comprise Zoryani and Yakushiv layers of Ratne suite with total thickness of about 70 m.

Thus, the thickness of the Ratne suite is 130 m (the maximum is in CK3), the Luchichiv suite is 63 m (the maximum is in 4596), the Babyne suite is about 150 m, the Zabolottya suite is about 60 m (boreholes 8265 and 4594), and the total thickness of the exposed section of the Volyn series is about 400 m.

The late Neoproterozoic igneous activity in the western part of the EEP is commonly regarded as an expression of rifting related to the break-up of the Precambrian supercontinent Rodinia, or its later successor Pannotia [e.g. Poprawa, Pacześna, 2002; Bogdanova et al., 2008; Shumlyanskyy et al., 2016]. Therefore, age control on the development of the effusive succession of the Volyn series provides direct constraints on timing of the break-up processes.

The results of geochronological dating of the Volyn series cited in [Bakhmutov et al., 2021, Table] show the age range of 580—545 Ma. These age determinations, which refer mainly to the upper part of the Volyn series revealed both in boreholes and outcrops, were presented by Compston et al. [1995], Shumlyanskyy and Derevska [2001], Shumlyanskyy and Andréasson [2004], Shumlyanskyy et al. [2006; 2016], Nosova et al. [2005], Elming et al. [2007], Paszkowski et al. [2019, 2021], Poprawa et al. [2020].The youngest dating was obtained for the Girsk suite of the upper Volyn series from the Kobryn-1 borehole (western Belarus), U-Pb dating of zircons in the tuff layer yielded an age of 545±4 Ma [Paszkowski et al., 2019]. Compton et al. [1995] obtained the U-Pb age of zircons in the tuff layer from the top of the Sławatycze Series (Poland), which correlated with the Volyn series, of 551±4 Ma. The upper age limit of the Volyn series are as follows: 580±9 Ma by $^{40}Ar/^{39}Ar$ dating of the Ratne suite from the Rafalovka quarry [Elming et al, 2007], and 579±4 Ma by U-Pb zircon dating of the Rataychitsy suite (lower part of the Volyn Series) tuffites from the Pinsk borehole (western Belarus) [Paszkowski et al., 2019]. U-Pb dating of zircons from high-Ti basalt and rhyolitic dacite from Ratne suite yielded the weighted average ages of 573±14 Ma and 571±13 Ma respectively[Shumlyanskyy et al., 2016]. These data were recalculated by [Poprava et al., 2020] and estimated at 569±12 Ma and 567±11 Ma, respectively.

Among the most recent papers, we should highlight La-ICP-MS dating of samples from pyroclastic and volcano-sedimentary rocks horizons from the Kobryn-1 and Pinsk boreholes (Belarus) performed by Paszkowski et al. [2019], where high-resolution geochronological data ranging in age from 545±4 Ma to 579±4 Ma. The SHRIMP dating of tuff samples from Krzyże IG-4, Mielnik IG-1 and Kaplonosy IG-1 boreholes (Poland) performed by Poprawa et al. [2020] shown the ranging in ages from 567.1±4.7 Ma to 551.0±4 Ma.

The data from several deep boreholes revealed that continuous sections of the Volyn series in the Lublin-Podlasie Basin (LPB) constrain the terminal phase of a rift-related effusive activity with an age range of 553±15 Ma to 545±4 Ma [Poprawa et al., 2020]. The presence of volcanic activity was also recorded in the Podillya Basin, where volcanogenic material have been observed in the bentonite layers of Mohyliv-Podilskyi group. U-Pb data by Soldatenko et al. [2019] of two such layers yielded ages of 556.78±0.18 Ma and 555.4±2.9 Ma. The U-Pb dating of zircons from nine samples of the Volyn series, along with indirect constraints from other data, indicated that the most intense development of lavas and pyroclastics took place at ca. 557—555 Ma and 567—560 Ma [Poprawa et al., 2020]. Most of the geochronological ages obtained by different authors fit this time range.

According to Krzemińska et al. [2022], there are three main phases. The initial phase (580—567 Ma) is represented by picritic lavas and tuffs with typical low values of Zr and TiO_2. The main phase (567—551 Ma) is represented by a significant volume of subalkaline basalt to andesite and tuffs. The terminal phase (551—547 Ma) is characterized by a significant decrease in the volume of eruptions, longer intervals between episodes of eruption and an increase of silica components.

It is noted that the geochronological ages of the final stage of volcanism have difference of about 10 Myr. The different ages between rift-related effusive activity, for example in the LPB and western part of the Orsha-Volyn Aulacogen, might indicate that to the east of the LPB the terminal eruptions might have taken place ~5 Myr later [Poprawa et al., 2020]. Therefore, magmatic activity could not have been simultaneous in different parts of the LPB, and this should be taken into account when correlating the magmatic events.

It is important to estimate the duration of volcanic activity in the complete stratigraphic succession of Volyn traps. Geochronological data of the Volyn series from the boreholes (Fig. 6 in [Poprawa et al., 2020]) provided concordant ages values which support the stratigraphy of the sequence. The age range between the lower and upper samples in the Kaplonosy IG-1 and Krzyźe-IG-4 boreholes is about 11 Myr, but the errors in age determinations are too large to accept this value as the time of the Volyn series formation. According to the data from the Kobryn-1 borehole [Paszkowski et al. 2019, Fig. 2], age values consistently range from 545±4 Ma to 569±4 Ma (between the lower and upper samples), which may indicate the formation time of Rataychitsy and Girsk suite of the Volyn series at this site between 16 and 32 Myr.

No direct geochronological data are available to estimate the duration of the accumulation of our stratigraphic succession in the Volyn area, as well as the corresponding duration of the pause in magmatic activity (e.g. between the Luchichiv suite and Zoryani beds). The gap between the formations of the basalt flow is confirmed by weathering crusts over rocks of the different strata [Kuzmenkova et al., 2011]. There are several age determination for Luchichiv and Ratne suites within the range of 580±9 Ma to 561±13 Ma with the overlapping of confidence intervals [Shumlyanskyy, Andréasson, 2004; Elming et al., 2007; Shumlyanskyy et al., 2016]. However, based on the papers regarding the formation of the Large Igneous Provinces (LIP), simplified assumptions about the accumulation duration of the Volyn traps can be made.

A distinguishing feature of the LIPs is a huge magma emplacement rate during short igneous pulse(s) lasting of about 1—5 Myr [e.g., Storey et al., 2007; Bryan, Ernst, 2008]. Such combination of large volumes of rocks during of short eruptions and high frequency of magmatic pulses leads to the rapid formation of large stretches of flood basalt. Analyses of duration of LIPs formation [e.g. Barry et al., 2010 and references therein] have revealed two main features relevant to the timing of eruptions and LIP formation: 1) most of the eruptions (70—90 %) are produced during one or two main pulses of eruptive activity; 2) that the pulse or pulses, or even the whole duration of activity in the LIP, could be short-lived geologically, lasting <5 Myr, and possibly even <1 Myr in some cases. The errors on the age estimates are too large that individual formations within the pulses of activity or individual eruptions could be resolved. In many cases, the errors encompass the age range of almost all eruptive units from top to bottom of the LIP body [e.g., Barry et al., 2010; Baksi, 2012], which is seen, for example, in the composite stratigraphic section of the LPB [Poprawa et al., 2020].

Thus, the thickest volume of Volyn traps might have occurred over a short interval likewise in other LIPs. At the same time, the most intense activity of the effusive process was revealed for time spans of ca. 557—555 Ma and ca. 567—560 Ma [Poprawa et al., 2020]. The duration of the pause of magmatic activity is estimated to be between 2 Myr and 19 Myr [Kuzmenkova et al., 2011]; most of the obtained geochronological ages fit to these ranges. The lateral extent of effusive activity was wider at those times and abovementioned episodes are recorded in the LPB, the western art of the Orsha-Volyn aulacogen, and the Podillya region of western Ukraine [Poprawa et al., 2020].

Several magnetozones were distinguished in magnetostratigraphy studies of several boreholes from Ratne region which penetrated the Volyn traps upper to the top of Babyne Suite [Glevasskaya et al., 2006]. In a composite stratigraphic section «... four reverse, two normal and one transitional magnetozones can be distinguished, which indicates the instability of the geomagnetic field in this period of time» [Glevasskaya et al., 2006, p. 128]. Taking into account the estimation of reversal rates of about 15 reversals per million years for the period of 560—545 Ma [Popov et al., 2002, 2005; Llanos et al., 2005; Levashova et al., 2021], the accumulation time of the Ratne suite should not be more than ~0.5 Myr. This is in agreement with the hypothesis that the formation of the VBP did not take longer than several million years. Unlike continuously deposited sedimentary sequences, the individual basalt flows «record» the geomagnetic field very fast, and the gaps in the «record» during the period of absence of magmatic activity should dominate. Thus, the evaluation of 0.5 Myr should be taken as minimal.

Sampling and laboratory methods. In previous article concerning the palaeomagnetism of the Vendian traps of Volyn [Bakhmutov et al., 2021] the methodology and results of palaeomagnetic studies of the Volyn traps oriented samples taken from quarries are describes in detail. The palaeomagnetic directions of natural remanent magnetization (NRM) were determined from oriented samples and the palaeomagnetic poles were calculated.

In this study, the samples from boreholes cores were collected with the «up-down» orientation and we can determine only the inclinations of the NRM components. The initial cores segments were sawn lengthwise into two equal semicylinders and laid down in boxes with 5-meter core segments in each box. Cores were documented according to the initial specification and our own data. To evaluate the variations of the magnetic susceptibility (MS), the MS values were measured along the cores using a hand KT-6 kappameter with a step of 0.2—0.3 m. The MS values of basalts and tuffs differ by one order and more [Bakhmutov et al., 2021], so the wells logging magnetic records along the CK3 and CK2 cores correlate well with each other and with the MS measurements by KT-6 kappameter along the core CK3 (see Fig. 2). The MS values inside the separate basalt flow vary several times, but tuffs are characterized by much lower values. Inside of some tuff levels the values differ by 2—3 times.

If there were doubts about the «up-down» orientation of the some cores segments they were omitted during sampling. Segments which appeared mechanically damaged, as well as from segments represented by lavabreccia, were not sampled. We were focussing mostly on basalts and baked contacts, the tuffs were sampled only in cores CK2 and CK3. Taking into account remagnetization problems in palaeomagnetic studies of lava flows [e.g., Valet et al., 1998; Vella et al., 2017], the sampling was performed mainly from the bottom parts of the basaltic flows, where the rocks could not have been reheated by the overlying flow.

Most of the samples from basalts, tuffs and baked contacts were taken from the reference core CK3 and from the backup core CK2. From the other cores the samples were taken only from basalt flows. The samples were cut into 20 mm cubic specimens using a diamond saw. Palaeomagnetic measurements were carried out in the laboratory of the Institute of Geophysics of the National Academy of Sciences of Ukraine in Kyiv. Specimens were stepwise thermally demagnetized (TD) using an MMTD80 oven up to 600—670 °C. After each heating step, the magnetic susceptibility at room temperature was measured with a MFK-1B Kappabridge to monitor possible mineralogical changes. Demagnetization steps were adjusted during thermal procedures from 10 to 50 °C. The NRM of specimens was measured using AGICO JR-6 spinner magnetometer. All measurements were conducted inside magnetically shielded rooms MMLFC, to minimize the acquisition of present-day viscous magnetization. Demagnetization results were processed by multicomponent analysis of the demagnetization path using Remasoft 3.0 software [Chadima, Hrouda, 2006]. Anisotropy of magnetic susceptibility (AMS) was measured with a MFK-1B Kappabridge, and magnetic anisotropy parameters were calculated with the Anisoft5 program.

Results and interpretations. ***Palaeomagnetic data.*** The initial values of NRM and MS of the samples taken from the reference core CK3 are presented on the left of Fig. 2. The discrepancy of NRM and MS for basalts and tuffs strongly differ by up to two orders of the magnitude. The maximum variations of magnetic parameters are in the upper part of the Ratne Suite represented by alternating of basalt flows, lavabreccias and tuffs. Although in single basalt flow the values can vary several times the main tendency for decrease of the MS from bottom to top of flow is dominated.

The average values of initial NRM, MS and Koenigsberger parameter (Q-ratio) are given in Table. A brief description of the magnetic parameters and results of principal component analysis for demagnetization samples for each suite are given below.

The Zabolottya suite is represented in the boreholes 4594 and 8265 by basalts 60 m thick. The range of NRM, MS and Q-ratio and the mean values (0.74 A/m, 0.05 SI, and 0.42, respectively) are given in Table. The more stable characteristic remanent magnetization components (ChRM) on the orthogonal projections of demagnetization paths (Zijderveld diagrams) appeared above 450 °C, and completely unblocked at 580 °C (Fig. 3, *a*—*c*). ChRM-components in the cores 4594 and 8265 have high positive inclination values (Fig. 3, *a*, *c*; Fig. 4), while in the core 4594 the short zone with high negative inclinations (Fig. 3, *b*) is allocated.

The overlying Babyne suite in the composite section of Volyn traps (Brest-Volyn structural-facial zone) reaches 200 m [Gozhik, 2013]. The suite is represented by dominant tuffs interbedded by one or two flows of tholeiitic basalts in the middle part. The maximum thickness of the Babyne suite was penetrated by boreholes CK3 and CK2 (about 150 m), and in core 4596 the thickness is 70 m. Tuffs are characterized by low values of NRM, MS, and Q-ratio, which in the lower part of the suite are 0.125 A/m, 0.009 SI, and 0.38, respectively (see Table). The NRM and MS values are 3—5 times higher for basalts. In these basalt samples high-temperature ChRM-component start to unblock at T>450—500 °C (see Fig. 3, *d*) and has positive and negative inclinations completely demagnetized up to 580—590 °C. Positive and negative inclinations of the ChRM-component are observed both in cores CK3, CK2 and in the bottom basalt flow of core 4596. Samples from tuffs and baked contacts (see Fig. 3, *e*) were completely demagnetized at temperatures of 660—670 °C indicating the presence of hematite. The components isolated at the unblocking temperature range of 450—580 °C and at higher unblocking temperatures (>600 °C) have the same inclinations. In the upper part of the Babyne suite tuffs and basalts from CK3 are characterized by negative inclinations of ChRM-components (see Fig. 4). In some samples several components on the demagnetization phase were distinguished (see Fig. 3, *f*): low-temperature component (up to

Mean values of magnetic parameters for basalts and tuffs within suites and beds

Suites, Beds (borehole)	Rocks	n	NRM, A/m	Magnetic susceptibility, SI	Q-ratio
Ratne Suites, Yakushiv Beds (CK3)	basalt	54	0.33—5.6 1.66	0.02—0.13 0.07	0.13—2.6 0.6
Ratne Suites, Yakushiv Beds (8262)	basalt	12	0.18—1.74 0.79	0.02—0.07 0.04	0.1—1.0 0.5
Ratne Suites, Zoryani Beds (CK3)	tuff	18	0.014—0.35 0.14	0.001—0.019 0.008	0.1—1.8 0.7
Luchichiv Suite (8262, 4596)	basalt	39	0.19—1.7 0.71	0.034—0.17 0.06	0.05—0.88 0.36
Babyne Suite (CK3, upper part)	basalt	10	0.2—2.05 0.9	0.018—0.09 0.05	0.01—1.9 0.7
Babyne Suite (CK3, 4596, middle, lower part)	basalt	15	0.24—1.4 0.78	0.002—0.04 0.03	0.37—1.14 0.65
Babyne Suite (CK3, lower part)	tuff	19	0.004—0.4 0.125	0.0003—0.02 0.009	0.15—0.86 0.38
Zabolottya Suite (4594, 8265)	basalt	33	0.2—2.1 0.74	0.014—0.08 0.05	0.1—1.7 0.42

n — number of samples used for mean calculation; range (underlined) and mean values of: NRM (natural remanent magnetization), magnetic susceptibility, Q-ratio (ratio of remanent magnetization to induced magnetization).

200 °C) probably of viscous origin, medium temperature component up to 450 °C, a component with unblocking temperatures in the range of 480—580 °C, and a high temperature component with Curie temperature >580 °C, which goes to the origin.

The thickness of the Luchichiv suite, composed of several (up to five) flows of tholeiitic basalts and volcanoclasts, in the composite stratigraphic succession can exceed 100 m. The Luchichiv suite thicknesses in the boreholes 4596 and 8262 are 63 and 55 m, respectively. From core 4596 the segment overlapping the Babyne suite, and from 8262 the segment below the boundary between the Luchichiv and Ratne suites were sampled. The stratigraphic correlation between these segments remains unknown. The samples were collected from basalt flows and baked tuffs on the contacts with basalts. The mean magnetic parameters of basalts samples (NRM, MS, and Q-ratio) are similar to those for basalts from the lower suites (see Table), while the NRM and MS values of baked tuffs are several times lower. The maximum of unblocking temperatures for basalt samples did not exceed 580—600 °C (see Fig. 3, *g*), and in tuffs the «tails» were unblocked at 640—650 °C or more (see Fig. 3, *h*). This behavior was also characteristic of basalts and baked tuff samples taken in quarries [Bakhmutov et al., 2021], where unblocking temperatures >600 °C were associated with the presence of hematite or titanohematite grains.

The overlying Ratne suite includes Zoryani volcanomictic beds and the Yakushiv beds. Basalts and volcanoclastics in CK3 and CK2 have a maximum thickness of about 130 m. Alternation of basalts, tuffs, and lava breccias leads to significant variations of the magnetic parameters in neighboring layers (see Fig. 2). The high-temperature ChRM component in basalt is characterized by unblocking temperature range of 500—600 °C and up to 660—670 °C in baked tuffs (see Fig. 3, *i*, *j*), which are similar to results from other suites. The direction of the ChRM-component in most samples is characterized by a positive inclination, but some levels show anomalous (<45°) and negative inclinations.

The identified polarity intervals with positive, negative, and anomalous (in the range of ±45°) inclinations of the ChRM components of the samples along all cores are shown in Fig. 4. If the data showed puzzling results, where dual polarity directions were found in neighboring samples in the same flow, these were rejected due to possible «up-down» orientation errors.

Palaeomagnetic results are traditionally accompanied by an investigation of carriers of remanent magnetization of rocks. The magnetic and mineralogical studies of the Volyn traps were presented previously in [Glevasskaya et al., 2000, 2006; Nawrocki et al., 2004; Elming et al., 2007]. Rock magnetic studies and electron microscopy data of low-Ti basalts of the Ratne suite revealed that main carriers of the ChRM component are heterophasically oxidized titanomagnetites with Curie temperature >550 °C represented by pseudo- and single-domain grains.

In recent publications on palaeointensity of Volyn basalts [Shcherbakova et al., 2020; Thallner et al., 2022] the thermomagnetic and electron microscopic studies of basalts from Ratne and Luchichiv suites confirmed the previous results and showed the Curie temperature of 550—590 °C indicating the presence of titanomagnetite with a low content of Ti. The temperature-dependent susceptibility curves of some samples of basalts and backed contact tuffs from the Ratne, Babyne and Zabolottya suites demonstrated another Curie temperature of ~650 °C probably due to a high degree of oxidation of the magnetite phase resulting in increases of Curie temperature. Magnetic grains carrying the ChRM are demonstrated the single domain (SD) or small pseudo-single-domain (PSD) behaviors which is encouraging in terms of their potential for obtaining both reliable palaeomagnetic directions and palaeointensity data.

At the same time, the reliability of palaeointensity experiments and palaeomagnetic data from the Ratne suite basalts with a high content of Ti and, respectively, low blocking temperatures (200—400 °C) are doubtful [Bakhmutov et al., 2021; Thallner et al., 2022]. The basalts with low blocking temperatures

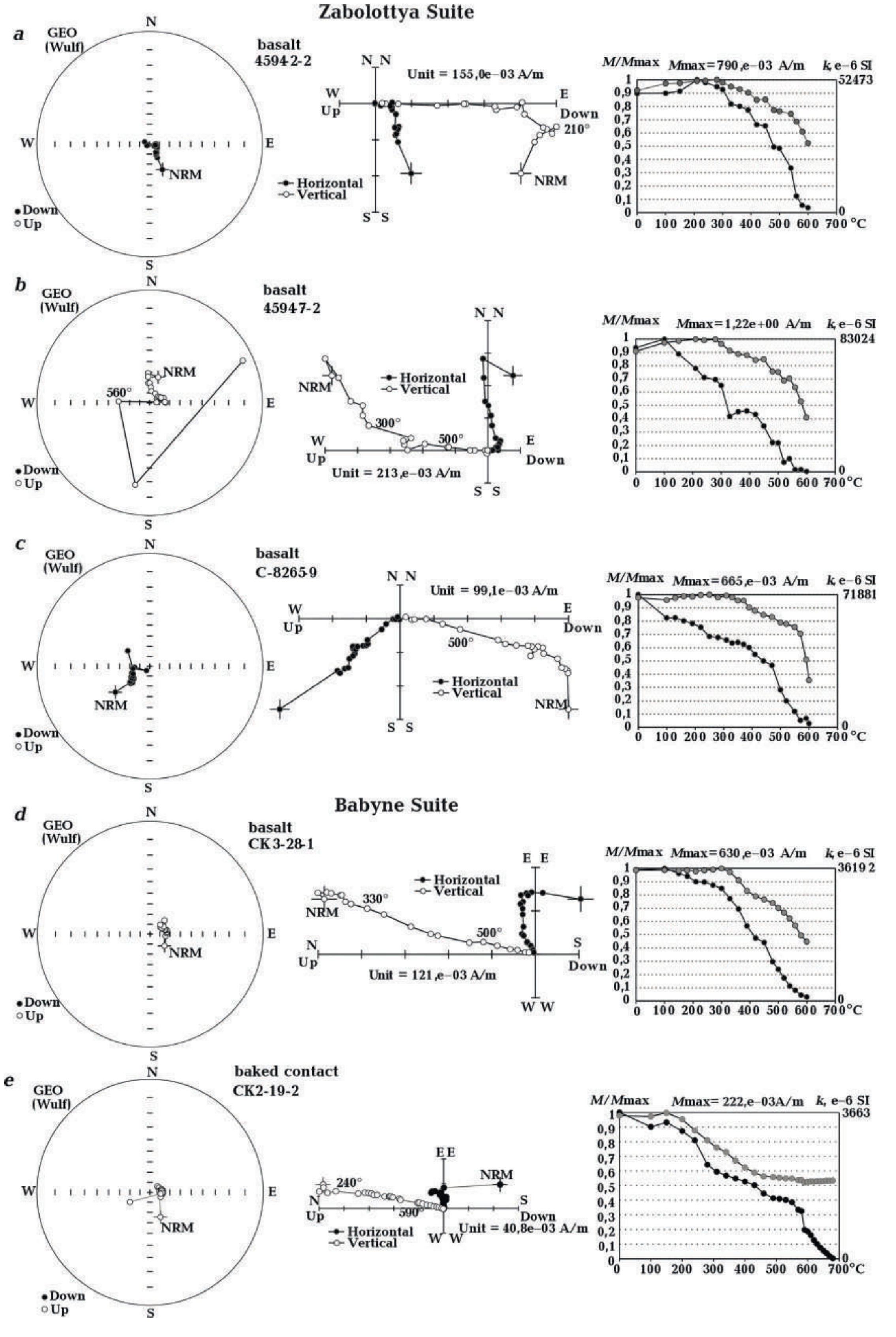
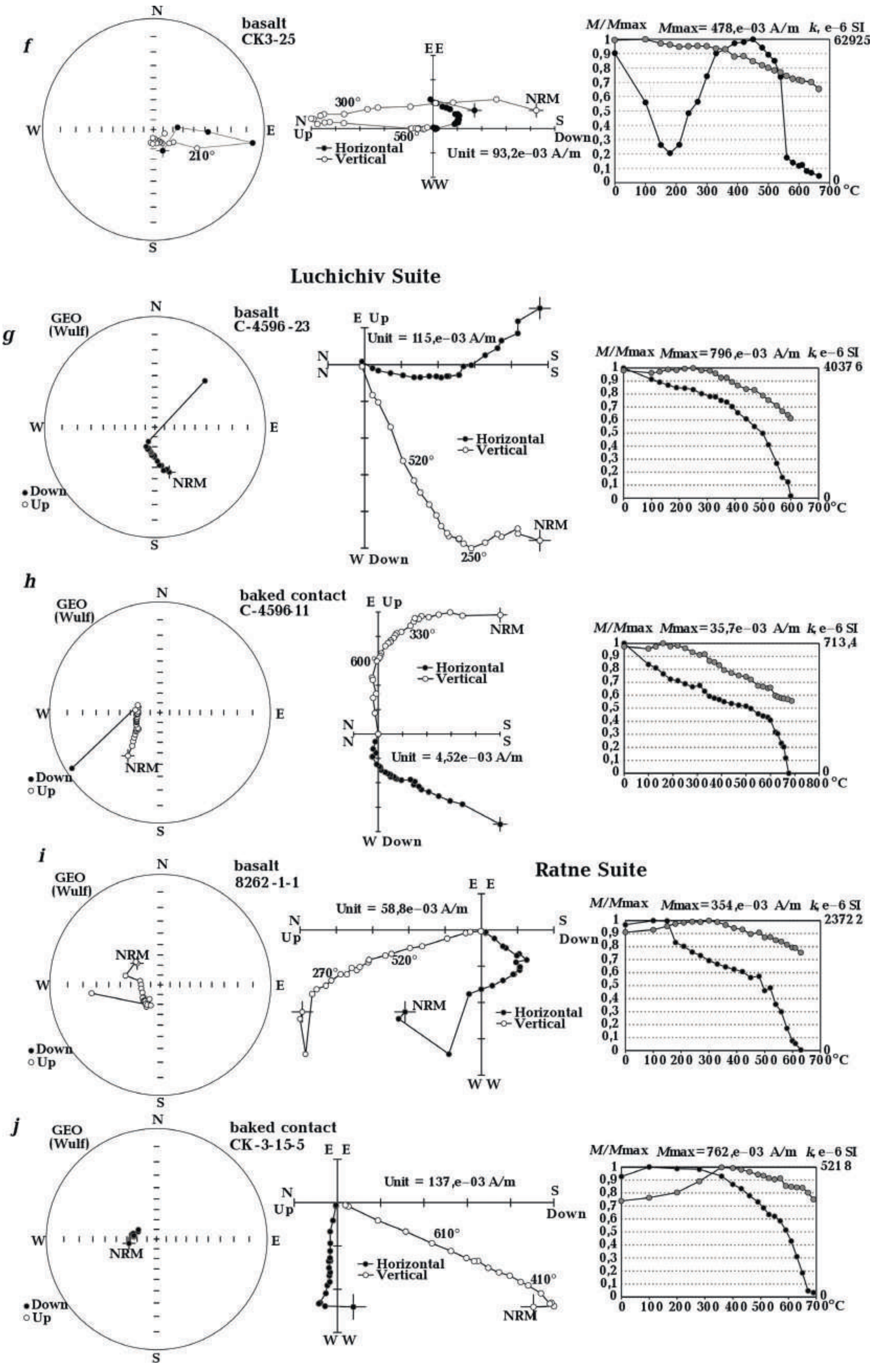


Fig. 3. Results of progressive thermal demagnetization of basalt and tuff specimens: left — stereographic projections of the NRM directions (black and white circles of the projection on the lower and upper hemispheres,



respectively); middle orthogonal projections of demagnetization paths (Zijderveld diagrams) on horizontal and vertical planes; right — NRM intensity (M/M_{max}) and magnetic susceptibility (k) decay during demagnetization.

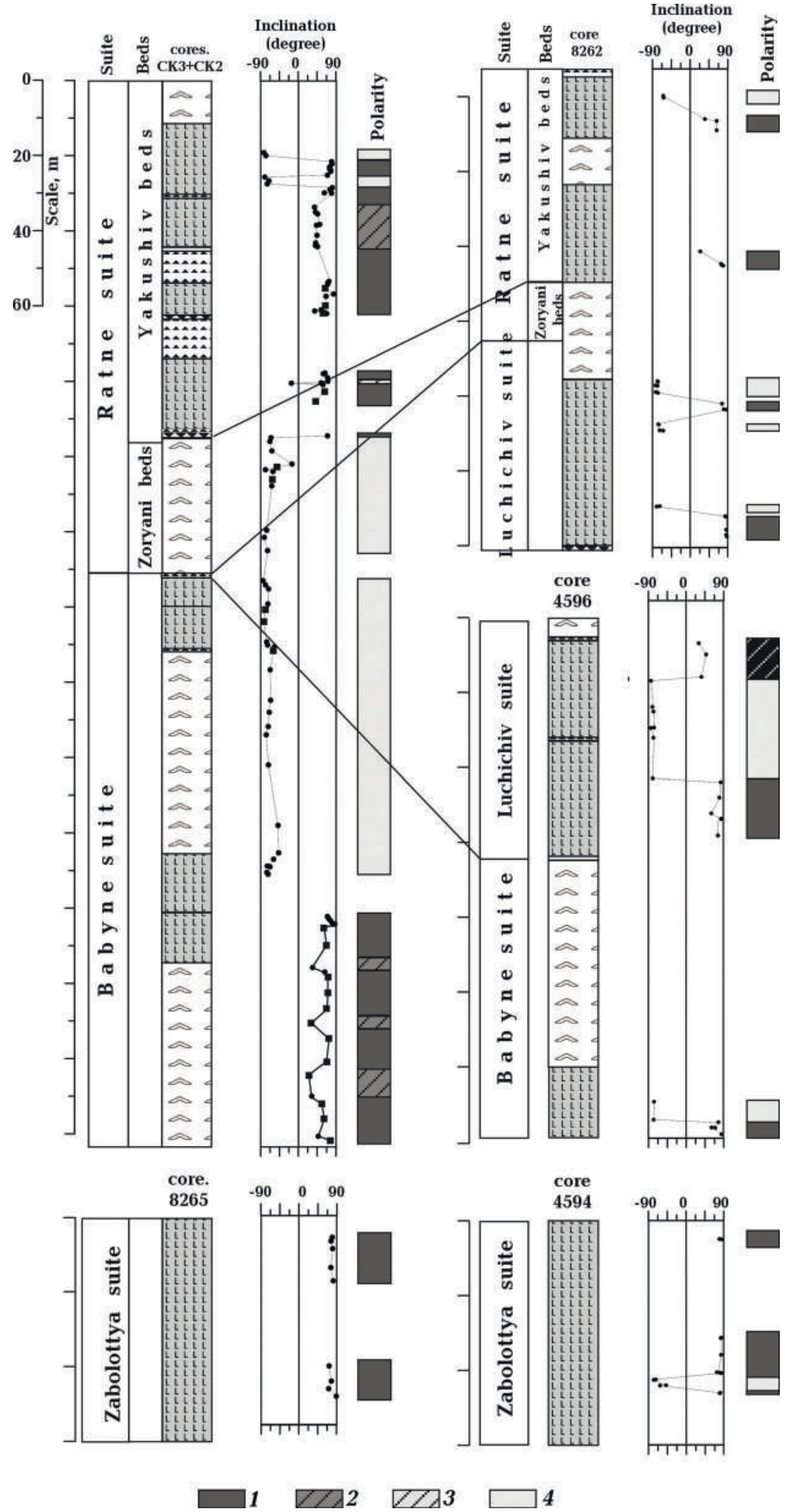


Fig. 4. Stratigraphy and magnetic inclination of ChRM component isolated from cores samples for the composed section the Volyn series: *1* — steep positive inclination; *2* — shallow positive (0°<*I*<45°) inclination; *3* — shallow negative (0°>*I*> −45°) inclination; *4* — steep negative inclination. The inclination values of ChRM component of samples from cores CK3 and CK2 are presented by filled circles and squares, respectively. The lithological legend is the same as in Fig. 2.

were not identified in the cores of our region.

Some papers mention the post-effusive stage of hydrothermal alteration of Volyn traps [Shumlyanskyy, Andreasson, 2004; Elming et al., 2007; Shumlyanskyy et al., 2016; Środoń et al., 2019 and references therein]. Two superimposed alteration processes were identified: the Ediacaran hydrothermal alteration, induced by meteoric waters, heated and put in motion by the cooling basalt, and the Caledonian and/or Variscan potassic alteration, which mostly affected porous tuffs and basalts with higher secondary porosity [Środoń et al., 2019]. The first one was developed immediately after the eruption due to the penetration of volcanic fluids into hot host rocks; the upper temperature limit of post-magmatic changes did not exceed 220 °C. The late diagenetic alteration affected porous tuffs to a greater extent than flood basalts, and within the flood basalts, it preferentially affected samples more intensely altered by the first alteration episode, i.e. with higher secondary porosity. The temperature of this late alteration was not higher than 85 °C could not significantly affect the primary magnetization of basalts.

Anisotropy of magnetic susceptibility. The anisotropy of magnetic susceptibility (AMS) data of basalts and tuffs samples taken from quarries are presented by [Bakhmutov et al., 2021]. In the «low-Ti» basalts the degree of anisotropy (the ratio of the maximum axis of the AMS ellipsoids to the minimum) is low (3—4 %) and in the tuffs (<1 %) it is quite insignificant [Bakhmutov et al., 2021]. AMS ellipsoids are characterized by predominantly oblate shapes and the directions of the K_{min} axes are well grouped normal to the bedding of rocks.

The similar results were obtained from the basalt samples of cores. AMS data of core CK3 are presented on the Fig. 5, *a*, and from cores 8265, 4594, 4596, 8262 on the Fig. 5, *b*. The degree of anisotropy ($1.01 \le P \le 1.06$) is low and its mean value is P=1.02. The oblate shape for AMS ellipsoids are predominates, and the mean direction of the minimum axis (K_{min}) is close to vertical (I=83.5°).

The ellipses on the Fig. 5, *b* mark a group of samples with the highest degree of anisotropy ($1.035 < P < 1.065$) and a pronounced oblate shapes of AMS ellipsoids which belong to the upper basalt flows of core 4596 (bottom of Luchichiv suite) and the lower basalt flow of core 8262 (top of Luchichiv suite). The stratigraphic correlation of these cores was not defined, but the similarity of AMS parameters is an argument in favor of their correct matching in Fig. 4.

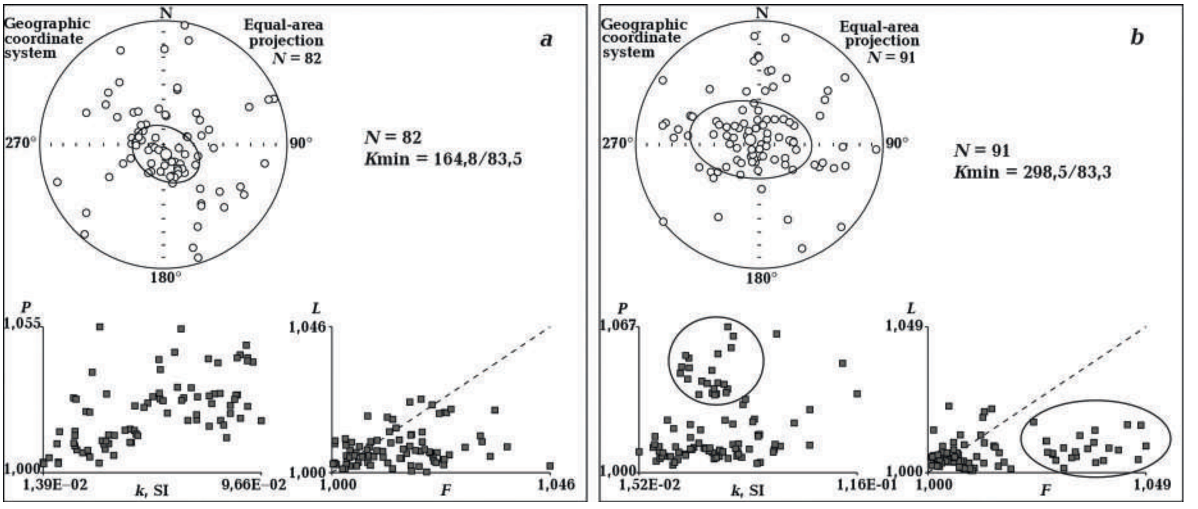


Fig. 5. Plots of anisotropy of magnetic susceptibility directional data on a stereographic projections, k versus P, F versus L for: basalts of the core CK3 (*a*) and other cores 4594, 4596, 8262, 8265 (*b*). The directions of the minimum principal axis K_{min} are presented in stereographic projections by circles. Degree of AMS ($P=K_{max}/K_{min}$) and other parameters (k — magnetic susceptibility; L — lineation, F — foliation) according to Tarling and Hrouda [1993], N — number of specimens.

Discussion. Effusive rocks of the Volyn series were formed from separate batches of mantle melts that possibly originated from different sources with specific geochemical and isotopic features [Shumlyanskyy, 2012]. All of the cycles of effusive activity are separated by tuff horizons or by temporal cessation in the volcanic activity. Clear stratification of basalt and tuff layers by the magnetic parameters are well observed. In tuff horizons the values of NRM and magnetic susceptibility are several times lower than those of basalts (see Fig. 2, Table). The basalts of the Ratne suite are characterized by higher values than the other rocks.

The inclinations of the ChRM component of samples from the cores are presented in Fig. 4. Correlation of cores allows trace the changes of inclination throughout the Volyn series. We have the following reason to claim that the isolated high-temperature ChRM component is primary: 1) dual polarity magnetization and similarity of data on basalts and tuffs samples with thermoremanent and depositional magnetization respectively; 2) identified magnetic minerals in basalts are titanomagnetites which co-existence of SD and MD grains, where the SD behavior linked to the oxy-exsolution structures formed at high temperatures during the cooling of the lava flows; 3) positive contact test for basalts and tuffs of the Rafalovka quarry [Shcherbakova et al., 2020; Bakhmutov et al., 2021] is confirmed by results from basalts and baked tuffs samples from cores; 4) consistency of our data with the other palaeomagnetic study of the Volyn series [Nawrocki et al., 2004; Glevasskaya et al., 2006; Elming et al., 2007].

The stratigraphic units are duplicated by different cores. Taking into account the minimum of 60 m thickness for the Luchichiv suite in core 4596 (reduced in cores CK3 and CK2) the entire section of the Volyn series is at least 400 m thick. We assigned «normal» polarity to samples with positive inclination, «reverse» polarity with negative inclination, and anomalous «low normal» or «low reverse» polarity to samples with inclination values of $-45°<0°<45°$.

In the composite section of the Volyn series (see Fig. 4) the basalts of Zabolottya suite are represented by two cores with predominantly high positive inclinations. The level with high negative inclination in core 4594 cannot be unequivocally interpreted as a polarity reverse. Here four samples in sequence with a negative inclination are located in two-meters segment, which is probably due to the incorrect orientation of the «up-down» core segment.

The Babyne suite, represented in three cores (CK2, CK3, 4596) by 150 m tuffs, have anomalous and positive inclinations in the lower part. As was shown in [Bakhmutov et al., 2021], tuffs are characterized by lower inclinations compared with basalts due to the «inclination error». The same diminished inclination in tuffs is typical throughout the entire section. In the basalt flows of the Babyne suite (at least two flows separated by a tuff layer as seen on CK3 log, Fig. 2, Fig. 4) a change of polarity occurred. In overlying tuffs and 20-m basalt flow negative inclinations have been revealed.

During the formation of Luchichiv suite basalts (cores 4596, 8262) at least two polarity reversals occurred (core 4596). Taking into account the data of core 8262 and the positive inclination of the lower part of the Ratne suite (tuffs of the Zoryani beds in CK3) there are minimum three polarity reverses in the Luchichiv suite. Basalts at the bottom of the Yakushiv beds and a sample of baked tuff at the contact with the Zoryani beds (core CK3) show a positive inclinations with the exception of one specimen of anomalous negative inclination in CK3. In the overly interbedding basalts and tuffs of Yakushiv beds the samples mostly show high positive and anomalous positive inclinations. There are a few specimens with reverse polarity in the uppermost basalt flow. Here we do not exclude the errors in «up-down» orientation of the core segments because the polarity change «records» within unit fast cooling basalt flow (see below) seems unlikely.

Thus, in the composite section of the Volyn series (see Fig. 4), we define at least six reverses of magnetic field polarity (by inclination data). However, we did not take into account the zones of polarity changes with insignificant 2 m thickness in core 4594, and two zones in the uppermost basalt flow of the Ratne suite (doubts of correct «up-down» orientation of the core segments). The Yakushiv beds are most heterogeneous and characterized by multiple interbedding of basalt flows and tuffs. Therefore, more episodes of polarity changes within Yakushiv beds cannot be excluded.

Our results are in a good agreement with other palaeomagnetic data from the Ratne area, where three episodes of polarity changes were identified in the boreholes penetrated the Volyn traps above the Babyne suite [Glevasskaya et al., 2006]. Unfortunately, the episode of the polarity changes (from normal to reversed) in cores 4596 and 8262 cannot be correlated with polarity change in Luchichiv suite traps from quarries [Bakhmutov et al., 2021].

The experiments on the palaeointensity determinations were carried out on the same collection of the cores samples and indicated the very low values of virtual dipole moments in the range of $(0.31—1.67)\cdot10^{22}$ Am^2 [Thallner et al., 2022]. These results are in good agreement both with the Luchichiv suite data reported in [Shcherbakova et al., 2020] and with the low time averaged field strengths value ($0.7\cdot10^{22}$ Am^2) of units with a similar age from Laurentia [Bono et al., 2019], supporting a global distribution of a weak field as reported in [Shcherbakova et al., 2020]. Such values are almost an order of magnitude weaker than the present geomagnetic field. Small-scale variations of palaeointensities throughout the entire section not only show extremely weak field strengths around polarity changes but could also suggest that the field strength never fully recovered between reversals [Thallner et al., 2022].

The duration of Volyn traps formation is a key issue for interpretation of magnetic polarity change frequency. As was noted in chapter «Geology and age of rocks» two stages of most intense volcanism took place at ca. 557—555 Ma and 567—560 Ma. Since the magmatic activity in different parts of the VBP was asynchronous, the correlation of various volcanogenic events is ambiguous. If the traps of the Volyn series formed during both of these stages, the activity in the VBP could be continued over a time span of approximately 10 Myr. Taking into account at least six episodes of polarity reversals during this time interval, the average frequency of geomagnetic reversals are comparable with those for Phanerozoic. Three superchrons are known for Phanerozoic and each lasted for at least several tens of millions of years: the Ordovician [Gallet, Pavlov, 1996; Pavlov, Gallet, 1998], Late Palaeozoic, and the youngest Cretaceous [e.g. Opdyke, Channell, 1996]. In other Phanerozoic times the random reversals of the geomagnetic field polarities were occurred. Thus, the numbers of reversals in Phanerozoic range from zero in superchrons to rather high frequency (7—8 per million years) in the Miocene, Middle Jurassic, Middle Cambrian, and up to 12 per Myr in the Jurassic [e.g. Opdyke, Channell, 1996; Pavlov, Gallet, 2005].

We favor the estimations of more rapid formation of the LIPs. As mentioned above, a relatively small area of VBP was formed not longer than a few million years. Considering the reversal rates (about 15 per 1 Myr) for the period 560—545 Ma [Iglesia-Llanos et al., 2005; Popov et al., 2002, 2005; Levashova et al., 2015; Meert et al., 2016] and even more [Levashova et al., 2015; Bazhenov et al., 2016], the accumulation of Volyn traps which «recorded» at least six reversals, could occur for no more than 0.5 Myr. Then the hypothesis of the «hyperactivity» of the magnetic field at the end of the Ediacaran, taking into account the strength of the geomagnetic field in order of magnitude lower than the present one, is confirmed.

Geomagnetic field polarity changes have been fairly well studied for the last 250—300 Myr. There are fewer data about the frequency of reversals in the Early Paleozoic, and for Precambrian our knowledge is remains very limited and fragmentary. Meanwhile, more than 7/8 of the Earth's geological history refers to Precambrian. Suppose the geomagnetic field experienced some significant long-term changes. They should be sought by comparing the most distant intervals of the Earth's history, such as the Cenozoic and Precambrian.

There are at least two points of view on the evolution of the geomagnetic reversal frequency over geological history. One is the hypothesis about the stabilizing influence of the inner core. Due to the high electrical conductivity of the inner core, it is part of the geodynamo and may have an effect on the dynamo processes [e.g. Hollerbach, Jones, 1993, 1995; Glatzmaier, Roberts, 1995]. During the periods of growth of the inner core, the frequency of polarity reversal should be decreased, and the frequency of reversals in the Precambrian could be higher than in the Phanerozoic. For the other hypothesis based on the numerical models [e.g., Roberts, Glatzmaier, 2001; Coe, Glatzmayer, 2006; Driscoll, Olson, 2009], if the inner core was small or did not exist, the geomagnetic field could be much more stable which raising the possibility that reversals may have been much less common in the distant geologic past than more recently. To test the proposed models and hypotheses, continuous magnetostratigraphic records that record the polarity of the Precambrian geomagnetic field are required.

The modern knowledge of low geomagnetic field intensity in Ediacaran concerns the problem of the formation time of the inner core. The nucleation of the inner core was a major transition for the geodynamo. This is a critical moment in Earth's history because the subsequent growth of the core is likely to have provided the main sources of energy for the geodynamo process. The formation time of the inner core stretches from early Archean to about 500 Ma in different models [e.g., Driscoll, 2016, and references herein]. Due to the changes in the outer core's energy associated with the inner core's formation, this process should be accompanied by a change in geomagnetic field generation. In some modeling studies, a sharp increase in intensity following inner core nucleation was predicted [Driscoll, 2016], while others emphasize changes mainly to the geometry of the field and the catastrophic scenario is less probable than the uniformitarian scenario [Landeau et al., 2017].

The potential key to resolving the problem of eventual constraints on the timing of inner core nucleation could be obtaining the new palaeomagnetic and palaeointensity data. This also applies to testing the Geocentric Axial Dipole hypothesis on which continental drift reconstructions rely. We shall consider these problems for the Ediacaran in the third part of the article.

Conclusions. New palaeomagnetic data for the most complete profile section of the Volyn traps revealed by several boreholes have been presented. Clear stratification of basalt and tuff layers by the magnetic parameters and wells logging magnetic records data along the CK3 and CK2 cores allowed to construct the composite section of theVolyn series succession of about 400 m thick. It is represented by the alternation of basalt flows with lava breccias and tuffs with variable susceptibility and remanent magnetization values.

For palaeomagnetic analyses, the samples from basalts, tuffs, and baked contacts were collected by «up-down» orientation, so only inclinations of the NRM components could be determined. Parameters of the isolated high-temperature ChRM component allow us to believe that this component is primary because: a) dual polarity magnetization and similarity of data on basalts and tuffs; b) the high-temperature ChRM component in the basalt samples was found at unblocking temperatures above 500—580 °C; no samples with unblocking temperatures of ChRM in the range of 250—400 °C; c) identified magnetic minerals in basalts are titanomagnetites which co-existence of SD and MD grains, where the SD pattern linked to the oxy-exsolution structures formed at high temperatures during the cooling of the lava flows, is the good candidate to carriers of ChRM; d) consistency of our data with the other results of palaeomagnetic studies of the traps of Volyn series above the Babyne suite.

Inclination changes throughout the composite section of the Volyn series showed at least six reversals. The key issue for interpreting magnetic polarity change frequency is the duration of the Volyn traps formation. The geochronological ages of these rocks, considering the data from neighboring regions, are in the range of 580—545 Ma. The errors in the age estimation are too large to resolve individual formations within the pulses of activity or individual eruptions. The analyses of geochronology data in different parts of the VBP have revealed two possible interpretations of the palaeomagnetic results.

If the main volume of Volyn traps formed in (at least two) stages of magmatic activity, the whole time interval could be approximately 10 Myr. Considering the number of polarity changes during this interval, the average frequency of geomagnetic reversals is comparable with those in the Phanerozoic. In this case, we can detect only a minimal number of the reversals because the lava flows form with interruption and cooling so fast, recording the magnetic field for a short time interval.

Another interpretation, based on the arguments that the formation of volcanic rocks might have occurred over a short time interval, as is common in other LIPs, considering the reversal rates (about 15 per 1 Myr) for the period 560—545 Ma, the accumulation of the main volume of Volyn traps took place much faster (e.g., 0.5 Myr). There are at least six reversals in the Volyn series. The palaeointensity determinations have shown that the geomagnetic field was about one order of magnitude weaker than the present-day field. This confirms the hypothesis of the «hyperactivity» of the magnetic field at the end of the Ediacaran.

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Палеомагнетизм вендських трапів Волині, південно-західна окраїна Східноєвропейської платформи. Ч. 2: магнітостратиграфія

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У статті наведено нові результати палеомагнітних досліджень вендських (едіакарійських) трапів Волинської базальтової провінції, розкритих шістьма свердловинами на північному заході України. Ця робота є продовженням попередніх досліджень верхньої частини волинської серії [Бахмутов и др., 2021]. В недавніх публікаціях [Shcherbakova et al., 2020; Thallner et ol., 2022] визначення палеонапруженості геомагнітного поля за зразками базальтів волинської серії показали наднизький дипольний моменту магнітного поля Землі, що відповідає іншим палеомагнітним даним для едіакарію і свідчить про вкрай слабке геомагнітне поле в цей період. Чітка стратифікація та кореляція шарів базальтів і туфів за магнітними параметрами дають змогу визначити інверсії магнітного поля вздовж геологічного розрізу волинської серії потужністю близько 400 м. У базальтах, туфах й обпечених контактах виділено високотемпературну характеристичну (ChRM) компоненту залишкової намагніченості, яка за всіма ознаками є первинною. За напрямками нахилення ChRM-компоненти виділено не менше шести інверсій магнітної полярності. Геохронологічний вік порід відповідає діапазону 580—545 млн років, але похибки у оцінці віку окремих базальтових потоків у межах імпульсів активності або окремих вивержень занадто великі для оцінювання часу формування всієї товщі. Тому ключовим питанням для визначення частоти інверсій магнітної полярності є тривалість утворення трапів. Розглянуто дві можливі інтерпретації палеомагнітних результатів. Згідно з першою, що враховує різні етапи магматичної активності, часовий інтервал утворення може становити близько 10 млн років, і тоді частота геомагнітних інверсій близька до середньої для фанерозою. Ми схильні до іншої інтерпретації, коли формування великих магматичних провінцій відбувалося протягом короткого проміжку часу (наприклад 0,5 млн років). З огляду на результати визначення палеонапруженості на тих самих зразках, які вказують на надзвичайно низьке геомагнітне поле, гіпотеза про «гіперактивність» поля наприкінці венду з частотою не менше 12 інверсій за 1 млн років отримує додаткове підтвердження.

Ключові слова: палеомагнетизм, магнітне поле едіакарію, волинські трапи.