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# Paleomagnetic and Tectonophysical Evidence of Geodynamics of Sarmatia in the Devonian (Based on the Example of the Ukrainian Shield)

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**Abstract**—As a result of paleomagnetic investigations the positions of Devonian magmatic complexes of the Ukrainian shield (Sarmatia) in the tropical latitudes of the Southern Hemisphere in the Late Devonian were reconstructed. The moderate-temperature magnetization components in complexes of different ages of the Ukrainian Shield and recorded manifestations of the Devonian tectonomagmatic events were determined.

*Keywords*: Paleomagnetism, Ukrainian Shield, Sarmatia, Devonian tectonomagmatic activization, tectonophysical investigation methods, stress deformations

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## INTRODUCTION

The East European Craton (Baltica) formed in the Paleoproterozoic as a result of the subsequent collision of three segments: Fennoscandia, Volga–Uralia, and Sarmatia. The final amalgamation of these segments occurred in the interval of 1.82–1.75 Ga (Gorbatschev and Bogdanova, 1993; Bogdanova et al., 2008) during the formation of Paleoproterozoic Columbia (Nuna) supercontinent (Hoffman, 1997; Rogers and Santosh, 2002). This event was preceded by the formation of the Volga–Sarmatia megacontinent as a result of the collision of the Volga–Ural and Sarmatian segments at about 2.1–2.0 Ga (Shchipansky and Bogdanova, 1996; Shchipansky et al., 2007).

However, the available paleomagnetic data for Fennoscandia (Damm et al., 1997, Fedotova et al., 1999) and Volgo-Sarmatia (“Ukraine,” (Elming, Mikhailova, and Kravchenko, 2001)) suggest that these two segments were at a considerable distance from one another in the age interval ranging from 1.77 to 1.76 Ga (Elming, Mikhailova, and Kravchenko, 2001, 2010). This does not allow us to unambiguously reconstruct the process of the amalgamation of segments of the East European Craton.

The Ukrainian Shield and the Voronezh crystalline massif comprise Sarmatia, the southernmost segment of the East European Craton. They had similar Precambrian histories of development and structure (Shchipansky and Bogdanova, 2006). According to traditional points of view, the Ukrainian shield is composed of six Archean and Paleoproterozoic megablocks/terrains and three suture zones between these megablocks (Shcherbak and Ponomarenko, 2000). The Archean megablocks are surrounded and partially overlain by Paleoproterozoic rocks, which formed in different tectonic settings, such as juvenile crustal accretionary belts (2.2–2.1 Ga) in the northwestern part and continental (passive) margins and intracontinental basins (2.5–2.1 Ga) in the central part of the Shield (Shchipansky et al., 2007).

The most intensive tectonomagmatic activization of Sarmatia, including the Ukrainian Shield, occurred in the Middle Paleozoic (Late Devonian), when the Ukrainian Shield was separated by the Pripyat–Dnieper–Donets aulacogen from the Voronezh and Belarusian massifs, which are situated in the northeast.

Recently, there are at least two competing models that consider the time and location of the formation of the Dnieper–Donets aulacogen. According to the first model, the initiation of the Dnieper–Donets aulacogen occurred at the location of an ancient Riphean aulacogen (Nikishin, 2002). According to the second model, it is an erroneous assumption that Late Proterozoic and Middle-Late Paleozoic processes were connected (Stovba, 2008), since in the Dnieper–Donets aulacogen Carboniferous and Devonian deposits lie at depths where, according to existing ideas, the Late Proterozoic (Riphean) graben must have existed. Moreover, ancient sedimentary rocks were not established here.

According to the most common model, a separated mantle plume or a cluster of mantle plumes at the rear of an active subduction system played the main role in the formation of the Dnieper–Donets aulacogen.

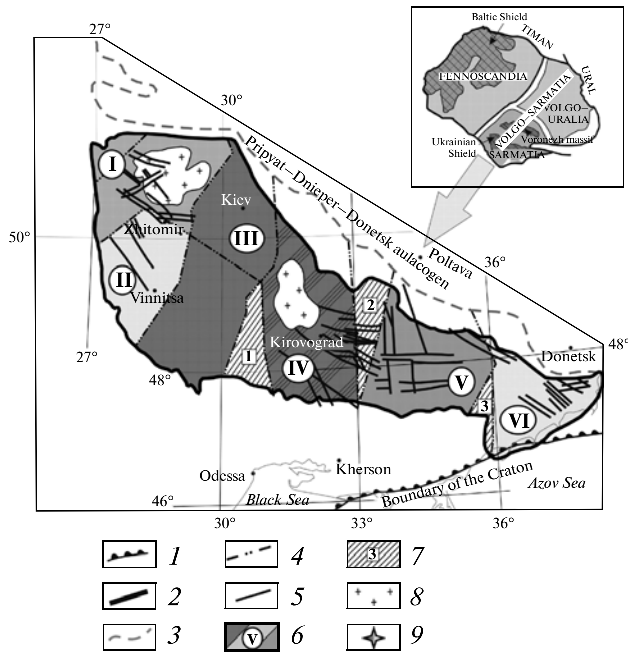


**Fig. 1.** A geological-structural scheme of the zonation of the Ukrainian Shield (after (Drunnik et al., 2003), as amended and supplemented). Megablocks, shown by figures in circles: I, Northwest; II, Podolskii; III, Bug–Rosinskii; IV, Ingul; V, Middle Pridneprovian; VI, Priazovian. Inter-block suture zones are shown by figures in squares: 1, Golovanevskaya; 2, Ingul–Krivoy Rog; 3, Orekh–Pavlograd; *1*, boundaries of the East European Craton; *2*, boundary of the Ukrainian Shield; *3*, boundary; *4*, intra-block fault zones; *5*, intra-megablock faults; *6*, megablocks; *7*, suture zones; *8*, plutons and large intrusive granite massifs; *9*, sampling sites of paleomagnetic samples.

In the upper part: three-segment structural model of the East European Craton (Gorbatschev and Bogdanov, 1993).

Thermal irregularities, which affected the basement rocks in distant areas and caused active rifting in different parts of Sarmatia and the East European Platform as a whole are evidence for the existence of a cluster of mantle plumes. At the same time, rift processes in different parts of the East European Craton did not occur simultaneously (Nikishin, 2002).

Both models of development of the Dnieper–Donets aulacogen assume that secondary heating of the ancient systems occurred, which in turn caused the appearance of secondary magnetization components of different natures in megablocks of the Ukrainian Shield. The classification of secondary magnetization components of different natures, as well as comparison of the directions of magnetization of the different terrains of the Ukrainian Shield, are necessary to reconstruct their relative rotation, as well as determination of the kinematics of the Sarmatian segment of the East European Craton in general.

Previous paleomagnetic investigations of Paleoproterozoic–Paleozoic complexes of the Ukrainian Shield (Elming, Mikhailova, and Kravchenko, 2001; Elming et al., 2010) revealed that the secondary magnetization component was recorded in rocks. This magnetization component was considered to consist of characteristic fully overmagnetized and moderate-temperature components. Secondary deformations in the Ukrainian Shield lithosphere were also distinguished during tectonophysical investigations.

It was established that in the Late Devonian the crystalline basement was broken up by faults, along which vertical movements (the formation of grabens and semi-grabens in the Dnieper–Donets aulacogene) and horizontal rotation of individual blocks relative to each other at stages of post-rift subsidence and folding occurred (Gintov, 2005).

## THE GEOLOGICAL POSITION OF THE STUDIED ROCKS

The Ukrainian Shield is composed of six Archean and Paleoproterozoic blocks/terrains (Fig. 1): Northwest, Dniester–Bug, Rosa–Tikich, Ingul, Middle Pridneprovian, and Priazovian (Shcherbak and Ponomarenko, 2000). The Ukrainian Shield is characterized by the alternation of blocks of the epi-Archean consolidation with narrow, meridionally elongated coeval mobile belts and suture zones.

At the end of the Paleoproterozoic the northwestern part of the Sarmatia was an active margin, which is confirmed by the presence of the Andean-type Osnitsa-Mikashevichi volcanic–plutonic belt. The age of formation of this zone is considered to be in the range of 2.00–1.96 Ga (Claesson et al., 2001; Shcherbak et al., 2008). In the rear of this structure the

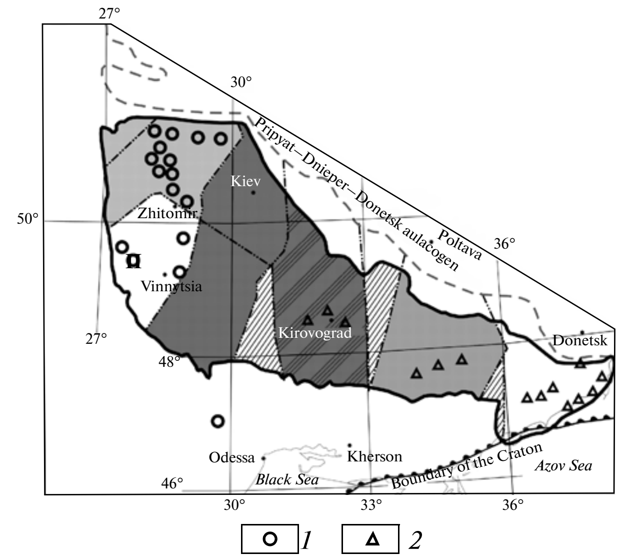


**Fig. 2.** The main areas of remagnetization of rocks in the Ukrainian Shield (the Sarmatian segment of the East European Craton) on the geological-structural scheme of zonation of the Ukrainian Shield (after (Drannik, Kostenko, and Esipchuk, 2003)).

Berdichev belt, made of highly metamorphosed granitoides (2.1–2.0 Ga) extends (Shcherbak et al., 2008).

Subsequent tectonic evolution was characterized by intensive tectonomagmatic reworking of the crust in the interval of 1.80–1.74 Ga, when the large Korosten and Korsun–Novomirgorodskii anorthosite–mangerite–charnockite–granite (AMCG) plutons intruded "as a result of postcollisional geodynamics (Bogdanova et al., 2006). Mafites (dikes and sills, associated with large AMCG plutons) formed in the last period of the Proterozoic evolution of the Sarmatia.

## ANALYSIS PROCEDURE FOR THE DEVONIAN TECTONOMAGMATIC ACTIVIZATION ON THE BASIS OF PALEOMAGNETIC AND TECTONOPHYSICAL DATA

To determine the effects of tectonomagmatic activization on the integrity of the Ukrainian Shield, as well as the preservation of the primary magnetization component, the results of paleomagnetic and tectonophysical investigations were used.

The paleomagnetic data for different terrains of the Ukrainian Shield from the Global Paleomagnetic Database (Pisarevsky, 2005) and recent publications (Bakhmutov, Elen'ska, and Konstantinenko, 2001; Iosifidi, Bakhmutov, and Arestova, 2009; Lubnina et al., 2007; Lubnina, Bogdanova, and Shumlyanskii, 2009; Elming, Mikhailova, and Kravchenko, 2001; Elming et al., 2010; Iosifidi et al., 1999) were analyzed. As a result of paleomagnetic investigations of different terrains of the Ukrainian Shield magnetization components were divided into the most stable high-temperature (at the beginning of the Zijderveld diagrams) and medium-temperature magnetization components. These data were used to construct maps of the distribution of the secondary magnetization components for the Sarmatian segment of the East European Craton (Fig. 2).

During these investigations two main tectonophysical methods were used, viz., structural and kinematic analyses, taking the recent analysis of the developed methods into account (Gintov, 2005). The method that was developed using the combination of structural–paragenetic and kinematic tectonophysical analyses allows one to study variations in the stress–strain state of the Earth's crust over time. The tectonophysical study of the global fracturing of rocks allows one to establish the positions of areas of study relative to the Earth's rotation axis (Gintov, 2005).

Paleomagnetic investigations are of great importance in determining the lateral position and horizontal displacements (including rotations) of single terrains of the Ukrainian Shield. In order to obtain valid data, we used basites that were weakly altered by superimposed processes, which were previously dated and mapped. Special attention was paid to the choice of objects that are appropriate for direct tests of paleomagnetic stability (the contact test, the conglomerate test, and the fold test). The modern methods of choice and laboratory studies were used to obtain standard paleomagnetic data ("key" poles) for the Devonian complexes of the Ukrainian Shield, as well as the identification of the superimposed Devonian secondary magnetization component in the Archean–Paleoproterozoic rocks of Sarmatia.

## STUDY RESULTS

On the basis of data that were obtained for remagnetized rocks, a map of secondary magnetization component distribution in Sarmatia was constructed (Fig. 1). Within the Ukrainian Shield and the zone of its junction with the Donbas terrain two types of secondary magnetization components were identified. The first type is a characteristic monopolar magnetization component, which was identified mainly in the western part of the Ukrainian Shield (Northwest, Dniester–Bug, Rosa–Tikich blocks, which have southwest declination and low positive inclination. Paleomagnetic poles, recalculated from the direction of the secondary magnetization component have a 60° scatter in latitude and lie mostly in the "loop" of the trajectory of the apparent migration of the paleomagnetic poles for the East European Craton in the age interval of 410–350 Ma (Fig. 3; Table 1). The Euler pole of rotation has the coordinates Plat = 9.8° and Plong = 73.2° (the rotation angle is 53.8°). This scatter of the poles can be explained by displacements along the meridional fault system that was developed in this part of the Ukrainian Shield (Gintov, 2005). The formation of a metachronous magnetization component in the

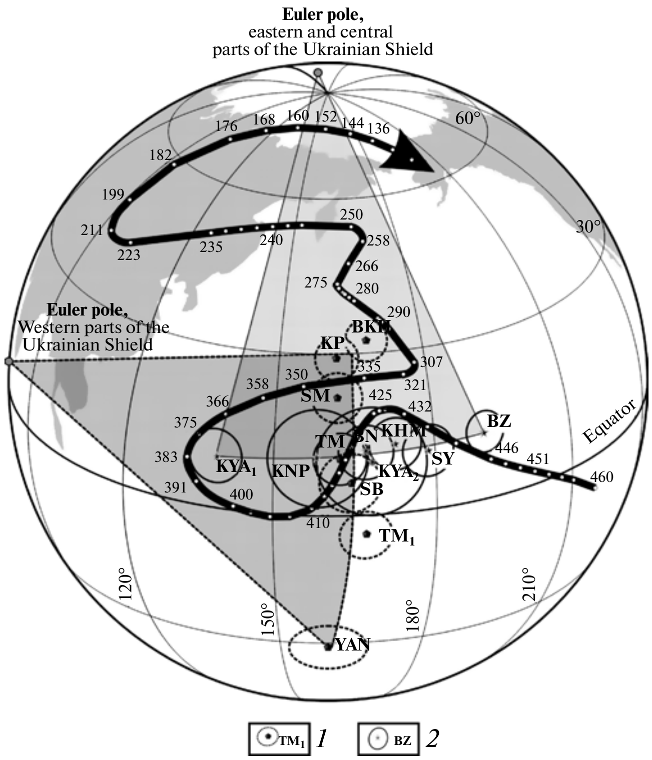


**Fig. 3.** Comparison of paleomagnetic poles, calculated from directions of secondary magnetization components with trajectory of apparent migration of the paleomagnetic pole of the East European Craton (Smethurst, Khramov, and Pisarevsky, 1998). *1*, paleomagnetic poles that were recalculated from the directions of high-temperature characteristic magnetization components; *2*, paleomagnetic poles that were recalculated from the directionsof moderate-temperature magnetization components that were determined in rocks of the Ukrainian Shield. The letter symbols near the paleomagnetic poles are given in Table 1.

Ukrainian Shield can be associated with the effect of secondary fluids during ore mineralization.

The second type of secondary magnetization components are presented by the moderate-temperature component that was identified during the study of Archean-Phanerozoic complexes along the boundary with the Dnieper–Donets aulacogene. These are characteristic of rocks of the central and eastern parts of the Ukrainian Shield that developed in the Ingul, Middle Pridneprovian, and Priazovian megablocks. The internal structure and kinematics of latitudinal zones suggests the common nature of the regional tectonic forces and stress fields that led to the development of these zones.

The paleomagnetic poles that were recalculated from the directions of secondary moderate-temperature magnetization components lie on the great-circle arc, scattering in longitude (60°) along the apparent migration of the pole of the East European Craton in the age interval of 441–385 Ma (Fig. 3). The Euler pole of rotation has the coordinates Plat = 86.5° and Plong = 4.7° (rotation angle is 58.6°). The appearance of this magnetization component in rocks is associated with manifestations of the Devonian mantle superplume and the formation of secondary magnetization due to long-term heating during the interval of 380–360 Ma. The monopolar magnetization component is of a thermoviscous nature. The results of cluster analysis of paleomagnetic directions for Paleozoic rocks of the East European Platform made it possible to distinguish the Late Devonian cluster (about 385 Ma), which corresponds to the most common directions (Shipunov, Shatsillo, and Orlov, 2007). It is probable that formation of this magnetization component was associated with displacements along latitudinal faults, which are widespread in the central and eastern parts of the Ukrainian Shield (Gintov, 2005).

Tectonophysical investigations within the Podolsk–Volyn Plate were mainly performed using the structural-paragenetic method, since there were insufficient data for the kinematic method. However, in the sequence of the undeformed platform cover, groups of fractures resulted from regional tectonic processes and global processes (global fracturing).

As a result of tectonophysical investigations of Silurian deposits of the Pridnestrovian block it was found that the axis of compression ($\sigma_1$) has an orientation of 50°/00° and the extension axis $\sigma_3$–320°/00° (Gintov, 2005). At this phase of deformation, the northeastern fault system was presented by rifts and the sublatitudinal fault system by sinistral faults.

**Table 1.** The paleomagnetic poles that were determined as a result of paleomagnetic investigations of Archean–Paleoproterozoic complexes of the Ukrainian Shield

| Sampling site | Index | Φ, °*N* | Λ, °*E* | $A_{95}$, ° | Age of rocks, Ma | References |
|---|---|---|---|---|---|---|
| Northwest block | | | | | | |
| Bekhi quarry | BKH | 32 | 168 | 5.1 | 1.77 | (Elming et al., 2001) |
| Bondari quarry | BN | 11 | 162 | 4.8 | 1.75 | (Lubnina et al., 2009) |
| Tomashgorod block | $TM_1$ | –4 | 167 | 5.3 | 1.79 | (Elming et al., 2010) |
| Sysly quarry | SY | 11 | 179 | 5.3 | 2.07 | (Elming et al., 2010) |
| Dniester–Bug block | | | | | | |
| Kazachii Yar quarry | $KYA_1$ | 10 | 139 | 5.8 | | (Iosifidi et al., 2009) |
| Kazachii Yar quarry | $KYA_2$ | 12 | 167 | 6.7 | | (Iosifidi et al., 2009) |
| Khmelnik quarry | KHM | 13 | 173 | 4.2 | 1.72 | (Elming et al., 2010) |
| Ingul block | | | | | | |
| Smila quarry | SM | 22 | 162 | 5.1 | 1.72 | (Elming et al., 2001) |
| Subbotsy quarry, dolerite dikes | SB | 66 | 164 | 5.6 | 1.77 | (Lubnina et al., 2009) |
| Subbotsy quarry, granites of the Korsun–Novomirgorodskii pluton | KNP | 10 | 168 | 10.1 | 1.78 | (Lubnina et al., 2009) |
| Middle Pridneprovian block | | | | | | |
| Bazavluk River | BZ | 13 | 190 | 5.7 | 1.8–2.1? | (Elming et al., 2001) |
| Krivoy Rog | KR | 29 | 162 | 4.4 | – | (Elming et al., 2001) |
| Yantsevskii quarry | YAN | –32 | 160 | 14.1 | – | (Iosifidi et el., 2009) |

Note: Φ and Λ are latitude and longitude of the paleomagnetic pole; $A_{95}$—radius of confidence circle of the paleomagnetic pole (in degrees).

The Lower Devonian sediments are characterized by widespread tectonic fracturing due to the effects of tangential forces. Tectonic deformations in this period resulted from northeastern compression–northwestern extension with NW-striking fold axes.

In Middle Devonian sediments the tectonic stresses caused by eastern horizontal compression are characterized by the axes: $\sigma_1$, 50°/00°; $\sigma_3$, 317°/07°; and $\sigma_2$, 137°/83°.

The kinematics of the Volyn–Podolia faults of this phase are similar to those in the Silurian phase of deformations. The sublatitudinal and submeridional faults were dextral and sinistral, respectively; the northwestern faults were not active.

A similar kinematics of movements can be established as well on the basis of paleomagnetic data. According to the trajectory of the apparent migration of the poles of the East European Craton (Smethurst, Khramov, and Pisarevsky, 1998), in the Ordovician–Early Silurian in the Ukrainian Shield, a part of the East European Craton moved from moderate into low latitudes of the Southern Hemisphere with a simultaneous counterclockwise turning (Fig. 4) In the Late Silurian–Early Devonian (425–410 Ma) a sharp change in the direction of movement of the Shield occurred: during 15 Ma it moved from equatorial into tropical latitudes of the Southern Hemisphere without rotation (Fig. 5a). The next sharp change in movement of the Ukrainian Shield occurred in the age interval of 391–375 Ma, when a sharp displacement of the Ukrainian Shield in the latitude occurred, as had occurred in the Late Silurian (Fig. 5a). In the same age interval, the counterclockwise to clockwise rotation of the East European Craton occurred.

As a result of investigations carried of the Silurian–Devonian sediments of Podolia the new version of the trajectory of the apparent migration of the Paleozoic segment of East European Craton was proposed (Fig. 5b), (Lubnina et al., 2007).

On the new trajectory of the apparent migration of the pole, the Silurian "cusp" is absent. According to this, the Silurian poles at 435–420 Ma lay close to the Devonian–Carboniferous poles (335–290 Ma) of the East European continent.

The new paleomagnetic poles suggest that the East European Craton moved at 450 Ma in the northwestern direction with simultaneous counterclockwise rotation from the moderate latitudes of the Southern Hemisphere into tropical (430–420 Ma) and near-equatorial (420–405 Ma) latitudes of the Southern

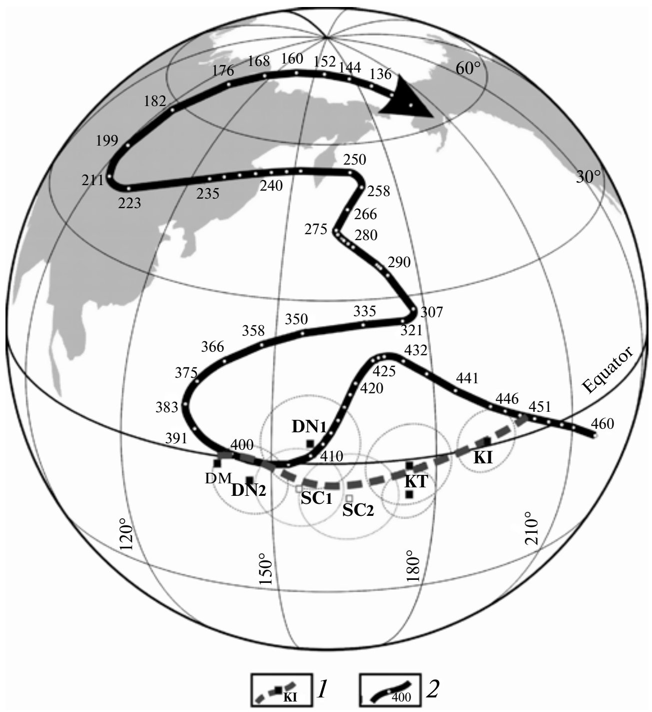


**Fig. 4.** Comparison of the paleomagnetic poles, calculated from the directions of moderate- and high-temperature magnetization components of Silurian-Devonian complexes of Podolia with the trajectory of apparent migration of the pole (TAMP) of the East European Craton (Smethurst, Khramov, and Pisarevsky, 1998). *1*, Silurian-Devonian poles of Podolia. The letter symbols are the paleomagnetic poles in Table 2; *2*, paleomagnetic poles of the East European Craton (Smethurst, Khramov, and Pisarevsky, 1998).

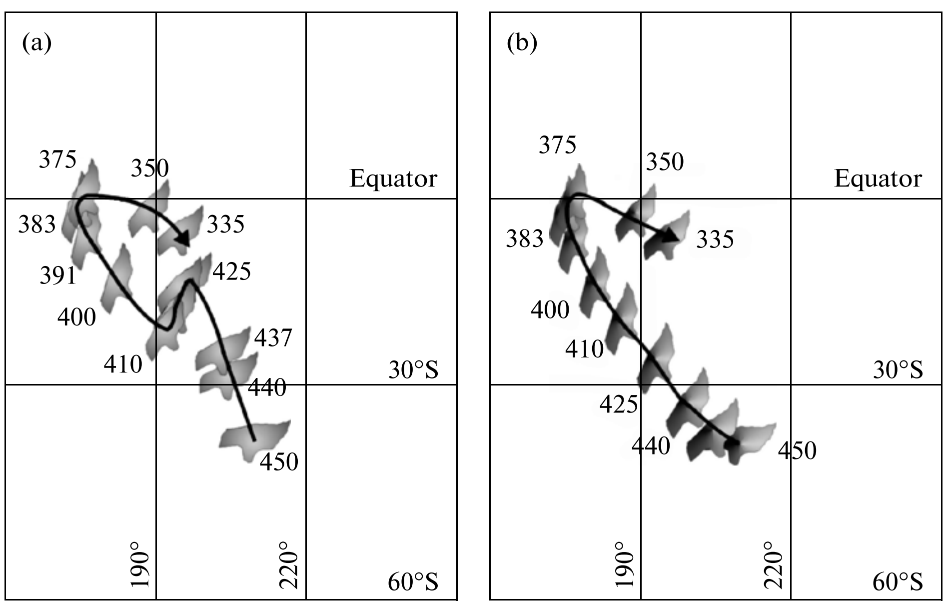


**Fig. 5.** Kinematics of movement of the Ukrainian Shield in the Early-Middle Paleozoic: (a) according to the trajectory of apparent migration of the pole (TAMP) of the East European Craton (Smethurst, Khramov, and Pisarevsky, 1998); (b) according to the paleomagnetic data, determined for the Silurian-Devonian complexes of Podolia (Lubnina et al., 2007). The figures are age datings of the paleomagnetic poles (Ma).

**Table 2.** The paleomagnetic poles that were recalculated from moderate- and high-temperature magnetization components ($J_n$) of Silurian–Devonian complexes of Volyn'-Podolia and Scandinavia

| Sampling site | Index | Φ, °*N* | Λ, °*E* | $A_{95}$, ° | Age of rocks, Ma | References |
|---|---|---|---|---|---|---|
| Kitaigorod, Podolia | KI | –1 | 10 | 6 | 430–435 | (Iosifidi and Khramov, 2004) |
| Kitaigorod, Podolia | KT | 7 | 355 | 7 | 430–435 | (Lubnina et al., 2007) |
| Ivane–Zolotoe–Podolia | IZ | 1 | 355 | 9 | 390–400 | (Lubnina et al., 2007) |
| Scandinavian Caledonides | $SC_2$ | 7 | 344 | 9 | 411 ± 7 | (Torsvik et al., 1992) |
| Scandinavian Caledonides | $SC_1$ | 6 | 335 | 8 | 416–428 | (Torsvik et al., 1990) |
| Dniester River, Ukraine | $DN_1$ | –4 | 337 | 9 | 419–423 | (Tret'yak, 1986) |
| Sediments, Dniester River | $DN_2$ | 4 | 326 | 7 | 390–400 | (Smethurst and Khramov, 1992) |

Note: Φ and Λ are the latitude and longitude of the paleomagnetic pole, respectively; $A_{95}$, the radius of the 95% confidence circle for the mean direction.

Hemisphere (Fig. 5b). It is probable that partial or complete remagnetization of rocks of the Podolsk–Volyn Plate resulted from the migration of fluids along the meridional and east–west trending faults.

## CONCLUSIONS

1. On the basis of the data that were obtained for the remagnetized rocks of the Ukrainian Shield, a map of the distribution of the secondary magnetization components of the Sarmatia was constructed. The belts and zones of remagnetization of rocks of Sarmatia, which correspond in their age to the main tectonic orogenic and plume stages of its evolution, were distinguished.

2. The formation of the secondary magnetization components is associated with the influence of secondary fluids during ore mineralization in the western part of the Ukrainian shield and with displacements in the central and eastern parts of Sarmatia along the latitudinal faults.

3. A paleomagnetic study of the Devonian deposits of the Ukrainian Shield

made it possible to distinguish moderate-temperature characteristic magnetization components, whose directions are similar to the previously determined Devonian magnetization components for Podolia (Lubnina et al., 2007; Smethurst and Khramov, 1992). In addition, a new variant of the Middle Paleozoic part of the trajectory of the apparent migration of the pole of the East European Platform was proposed.

## ACKNOWLEDGMENTS

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