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Paleomagnetic Data for Siberia and Baltica in the Context of Testing Some Geodynamic Models of the Formation of the Central Asian Mobile Belt

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Abstract—The synthesis of the paleomagnetic data for the Siberian (Siberia) and East European (Baltica) platforms shows that since the Early Paleozoic they could have experienced coherent movements as a part of consolidated continental agglomeration (a composite continent), which also includes the Arctida continent. Based on the paleomagnetic data, the relative positions of the Siberia and Baltica during the Ordovician is reconstructed, and a series of paleogeographical reconstructions describing the drift of the composite continent is suggested. The results of the lithologic–facial analysis of the sedimentation settings within the Ordovician basins of the Siberian and East European platforms and paleoclimatic markers are consistent with the suggested configuration and paleogeographical position of the composite continent. The suggested reconstructions and the ages of detrital zircons from the Early Paleozoic complexes of the platform margins and some objects of the Central Asian Mobile Belt (CAMB) reasonably well agree with the hypothesis (Sengör et al., 1993) which interprets the formation of the structure of CAMB Paleozoides as a result of the evolution of the island arc stretching along the margins of Siberia and Baltica.

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INTRODUCTION

The Central Asian Mobile Belt (CAMB) is the world's largest Paleozoic folded system assembling the Early Precambrian continental blocks—East European (Baltica) and Siberian (Siberia) cratons, Tarim, and smaller structural units—into a single continent of Northern Eurasia. The formation of CAMB is associated with the interaction between the lithosphere of the Paleo-Asian Ocean and continental masses during the Late Precambrian–Paleozoic. The CAMB has an extremely complicated internal structure in which the terranes with a different geodynamic nature and age are combined together, predominantly along the strike-slip faults (Shenger et al., 1994; Buslov, 2011; Metelkin, 2010; Sengör et al., etc.). The geodynamical models describing the CAMB formation can be classified into three groups according to their predominant concepts: accretion (Didenko et al., 1994), accretion–collision (Buslov et al., 2001; Buslov, 2011), and island–arc (Shenger et al., 1994; Sengör et al., 1993).

The supporters of the accretionary model interpret the CAMB-composing terranes as the relics of an island arc system of a different age, which developed within the Paleo-Asian Continent during the Vendian–Ordovician independently of the Laurasian cratons and were incepted on the continental crustal clocks split off from Gondwana. These island-arc complexes successively accreted to each other and were subsequently docked to the Siberian continent along the systems of strike-slip faults that inherited the ancient transform faults.

In the accretion–collision model, it is assumed that an active margin of the island-arc type existed in the Vendian–Early Cambrian on the southern Epi-Baikalian margin of the Siberian continent. The accretion–collision processes resulted in the formation of a superterrane in the frontal part of this active margin—the Kazakhstan–Baikal composite continent incorporating the Precambrian microcontinents and the Gondwana group terranes. The subsequent CAMB evolution is considered as the interaction of the Kazakhstan–Baikal continent (CAMB element) with Siberia and Baltica. A significant role in the formation of the structures in this process was presumably played by the Late Paleozoic movements along the systems of large-amplitude strike-slip faults, which violated the initial tectonic zonation of the superterrane and were due to the relative rotation of the cratons.

The island-arc model, also referred to as the SNB model (Shenger et al., 1994; Sengör et al., 1993), accounts for the CAMB structure by the deformation and multiple reconstitution of the fragments of the hypothesized Kipchak island arc along the systems of high-amplitude strike-slip faults. The Kipchak arc nucleated in the Vendian along the Uralian margin of Baltica and the Yenisean margin of Siberia and then evolved in the Paleozoic. This arc was incepted within the band of the continental crust rifted off from the Yenisean and Uralian cratonic margins, with the subduction of the lithosphere of the Paleo-Asian Ocean beneath the Kipchak arc directed towards the cratons. The authors of the model consider the Aleutian arc in the Pacific as a present-day analog of the Kipchak arc. The cornerstone and boundary condition in the SNB model lie in the relative positions of Siberia and Baltica in the Vendian—the beginning of the Paleozoic: it is assumed that at that time the cratons were structurally matched and faced each other by their present-day northern margins so that the Uralian margin of Baltica extended the Yenisean margin of Siberia, sharing the same strike with it.

Thus, in contrast to the accretion or accretion—collision CAMB formation models, the SNB model is critically constrained by the mutual layout of Siberia and Baltica in the Vendian—beginning of the Paleozoic and it can be tested with the use of the paleomagnetic data for these cratons.

The aim of this paper is to analyze the published paleomagnetic data for the Ordovician of Siberia and Baltica—the only isochronous level of Early Paleozoic for which there are a significant number of high-quality paleomagnetic results for both cratons. We use these data for reconstructing the relative layout, kinematics, and paleogeographical position of Siberia and Baltica in the Ordovician in the context of testing the SNB model; based on these data, we also construct the apparent polar wander path (APWP) curves for these cratons. For testing the SNB model we additionally consider the results of the analysis of the geochronology data for detrital zircons from the Early Paleozoic platform complexes of the Yenisean margin of Siberia, the Uralian margin of Baltica and CAMB, as well as the paleogeographical data.

THE ANALYSIS OF SIBERIA AND BALTICA PALEOMAGNETIC DETERMINATIONS FOR THE ORDOVICIAN

The analysis described below is aimed at revealing the regularities in the distribution of the paleomagnetic directions for the Ordovician of Siberia and Baltica. This will allow us to determine the general character of the paleomagnetic poles' migration during this time, i.e., to construct the APWP curves for the platforms for the considered time interval and synthesize the these data within the common paleogeographical model. The old paleomagnetic determinations which were obtained with the use of not particularly detailed demagnetizations and can only be considered as historical facts at present are not used in the analysis. However, it should be recognized that the first pioneering works on the paleomagnetic investigation of the Ordovician rocks in the territory of the former Soviet Union were carried out by the geophysicists of the Paleomagnetic laboratory of the All-Russia Petroleum Research Exploration Institute (VNIGRI), Leningrad (formerly, all-USSR Oil Exploration Institute) under the guidance of A.N. Khramov. It is these results that formed the basis of the first paleogeographic reconstructions and geodynamical models (Zonenshain et al., 1990; Khramov et al., 1974; 1982) which determined the trend of the present-day research.

Initial Data

Baltica. To date, the paleomagnetic determinations have been obtained for all the Ordovician stages[1] (Table 1). The objects from which the paleomagnetic poles are calculated are located in regions geographically distant from each other (Leningrad oblast, Estonia, and Sweden). Most of the data are obtained for the Middle Ordovician (Dapingian and Darriwilian); fewer determinations are made for the upper part of the Lower Ordovician (Floian) and the base of the Upper Ordovician (Sandbian); the paleomagnetic data for Tremadocian, Katian, and Hirnantian are absent.

Siberia. We primarily note that in order to avoid probable errors associated with local and regional tectonic factors, our analysis only includes the determinations from the objects located within the Angara—Anabar block—a united tectonically rigid structure spanning the western and northern parts of the Siberian Platform, for which the bulk of the paleomagnetic data have been obtained. We consciously disregarded the individual results obtained for the so-called transition zone between the Angara—Anabar and Aldan blocks (the upper reaches of the Lena River), which are supposed to have undergone local rotations (for more detail see (Pavlov et al., 2008) and the references therein). The only exception was the determination from the Upper Ordovician rocks of the Nyuya River (Powerman et al., 2013) pertaining to the Aldan block, which was taken into account because of the acute shortage of data for this age interval. When comparing this result to the main body of the data, we introduced a correction for the Middle Paleozoic rotation of the Aldan block according to (Pavlov et al., 2008)[2]. The

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[1] For the rocks from which the paleomagnetic determinations were used in our analysis, the ages were revised according to the International Stratigraphic Scale 2016 (Ogg et al., 2016).

[2] Counterclockwise rotation by 20° about the Euler pole with coordinates 117° E, 62° N.

Table 1. Ordovician paleomagnetic poles of Siberia and Baltica

n	PLong	PLat	A95	Tmean	Tmin	Tmax	Tgroup	Data source
Baltica poles								
1	214.0	–5.0	5.0	456.45	454.6	458.3	1	(Torsvik and Trench, 1991b)
2	215.0	–3.0	13.0	457.8	455.6	460.0	1	(Torsvik and Trench, 1991a)
3	222.0	–12.0	5.0	458	457.0	459.0	1	(Rodionov et al., 2002)
4	229.0	–14.0	4.0	459.8	458.6	461.0	2	(Torsvik and Trench, 1991b)
5	234.0	–18.7	6.8	460.6	454.0	467.2	2	(Torsvik et al., 1995b)
6	227.3	–17.9	11.3	463.35	460.2	466.5	2	(Plado et al., 2016)
7	228.4	–29.1	7.0	463.45	461.5	465.4	2	(Gurevich et al., 2005)
8	226.0	–18.0	5.0	463.8	461.0	466.6	2	(Torsvik and Trench, 1991a)
9	226.0	–30.0	2.0	463.8	461.0	466.6	2	(Claesson, 1978)
10	235.0	–30.0	9.0	463.8	461.0	466.6	2	(Perroud et al., 1992)
11	219.1	–11.4	6.7	465.1	460.2	470.0	2	(Plado et al., 2010)
12	242.9	–5.4	3.9	465.4	460.8	470.0	2	(Lubnina et al, 2005)
13	231.0	–19.0	9.0	467.3	466.3	468.3	3	(Torsvik and Rehnström, 2003)
14	237.6	–24.7	3.0	467.7	465.4	470.0	3	(Gurevich et al., 2005)
15	239.1	–34.7	4.0	468.5	461.0	476.0	3	(Smethurst et al., 1998)
16	230.8	–25.0	7.2	472.4	470.0	474.8	3	(Plado et al., 2010)
17	235.0	–18.0	4.0	472.5	469.0	476.0	3	(Khramov and Iosifidi, 2009)
Siberian poles								
1	124.1	–13.9	5.9	446.4	443	449.7	1	(Gallet and Pavlov, 1996)
3	152.0	–27.5	3.6	452.1	447.6	456.5	1	(Powerman et al., 2013)
2	140.2	–29.5	6.4	453.9	449.7	458	1	(Pavlov et al., 2012)
4	152.4	–24.1	3.3	458.8	458	459.5	2	(Pavlov et al., 2008)
6	158.0	–22.0	4.0	458.8	458	459.5	2	(Pavlov et al., 2008)
5	157.6	–22.7	2.8	459.2	457.4	461	2	(Gallet and Pavlov, 1996)
7	156.6	–29.8	3.1	463.3	461	465.5	2	(Gallet and Pavlov, 1996)
8	152.7	–30.9	2.8	463.3	461	465.5	2	(Pavlov and Gallet, 1998)
9	153.2	–35.2	3.6	463.3	461	465.5	2	(Pavlov et al., 2012)
11	158.2	–36.4	6.5	469.8	465.5	474	3	(Pavlov et al., 2012)
10	151.7	–33.9	1.9	471.6	465.5	477.6	3	(Gallet and Pavlov, 1996)
13	137.5	–40.3	6.9	479.8	477.6	482	4	(Gallet and Pavlov, 1996)
12	143.5	–39.7	6.1	481.5	477.6	485.3	4	(Pavlov et al., 2017)
14	127.2	–35.2	4.1	482.1	477.6	486.5	4	(Pavlov and Gallet, 1998)
15	138.0	–36.0	4.7	482.1	477.6	486.5	4	(Rodionov and Gurevich, 2010)

n, pole number; PLong/PLat, longitude and latitude of paleomagnetic pole; A95, confidence circle radius at 95% probability; Tmean/Tmin/Tmax, mean/minimal/maximal rock age (Ma) from which paleomagnetic determination is obtained (correlation of regional Ordovician horizons of Siberia and Balto-Scandia (*Zonal'naya*..., 2006) to International Stratigraphic Scale (Ogg et al., 2016); Tgroup, age groups (explanations presented in text).

determination from the Upper Ordovician of the Lena River (Aldan block) (Torsvik et al., 1995a) was not considered because of the presumed Devonian age of magnetization in this case (Powerman et al., 2013). The paleomagnetic determinations from Siberia that were included in the analysis are obtained from the remote regions; they have a clear stratigraphic correlation (frequently as accurate as up to a stage) and, to some extent, characterize all the Ordovician stages (Table 1).

For the joint analysis of the paleomagnetic data for Siberia and Baltica, the determinations were subdivided into four age groups (Fig. 1) approximately corresponding to (1) Sandbian–Hirnantian, (2) Darriwilian (statistically most reliable (best substantiated)

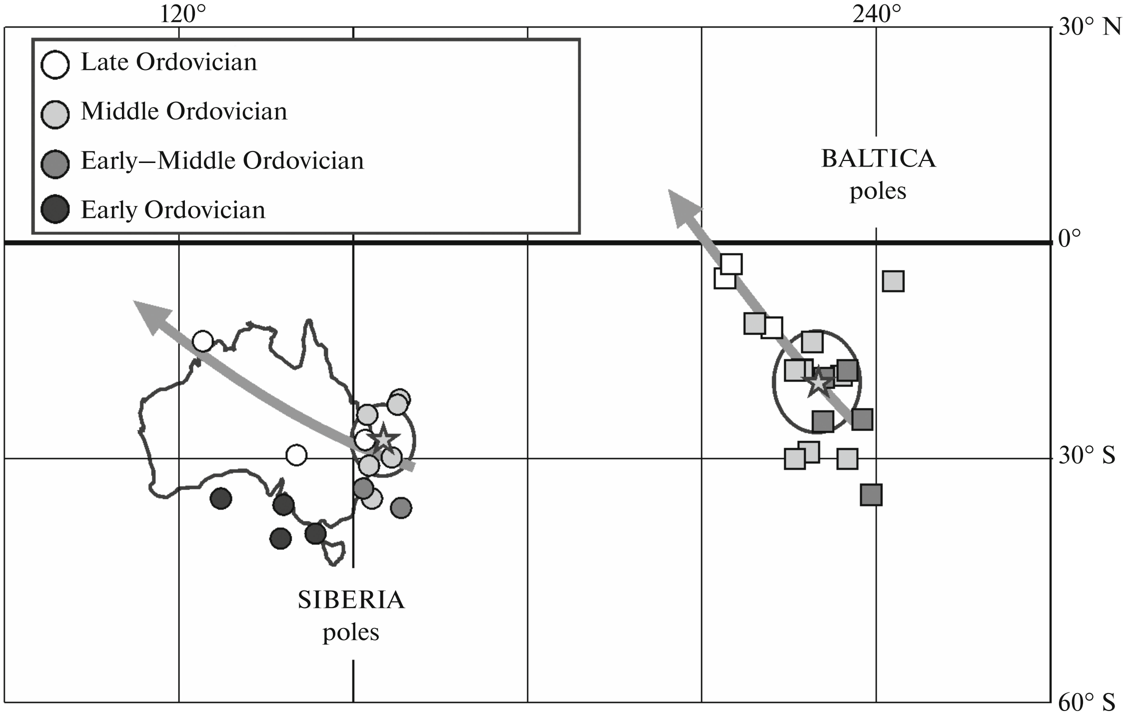

Fig. 1. Ordovician paleomagnetic poles for Siberia and Baltica (in accordance with Table 1). Circles and boxes show paleomagnetic poles of Siberia and Baltica, respectively. Asterisks and corresponding (confidence) circles are averaged Middle Ordovician (Darriwilian) poles. Arrows show geometrical approximation of migration trends of Late Ordovician poles (large circle drawn through Late Ordovician individual poles and averaged Darriwilian pole).

group), (3) Floian–Dapingian, and (4) Tremadocian (data for Siberia alone).

The Displacement Trends of the Ordovician Poles for Siberia and Baltica

There is a certain regularity in the distribution of the Ordovician poles for Siberia and Baltica (Fig. 1). The Siberian data demonstrate a sublatitudinal displacement of the Early Ordovician poles, an insignificant submeridional displacement of the Middle Ordovician poles, and an SE–NW trend for the Late Ordovician poles. The distribution and displacement trends of the Baltica poles are similar although less manifest. This is probably due to the fact that the paleomagnetic determinations from the Siberian Platform were obtained over narrower time intervals corresponding to stages, whereas the Baltica poles (Fig. 1, Table 1) are the averages over the intervals covering two stages, including those pertaining to different series of the Ordovician system. Clearly, depending on the quantitative ratio between the contributions of the individual directions of some age that are included in the paleomagnetic determination, the calculated average direction will be displaced towards the statistically better substantiated age group. From this it follows that the age of the geomagnetic pole calculated over the stratigraphically nonuniform set of directions will be not identically to the average age of the rocks. The wider the averaged time interval (and the larger the displacement of the paleomagnetic pole characterizing the drift of the platform) the larger the discrepancy between these ages can be. Correspondingly, this effect noticeably impedes the construction of APWP tracks for a relatively narrow, in the paleomagnetic sense, time interval spanning one or two stratigraphic stages during which the displacement of the pole is close to the resolution of the paleomagnetic method.

When it is required to identify the trends of the paleomagnetic pole's displacement over narrow time intervals, the probable technical solution of the considered problem lies in the geometrical approximation of the directions (poles) close to each other in age of the great-circle arc[3]. The displacement of the paleomagnetic pole (or, identically, the movement of the corresponding block), just as any movement on a sphere, is described by the rotation along a small-circle arc. For the small amplitudes of this displacement (in the case considered, on the scale of one stage of the Ordovician system), the motion can be *approximately* represented as a displacement along the great-circle arc. The larger the radius of the small circle describing the displacement of the pole and the shorter the ana-

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[3] For these calculations we used the computer program for the analysis and presentation of paleomagnetic data (Enkin, 1994).

Table 2. Synthesis of paleomagnetic data for Ordovician of Siberia and Baltica

	N	Long	Lat	*k*	A95
Trends of migration of poles in Late Ordovician*					
Baltica	4	300.9	42.4		4.8
Siberia	4	190.0	55.2		13.1
Averaged Darriwilian poles (group 2)					
Baltica	9	229.8	–19.5	55.5	7.0
Siberia	6	155.1	–27.5	196.0	4.8
Combined averaged poles**					
group 1 (~454 Ma)	6	138.9	–20.4	51.6	9.4
group 2 (~462 Ma)	15	155.1	–27.5	82.7	4.2
group 3 (~470 Ma)	7	159.4	–32.5	131.4	5.3
group 4 (~481 Ma)	4	136.4	–37.9	183.6	6.8
Euler poles***					
Version A	Long = 33.2; Lat = 73.5; angle = 86.3				
Version B	Long = 51.6; Lat = 80.1; angle = 79.9				

N, number of paleomagnetic poles used in statistics; Long/Lat, longitude/latitude; *k*, concentration parameter; A95, confidence circle radius for 95% probability; *angle*, angle of rotation about Euler pole (clockwise rotation in case of reducing data for Baltica to Siberian coordinates). *, normals to large circles approximating migration trends of Late Ordovician poles from averaged Darriwilian poles. **, for reducing Baltica poles to Siberian coordinates, version B of Euler pole is used. ***, in calculations of version A of Euler pole, paired data for displacement trends of Late Ordovician poles and averaged Darriwilian poles are used; in calculations of version B of Euler pole, paired data for average Darriwilian poles and Upper Permian poles are used (in accordance with (Shatsillo, 2015a)). Other explanations are presented in text.

lyzed time interval, the closer this approximation is to the reality.

We applied this approach for analyzing the trends of the poles' displacements in the Late Ordovician with the use of the data on the averaged Darriwilian poles. The calculated geometrical parameters of the displacement trends for the Late Ordovician poles of Siberia and Baltica (Table 2, Fig. 1) indicate that they are very similar. The revealed regularity allows us to hypothesize that during the Ordovician, Siberia and Baltica could have experienced coherent movements and probably constituted a united lithospheric plate. If this hypothesis is valid, there should be such a point in the geographic space (Euler pole) the rotation about which can align the Siberian paleomagnetic poles with the Baltica poles and bring the cratons to their relative position in the Ordovician.

Synthesis of the Paleomagnetic Data for the Ordovician of Siberia and Baltica

In the calculations of the Euler pole for aligning the Ordovician data for Siberia with those for Baltica, we used two independent characteristics: (1) the position of the averaged Darriwilian poles for these platforms (the statistically most reliable age group) and (2) the position of the normals to the great circles approximating the displacement trend of the Late Ordovician poles (the age group marked with a manifest displacement trend). Geometrically, the probable positions of the Euler poles for aligning each dataset constitute a great circle perpendicular to the center of the arc drawn through the averaged poles (1) or through the normals to the great circles (2). The Euler pole which delivers the best fit for the entire dataset is located at the intersection of the calculated great circles for (1) and (2) (Fig. 2). The angle of rotation about the Euler pole is calculated from the difference in declinations under the conversion of the averaged Darriwilian poles for platforms into the coordinates of the Euler pole (see (Shatsillo, 2015a) for more detail). The results of the calculations are presented in Table 2. Figure 3 shows the overall layout of the Ordovician poles reduced to the Siberian coordinates by rotation about the calculated Euler pole. These constructions resulted in the perfect alignment of the Siberian and Baltic paleomagnetic data; in particular, the poles for Floian–Dapingian (which were not used in the calculations of the Euler pole) have become coincident. This convergence of the data reinforces our suggestion that during the Ordovician, Siberia and Baltica could have been parts of a single lithospheric plate. Previously, a similar conclusion was derived from the preliminary analysis of the paleomagnetic data for the Late Vendian–Paleozoic (Shatsillo, 2015b). In light of this, it would be reasonable to focus on comparing the calculated Euler pole with the Late Paleozoic pole of the relative rotation of Siberia and Baltica during their assembly into the Pangaea, which was derived from the paleomagnetic and structural–geological data (Shatsillo, 2015a). As seen from Fig. 2 and Table 2, the

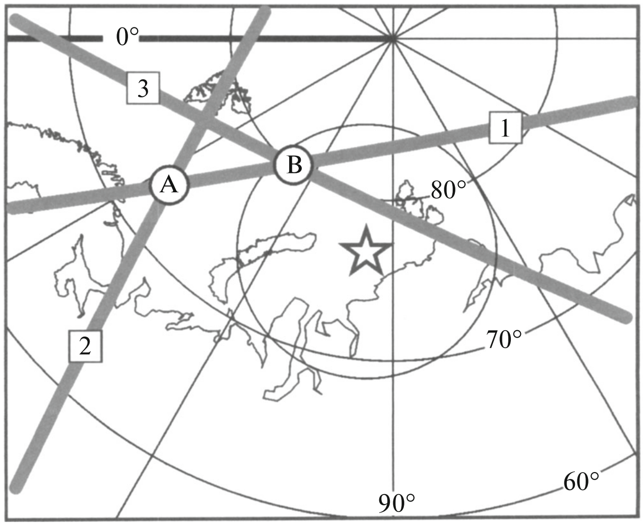

Fig. 2. Calculated Euler poles: thick gray lines and corresponding numbers in boxes show geometrical areas (large circles) characterizing probable positions of rotation poles, for aligning paleomagnetic data for Siberia with data for Baltica, calculated from (1) averaged Darriwilian poles; (2) trends of Late Ordovician poles; (3) Early Permian poles (in accordance with (Shatsillo, 2015a)). Letters in circles indicate versions of calculated Euler poles for paired data according to Table 2. Asterisk and corresponding (confidence) circle show pole of Permian rotation of platforms calculated from regional structural data (in accordance with (Shatsillo, 2015a)). Other explanations are in text.

Euler poles calculated for the age levels spaced ~200 Ma apart are very close. All these observations mean that since as early as the Ordovician or, probably, even the Late Vendian (Shatsillo, 2015b), Siberia and Baltica made up a united continental agglomeration with the configuration determined by the diachronous relative rotations of these cratons about the stable pole of rotation. According to this hypothesis, the paleomagnetic poles for Siberia and Baltica can be jointly used for constructing the combined APWP track.

In the subsequent constructions, we use the Euler pole calculated from the paired data for the averaged Darriwilian poles and from the Early Permian poles (Fig. 2, Table 2, option B). This is due to the fact that (1) this calculation version better agrees with the rotation pole of the platforms calculated from independent structural data (Shatsillo, 2015a) (Fig. 2), and (2) due to the incomplete age coincidence and limited number of analyzed determinations, the calculations based on the Late Ordovician trends of the poles' displacements yield coarse and probably biased estimates. We note that in the comparison of the paleomagnetic data for Siberia and Baltica using the Euler pole of option B, the displacement trends of the Late Ordovician poles differ statistically insignificantly (the angular distance between the normals to the large circles approximating the trends corresponds to 14.6° against the critical value of 16.1°), whereas the concentration parameter of the distribution of the Floian–Dapingian poles (group 3 of the joint set) increases by ~10%.

Based on the entire set of the paleomagnetic data for the Ordovician of Siberia and Baltica, we constructed the combined APWP curve (Fig. 4, inset, Table 2). At the current level of detail in our paleomagnetic knowledge about the Ordovician of Siberia and Baltica, more-or-less-reliable poles can be calculated for four age groups (the age estimate for each group is obtained by averaging the ages of all the determinations included in this group): (1) ~454 Ma (the middle of the Late Ordovician), (2) ~462 Ma (the end of the Middle Ordovician), (3) ~470 Ma (the Early/Middle

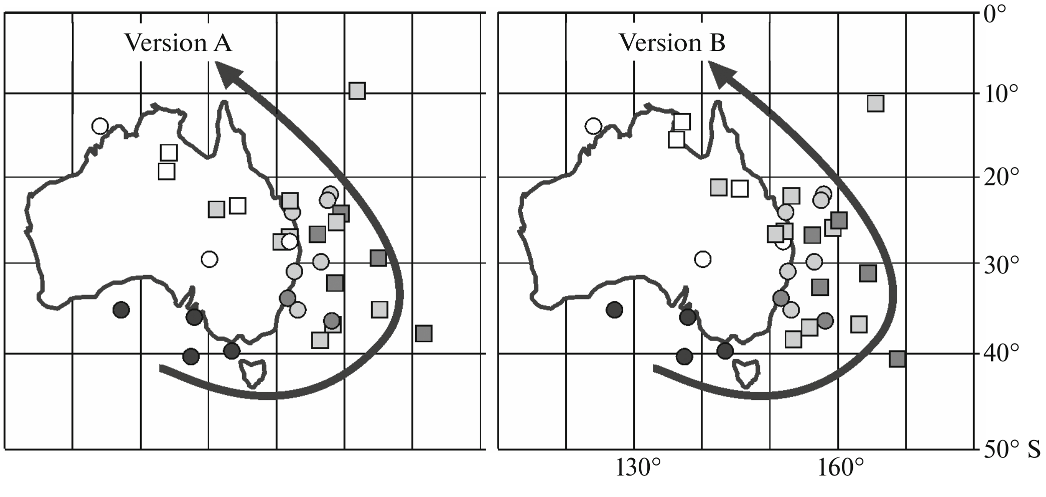

Fig. 3. Pattern of distributions of paleomagnetic poles for Siberia and Baltica reduced to Siberian coordinate system with different options of Euler poles (versions A and B in Table 2). Circles and boxes correspond to paleomagnetic poles of Siberia and Baltica, respectively; arrow shows direction of displacement of poles from Early to Late Ordovician. Other explanations are presented in Fig. 1, Table 2, and text.

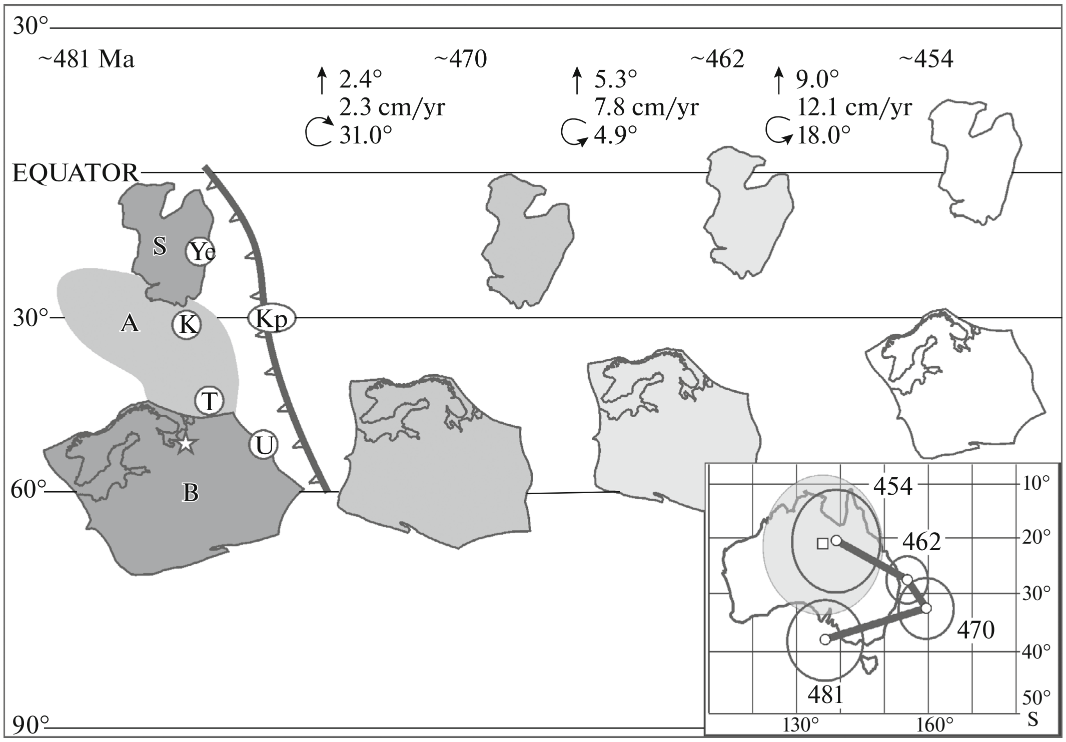

Fig. 4. Layout of Siberia and Baltica within composite SAB (Siberia–Arctida–Baltica) continent, paleogeographic position of latter and character of Ordovician drift along paleomeridian. Inset: combined APWP curve for Siberia–Baltica pole in Siberian coordinates. S, Siberia; A, Arctida (conditional contour); B, Baltica; U, Uralian margin; Ye, Yenisean margin; Kp, hypothetical Kipchak island arc. Arctida structures: T, proto-Uralides–Timanides orogen; K, Kara block. Circular arrows and corresponding numbers show direction and degree of rotation (in degrees). Vertical arrows and corresponding numbers show direction of latitudinal drift, extent of displacement (in degrees), and drift velocity (in cm/yr). Asterisk marks reference point (Arkhangel'sk) for which kinematic parameters of SAB continent are calculated. Inset: box and corresponding confidence circle in gray indicate Middle–Late Ordovician paleomagnetic pole for Kara block of Arctida (Metelkin et al., 2005) reduced to Siberian coordinates with version B of Euler pole (Table 2).

Ordovician boundary), and (4) ~481 Ma (the beginning of the Early Ordovician).

TECTONIC INTERPRETATION

Relative Positions and Drift of Siberia and Baltica during the Ordovician

Based on our hypothesis of the Paleozoic drift of Siberia and Baltica moving as parts of a common lithospheric plate whose Pre-Pangaean rearrangement was determined by the relative rotation of the cratons about the single Euler pole, it is possible to reconstruct the layout of the studied continental blocks. Using the calculated Euler pole and the corresponding rotation angle (Table 2, option B) for one of the cratons, we reconstructed the relative positions of the cratons in the Ordovician according to which Siberia faced (by its Taimyr margin) the Timan margin of Baltica (Fig. 4). The lithospheric plate which incorporated Siberia and Baltica was elongated in the meridional direction, and the cratons were spaced ~2000 km apart from each other. The cratons were located in different climate zones: Baltica in the subpolar–temperate zone, and Siberia in the equatorial zone. The space separating Siberia and Baltica was not oceanic. As is convincingly demonstrated by some models based on the geological data (Kuznetsov, 2006; 2007; 2009; Kuznetsov et al., 2010), the Proto-Uralides–Timanides or Timanides complexes (the NE framing of Baltica in the present coordinates) were a fragment of the epi-Grenville (?) Arctida continent; they extended farther northeast (in the present coordinates) by the continental crustal blocks nowadays forming the shelf and archipelagoes of the Arctic Ocean. The integrity of the blocks was preserved as long as up to the Mesozoic. In other words, the space between Siberia and Baltica was occupied by the Arctida continent which was estimated to have collided with Baltica in the Early Cambrian (Kuznetsov et al., 2014). The suggested model is consistent with the paleomagnetic data for the October Revolution Island (the Kara block of Arctida) from the Middle–Upper Ordovician rocks of which the paleolatitude is estimated at 14.4° ± 12° S (Metelkin et al., 2005), in perfect agreement with a series of our paleoreconstructions for that time (Fig. 4). With allowance for the Meso–Cenozoic motions during the opening of the Eurasian and Canadian spreading basins of the Arctic Ocean (Shatsillo, 2015b), the suggested scheme can also incorporate the paleomagnetic data for the Ordovician of the New Siberian (Novosibirskii) block of Arctida (the Bennett and Kotel'nyi islands) (Vernikovskii et al., 2013). The spatial connection of the New Siberian Archipelago with the northeast of the Siberian Platform in the Early Paleozoic is suggested by the recent paleobiogeographic and sedimentological data (Danukalova et al., 2014). This also supports our reconstruction, which implies that Siberia, Baltica, and Arctida made up a united whole in the Ordovician.

Based on the averaged paleomagnetic poles of the combined APWP track for Siberia–Baltica (Table 2), we have calculated the latitudinal drift velocities, as well as the direction and amount of rotation of the composite Siberia–Arctida–Baltica (SAB) continent in the Ordovician (Fig. 4). According to the obtained data, during the considered time interval, SAB experienced a directed latitudinal drift in the northward direction. Drift velocity increased from ~2 cm/yr in the Early Ordovician to ~12 cm/yr in the Late Ordovician. The Middle Ordovician concurs with the change in the SAB's rotation direction from dextral (clockwise) to sinistral (counterclockwise), which is reflected in the bend of the APWP curve (Fig. 4). The sharp change in the sense of the motion of SAB could perhaps be associated with the global rearrangement of the motion of the entire ensemble of the lithospheric plates which, in turn, can be considered as a precursor of the largest tectonic event of the Early–Middle Paleozoic: the closure of the Iapetus Ocean and the collision of SAB and Laurentia.

Evolution of Sediments in the Ordovician Basins of Baltica and Siberia and the SAB Model

The comparative analysis of climate-dependent shallow-water facies in the Ordovician successions of Siberia and Baltica shows that the long-term changes in lithology on these two paleocontinents were drastically different at that time. The Ordovician succession in Baltica starts with quartz and glauconite sandstones (composing a major part of the Lower Ordovician), which are similar to the coldish Nubian facies of the Ordovician of Gondwana. At the very end of the Lower Ordovician and in the Middle Ordovician, siliciclastic sedimentation is gradually replaced by carbonate sedimentation; initially, there are highly condensed cold-water limestones abundant with glauconite (the lower part of the Middle Ordovician). Upwards the succession, the thicknesses of the stratigraphic units (regional stages) gradually increase and carbonate mud content in them grows. The change from temperate-climate carbonates to typical tropic dolomites and limestones takes place starting from the middle of the Upper Ordovician. Even at the very end of the Late Ordovician, at the time when Gondwana was covered with ice sheet, oolite grainstones, typical of a tropical climate, were deposited on Baltica (Dronov and Rozhnov, 2007). The described trend is well accounted for by the Ordovician drift of Baltica from the high latitudes of the Southern hemisphere towards the low latitudes (Fig. 4).

The evolution of sediments in the Ordovician succession of Siberia followed exactly the opposite scenario. Here, the section begins with a thick (up to 600 m) series of tropical limestones and dolomites with all the features of low-latitude sedimentation, including the abundance of stromatolite structures, oolitic grainstones, flat-pebble conglomerates, and signs of karstification. The lagoonal facies contain gypsum, anhydrites, and numerous pseudomorphoses on halite crystals. In the second half of the Middle Ordovician, this huge carbonate platform suddenly ceases to exist, and the tropical carbonate sedimentation practically all over the Siberian Platform is changed by siliciclastic (Baykit sandstones and analogs). It is worth noting that the appearnce of typical Nubian facies in the Middle Ordovician of Siberia is accompanied by the occurrences of giant trilobite trace fossils (Kushlina and Dronov, 2011), which are believed to be characteristic of the cold-water Gondwana area (Neto de Carvalho and Baucon, 2016). The top portions of the Middle and the entire Upper Ordovician in the Tunguska Basin of the Siberian Platform are represented by a relatively thin (at most 100 m) series of cold-water carbonates (Dronov, 2014). With allowance for the low-equatorial latitudinal position of Siberia throughout the entire Ordovician, as indicated by the paleomagnetic data, the appearance of cold-water carbonates in the second half of the Middle Ordovician can perhaps only be explained by the emergence of cold currents.

Overall, the described severe dissimilarity in the evolution of sediments in the Ordovician of Siberia and Baltica does not challenge the inclusion of these paleocontinents into a single continental SAB agglomeration (Fig. 4). At the same time, the cardinal changes in the sedimentation pattern of the Siberian basin (the Middle Ordovician destruction of the tropical carbonate platform and widespread dissemination of the siliciclastic facies which are, however, barely reflected in the evolution of the Baltica basins) need to be better understood.

SNB Model in Light of the SAB Concept and the Geochronological Data

As noted in the introduction, the cornerstone of the SNB model lies in the relative positions of Siberia and Baltica in the Vendian and Early Paleozoic. In accordance with the SNB model, at the boundary of the Precambrian and Paleozoic, Siberia and Baltica (1) made up a united continent and (2) faced each other by their present northern margins so that the Uralian margin of Baltica accreted the Yenisean margin of Siberia (Sengör et al., 1993, Fig. 3a). As seen from the SAB reconstruction (Fig. 4), this condition for the Ordovician is generally satisfied, which however implies the connection of Siberia and Baltica through the Arctida continent. A similar SAB configuration is also presumed for the Late Vendian (Shatsillo, 2015b). This logically suggests that the basement of the hypothetical Kipchak arc which, according to the SNB scheme, is formed on the band of continental crust rifted from the Uralian–Yenisean margin of Siberia–Baltica in the Vendian–Cambrian, should have contained the fragments of both Baltica and Siberia and the Arctida fragments. If this is the case, the footprints of SAB (the Precambrian complexes of the Uralian–Yenisean periphery of SAB) should be presently observed within CAMB in association with the Early Paleozoic island arc complexes. However, the track of the initial rifting and island-arc volcanism of the Kipchak arc should be present in the Early Paleozoic sedimentary strata of the Yenisean–Uralian SAB margin (the Uralian margin of Baltica and the Barents part of Arctida, as well as the Yenisean margin of Siberia) in the form of a tuffaceous admixture.

Do similar geological signs within CAMB also exist in the platform margins? The answer can be derived from the regional analysis of the geochronological data for the detrital zircons contained in the Early Paleozoic sedimentary formations of the platforms and fold belt and from comparing these data with the established geochronological images of SAB and its parts. The data on the age of detrital zircons allow us to obtain (1) an integral estimate for the ages of the source rocks of the sediments deposited in a certain region and (2) the age of cosedimentation aerial volcanism, if any. In the context of testing the SNB model, fundamentally important geochronological and isotope-geochemical data have been to date obtained for the following regions:

(1) The Uralian part of CAMB (East Uralian Uplift and Sakmar zone, the Lower to Middle Ordovician terrigenous strata: the Mayachnaya, Rymninsk, and Kidryas formations) (Kuznetsov et al., 2016). The U-Pb ages and Lu-Hf isotope data for the detrital zircons from these objects show that the Ordovician sandstones composing them could have been formed due to the erosion of complexes similar in age and isotopic characteristics to the Arctida basement complexes, with the contribution of the Cambrian igneous (probably island arc) complexes. This may indicate that the sediments composing the Ordovician strata of the East Uralian Uplift and Sakmar zone of South Urals were derived from the fragments of an island arc (or a series of island arcs) that was incepted at the Arctida fragments. The fact that the Kidryas Formation of the Sakmar zone contains olistostroms, including Early Cambrian archaeocyata limestones (Kuznetsov, 2009 and references therein) may testify to the location of an island arc in the low warm latitudes close to Siberia, the homeland of archaeocyata—the organisms which are not known in the Cambrian cold-water deposits of Baltica. In turn, this prompts the idea that the island arc's basement could primarily pertain to the near-Siberian part of Arctida. An alternative interpretation of the geochronological data for the detrital zircons from the Ordovician sandstones of the Southern Urals was suggested previously and considered complexes similar to the Cadomides of Europe and the southern framing of Baltica (Scythian–Turan Plate) as the source formations (Kuznetsov, 2009; Kuznetsov et al., 2017).

(2) The Upper Cambrian–Lower Ordovician strata of the western zone of Polar and Sub-Polar Urals (Manitanyrd Group, Pogurei, and Sablya formations (Soboleva et al., 2012; Nikulova et al., 2016; Miller et al., 2011)). Tectonically, these strata are considered as the structural elements of the lower horizons of the Pechora Plate sequences and, simultaneously, as the structural elements of the passive margin of the continent (Puchkov, 2010) of which this plate had been a part in the Early Paleozoic. According to the standpoint (Kuznetsov and Romanyuk, 2014), these strata are considered as the complexes of the rift basin that separated the block from the continent, whereas the Maloural'skaya Island Arc developed in the Middle Paleozoic. Irrespective of the concepts of the geodynamic nature of the Manitanyrd Group, and the Pogurei and the Sablya formations, the basement underlying them is composed of the dislocated Neoproterozoic complexes of Proto-Uralides–Timanides, i.e., the complexes that were formed as a result of the collision of Arctida and Baltica at the Late Vendian–Cambrian boundary, which marked the formation of the Arct-Europe composite continent (Kuznetsov et al., 2007; 2010). The range of ages of detrital zircon from the sandstones of these units indicates that the terrigenous material for their formation was derived from the Proto-Uralides–Timanides orogen (i.e., basement); besides, there is also a significant zircon population with ages close to the time of the sedimentation of these rocks (Soboleva et al., 2012; Nikulova et al., 2016). The ages of the youngest zircons of 481, 508, and 495 Ma (the Manitanyrd Group and the Pogurei and Sablya formations, respectively) are interpreted as reflecting the episodes of con-sedimentation magmatism associated with rifting in the Uralian margin of Arct-Europe (Soboleva et al., 2012; Nikulova et al., 2016). The Sablya Formation sandstones of Sub-Polar Urals are underlain by volcanic-sedimentary rocks, consistent with the rift model (Nikulova et al., 2016); here, volcanics are absent higher in the section. In contrast to the Subpolar Ural objects, the sandstones of the Polar Urals Manitanyrd Group and Porurei Formation are not closely associated with the volcanics which could have been a source of the young zircons, except for the thin basaltoid flow located within the basal level of the Manitanyrd Group in the western part of the Engane-Pe Uplift (Soboleva et al., 2012). The Lower Ordovician (Upper Cambrian–Lower Ordovician) terrigenous rocks containing the con-sedimentation (tuffaceous) zircons are located higher

in the sections than the units largely composed of volcanics. The basaltoid flows which are in some (rare) cases associated with these rocks are barely capable of providing coeval zircons because basalts are extremely poor in a primarily magmatic zircon. Hence, we may hypothesize that tuffaceous zircons could have been provided by the pyroclastic material formed during the island arc volcanism which started almost simultaneously with the Early Paleozoic rifting processes.

(3) The Upper Cambrian strata of the Yenisean margin of the Siberian Platform (Evenki Formation of Yenisei Ridge). Besides the Meso–Neoproterozoic non-Siberian zircon populations and the Archaean–Early Proterozoic zircon populations typical of the Siberian basement, the terrigenous-carbonate deposits of the Evenki Formation, a structural element of the platform's basement in the western regions of the Siberian Platform, also contain grains with ages close to the time of the sedimentation of the rocks (Priyatkina et al., 2016). To all appearances, these young zircons have a con-sedimentation age, tuffaceous nature, and non-Siberian source because the manifestations of Late Cambrian magmatism in the territory of the Siberian Platform are not known. It is logical to relate the origin of con-sedimentation zircons in the Upper Cambrian Evenki Formation to the island-arc aerial volcanism which took place in the Cambrian within the structures whose relics are known within the present CAMB. The Vendian–Cambrian island arc probably supplied zircons with an age of ~540 Ma contained in the rocks of the Vorogovka Group of the Late Neoproterozoic widespread in the northwest regions of Yenisei Ridge (Letnikova et al., 2016).

In the context of the question discussed, it is perhaps interesting to consider the data on the ages of detrital zircons from the Paleozoic meta-sedimentary deposits of Mongolia (Rojas-Agramonte et al., 2010; Kröner et al., 2011) which contain information about the ages of the rocks composing the Vendian–Cambrian island-arc complexes in this part of CAMB. Based on the geochronological data, the authors of the cited papers hypothesized that the basement of the island-arc complexes was composed of the Tarim block outliers. In our opinion, the obtained age ranges rather suggest a combined source, including the complexes of the Early Precambrian basement of Siberia (or their redeposition products) and the Neoproterozoic complexes of the Proto-Uralides–Timanides; however, this idea is remains insufficiently substantiated.

Thus, the review of the geochronological data for detrital zircons from the Early Paleozoic rocks within the margins of Baltica, the Siberian craton, and CAMB structures suggests that (1) in the Vendian–Cambrian, island-arc systems (or a united system) acted within the Paleo-Asian Ocean in the vicinity of the Yenisean and Uralian margins of Siberia and Baltica (and Arctida); (2) at least some of the Vendian–Cambrian island arcs of the Paleo-Asian ocean originated on the continental crust represented by the fragments of Baltica, Arctida, and probably Siberia (or their combination); and (3) the initial stages of the formation of Vendian–Cambrian island arcs (passive margin rifting) are tracked in the Uralian margin of Arctida (Sub-Polar Urals). Of course, this conclusion does not prove the SNB model but provides additional arguments in support of the tested concept.

CONCLUSIONS

Based on the conducted combined analysis of the paleomagnetic, geological, and geochronological data, we suggests several more-or-less substantiated conclusions and hypotheses presented below.

(1) The paleomagnetic data for Siberia and Baltica show similar trends of the migration of the paleomagnetic poles in the Ordovician. The similarity of these trends suggests that the considered continental blocks in the Ordovician could have experienced coherent displacements; they i.e., could have composed a common lithospheric plate. The best alignment of the Ordovician paleomagnetic poles for Siberia and Baltica is achieved by their rotation about the Euler pole located within the Kara Sea. As was shown (Shatsillo, 2015a), a similar Euler pole describes the rotation of Siberia relative to Baltica during the amalgamation of the northern part of Pangaea, i.e., the formation of North Eurasia in its Early Mesozoic configuration, which is close to the present configuration. This suggests that throughout the entire Paleozoic and, perhaps, even starting from the Late Vendian (Shatsillo, 2015b), Siberia and Baltica made up a consolidated continental agglomeration with the configuration determined by the rotation of the cratons about the same Euler pole. If this conclusion is valid (and we have not found any data to challenge it), the paleomagnetic data for the Paleozoic of Siberia and Baltica, with the corresponding tectonic corrections, can be jointly used for creating paleo-reconstructions and developing the combined (joint) APWP curve.

(2) The paleotectonic reconstruction based on the combined set of the paleomagnetic data for the Ordovician of Siberia and Baltica indicates that (a) during the Ordovician, the northern (Taimyr) margin of Siberia faced the northeastern (Timan) margin of Baltica, spaced ~2000 km apart; (b) the territory between Siberia and Baltica was occupied by the Arctida continent. This is, inter alia, consistent with the paleomagnetic data for the Ordovician of the Kara block (Severnaya Zemlya Archipelago) (Metelkin et al., 2005) which was part of Arctida; and (c) since the collision of Arctida and Baltica is estimated to have occurred in the Late Vendian–Early Cambrian (Kuznetsov et al., 2014), whereas the relative positions of Siberia and Baltica in the Late Vendian are presumed to be similar to their Ordovician positions (Shatsillo, 2015b; Shatsillo et al., 2015 and references therein), all these three blocks can be deemed to have formed the Siberia–

Arctida–Baltica (SAB) composite continent at the end of the Vendian–beginning of the Paleozoic.

(3) The SAB continent was elongated along the meridian and stretched from the subpolar to the equatorial climate belts in the Southern hemisphere. The Baltic fragment of SAB occupied the midlatitude and high-latitude regions, whereas the Siberian fragment spanned the low-latitude area. During the Ordovician, SAB drifted northwards by ~2–8 cm per annum in the Early and Middle Ordovician and somewhat faster (by up to 12 cm per annum) in the Late Ordovician. The Late Ordovician jump in the velocity of the latitudinal drift of SAB was preceded by a change in the direction of the SAB rotation (from clockwise in the Early Ordovician to counterclockwise). The facies content and lithological features of the rocks deposited within the Ordovician basins of Siberia and Baltica agree with the concept of the latitudinal drift of the Baltic fragment of CAMB from the high latitudes of the Southern hemisphere to the low latitudes and with the low-latitude position of the Siberian fragment, at least at the beginning of the Middle Ordovician. The emergence of cold-water carbonates in the Siberian sections in the second half of the Middle Ordovician could be accounted for by the emergence of cold currents, which requires further investigation. Quite probably, the Middle Ordovician restructuring of the system of currents in the World Ocean was related to the global tectonic rearrangement of the entire ensemble of the lithospheric plates and the change in the pattern of their motion which, in turn, could have been a precursor of the Middle Paleozoic's largest tectonic event—the collision of Baltica (the Baltic part of CAMB) and Laurentia and which could have been a cause of the change in the character of the CAMB's drift in the Middle Ordovician.

(4) The analysis of the geochronological data for the detrital zircons from the Cambrian-Ordovician formations of the Uralian margin of Baltica, the Yenisean margin of Siberia, and some CAMB objects permits the possibility of relics of the continental crust of Arctida and probably Siberia (or their combination) within the CAMB structures. These SAB fragments could have served as the basement for the Vendian–Cambrian island-arc complexes presently composing a significant part of CAMB. The separation of these SAB fragments from the continental mass was caused by the Vendian–Cambrian rifting in the Yenisean–Uralian margin of the continent. This conclusion to a certain extent agrees with the SNB model (Sengör et al., 1993) where the Early Paleozoic evolution of CAMB is considered as the result of the activity of the giant Kipchak island arc stretched along the Yenisean–Uralian margin of Siberia and Baltica, which was incepted on the band of the continental crust that rifted off from the cratons in the Vendian–Cambrian. The SAB configuration suggested by us generally agrees with the key points of the SNB model according to which in the Vendian–Early Cambrian, Siberia and Baltica should have faced each other by their present northern margins. Our constructions are not intended for proving the validity of the SNB model; however, our conclusions are overall consistent with the described concept and may indicate that (probably an appreciable) part of the Vendian–Cambrian island arc complexes which are currently present in the CAMB structure were incepted on the fragments of the Siberia–Arctida–Baltica composite continent rather than on the fragments of Gondwana or Tarim block, as suggested by other authors (Didenko et al., 1994; Buslov et al., 2001; Rojas-Agramonte et al., 2010; Kröner et al., 2011; etc.).

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