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The Positions of Microcontinents in the Northern Tien Shan and Eastern Urals in the Ordovician and Silurian from Paleomagnetic Data

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Abstract—The location of the Issyk Kul Early Paleozoic microcontinent in Middle–Late Ordovician time was established at a latitude of 9.8 ± 2.4° as a result of examining the paleomagnetic properties of the Middle Ordovician molasse in the Kirgyz Range of the Tien Shan. This paleomagnetic study of the Middle–Upper Ordovician rocks from the East Ural microcontinent resulted in establishing its location at a latitude of 4.0 ± 3.2°. The microcontinent was located at that time at a distance of over 750 km (along a paleomeridian) from the nearest margin of the Baltic continent. Early Silurian paleomagnetic latitudes—9.1 ± 4.5° and 12.2 ± 3.4°—were determined in various parts of the East Ural microcontinent. They are close in value to the paleolatitude of the nearest margin of the Baltic continent. The paleomagnetic data also support a model, according to which the Early Silurian volcanics of the Eastern Urals had accumulated on the East Ural microcontinent.

Paleomagnetic investigations have resulted in determining the Early Paleozoic paleolatitudes of large continents: Paleogondwana, Baltia, and Siberia [17, 29, 41, 42]. In the Early Paleozoic, numerous microcontinents and island arcs existed between these continents in a vast space of the Paleotethys Ocean, which were later incorporated into Eurasia and the crust of which makes up a considerable portion of this present-day continent. The paleomagnetic study of these areas has recently been initiated for the purpose of Early Paleozoic tectonic reconstructions. In this study we examined the paleomagnetism of the Ordovician and Silurian rocks from the Northern Tien Shan and the Eastern Urals.

NORTHERN TIEN SHAN

The suture of the Turkestan Ocean, which existed from the Vendian or Early Cambrian to the Late Paleozoic, divides the Paleozoic structures of the Tien Shan into the North Turkestan and South Turkestan domains (Fig. 1). The sutures of the Terskei and Ili Early Paleozoic oceanic basins divide the North Turkestan domain into terranes. The area between the Terskei and Ili sutures is occupied by the Issyk Kul terrane, whose Ordovician rocks were the target of our paleomagnetic study. This terrane consists of rocks of the Early Paleozoic microcontinent, upon which the rocks of the oceanic crust and oceanic island arcs of the Terskei and Ili basins were thrust.

We examined the paleomagnetism of the Middle Ordovician molasse on the northern slope of the Kirgyz Range in its middle segment. The lower portion of the exposed succession (Karabalta Formation 3000 m thick) consists of massive and thin-bedded mudstones and fine-grained sandstones with limestone lenses. Llanvirnian trilobites and Llandeilian graptolites were found in this formation [13, 30], and Llandeilian brachiopods were found near its top [5]. These rocks are overlain unconformably, with conglomerates at the base, by polymictic and quartz–feldspathic, largely red-colored sandstones, and siltstones enclosing interlayers of oolitic limestone (Chon-Kaindy Formation over 3000 m thick). This rock sequence encloses numerous cross-bedded bands, and casts of ripple marks and raindrops, as well as shrinkage and cracking, were observed there. Early Llanvirnian conodonts were found in the Chon-Kaindy Formation in the valley of the river of the same name [13]. This formation is conformably overlaid by the Dzhartash Formation (over 1000 m thick) of thin-bedded carbon–clayey siltstones and limestones with quartz sandstone interlayers. Early Llandeilian conodonts were found in the rocks of this formation [13]. Scarce interlayers of tuff and lavas of acid and basic compositions were encountered in various parts of this rock succession.

A total of 116 specimens of siltstones and fine-grained sandstones were collected for paleomagnetic measurements from the Middle Ordovician Chon-Kaindy Formation in the valleys of the Chon-Kaindy and Cholok-Kaindy rivers on the northern slope of the Kirgyz Range (Fig. 1). The coordinates of the Kaindy sampling locality are 42°39′ N and 73°45′ E.

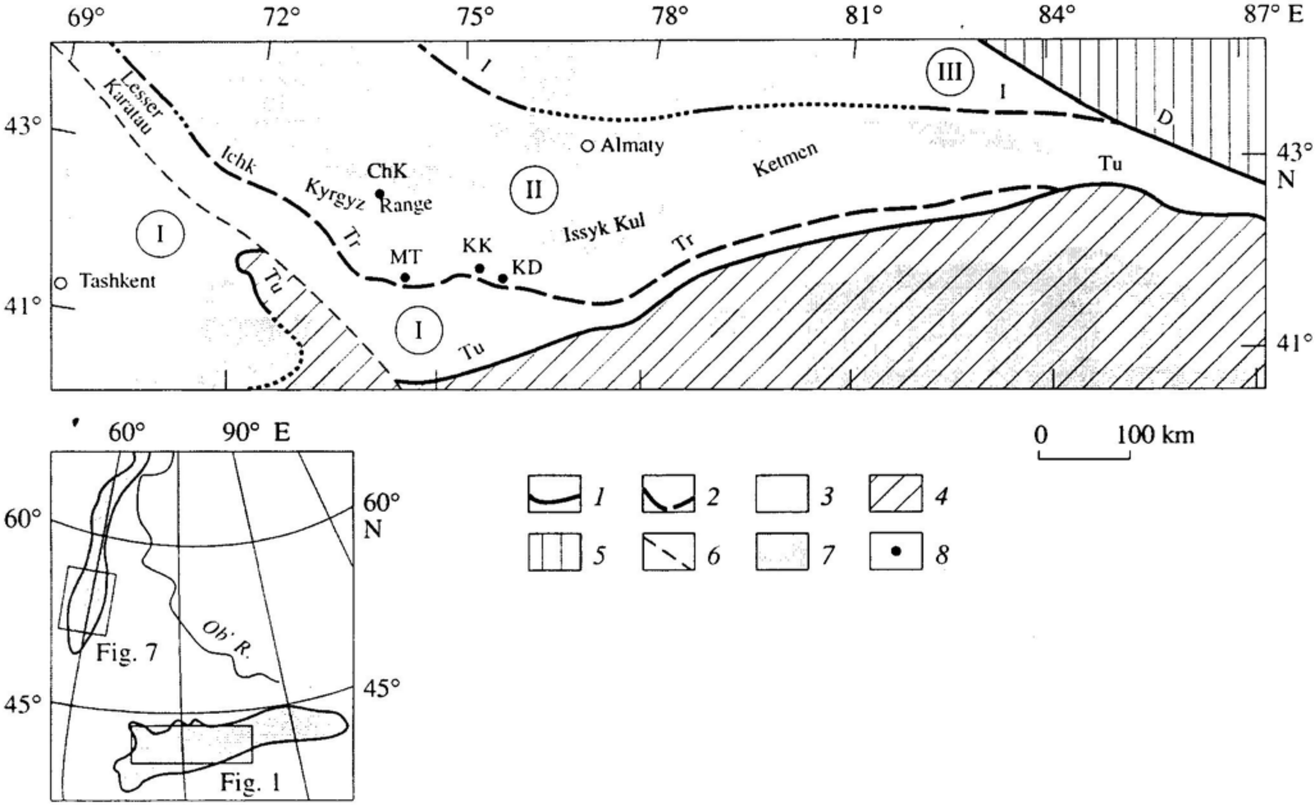

Fig. 1. Paleozoic oceanic sutures and tectonic zones in the Tien Shan. (*1*) Late Paleozoic sutures: Tu—Turkestan, D—Dzungarian; (*2*) Early and Middle Paleozoic sutures: I—Ili Silurian (?), Tr—Terskei Middle–Late Ordovician; (*3*) North-Turkestan domain, Early Paleozoic terranes: I—Syr-Darya, II—Issyk Kul, III—Borokhoro; (*4*) South-Turkestan domain; (*5*) Late Paleozoic Bogdashan terrane; (*6*) Talas—Fergana strike-slip fault; (*7*) Cenozoic depressions; (*8*) Localities of paleomagnetic examination of Early Paleozoic rocks (KD in the Karadzhorgo Range, KK in the Karakatty Ridge, MT in the Moldotau Ridge, ChK in the valleys of the Chon-Kaindy and Cholok-Kaindy rivers on the northern slope of the Kyrgyz Range); Ichk is the Ichkeletau Ridge. Location of Figs. 1 and 7 is shown in the location sketch map. The territories of the Urals and Tien Shan are shaded.

Methods and Results of the Paleomagnetic Study

All paleomagnetic specimens were subjected to a complete step-by-step thermal demagnetization in an oven installed into a two-layer Mumetal screen (residual field in the oven was below 20 nT). During each heating step, the positions of specimens in the oven were changed in a random way to compensate the superposed laboratory magnetization. The heating steps were changed from 50°C within the low-temperature range to 20–10°C when approaching the Curie temperatures of magnetite and hematite. The components of natural residual magnetization (NRM) were segregated in the process of analyzing the thermal demagnetization data using special algorithms and software courtesy of P. Enkin. Grouping and correlation tests were used [34, 39, 40].

A strong scatter of the initial rock magnetization characterized the examined collection of specimens. The rocks were subdivided into poorly magnetic (0.8–1.7 mA/m), medium magnetic (2–32 mA/m), and highly magnetic (35–63 mA/m). The medium-magnetic group of specimens was found to be most efficient. It turned out upon processing the whole collection that 27 out of the 116 specimens were not suitable for paleomagnetic determinations due to the chaotic changes of the NRM direction from one heating step to another. The remaining 89 specimens revealed two prefolding magnetization components, B1 and B2, which differed in their orientation. The low-temperature component (100–250°C) is close to the orientation of the present-day magnetic field in the study area.

We succeeded in segregating the medium-temperature component B1 in 25 specimens (T = 200–600°C). The fold test was positive (Figs. 2, 3, Tables 1, 2). Southeastern compass points and a negative magnetic inclination characterized this component.

We succeeded in discriminating the high-temperature (T = 300–690°C) prefolding magnetization component B2 in 68 specimens (Tables 1, 2). This component was most frequently found in a temperature range of 620–690°C. Hematite was found to be its bearer judging from the blocking temperature value (Fig. 3). The component displayed a variable polarity. Eastern compass points and a negative inclination characterized it in 59 specimens, while in 4 specimens it was found to be oriented westward and showed a positive inclination (Fig. 2).

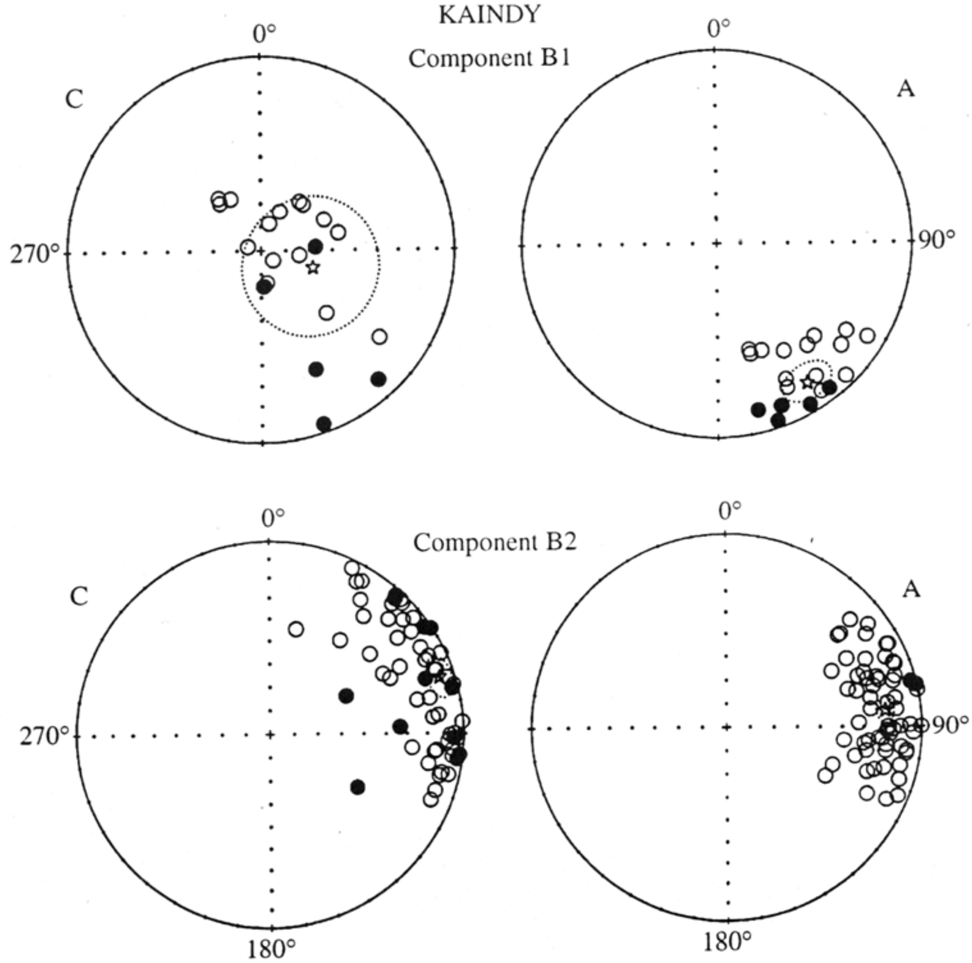

Fig. 2. Stereograms of the projections of paleomagnetic vector directions in the contemporary (C) and ancient (A) coordinate systems from the Tien Shan collection. Solid circles show the projections of vectors on the lower hemisphere; open circles show the same on the upper hemisphere. Stars indicate average paleomagnetic directions; the confidence oval is shown.

Conclusions

The paleomagnetic examination of the Middle Ordovician rocks from the Kirgyz Range resulted in detecting two prefolding magnetization components, which originated before the Late Ordovician folding in this area. Both components have close ages, because the rocks examined had been formed shortly before their compression into folds.

Judging from the resulting paleomagnetic data, the examined portion of the Issyk Kul terrane located in the

Table 1. Results of the paleomagnetic examination of the Tien Shan rock collection, Kaindy locality (O_2)

Statistics	N	n	Modern coordinate system				Ancient coordinate system				%
			D°	I°	k	α_{95}°	D°	I°	k	α_{95}°	
B1—prefolding medium-temperature component (Kaindy-1)											
Sample-based	25	20	108.4	−67.4	2.2	29.4	**147.2**	**−16.1**	**14.0**	**9.1**	100
B2—prefolding high-temperature component (Kaindy-2)											
Sample-based	68	63	71.8	−11.0	7.9	6.3	**83.9**	**−19.1**	**17.0**	**4.3**	100
Site-based		11	67.9	−9.9	12.5	12.0	**81.6**	**−19.6**	**25.7**	**8.3**	100

Note: N is the number of samples in which a high-temperature (medium-temperature) component was segregated; n is the number of specimens (sites) that were included in the statistics; I and D are paleomagnetic inclination and declination, respectively; α_{95} is the radius of the confidence oval; k is the concentration in Fischer's statistics; % is straightening at k max in percent.

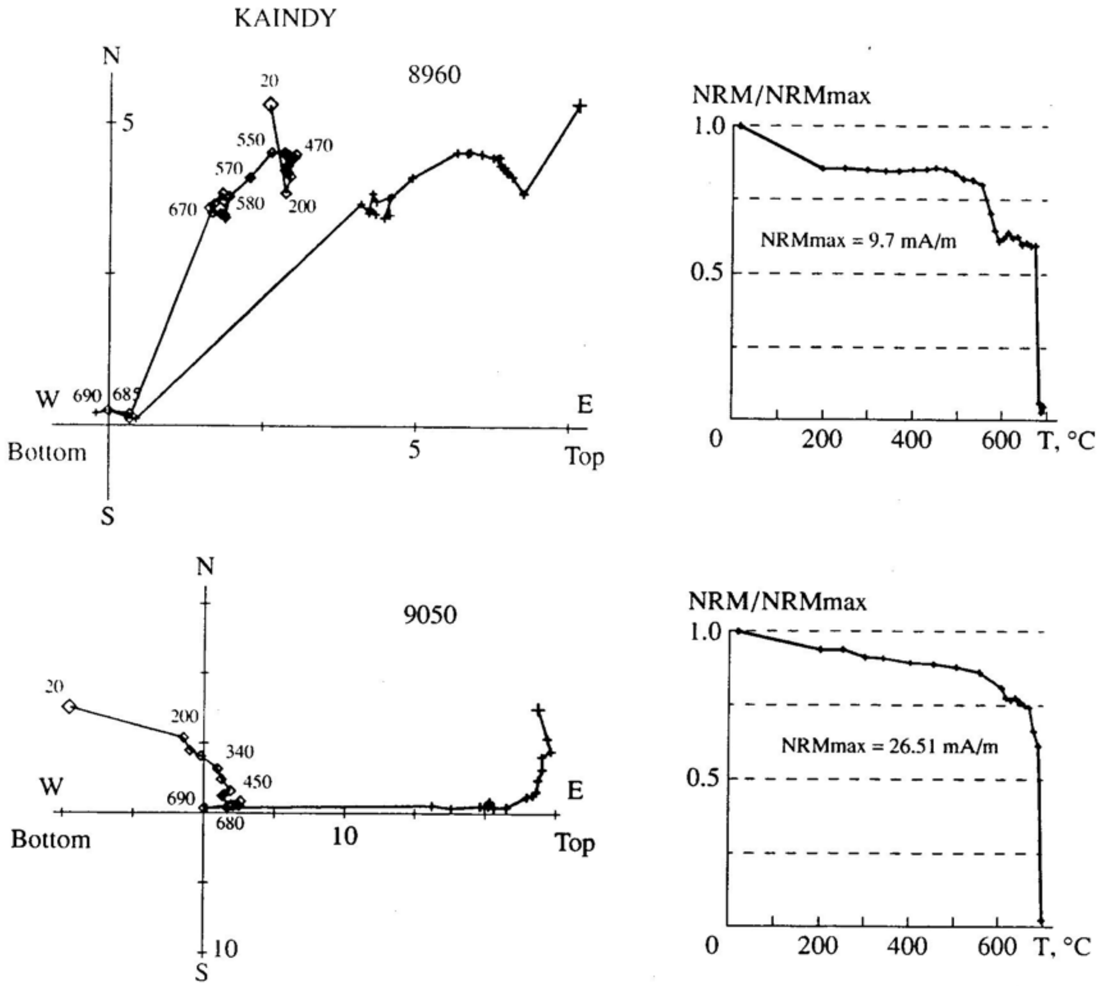

Fig. 3. Zijderveld's temperature diagrams and thermal demagnetization curves for the Tien Shan collection. The magnetization intensity is given in mA/m. NRM is natural remanent magnetization at a given temperature. Rhombs and crosses show the resultant projections of thermal demagnetization into the vertical and horizontal planes.

Middle–Late Ordovician at a latitude of 9.8 ± 2.4° either in the northern or in the southern hemisphere. The angle between the declinations of the two prefolding components was found to be 63°, which indicates a considerable rotation of the study area in the Middle–Upper Ordovician.

Discussion

Let us discuss the result of the paleomagnetic study in the context of the tectonic evolution of the region. Geodynamic models of the tectonic evolution of the North Turkestan domain or its portions in the Late Proterozoic and Early Paleozoic were suggested by numerous researchers [4, 11, 14, 16, 27, 35, 38, etc.]. They showed minor diffreences caused by the amount and quality of the factual evidence used. The principal features of the Late Proterozoic and Early Paleozoic evolution of the North Turkestan domain can be visualized as follows.

In the Riphean, the North Turkestan domain was situated in the continental environment. Carbonate sediments, quartz sand, and clay accumulated in marine basins. Three pulses of tectono-magmatic activity were distinguished at the 1300-, 1100-, and 850-Ma levels. The last of these pulses resulted in the accumulation of thick successions of continental rift-related volcanics. This may have been caused by the rise of a mantle plume, which preceded a breakup of the continental crust and spreading.

In the Early Sinian, the continental rifting processes continued, which is supported by the occurrence of coeval rift-related deposits in the territories of the Syr-Darya and Issyk Kul terranes. The rifting resulted in the breakup of the Riphean continent and in the origin of the Terskei oceanic basin, which divideded the Riphean continent into the Syr-Darya and Issyk Kul microcontinents. There are data suggesting the existence of the Terskei oceanic basin in Sinian time when accretion processes occurred on its margin, which resulted in the

Table 2. Results of paleomagnetic testing, after [39, 40]

Component	Statistics	Test							
		Equalization		Grouping			Correlation		
		S	S *cr*	F *c*	F *cr*	F *a*	R *c*	R *cr*	R *a*
		Kaindy (é$_2$)							
B1	By specimens (20)	**6.3**	1.7	–	–	–	0.697	0.609	**0.319**
B2	By specimens (63)	2.1	2.1	–	–	–	0.847	0.787	**0.692**
B2	By sites (11)	**2.2**	1.3	8.63	1.96	**1.80**	0.707	0.394	**0.373**
		Bagaryak (S_1)							
A	By specimens (56)	0.60	1.4	–	–	–	**0.158**	0.404	0.656
B	By specimens (40)	**1.8**	1.5	9.31	2.23	**1.61**	0.689	0.442	**0.347**
B	By sites (6)	**4.6**	3.0	–	–	–	–	–	–
		Varna (S_1)							
B	By specimens (26)	1.3	1.6	4.17	2.57	**0.35**	0.625	0.527	**0.370**
B	By sites (4)	**15.9**	4.3	–	–	–	–	–	–
		Bagaryak–Varna (S_1)							
B	By specimens (66)	**2.0**	1.3	10.66	1.84	**1.59**	5.38	2.65	**2.08**
B	By sites (10)	**5.2**	2.2	8.74	3.63	**1.36**	0.855	0.815	**0.430**
		Toguzak (é$_{2-3}$)							
A	By specimens (70)	0.2	1.3	–	–	–	0.391	0.380	0.906
B	By specimens (10)	**3.7**	2.2	–	–	–	0.872	0.815	**0.585**

Note: $S = k_c/k_a$, where k is concentration; F and R are statistical sample values (*c* in contemporary and *a* in ancient coordinate systems; *cr* is a critical value); grouping and correlation tests are positive (prefolding magnetization) at R_a and F_a below critical; the equalization test is positive at $S > S_{cr}$; underlined are data that determine the magnetization time.

formation of pre-Vendian thrust nappes in the Karadzhorgo ridge [28]. Fragments of oceanic crust rocks were included during the Vendian into sediments that accumulated on the continental crust in the Lesser Karatau [6]. Hence, some portion of the Terskei oceanic crust must have been deformed by that time and experienced abrasion or erosion. As for the Ili oceanic basin, there are data suggesting its existence since the Early Cambrian. The Pb–Pb zircon dating of the ophiolites from the South Kazakhstan portion of this basin yielded a value of 510 Ma [36]. Thus, the Issyk Kul terrane existed as a microcontinent bordered by basins with oceanic crust from the beginning of the Paleozoic. During the Cambrian and earliest Ordovician, the margins of the Issyk Kul microcontinent were passive (Fig. 4).

In the Early Paleozoic, the Terskei oceanic basin was a marginal basin of the Turkestan Ocean and was separated from the latter by the Syr-Darya microcontinent. An oceanic volcanic island arc or, more probably, an ensemble of ensimatic island arcs was active in the Terskei basin at that time. The island-arc ensemble and its parts are known as the Karadzhorgo, Kapkatash, Sarybulak; Choloi, and East-Terskei arcs [4, 14, 27, etc.]. We will use the first of these names for the whole ensemble. The rocks of the Karadzhorgo oceanic island arc are intruded by small massifs of Early Ordovician granitoids, which were dated by U–Pb and Pb–Pb zircon methods as 500–470 Ma old [16].

The Karadzhorgo island arc had divided the Terskei basin into two basins: the Naryn back-arc and the Kensai fore-arc basins. The bottom sediments of the Kensai basin crop out in the Ichkeletau Ridge. A tectonic slice there consists of variegated siltstones, sandstones, and mudstones containing Arenigian graptolites and enclosing interlayers of chert and limestone and turbidite bands (Kensai Formation). The sandstone composition suggests that two source areas exist. One of them was the Karadzhorgo island arc, which supplied fragments of intermediate, acid, and basic volcanics. The Issyk Kul microcontinent was the other source area, which supplied quartz, plagioclase, mica, and quartzite and granite fragments [15]. These deposits seem to have accumulated during the late stage of the fore-arc basin's existence, not long before its closing. The subduction of the oceanic crust of the Kensai basin occurred under the Karadzhorgo volcanic arc, while the obduction occurred upon this arc. In the frontal part of the arc there originated an accretionary prism, which is overlain with an angular unconformity by the Late Arenigian–Llanvirnian marine sediments.

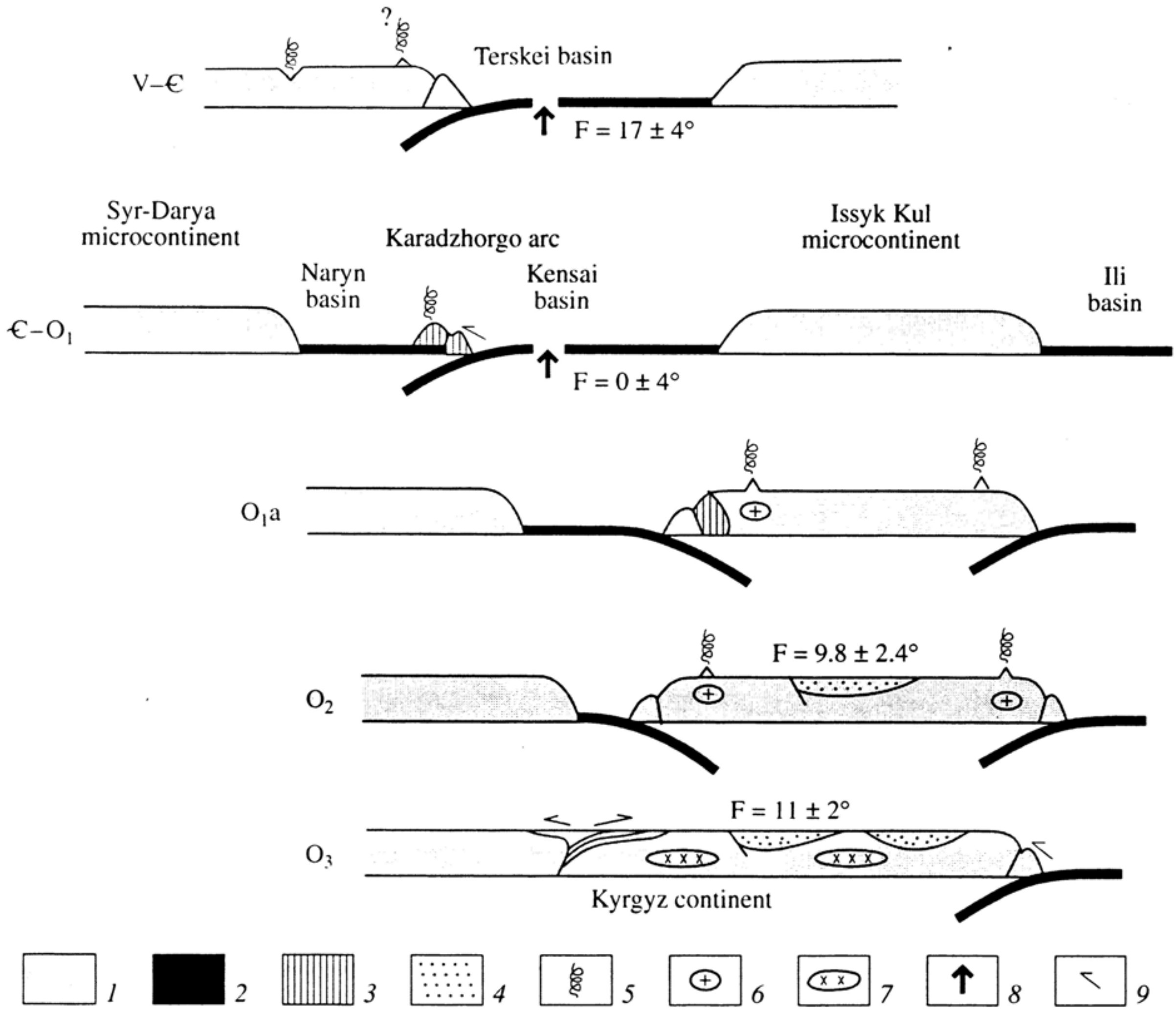

Fig. 4. Geodynamic models of the Northern Tien Shan. (*1*) continental crust; (*2*) oceanic crust; (*3*) rocks of the Karadzhorgo island arc; (*4*) orogenic and rift-related molasses; (*5*) volcanoes; (*6*) subduction-related granites; (*7*) collision-related granites; (*8*) spreading zone in the oceanic crust; (*9*) direction of obduction, overthrusting; F is paleolatitude from paleomagnetic data.

Cumulous gabbro, dikes, and pillow basalts from the oceanic crust of the Kensai fore-arc basin (which are currently allochthonous) were subjected to a paleomagnetic study in the Karakatty and Karadzhorgo Ranges [7–9]. The pillow basalts from the Karakatty Range enclose chert lenses with Late Cambrian conodonts. The results of the measurements of the prefolding magnetization component in the basalts indicate that they were in the Late Cambrian or in the Early Ordovician at a latitude of 0.4 ± 4.2°. A study of the paleomagnetism of the basalt dikes cutting the basalts in the Karadzhorgo Range yielded a similar result: a paleolatitude of 2.0 ± 2.9° (Table 3).

The prefolding, possibly, initial magnetization component in gabbro from the Karadzhorgo Range originated in the northern or southern hemisphere at a latitude of 16.7° ± 3.7°. The age of the gabbro has not been determined but can be placed in the interval Vendian–Tremadocian. The gabbro originated presumably in the Vendian or in the earliest Cambrian before the Terskei basin was divided into the Kensai and Naryn basins by an island arc. This is supported by the difference in the paleolatitudes determined in gabbro from the Karadzhorgo Range and in basalts from the Karakatty Range.

In the Arenigian, the Kansai basin closed and the Karadzhorgo arc docked onto the Issyk Kul microcontinent (collision-1). The volcanic rocks of the Karadzhorgo island arc with Middle Arenigian conodonts are common in the Karakatty Range, and the rocks of continental origin are abundant in the upper portion of its succession, which is the result of an island arc–microcontinent collision [14, 16].

As a result of the Arenigian collision, the rocks of the former Karadzhorgo island arc formed an accretionary prism in the Issyk Kul microcontinent, upon which turbidite accumulation commenced. After collision-1, the subduction of the oceanic crust of the Naryn basin began under the Issyk Kul microcontinent. As a conse-

Table 3. Paleomagnetic latitudes determined in the territory of the Issyk Kul Early Paleozoic terrane

Object of study	Rocks, location	Age of magnetic component	Paleolatitude, absolute value	Reference
Terskei oceanic crust	Cumulative gabbro, Karadzhorgo Range (component 1)	V–Є (?)	16.7 ± 3.7°	[9]
	Pillow basalt, Karakatty Ridge	$Є_3$–O_1	0.4 ± 4.2°	[8]
	Basalt dikes, Karadzhorgo Range	$Є_3$–O_1	2.0 ± 2.9°	[9]
	Cumulative gabbro, Karadzhorgo Range (component 2)	O_3 (?)	13.7 ± 3.3°	[7, 8]
Molasse in intracontinental basins	Siltstones, sandstones, Kyrgyz Range	O_{2-3}	9.8 ± 2.4°	This paper
	Siltstones, sandstones, Moldotau Range	O_3	11 ± 2°	[3]

quence, a magmatic belt was formed in the Middle Ordovician at the Terskei margin of the Issyk Kul microcontinent.

The subduction of the oceanic crust under the Ili margin of the Issyk Kul microcontinent commenced earlier than that at the Terskei margin, because the subduction-related volcanics were added to the deposits of the Ili margin in the Tremadocian. A marginal belt of subduction-related volcanics and granites also originated there. Thus, the Issyk Kul microcontinent was transformed in the Ordovician into a continental (ensialic) volcanic island arc with two marginal magmatic belts. The volcanism continued in both magmatic belts until the Caradocian, although its character changed in the Late Ordovician from the subduction-related to the collision-related type.

The subduction of the oceanic crust of the Naryn basin under the Issyk Kul microcontinent resulted in the closure of the Terskei oceanic basin and a collision between the Issyk Kul and Syr-Darya sialic blocks (collision-2). This event was marked by the cessation of turbidite accumulation at the southern margin of the Issyk Kul terrane in the late Middle Ordovician. During collison-2 in the late Middle Ordovician–early Late Ordovician, rocks of various provenance were thrust over the Issyk Kul terrane. They were derived from (a) the continental slope; (b) the accretionary prism consisting of the rocks of the Karadzhorgo oceanic arc and the Kensai back-arc basin; (c) the oceanic crust of the Terskei basin; and (d) the margin of the Syr-Darya microcontinent. Collision-2 resulted in the formation of the Kirgyz continent, which combined the Issyk Kul and Syr-Darya Early Paleozoic terranes. The origin of a superimposed postfolding magnetization component in the above-mentioned gabbroids of the Karadzhorgo Range at a latitude of 13.7 ± 3.3° (Table 3) was obviously related to these processes.

At approximately the same time, i.e., in the Middle Ordovician, the rocks of the oceanic crust of the Ili oceanic basin were obducted onto the northern margin of the Issyk Kul terrane. The obduction of the ophiolites might have accompanied the formation of an accretionary prism or could result from the collision and the closure of the oceanic basin. The Ili margin of the Issyk Kul terrane includes collision-related Late Ordovician–Silurian granites, and island arc-related volcanics with Early Silurian fossil remains occur in the Southern Ketmen Ridge. These volcanics suggest an accretion-related origin of the Middle Ordovician nappes in the Ili margin and the later closure of the Ili oceanic basin.

The events that occurred at the margins of the Issyk Kul terrane caused the deformation of its crust, which resulted in the formation of intracontinental orogenic and taphrogenic depressions. Thick molasse successions accumulated in these depressions in the Middle and Late Ordovician, which were folded at the end of the Late Ordovician. The above-mentioned results of the paleomagnetic study of the Middle Ordovician molasse allowed us to determine the position of the Issyk Kul terrane (in the northern or in the southern hemisphere) at a latitude of 9.8 ± 2.4°. The paleomagnetic study of the red-colored molasse in the Moldotau Ridge [3], which contains Late Caradocian brachiopods, yielded a similar result: 11 ± 2° (Table 3). It cannot be ruled out that the magnetization of the molasse rocks is Late Ordovician in both cases.

The Issyk Kul terrane was located in the Vendian–Early Cambrian at a latitude of 13°–20° and near the equator in the Ordovician, and, in the case of its forward movement, it must have moved into the other hemisphere to a latitude of ~10° by the Late Ordovician. The paleomagnetic data are not sufficient to estimate the direction of this motion.

We attempted to determine the orientation of the Issyk Kul terrane based on the paleomagnetic declinations. This terrane has an elongated form, and currently its longer axis is oriented roughly E–W. A wide strike-slip zone has been discovered in the Tien Shan, which occupies most of the latter's territory, where the differentiated rotations of its individual blocks (and paleo-

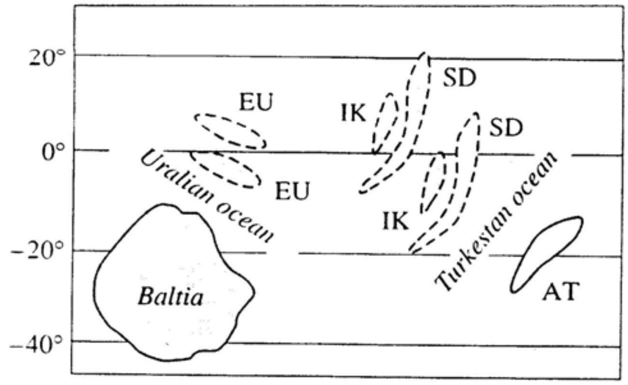

Fig. 5. Reconstruction of the location of microcontinents with respect to paleolatitudes in the Middle Ordovician from paleomagnetic data. Two possible options for the location of the examined microcontinents are shown: in the southern and the northern hemispheres. Microcontinents: AT is Alai–Tarim; EU is East Ural; SD is Syr-Darya; IK is Issyk Kul.

magnetic vectors) by angles of variable magnitudes had occurred in the Permian and post-Permian [2]. For the areas located within this zone, complex corrections must be introduced into the values of the magnetic declination for determining the orientation, which greatly impair the accuracy of the reconstruction. The Middle Ordovician rocks are located in the area of the Kyrgyz Range examined outside the strike-slip zone. This allowed us to determin the probable orientation of the longer axis of the Issyk Kul terrane in the Middle–Late Ordovician (Fig. 5), using the values of the paleomagnetic declination.

EASTERN URALS

The Baltic and Kazakhstan sialic blocks were separated by the Ural paleoocean in the Paleozoic. The time of the origin of this ocean is still uncertain, some geologists dating it to the Riphean (12, 21, 22), others, to the Late Cambrian–Early Ordovician [18, 20, etc.]. The Ural paleoocean included microcontinents and oceanic island arcs, the Ordovician and Silurian deposits of which were the targets of our paleomagnetic investigation.

Ordovician

In the Middle Ordovician, the East Ural (Mugodzhary) microcontinent was separated by oceanic basins from the Baltic and Kazakhstan sialic blocks (Fig. 6). The age of the Lower Paleozoic rocks in this block ranged from the Tremadocian through the Caradocian. The rocks were carbonate and clastic shallow-water deposits and rift-related alkaline volcanics. The Ordovician and Silurian deposits of the Eastern Urals underwent intense deformation in the middle of the Devonian and in the Late Paleozoic [19, 26].

The Middle and Upper Ordovician rocks of the East Ural microcontinent from the Srednii Toguzak River in the Southern Urals were the targets of our paleomagnetic study. These rocks were examined in opencast mines on the southern bank of the river opposite the Zarechie settlement (53°27′ N and 61°06′ E) (Fig. 7, T). Conglomerates with pebbles of basic volcanics and graywacke sandstones enclosing siltstone and mudstone interlayers with a total exposed thickness of 100 m crop out there. The sandstones contain the remains of Middle–Late Ordovician brachiopods, trilobites, and crinoids; the succession is most probably of Caradocian age [1]. A total of 110 sandstone and siltstone samples were collected there for paleomagnetic examination. The technique of the paleomagnetic study of the Uralian collection was similar to that described above.

The rocks examined showed an average magnetization of 0.24–12.85 mA/m. The collection was heterogeneous, and the samples were subdivided into three groups. The first group (12 samples) could not be used for paleomagnetic studies, either because of the chaotic changes in the NRM orientation from one heating stage to another or because its specimens have been completely remagnetized by the contemporary field. The second group included 63 samples showing one or two components: low temperature (100–200°C) and medium temperature (250–560°C). The third group consisted of 40 specimens that showed three magnetization compo-

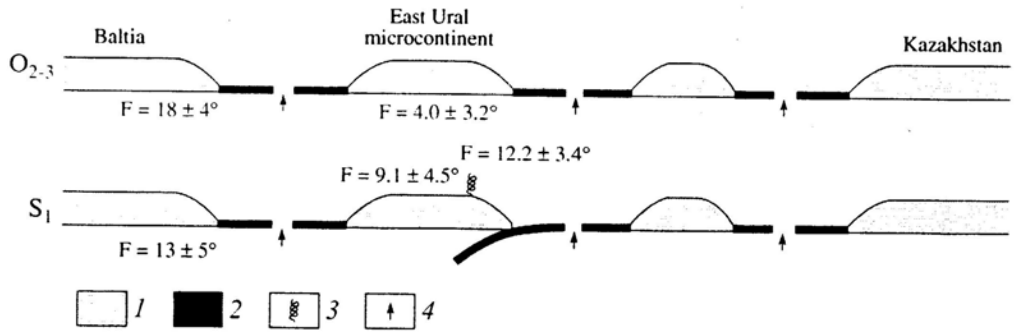

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Fig. 6. Geodynamic models of the Southern Urals (modified after [15, 36]). (*1*) Continental crust; (*2*) oceanic crust; (*3*) subduction-related volcanism; (*4*) spreading zone in the oceanic crust; F is paleolatitude by paleomagnetic data.

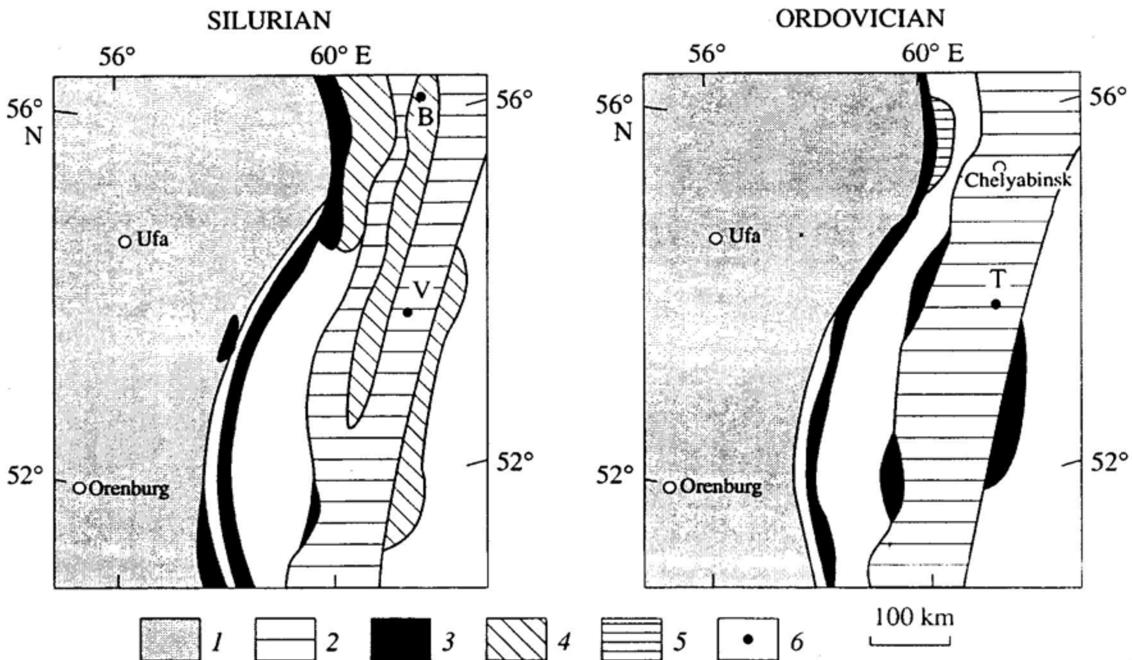

Fig. 7. Localities studied in the Eastern Urals (see Fig. 1). Sketch maps are modified after [12]. (*1*) Baltic continent including sediments on the shelf and continental slope; (*2*) East Ural microcontinent: shallow-water carbonate and terrigenous sediments; (*3*) oceanic basalts and deep-sea sediments; (*4*) calc-alkaline and contrast volcanics and associated sedimentary rocks; (*5*) alkaline intrusions; (*6*) paleomagnetic study localities: B—Bagaryak, V—Varna, T—Toguzak.

nents: low temperature (100–250°C), medium temperature (200–590°C), and high temperature (440–660C°) (Fig. 8).

The low-temperature component corresponds to the orientation of the contemporary magnetic field. The medium-temperature component A is postfolding in most of the specimens (equalization test was negative) and is usually close to the orientation of the Late Paleozoic remagnetization (Fig. 9, see Fig. 8; Table 4, see Table 2).

The high-temperature component was detected in 40 specimens. In 11 specimens this component was found to be in the present-day coordinate system with a direction close to the direction of the Late Paleozoic remagnetization; these specimens were discarded. The prefolding orientation of high-temperature magnetization (component B) was detected in ten specimens using its components and in 19 specimens using the circles of remagnetization (Figs. 8, 9; Tables 2, 4). The best specimens showed an initial magnetization ranging from 3.6 to 4.7 mA/m. An equalization test based on ten components and five sites, including the components and circles of remagnetization, was positive. A correlation test using ten components was also positive.

Silurian

The Silurian deposits in the East Ural zone include three major types: carbonate, siliceous–shaly, and volcanic. No stratigraphic contacts between them were known, this resulting in various assumptions concerning their initial relationships. The carbonate and siliceous–shaly Silurian deposits belong to the sedimentary cover of the East Ural microcontinent. The Silurian volcanic succession consists of Llandoverian rhyolite–dacite and basalt-rhyolite tuffaceous rocks and Wenlockian andesite–dacite extrusive rocks. The petrochemical features of these extrusive rocks are typical of continental-margin volcanics [33].

We examined the paleomagnetism of the Llandoverian rocks from a succession of the siliceous–shaly type near the settlement of Varna and from tuffaceous deposits in the Bagaryak River valley.

1. The Varna locality (53°23′ N, 61° 00′ E) is situated on the right bank of the Nizhnii Toguzak River near the settlement of Varna (Fig. 7, C). Here, carbonaceous–clayey and siliceous shales are exposed in an opencast mine; they enclose beds of small-grained quartz and quartz–plagioclase sandstones, siltstones, and mudstones with Late Llandoverian graptolites [26]. A total of 86 sandstone samples collected from a 20-m-thick member consisting of sandstones and siltstones and pressed into a fold were subjected to paleomagnetic examination.

The rocks at the Varna locality are weakly magnetic: from 0.07 to 0.98 mA/m. We succeeded in segregating the components in 49 specimens. Two components were segregated. The component that was recognized within a temperature interval of 100–250°C was close to the orientation of the contemporary magnetic field. In several

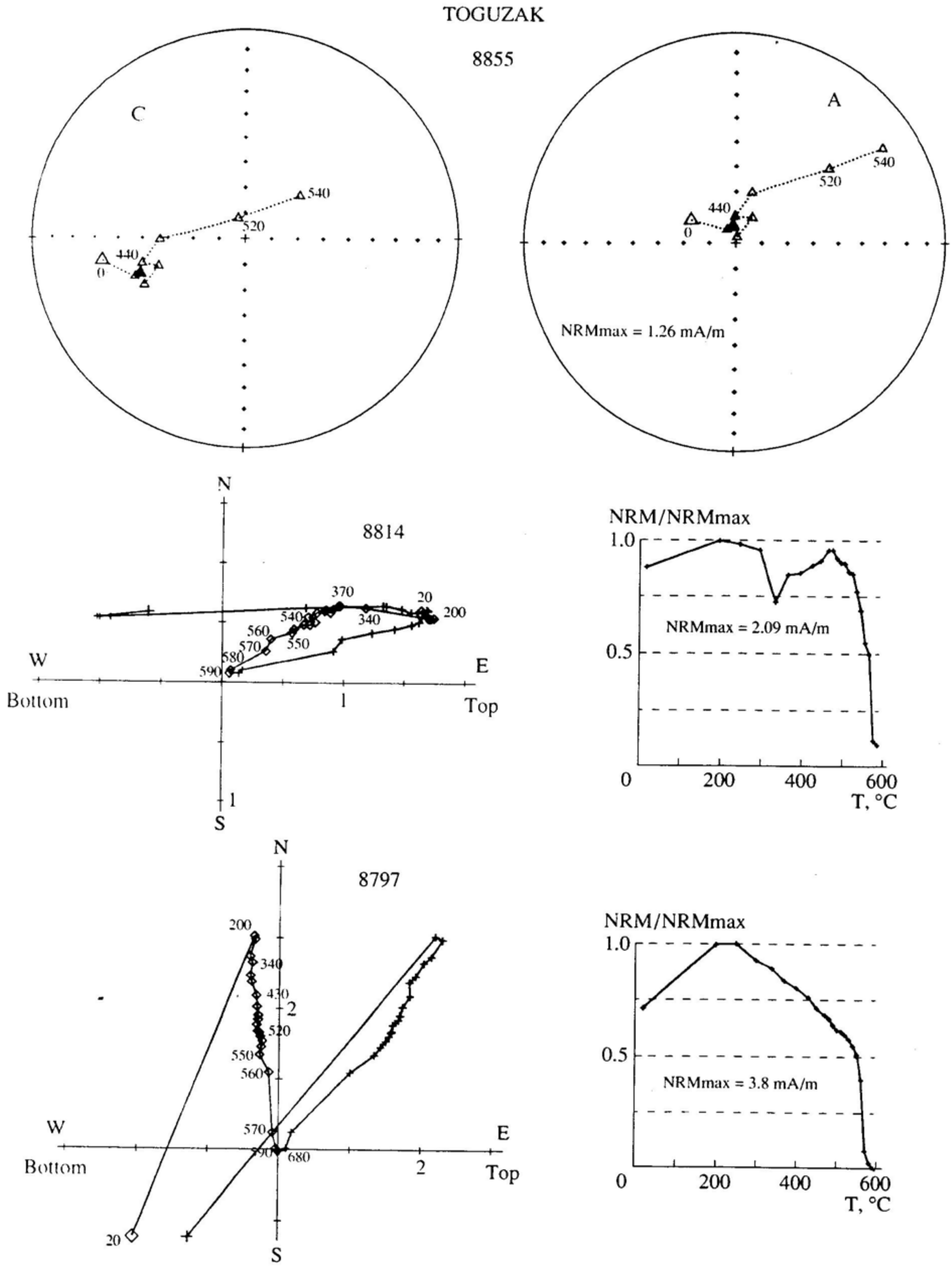

Fig. 8. Zijderveld temperature diagrams and thermal demagnetization curves for the Toguzak locality. The magnetization intensity is given in mA/m. An example of segregating a remagnetization circle is shown at the top of the figure. Points below T = 470°C lie in the region of the Late Paleozoic remagnetization; points at T = 470–540°C make a remagnetization circle that crosses the region of the projections of prefolding magnetization components. C and A are contemporary and ancient coordinate systems, respectively.

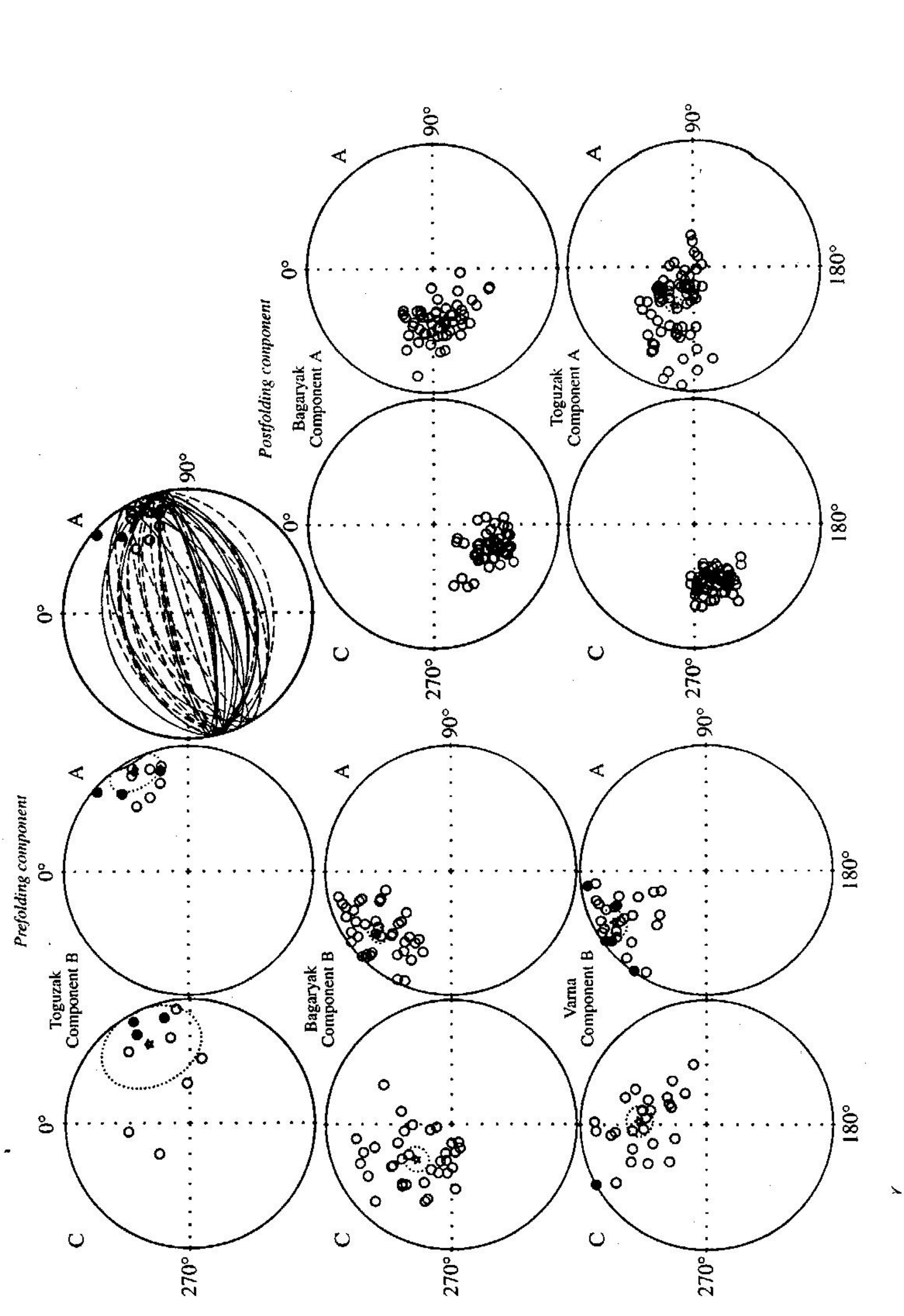

Fig. 9. Stereograms of projections of paleomagnetic vector directions in the contemporary (C) and ancient (A) coordinate systems from the Uralian collection. Solid circles show projections of vectors on the lower hemisphere; open circles show the same on the upper hemisphere. Stars show average paleomagnetic directions, and the confidence oval is shown.

Table 4. Results of the paleomagnetic examination of the Ural collection

Locality	N	n	Contemporary coordinate system				Ancient coordinate system				%
			D°	I°	k	α_{95}°	D°	I°	k	α_{95}°	
			A—postfolding component (PZ_3)								
Bagaryak (S_1)	58	56	**203.1**	**−48.7**	**31.8**	**3.4**	261.0	−54.7	19.8	4.3	0
			B—prefolding component (S)								
	55	40	315.0	−57.4	8.7	8.1	**319.0**	**−23.4**	**16.0**	**5.8**	100
		(6)	323.4	−59.8	13.7	19.2	**320.2**	**−23.9**	**62.8**	**8.5**	90
			B—prefolding component (S)								
Varna (S_1)	28	26	2.8	−45.6	9.6	9.3	**330.2**	**−17.8**	**12.5**	**8.0**	130
		(4)	357.8	−42.3	29.3	17.3	**330.8**	**−16.3**	**464.7**	**4.3**	110
			B—prefolding component (S)								
Bagaryak–Varna (S_1)	83	66	337.7	−55.5	7.1	7.1	**323.5**	**−21.9**	**14.3**	**4.8**	100
		(10)	341.7	−54.3	12.0	13.6	**324.6**	**−20.9**	**62.9**	**5.9**	100
			A—postfolding component (PZ_3)								
Toguzak (O_{2-3})	97	70	**251.1**	**−49.5**	**58.1**	**2.2**	296.1	−62.2	10.9	5.4	0
			B—prefolding component (O_{2-3})								
	40	10	63.2	−29.0	3.6	29.6	**61.7**	**−10.5**	**13.3**	**13.8**	90
		29*	67.4	−28.3	6.1	11.8	**67.2**	**−8.0**	**20.4**	**6.1**	–
		(5)**	64.7	−27.7	3.5	47.9	**67.8**	**−3.0**	**19.9**	**17.6**	90

Note: N is the number of specimens in which components were segregated; n is the number of specimens (sites) that were included in the statistics; I and D are paleomagnetic inclination and declination, respectively; α_{95} is the radius of the confidence oval; k is the concentration determined from Fischer's statistics; % is straightening at k max in percent. D and I were determined from the majority of data obtained from the samples.

* 29 (10 components and 19 remagnetization circles).

** 5 sites, 29 specimens.

specimens, the orientation of this component coincided with the orientation of the Late Paleozoic remagnetization. Component B was recognized in 28 specimens in a temperature interval of 100–500°C (most often between 250 and 450°C); this is a prefolding component, and both of our equalization and correlation tests were positive (Fig. 10, see Fig. 9; Tables 2, 4). Component B was found to be bipolar (18 and 8 specimens), and the reversal test was positive (F = 11.6 at F critical = 17.4).

2. The Bagaryak locality (56°12′ N, 61°50′ E) is situated in the Bagaryak River Valley near the settlement of Zotino (Fig. 7, B) where proximal tuff turbidites crop out. They consist of tuff gravelstone, tuff sandstone, tuff siltstone, and pelitic tuffite with interlayers of carbonaceous mudstone. Both the composition and thickness of the stratification rhythms are variable, and a gradational stratification is distinctly pronounced. The tuffaceous material is of a dacite composition. The apparent thickness of this succession is approximately 300 m. Late Llandoverian graptolites were determined in the carbonaceous mudstones [31]. Up the sequence, the lower elements of the rhythms grow coarser, and farther up the sequence, the rhythmical stratification vanishes, and massive tuff sandstones make up the succession. The volcanic fragments in this succession are of a rhyodacite and andesite composition, and fragments of reef limestone enclosing Wenlockian crinoids were encountered [31]. A total of 111 specimens of tuff sandstone, tuff siltstone, and pelitic tuffite from the lower, Late Llandoverian, portion of the Bagaryak succession were subjected to paleomagnetic examination.

The initial magnetization of specimens from the Bagaryak succession varied from 0.14 to 6 mA/m. The specimens with an initial magnetization of 0.7–1.46 mA/m yielded the best results. Four specimens showed chaotic changes of NRM orientation from one heating stage to another, and hence were discarded. A low-temperature component (T = 100–340°C), which coincided with the orientation of the contemporary field, was recognized in most of the specimens. A medium-temperature, postfolding component and a high-temperature, prefolding one were recognized in 107 specimens. Out of this number, both components were recognized only in 6 specimens, the postfolding component alone was recognized in 52 specimens, and the prefolding component, in 49 specimens. The paleomagnetic orientation in 15 specimens from the last group was close in the present-day coordinate system to

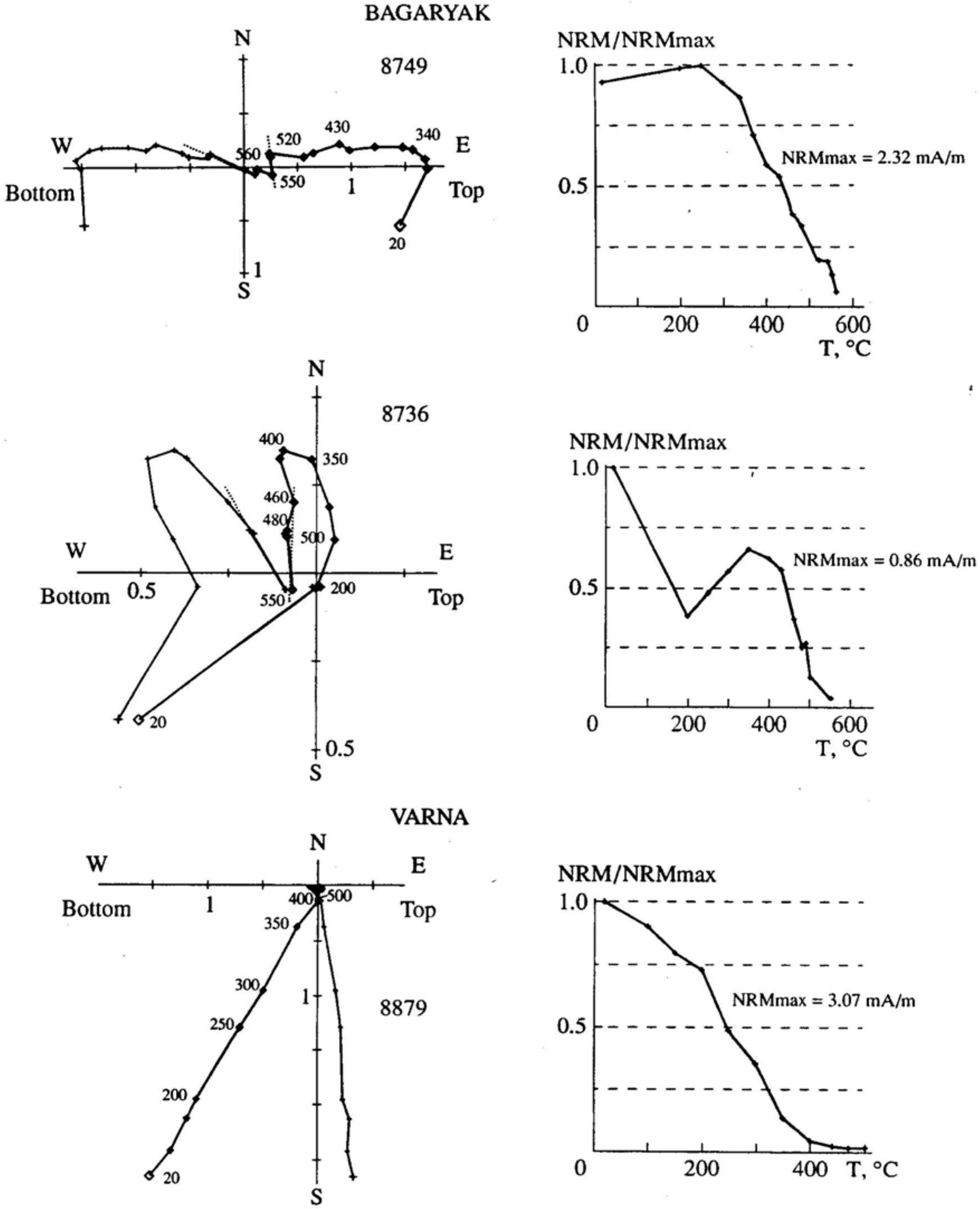

Fig. 10. Zijderveld's temperature diagrams and thermal demagnetization curves for the Bagaryak and Varna localities. The magnetization intensity is given in mA/m.

the direction of the contemporary field, and these specimens were discarded.

The medium-temperature postfolding component A (Figs. 9, 10; Tables 2, 4) was recognized in the temperature interval from 250 to 540°C. It is close in the present-day coordinate system to the inclination of the Late Paleozoic magnetic field and differs from it by a declination of 40°–50°.

The high-temperature component B was found to be prefolding, judging from a fold test (Figs. 9, 10; Tables 2, 4). It was recognized in a temperature interval of 340–580°C (more often between 400 and 560°C), and in 6 specimens, in an interval of 480–570°C. Component B orientation differs in the present-day coordinate system from the direction of the Late Paleozoic remagnetization. It showed a northwestern orientation

Table 5. Calculated paleolatitudes

Locality	Geographical coordinates of the locality	Magnetization age	I°	α_{95}°	φ°
		Northern Tien Shan			
Kaindy-1(O_2)	42°39′ N, 73°45′ E	O_{2-3}	16.1	9.1	8.2 ± 5.0
Kaindy-2 (O_2)	42°39′ N, 73°45′ E	O_{2-3}	19.1	4.3	9.8 ± 2.4
		Eastern Urals			
Bagaryak (S_1)	56°12′ N 61°50′ E	S	23.4	5.8	12.2 ± 3.4
Varna (S_1)	53°23′ N 61°00′ E	S	17.8	8.0	9.1 ± 4.5
Toguzak (O_{2-3})	53°27′ N 61°06′ E	O_{2-3}	8.0	6.1	4.0 ± 3.2

Note: I is the inclination of the average NRM vector in the ancient coordinate system; α_{95}° is the radius of the confidence oval; φ° is paleolatitude (absolute value) and its determination error.

and negative inclinations in 28 specimens, while southeastern declinations and positive inclinations were found in 12 specimens. The reversal test was positive (F = 10.5 at F critical = 12.4). Table 4 also shows integrated data for prefolding magnetization components for the whole of the Silurian collection; their fold tests were also positive.

Discussion and Conclusions

Our paleomagnetic study of the Middle–Upper Ordovician and Lower Silurian rocks from the Eastern Urals resulted in detecting prefolding paleomagnetic components older than the Middle Devonian, which was the time of fold formation in the study area. The prefolding paleomagnetic orientations in the Ordovician and Silurian rocks differ significantly from one another, which indicates their different ages. This suggests that we determined the initial paleomagnetic orientations. The positive reversal test in the Silurian rocks of the examined collection also supports this assumption.

The paleomagnetic data obtained on the rocks from the Toguzak locality suggest that the East Ural terrane was in the Middle–Late Ordovician at latitude of 4.0 ± 3.2° either in the northern or in the southern hemisphere (Table 5). A paleolatitude of 1 ± 10° was determined earlier using Arenigian rocks from the same terrane [23]. A paleolatitude of 4 ± 4° was determined for the Late Cambrian–Tremadocian rocks from the Lemva zone in the Polar Urals [10], i.e., at the Uralian margin of the Baltic continent. Similar paleolatitudes were determined using Upper Ordovician and Lower Silurian rocks from the oceanic crust in the Northern Urals [25]. These data are in good agreement with our results.

According to our data, the Bagaryak locality was located in the Early Silurian at a latitude of 12.2 ± 3.4°, and the Varna locality, at a latitude of 9.1 ± 4.5°. A paleolatitude of 12 ± 15° (I = 23.1°, α_{95} = 19.9°) was independently determined at the Bagaryak locality [24].

Some geologists believe that the Silurian carbonate and volcanic deposits of the Eastern Urals originated in separate terranes (in a microcontinent and in an ensimatic island arc, respectively), which were separated by an oceanic basin [18, 32]. The paleomagnetic paleolatitudes that were determined using the rocks from the microcontinent and the presumed island arc are identical. This favors a model according to which the subduction occurred in the Silurian at the margin of the East Ural microcontinent (Fig. 6).

The East-Ural microcontinent is elongated in shape, with its longer axis now trending N–S. According to the paleomagnetic data, the longer axis of the microcontinent was oriented NE–SW in the Middle Ordovician and NW–SE in the Early Silurian.

CONCLUSIONS

The results of our paleomagnetic studies (Table 5) and comparison of the results with the data available in the literature suggest the following conclusions.

(1) The paleomagnetic study of the Middle Ordovician molasse in the Kirgyz Range resulted in determining a paleomagnetic inclination of 19.1 ± 4.3°. This suggests that the Issyk Kul Early Paleozoic microcontinent was located in the Middle–Late Ordovician at a latitude of 9.8° ± 2.4° in the northern or southern hemisphere. This result is in agreement with the other paleomagnetic determinations of the paleolatitude using Lower Paleozoic rocks from the Northern Tien Shan. The analysis of paleomagnetic orientations suggests a rotation of the study area in the Middle–Late Ordovician.

(2) As a result of the paleomagnetic examination of the Early–Middle Ordovician rocks in the Tarim area, their location was determined at a latitude of 18.4 ± 11° (D= 227.1, I = –33.7, k = 10.8, and α_{95} = 15.4) [37]. As the Terskei oceanic basin was near its closing at that time, a comparison of the paleolatitudes of the Tarim and Issyk Kul terranes allows one to estimate the width of the Turkestan Ocean. If the Issyk Kul and Tarim basins were located in the same hemisphere, then the Turkestan Ocean had a width of not more than 2500 km along the paleomeridian (Fig. 5).

(3) According to our paleomagnetic data, the East Ural microcontinent was located in the Middle–Late Ordovician at a latitude of 4.0 ± 3.2°, whereas paleolatitudes of 9.1 ± 4.5° and 12.2 ± 3.4° were determined for the Early Silurian in various parts of this microcontinent (north or south of the equator).

(4) The Early Ordovician siliceous–shaly and volcanic rocks in the Eastern Urals accumulated at close paleolatitudes, and the subduction-related volcanic activity obviously occurred on the East Ural microcontinent in the Silurian.

(5) A paleolatitude determination at a site on the margin of Baltia, nearest to the Toguzak section, relative to the paleomagnetic pole of Baltia for the time line of 460 Ma ago [17] yielded 18° S ±4° If the East Ural microcontinent was located in the same hemisphere with Baltia in the Middle–Late Ordovician (Fig. 10), the distance from this microcontinent to the nearest margin of Baltia was > 750 km along the paleomeridian.

(6) The paleolatitudes of the sites on the Baltian margin that were nearest to the Varna and Bagaryak sequences, which were determined relative to the paleomagnetic pole of Baltia for a time of 430 Ma [17], are equal to 14.6° S ±5° and 12.3° S ±5°, respectively. If Baltia and the East Ural microcontinent were located in the same hemisphere, then the comparison of these values with the Early Silurian paleolatitudes of the microcontinent (9.1 ± 4.5° and 12.2 ± 3.4°) suggests its close paleolatitudinal position with respect to the margin of Baltia at that time.

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