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Devonian paleomagnetism of the North Tien Shan: Implications for the middle-Late Paleozoic paleogeography of Eurasia

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Abstract

The Ural–Mongol belt (UMB), between Siberia, Baltica and Tarim, is widely recognized as the locus of Asia's main growth during the Paleozoic, but its evolution remains highly controversial, as illustrated by the disparate paleogeographic models published in the last decade. One of the largest tectonic units of the UMB is the Kokchetav–North Tien Shan Domain (KNTD) that stretches from Tarim in the south nearly to the West Siberian Basin. The KNTD comprises several Precambrian microcontinents and numerous remnants of Early Paleozoic island arcs, marginal basins and accretionary complexes. In Late Ordovician time, all these structures had amalgamated into a single contiguous domain. Its paleogeographic position is of crucial importance for elucidating the Paleozoic evolution of the UMB in general and of the Urals in particular. The Aral Formation, located in Kyrgyzstan in the southern part of the KNTD, consists of a thick Upper Devonian (Frasnian) basalt–andesite sequence. Paleomagnetic data show a dual-polarity characteristic component (Dec/Inc = 286°/+56°, α_{95} = 9°, k = 21, N = 15 sites). The primary origin of this magnetization is confirmed by a positive test on intraformational conglomerates. We combine this result with other Paleozoic data from the KNTD and show its latitudinal motion from the Late Ordovician to the end of the Paleozoic. The observed paleolatitudes are found to agree well with the values extrapolated from Baltica to a common reference point (42.5°N, 73°E) in our sampling area for the entire interval; hence coherent motion of the KNTD and Baltica is strongly indicated for most of the Paleozoic. This finding contradicts most published models of the UMB evolution, where the KNTD is separated from Baltica by a rather wide Ural Ocean containing one or more major plate boundaries. An exception is the model of Şengör and Natal'in [A. M.C. Şengör, B.A. Natal'in, Paleotectonics of Asia: fragments of a synthesis, in: A. Yin and M. Harrison (eds.), The tectonic evolution of Asia, Cambridge University Press, Cambridge (1996) 486–640], in which coherent paleolatitudinal motion of Baltica and the KNTD is hypothesized — the latter as part of the Kipchak Arc. We suggest a parallel hypothesis, which explains coherent motion of the KNTD and Baltica. In particular, we argue that if a basin with oceanic crust ever existed between the KNTD and Baltica, it was a narrow one without (significant) active spreading in Middle to Late Paleozoic time. Notably, the paleogeographic position of Siberia during the Middle Paleozoic and hence, the width of the Khanty–Mansi Ocean between Siberia, on the one

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hand, and Baltica–KNTD, on the other hand, remains largely unconstrained, because of the paucity of high-quality Silurian, Devonian and Carboniferous paleomagnetic results from Siberia.

Keywords: Ural–Mongol belt; Kazakhstan; paleomagnetism; paleolatitudes; Late Paleozoic; Ural Ocean

1. Introduction

The Ural–Mongol mobile belt (UMB) stretches for nearly 10,000 km from the Arctic Ocean along the Ural Mountains between Europe and Asia and then onward through Central Asia to almost the Pacific (Fig. 1a). It is one of the largest and most complex mobile belts on the Earth; moreover, its various parts differ considerably from each other in their structural make-up. The Urals, an orogenic belt of more than 2000 km in length (Fig. 1a), display a linear structural pattern, with long narrow sets of folded and imbricated thrusts (e.g., [2]), comparable to the larger-scale aspects of other orogenic belts such as the Rocky Mountains, the Andes, or the Himalayas. The Urals commonly contain Middle Paleozoic island-arc complexes, flysch sequences deposited in marginal seas, and ophiolites as features of relevance to plate-tectonic interpretations.

In contrast to the Urals, the central part of the UMB, that is Kazakhstan, the Altai, and northwestern Mongolia, has a mosaic structure (Fig. 1a). No prevailing structural trend can be observed here. Microcontinents with Precambrian basement are tectonically juxtaposed with Early Paleozoic subduction-related volcanic complexes, accretionary wedges and flysch sequences; short tectonic units often form T- or Y-like junctions. From the end of the Ordovician through the Permian, many strike-slip faults were active and caused the horizontal imbrication of the amalgamated island-arc segments, microcontinents and accretionary wedges. The Late Paleozoic South Tien Shan and Junggar–South Mongol linear fold-thrust belts bound this region to the south.

A number of publications have presented models for the tectonic evolution of the UMB [1–11], and many of them are very dissimilar. Some authors advocate that the belt was formed by the closure of a Paleoasian Ocean, in which an archipelago of scattered Precambrian microcontinents, oceanic basins and island arc segments existed in the Paleozoic (Fig. 2a). The most important role in the amalgamation of the UMB is ascribed to the diachronous opening and closing of the intervening oceans and, therefore, to diachronous collisions of microcontinents and island arcs. The mosaic structure of the central part of the UMB is assumed to have existed early on and has therefore been called “primary” in this set of models [3–6,10,11]. The basic concepts of such models are similar, but they vary markedly in their details. For instance, some models assume that most microcontinents and island arcs docked to Siberia and formed a composite Siberian–Kazakhstanian continent already in the Ordovician or Silurian [4,5,11], whereas in other models several of these units are thought to collide with each other first, thereby forming an independently moving mid-Paleozoic Kazakhstanian continent [6,10].

A completely different group of models advocates the existence of a continuous volcanic arc system [1,2,7–9]. For instance, Şengör and Natal'in [1] assumed that there was a long continuous Kipchak Arc connecting the Siberian and Baltica cratons in the Early Paleozoic (Fig. 2b). The kinematics of the arc are therefore linked to the motions of Siberia and Baltica. Oceanic crust was subducting westward under the Kipchak arc during most of the Early Paleozoic, and large accretionary wedges were formed. By the Carboniferous, the fragments of the ancient structure had amalgamated into a continent-sized domain, which from that time on can be called the Kazakhstanian continent. The other models of this group differ from that of Şengör and Natal'in [1] in several ways. Yakubchuk et al. [7,8] assume the existence of two parallel island arcs, while giving a leading role to strike-slip motion and imbrications of island-arc segments. Puchkov [2] and Stampfli and Borel [9] suggest that in the Early Paleozoic the island arc had a rather complicated configuration, but they do not ascribe an important role to strike-slip motions.

The fact that so many dissimilar models can co-exist means that we lack major knowledge about the paleogeography and kinematics of the UMB constituents. Thus, our views on the formation of the Eurasian supercontinent are very preliminary at best. Such a situation is largely due to the scarcity and often poor quality of paleomagnetic data from the region. Were a framework of abundant paleomagnetic results from rocks of different ages and different tectonic units of the UMB available, more stringent constraints on the tectonic evolution of the whole belt could be imposed.

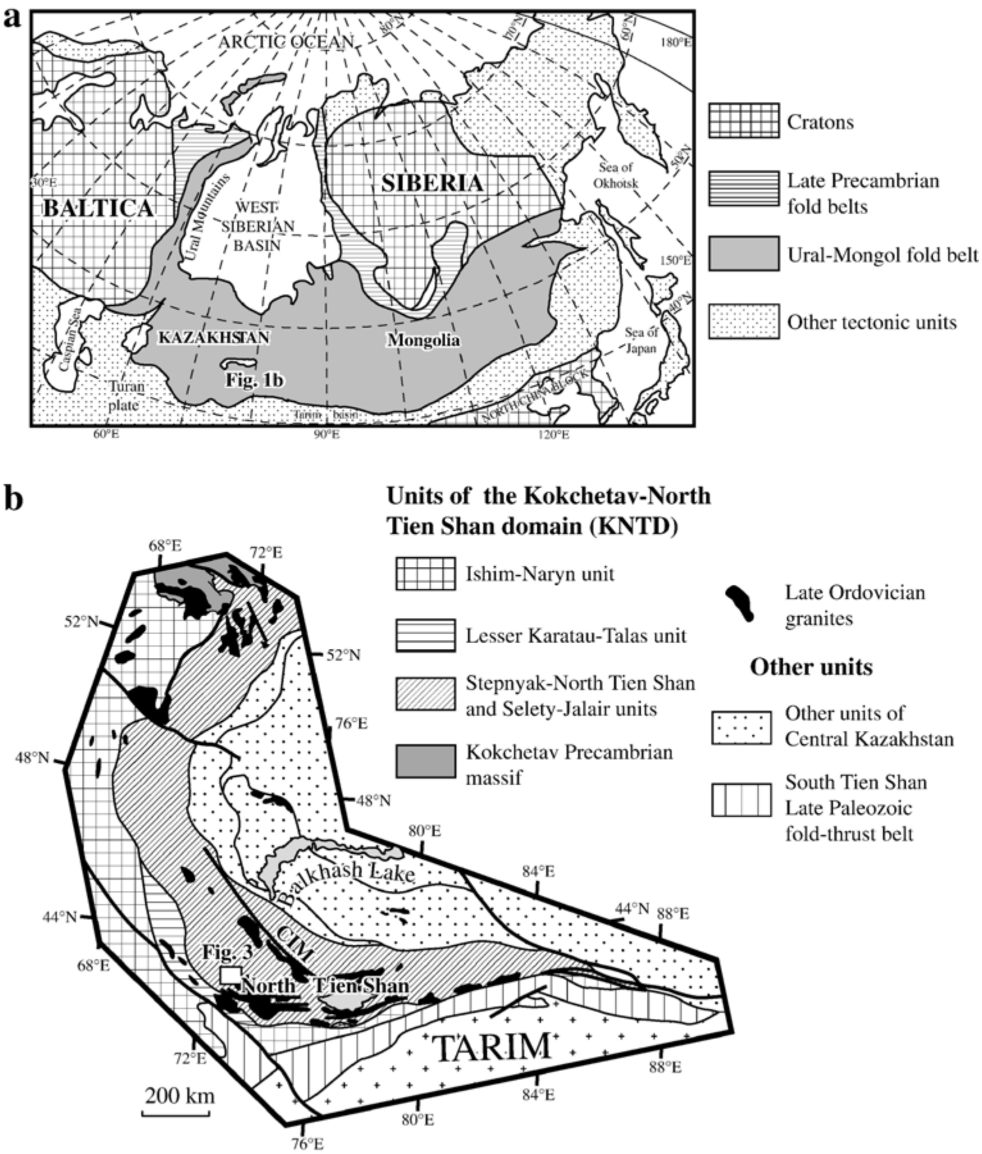

Fig. 1. (a) Location map of the Ural–Mongol belt with the outlines of the Kokchetav–North Tien Shan domain (KNTD) as a thick polygon. (b) Tectonic zones of the KNTD with the position of the study area (rectangle labeled Fig. 3).

Published pre-Permian paleomagnetic data come mainly from the North Tien Shan, north of the Tarim continental block (Fig. 1b) [12–15]. In particular, Bazhenov et al. [14] noticed a good fit of paleomagnetic inclination data from the North Tien Shan with the latitudinal motion of Baltica. However, the validity of this conclusion was strongly undermined by the data scarcity from the Early Silurian to the end of the Early Carboniferous. This gap was partly filled by Early Silurian data from South Kazakhstan [15], and in this study we present new paleomagnetic results from Upper Devonian volcanic rocks in the North Tien Shan. With these results added, a temporal sequence of nine paleomagnetic results is available for Late Ordovician to Late Permian time for this area. It allows us to reconstruct the paleolatitudinal movements of this part of Kazakhstan and Kyrgyzstan and to uncover some implications for the tectonic evolution of the UMB.

2. Regional tectonic setting

One of the major tectonic units of the UMB is the Kokchetav–North Tien Shan domain (KNTD), which stretches from north of Tarim and its marginal South

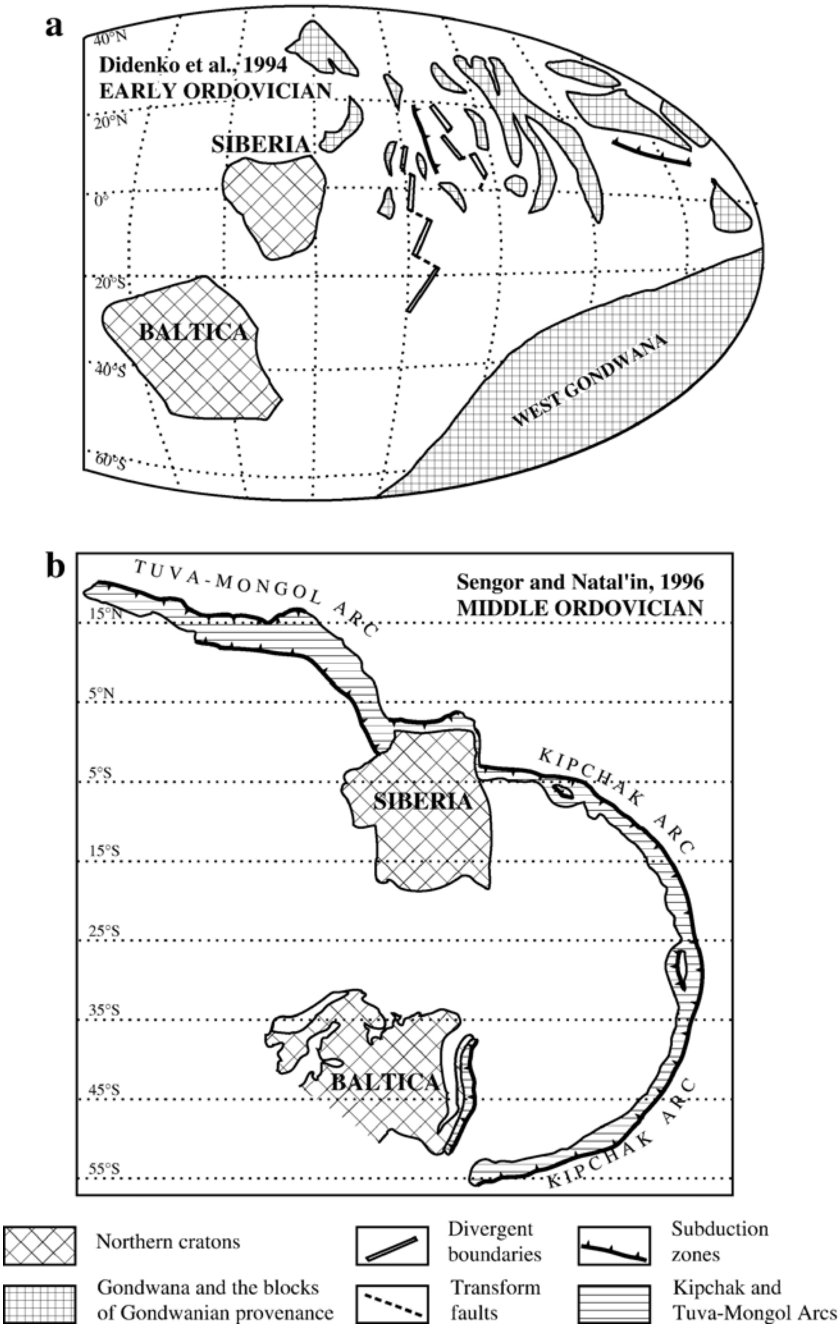

Fig. 2. Palinspastic reconstructions of the Ural–Mongol belt: (a) after Didenko et al. [5], depicting Early Ordovician time; (b) after Şengör and Natal'in [1], depicting Middle Ordovician time. Both reconstructions are simplified.

Tien Shan fold belt to the Kokchetav massif in the north (Fig. 1). This domain is located in the central part of Kazakhstan and in the north of Kyrgyzstan, and has a boomerang-like shape, with a nearly N–S trending northern arm and an E–W trending southern one. The KNTD comprises Precambrian microcontinents and Early Paleozoic island-arc volcanic rocks, flysch sequences, and marine sedimentary basins that had assembled and were intruded by numerous granite plutons by the end of Ordovician time.

Four more or less parallel tectonic zones (called “units” in Fig. 1b) can be recognized in the KNTD ([16], and references therein). The westernmost Ishim–Naryn zone extends over nearly 2000 km from North

Kazakhstan to the central Tien Shan. Neoproterozoic (upper Riphean) rhyolites and bimodal rhyolite–basalt series at the section's base are overlain by Cryogenian–Ediacaran (=Vendian) to Cambrian sediments, mainly black shale. One or two members of glaciomarine diamictites are often present in the Vendian part of the section, and some limestone horizons and lenses top the Cambrian section. The early-Middle Ordovician part of the section is mainly terrigenous, whereas the Late Ordovician is represented by flysch and, locally, volcanic rocks of island-arc affinity. On the whole, the Precambrian–Early Paleozoic sections are very similar along the entire zone ([16], and references therein) testifying to its continuity at least since the Vendian.

In the Lesser Karatau–Talas zone (Fig. 1b), the Neoproterozoic (Upper Riphean) carbonates and clastics are overlain by Cryogenian–Ediacaran redbeds with silicic tuffs and Cambrian to Middle Ordovician carbonates. Diamictite horizons are also known from the Cryogenian of this zone.

Farther to the east there are the Stepnyak–North Tien Shan and Selety–Jalair zones (Fig. 1b). Precambrian blocks of various size, covered by relatively thin Ediacaran–Cambrian sediments, are tectonically juxtaposed with Cambrian–Ordovician island-arc complexes, ophiolites and flysch. In the Stepnyak–North Tien Shan zone, subduction-related Llandeilian to Middle Caradocian volcanic rocks are replaced by upper Caradocian–Ashgillian mostly terrigenous rocks. To the east, in the Selety–Jalair zone, the middle-Late Ordovician section is represented by flysch and coarse-grained terrigenous rocks.

Most of the KNTD was deformed at the end of the Late Ordovician ([16], and references therein), at the same time that numerous granites were intruded throughout the domain (black patches in Fig. 1b). These intrusions stitch different zones; hence, at least since that time, this domain can be regarded as a single tectonic unit. From the Silurian until the end of the Paleozoic, Early Paleozoic complexes of this domain constituted the basement for Andean-type convergent-plate boundary activity ([16], and references therein). Subduction-related volcano-sedimentary complexes of Silurian–Permian age are also deformed. Moreover, different parts of the KNTD may have been displaced with respect to each other along strike-slip faults. Post-Ordovician displacements, however, did not disrupt the overall integrity of this domain. Therefore, since the Late Ordovician, the KNTD can be considered as a single block, although not necessarily a rigid one.

The North Tien Shan (NTS) *sensu stricto* is located in the south of the Stepnyak–North Tien Shan zone (Fig. 1b). It trends E–W parallel to the present range for about 500 km in North Kyrgyzstan and South Kazakhstan. In the NTS,

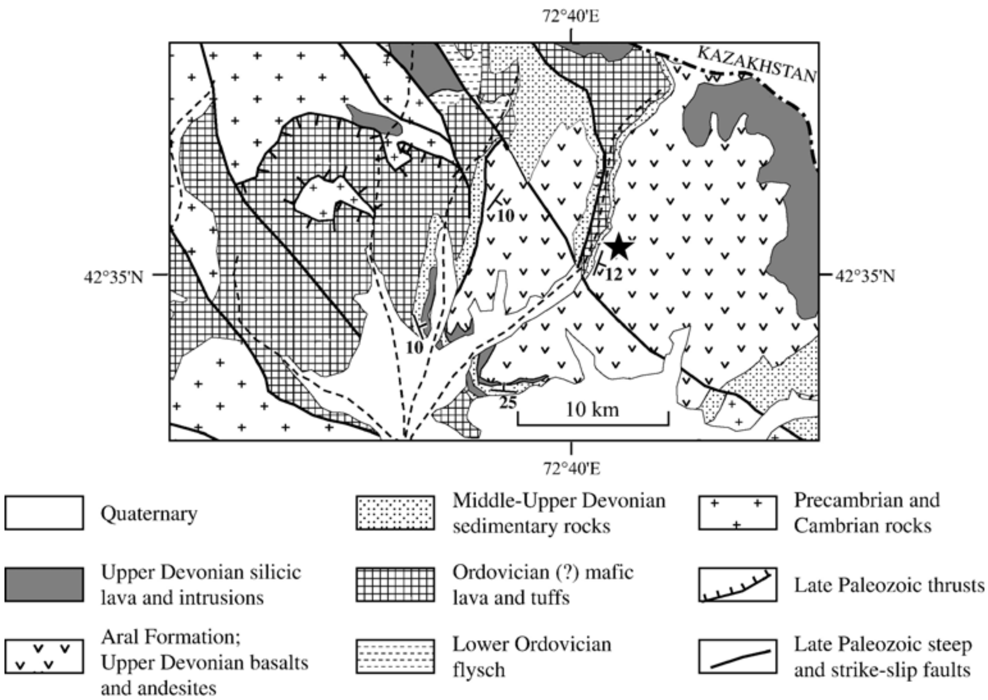

Fig. 3. Geological map of the Aral area on the southern slope of the Kyrgyz Range, North Tien Shan (Kyrgyzstan) with the position of the sampling locality of the Upper Devonian Aral Formation (star).

shelf and continental slope complexes of Precambrian age crop out as disrupted blocks and their original relationships are unclear. Cambrian to Lower Arenigian rocks include subduction-related volcanic rocks, marginal basin deposits, rift-related sediments, and passive margin sedimentary wedges, which are regarded as the remnants of a basin with oceanic crust [17]. The closing of this basin by early-Middle Arenigian time resulted in thrusting and deformation of all older complexes and intrusion of granites.

Middle Arenigian conglomerate and olistostromes overlap the Cambrian to Early Arenigian complexes with a major angular unconformity [17]. A thick pile of differentiated volcanic rocks of Late Arenigian to Early Caradocian age accumulated in the northern and central parts of the NTS; this series is considered an equivalent of modern active continental margins [18]. Along the southern boundary of the NTS, volcanic rocks are replaced by terrigenous and volcano-clastic rocks of similar ages, which are conformably covered by Upper Ordovician red sandstones and siltstones with limestone interbeds. The sequence is intruded by numerous large granite plutons during the Late Ordovician, and smaller bodies of granite were emplaced in the Silurian [17]. Due to the lack of Silurian rocks in most of the NTS, the age of deformation here cannot be defined better than as pre-Early Devonian.

Devonian mafic and felsic subaerial volcanic rocks reside with a major unconformity on lower Paleozoic

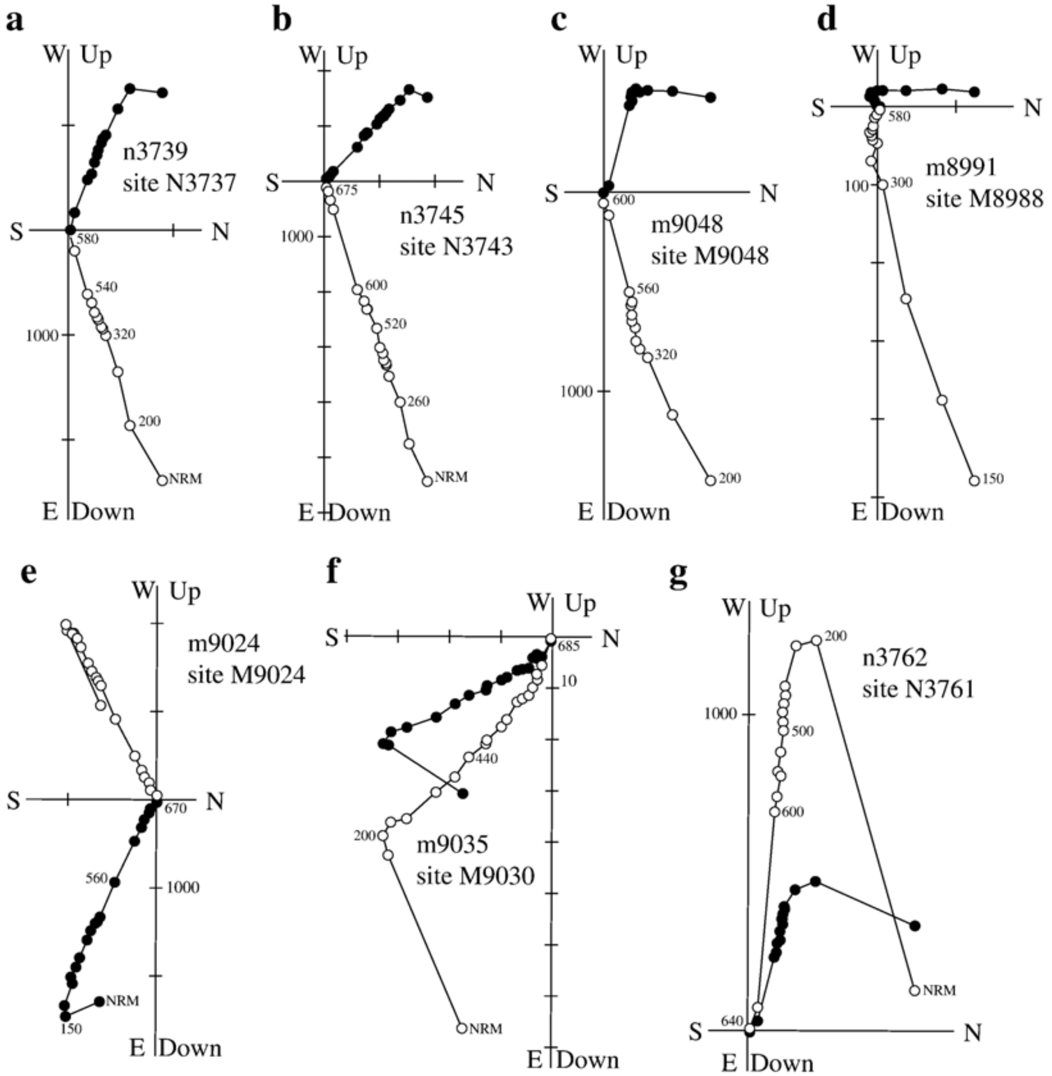

Fig. 4. Representative thermal demagnetization plots of the Upper Devonian volcanic rocks in stratigraphic coordinates. Full (open) dots represent vector endpoints projected onto the horizontal (N–S vertical) plane. Temperature steps are in degrees Celsius. Magnetization intensities are in mA/m. For clarity, NRM points are omitted from some plots.

rocks and are themselves overlain conformably or with slight unconformity by upper Visean to lower Bashkirian (i.e., mostly Lower Carboniferous) redbeds in the North Tien Shan [17]. All the pre-Permian complexes are overlain by Early Permian volcanic rocks either with an unconformity or with disconformity and basal conglomerates. A prominent angular unconformity between Permian and Lower Jurassic rocks indicates strong deformation in the latest Paleozoic and/or Triassic. Finally, the entire Tien Shan was affected by Late Cenozoic deformation. It should be stressed that the intensities of deformation events vary laterally, and it is often difficult to evaluate the relative magnitude of each separate deformation at a given locality.

3. Geologic description of the study area and sampling

Our study concentrated on the southern slope of the Kyrgyz range, where a thick volcano-sedimentary sequence is exposed (Fig. 3). These volcanic rocks are gently dipping in the west and south but more intense fault-related deformation is observed farther to the east and north. The age of the lower half of the sequence is poorly known; these volcanic rocks may be as old as Ordovician, or even Cambrian (I.L. Zakharov, 1986, pers. comm.; A.P. Bashkirov, 1998, pers. comm.), and are labeled Ordovician (?) in Fig. 3. These older, undated volcanic rocks are overlain without angular unconformity by arkosic sandstones and siltstones (stippled pattern in Fig. 3) that contain late-Middle Devonian (Givetian) microfossils and pollen. The sediments, in turn, are conformably overlain, with a several meter thick basal conglomerate, by the Aral Formation, which we sampled and report on here. The Aral Formation is represented by black to dark grey or violet basalt and andesite flows with some lenses and intercalated layers of pink conglomerate and arkose sandstone. Flows have thicknesses of a few meters. The foraminifera *Bisphaera malevkensis Bis.*, *Cribrosphaeroides* cf. *simplex Reitl.*, and *Parathurammina* cf. *Paulis Byk.*, collected from calcareous sandstones, indicate that these rocks are Late Devonian, likely Frasnian, in age (A.V. Dzhenchuraeva, 2005, pers. comm.). Higher in the section, the basaltic–andesitic

Table 1
Site-mean directions of the high-temperature components from the Upper Devonian volcanic rocks, Aral Formation, North Tien Shan

S	N/N_0	*B*	In situ		Tilt-corrected		*k*	α_{95}°
			D°	*I*°	*D*°	*I*°		
M9030*	6/6	130/12	145.0	70.9	139.5	59.2	30	12.6
N3767	6/6	130/12	301.1	16.0	300.3	27.9	134	5.8
M9024	6/6	130/12	127.5	−32.4	127.0	−44.4	102	6.8
N3761*	6/6	130/12	239.6	−81.3	280.7	−73.0	29	12.7
N3755	6/6	130/12	311.3	52.1	311.9	64.1	248	4.3
N3749	6/6	130/12	283.2	28.3	279.4	38.8	71	8.0
N3743	5/6	130/12	309.0	46.8	308.6	58.8	50	10.9
N3737	6/6	130/12	293.9	36.6	290.6	48.1	81	7.5
N3731	6/0	130/12	Scattered data					
M9006	6/6	130/12	281.6	30.9	277.1	41.2	10	22.6
M8994	5/6	130/12	255.7	44.1	244.5	50.1	21	17.5
M8988	4/6	130/12	279.2	61.3	262.0	70.7	33	16.3
N3725	6/0	130/12	Scattered data					
M8982	3/6	130/12	283.1	48.8	274.5	59.1	97	12.6
M9060	6/6	129/14	308.0	51.7	307.5	65.7	11	20.8
M9054	6/0	129/14	Scattered data					
M9048	6/6	129/14	292.0	41.5	286.8	54.7	12	19.8
N3791	6/6	129/14	279.4	35.1	273.8	45.2	24	8.1
N3785*	5/6	129/14	200.5	−8.5	203.1	−12.8	20	17.6
M9042	6/0	129/14	Scattered data					
N3779	6/6	129/14	287.1	59.6	271.1	71.7	95	14.1
N3773	6/6	129/14	302.4	65.5	292.9	79.2	224	4.6
M9036*	3/6	129/14	324.4	68.1	346.4	81.0	63	18.4
Mean	(15/23)		291.5	44.3			22	8.4
					286.0	56.1	21	8.6

S, the site number; the sites are presented in stratigraphic order from the section base (site M9036) upward (thus, the youngest site is M9030); * — sites (with directions in italics) are excluded from the calculation of the mean (see text for explanations of the reasons). N/N_0, number of samples (or sites, where in parentheses) accepted/studied; *B*, azimuth of dip/dip angle; *D*, declination; *I*, inclination; *k*, concentration parameter [21]; α_{95}, radius of the cone of 95% confidence.

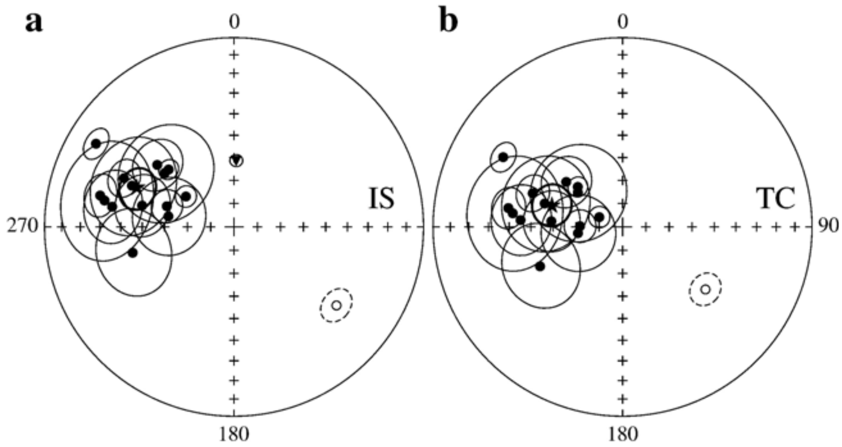

Fig. 5. Stereoplots of ChRM site-mean directions from the main cluster with associated 95% confidence circles (thin lines) of the Upper Devonian volcanic rocks of the Aral Formation from the North Tien Shan in (a) geographic (IS = in situ) and (b) stratigraphic (TC = tilt-corrected) coordinates. The star with its associated 95% confidence circle (thick line) is the overall mean direction of the ChRM and the inverted triangle is the in-situ mean of the low-temperature component. (a–b) Only the directions used to calculate the paleopole have been plotted. Solid (open) symbols and solid (dashed) lines are projected onto the lower (upper) hemisphere.

Aral Formation is capped by Upper Devonian silicic volcanic rocks (not sampled). No younger rocks overlie Devonian rocks in this area.

The total thickness of the Aral Formation section is about 1100–1200 m; however, the upper two-thirds of the section crop out on steep slopes and are difficult to access. The lower 400 m thick interval that was studied starts from the contact with underlying arkoses and comprises numerous basalt and andesite flows with several thin sedimentary intercalations and two up to 10 m thick conglomerate beds. We sampled 23 flows (sites) that are spread approximately uniformly across the studied interval; more than ten cooling units from the same interval were skipped because of fracturing, strong weathering, or poor quality of exposure. Six hand samples oriented with a magnetic compass were taken from each flow. The studied section is a gentle monocline dipping to the ESE at 10 to 12°. The age of the tilting of this section, or of other sections in the area (Fig. 3), is not known and may be as young as Late Cenozoic. This invalidates a fold test. We could not find basaltic or andesite pebbles, so sampled 16 rhyolitic clasts from two intraformational conglomerate horizons in the upper third of the sampled interval.

4. Paleomagnetic study

4.1. Methods

The collection was studied in the paleomagnetic laboratory of the Geological Institute of the Russian Academy of Science in Moscow. Cubic specimens of 8-cm^3 volume were sawed from hand blocks. One specimen from each hand-sample was stepwise demagnetized in 15–20 increments up to 685 °C in a home-made oven with internal residual fields of approximately 10 nT and measured with a JR-4 spinner magnetometer with a noise level of 0.05 mA/m^{-1}. Demagnetization results were plotted on orthogonal vector diagrams [19], and linear trajectories were used to determine directions of magnetic components by a least-squares fit comprising three or more measurements [20]. The characteristic remanent magnetization, ChRM, was determined without anchoring the final linear segments to the origin of the vector diagrams. Components isolated from samples were used to calculate site-means [21]. In some cases, when identification of remagnetization circles was more reliable than that of component directions, these circles were combined with direct observations as suggested by [22]. Paleomagnetic software written by Randy Enkin and Stanislav V. Shipunov for the IBM PC and by Jean-Pascal Cogné for the Macintosh [23] was used in the analysis.

4.2. Paleomagnetic results

The intensity of natural remanent magnetization (NRM) ranges from 0.01 to 6 A/m in the Aral Formation volcanic rocks. The NRM intensity does not vary significantly within a flow but may differ by one or two orders of magnitude between flows.

A low-temperature component, LTC, is usually removed below 300 °C in most samples, after which a single characteristic component (ChRM) could be isolated

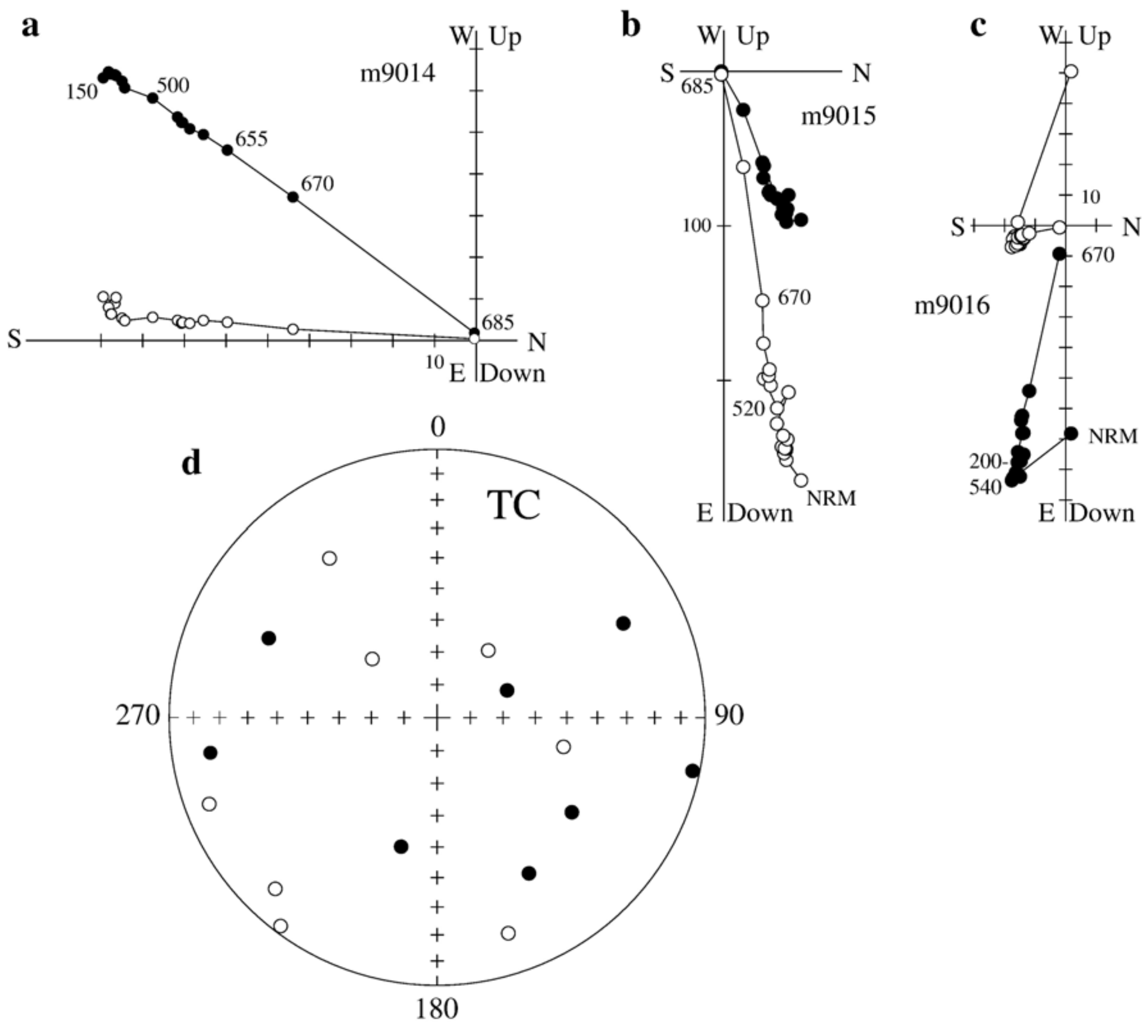

Fig. 6. (a–c) Representative thermal demagnetization plots of volcanic cobbles in intercalated conglomerates within the Upper Devonian volcanic sequence, in stratigraphic coordinates. (d) Stereoplot of ChRM directions of the same in stratigraphic coordinates. Other explanations as in Figs. 4 and 5.

(Fig. 4a–c). In other samples, the low-temperature component, LTC, is more dominant and, sometimes, may account for more than 90% of the total NRM intensity (Fig. 4d). LTC directions are reasonably grouped at all sites but one, and its overall mean direction (D=2°, I=61°, α_{95}=3°) is close to the present-day dipole field (D=0°, I=62°) in the area. Despite the presence of this strong LTC, the ChRM could still be isolated in most cases.

In four flows out of 23 sampled, the ChRM is very scattered at the within-site level; these sites with $\alpha_{95}>25°$ were excluded from consideration. For sites M9030, N3761, and N3785, the ChRM's are reasonably well clustered at the site level, but the corresponding site-mean directions deviate significantly from the overall mean (italicized in Table 1). The demagnetization characteristics of these sites (Fig. 4f, g) are similar to those of the main cluster (Fig. 4a–e). We hypothesize that the anomalous site-mean directions are due to the behavior of the geomagnetic field and not, for instance, to unresolved overprinting. The mean at site M9036 is based only on component directions from two samples and one remagnetization circle; in addition, the corresponding confidence circle overlaps the LTC overall mean direction. We doubt the reliability of M9036 site-mean and exclude it from analysis.

The remaining downward site-mean directions of normal polarity form a cluster (Fig. 5), with one additional site-mean direction of opposite polarity (Figs. 4e and 5). The studied section is monoclinal, so a fold test could not be applied (Fig. 5a, b; Table 1).

After removal of a weak low-temperature remanence a ChRM that decayed to the origin was isolated from all

Table 2
Summary of Paleozoic paleolatitudinal data for the North Tien Shan

Locality	Age	N	$I°$	$\alpha_{95}°$	Plat°	PFT	REF
A	O_1car_e	13	−18	4.0	−9±3	F	[14]
B	O_1car_l	17	17	5.0	−9±3	F,R	[14]
C	O_1ash	7	−11	8.8	−6±5	F	[14]
D	S_e	7	23	13.8	11±8	F	[15]
E	D_e	4	37	12.3	21±9	F,R	[12]
F	D_l	14	55	9.0	36±9	C	L*
G	C_1v–s	14	31	6.4	16±2	F	[14]
H	C_2b	9	28	5.2	15±3	F	[14]
I	P_l	36	50	2.6	30±2	–	[14]

Age, the age of the studied rocks: O — Ordovician, S — Silurian, D — Devonian, C — Carboniferous, P — Permian; stages: car — Caradocian, ash — Ashgillian, v–s — Visean–Serpukhovian, b — Bashkirian; e = Early, l = Late. N, number of accepted sites; Plat, paleolatitude (negative values for the southern hemisphere) with confidence limits; PFT — positive field tests: F — fold test, R — reversal test, C — conglomerate test; α_{95} is the radius of the cone of 95% confidence. Paleomagnetic data are presented assuming normal polarity, with directions in stratigraphic coordinates. REF, references: L*, this study. Other explanations are as for Table 1.

volcanic clasts from the intraformational conglomerates (Fig. 6a–c). The ChRM directions are randomly distributed (Fig. 6d), and the normalized vector-resultant $R=0.17$ is much less than the critical value of 0.40 [24]. Therefore, the conglomerate test is positive.

As stated above, the section examined is comprised of andesite and basalt flows, whereas the intraformational conglomerates contain well-rounded cobbles of mostly silicic volcanic rocks. This means that despite accumulation of the conglomerates during hiatuses between eruptions of basic lava flows, the latter have not been eroding, and the cobbles were derived from other nearby complexes. Demagnetization properties of mafic volcanic rocks (Fig. 4) and acidic flows (Fig. 6a–c) are similar, and no common directional component can be isolated from the cobbles. Thus it is unlikely that all host rocks were remagnetized, while the cobbles in the conglomerates were not even slightly affected. It is more likely that the cobbles in the conglomerates preserved a primary magnetization, and that the ChRM of host rocks is also of primary origin.

The ChRM in host volcanics (Fig. 4b,e) and cobbles (Fig. 6a,c) resides in both magnetite and hematite in varying proportions, but its directions do not depend on magnetic mineralogy. Such a pattern is likely to be due to high-temperature oxidation during emplacement of volcanic units and before conglomerate accumulation, indicating a primary nature of magnetizations [25].

Fifteen accepted sites span the studied part of the section of about 400 m in thickness (Table 1) that includes more than thirty flows with some layers of fine-grained sediments and conglomerate and most probably was accumulating long enough for secular variation to be adequately averaged. The conglomerate test is positive, and the magnetization of opposite polarity in one site is antipodal to that of the fourteen other sites either above or below it. We can conclude that the studied magnetization is of primary origin, and argue that the overall mean direction in the studied rocks is an accurate estimate of the ancient Late Devonian geomagnetic field.

4.3. Other paleomagnetic data from the KNTD

The tectonic evolution of the North Tien Shan zone and, on a broader scale, of the entire KNTD is very complicated and poorly understood prior to the Late Ordovician [17]. As mentioned above, the KNTD can be regarded as a coherent unit only since that time. Thus, we limit our analysis to the interval from the Late Ordovician to the Late Permian. Three paleomagnetic studies, previously published since the early 1990’s, report results for Paleozoic rocks from the North Tien Shan (8 useable poles, Table 2).

Red beds from the western part of this area yield Late Ordovician (Middle Caradocian, Late Caradocian and Ashgillian) and early-Middle Carboniferous (Visean–Serpukhovian and Bashkirian) primary magnetizations [14]; in addition, prefolding secondary components, of presumably Late Permian age, could be isolated (Fig. 7, Table 2).

Paleomagnetic data from Lower Silurian and Upper Silurian–Lower Devonian redbeds from the Chu–Ili Mountains (CIM in Fig. 1b) were published by Alexyutin et al. [15]. As seven sites out of eight studied are from Lower Silurian rocks and only one is from the younger strata, we excluded the latter and calculated an Early Silurian direction (Table 2).

A result from Early Devonian redbeds [12] is based on stepwise thermal demagnetization; however, the final component was not always well-isolated judging by the orthogonal plots presented in the paper. The fold test is positive on a regional scale, but the authors had to combine several small collections (about 10 samples each) from different parts of the North Tien Shan. On the other hand, two clusters of normal and reversed polarity are antipodal and yield a positive reversal test. This could be taken to indicate a primary origin of the magnetization. With reservation, we included this result in our analysis.

Burtman et al. [13] published a study of Upper Devonian redbeds from the North Tien Shan. They regarded an intermediate temperature component, which clearly misses the origin, as the primary one and used it for tectonic interpretations. This intermediate component is

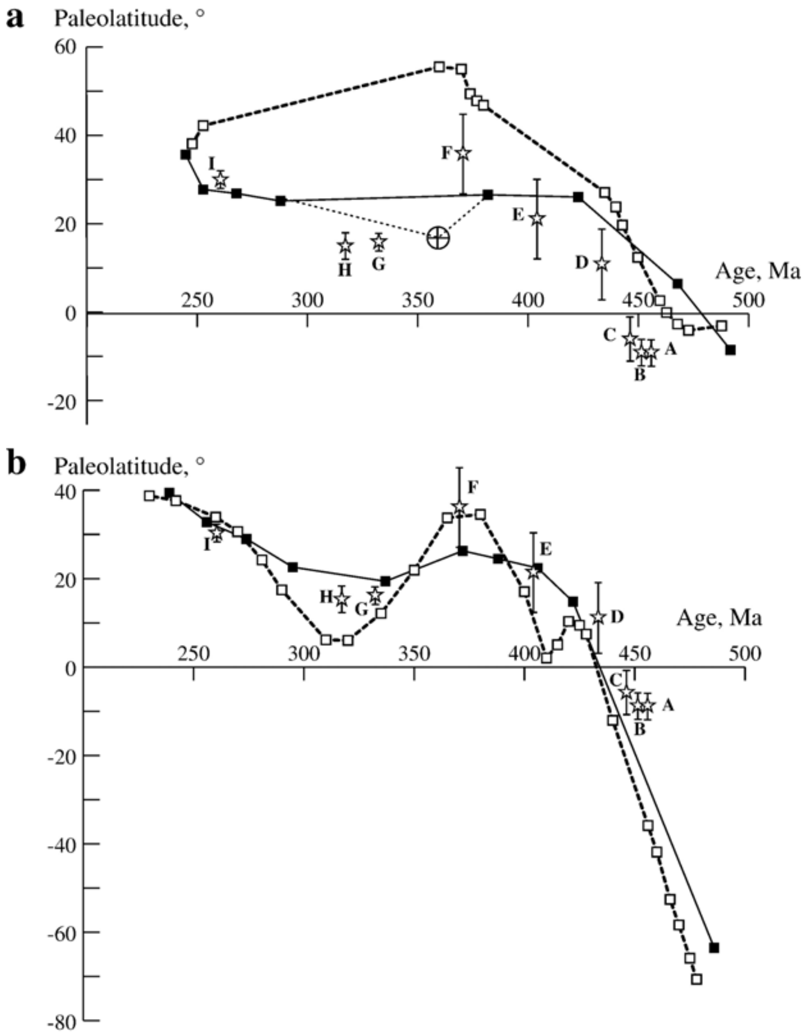

Fig. 7. Paleolatitude versus age plot for the reference values extrapolated from Siberia (a) and Baltica (b) to the North Tien Shan location of 42.5°N, 73.0°E and the observed paleolatitudes for results from this area (stars with vertical error bars, keyed as in Table 2). Solid and open squares, connected by solid and dashed lines, are the reference paleolatitude curves derived from the APWP's: for Siberia — of Van der Voo [30], and Smethurst et al. [31], respectively. Similarly, this was done for Baltica — path of Van der Voo [30], and of Smethurst et al. [32], respectively. Crossed circle in (a) is the Devonian–Carboniferous result of Kravchinsky et al. [29].

prefolding, but this is not decisive in this particular case as several folding events affected the study area. Because no high temperature component was isolated and discussed, we did not use this result.

Reported thus far only in abstract form [26] is a Middle Devonian result from the Kurgasholak Formation in the North Tien Shan, about 300 km to the ESE from our Aral Formation locality. We have not included this result in Table 2, because it is not yet peer reviewed. However, we note that the directions from the two formations are rather similar. The Kurgasholak Formation yields a dual-polarity magnetization Dec/Inc = 286°/+46°, α_{95} = 7.8°, k = 29, N = 13 sites, compared to the Aral Formation result with Dec/Inc = 286°/+56°, α_{95} = 9°, k = 21, N = 15 sites.

There are no Late Ordovician to Permian paleomagnetic results based on adequate demagnetization and component analysis from the central and northern parts of the KNTD. Nevertheless, many geologic features can be traced all the way along this domain; as discussed above, there is geologic evidence that all four KNTD units shown in Fig. 1b were amalgamated by the end of the Ordovician. It seems permissible to apply the paleogeographic implications from our new Devonian paleopole to the entire KNTD, but we also note that if this assumption is wrong, it does not alter our

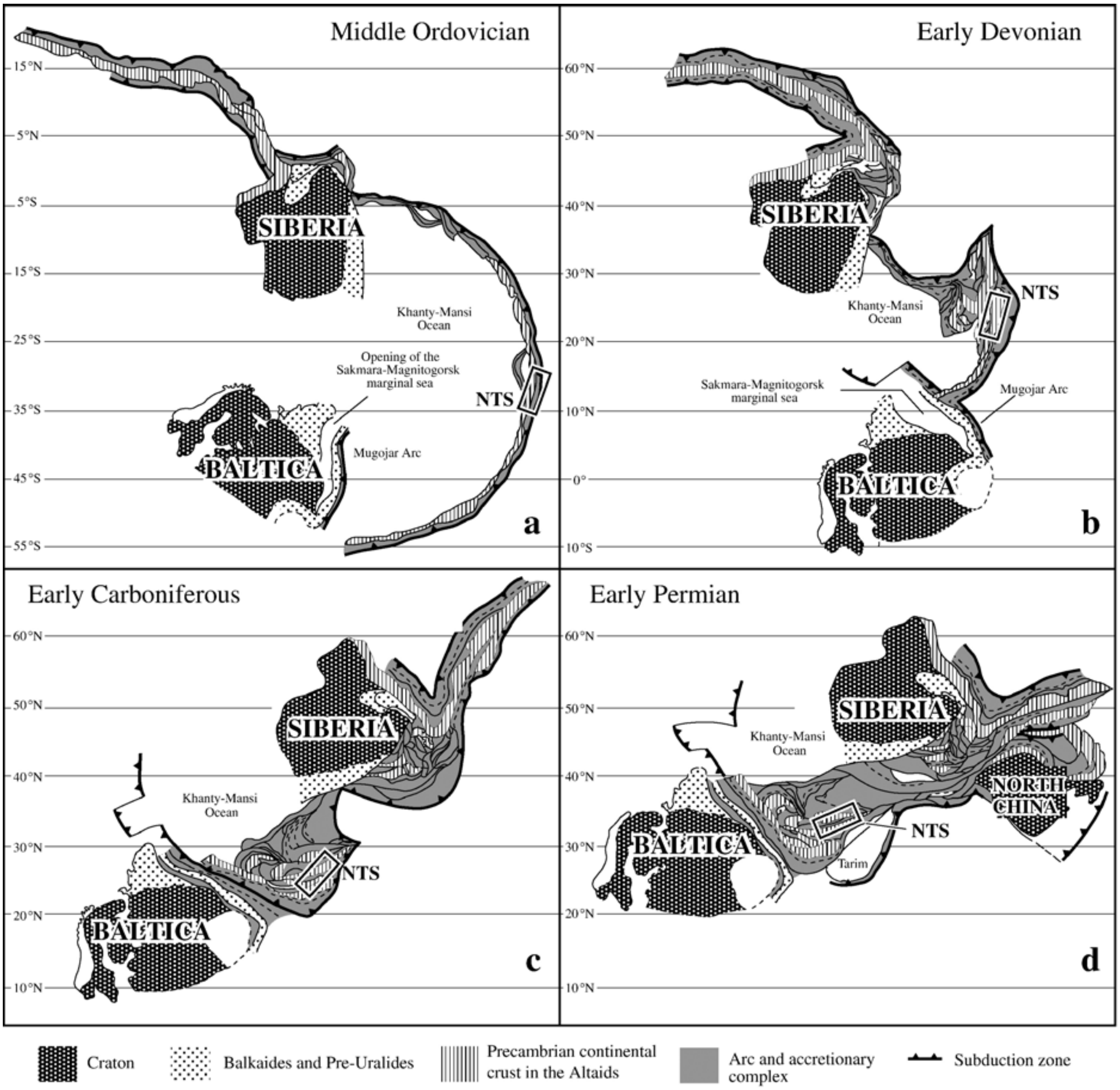

Fig. 8. A selected set of paleogeographic reconstructions of Baltica, Siberia, and the evolving Ural–Mongol Belt, after Şengör and Natal'in [1]. A rectangle denotes the position of various sampling areas in the North Tien Shan. Reprinted by permission from CambridgeUniversity Press, Copyright 1996, and the authors [1].

conclusions for the sampling areas of the North Tien Shan *sensu stricto*.

5. Interpretation and discussion

5.1. Declinations and rotations

All paleomagnetic data (Table 2) are from the southern part of the boomerang-shaped KNTD (Fig. 1b). This area in the North Tien Shan has suffered several deformation events, the latest of which was in the Late Permian to Early Triassic and involved significant but variable counterclockwise rotations [27]. These rotations sometimes occurred on a local scale and are best interpreted as having been caused by major strike-slip faults crossing the region. Earlier phases of clockwise as well as counterclockwise rotations have been documented [28], and paleomagnetic data of similar age show much larger variations in declination than in inclination, resulting in banana-type or girdle distributions of directions. For instance, Late Ordovician declinations from three different formations in the western part of the North Tien Shan zone differ by as much as 60° [14]. The absence of paleomagnetic results from the central and northern parts of the KNTD precludes a discussion of rotations there, but these are quite likely judging by the generally strong middle-Late Paleozoic deformation throughout this domain. At this time neither the magnitude of rotations nor their ages can be properly evaluated, because the limited declination data that do exist are inadequate for a meaningful analysis. Thus, our current interpretation is confined to an analysis of paleolatitudes.

5.2. Inclinations and paleolatitudes

Our aim is to compare the paleolatitudes derived from the sequence of Late Ordovician to Late Permian paleomagnetic data for the KNTD with those of the major cratons around the Ural–Mongol mobile belt (UMB). However, only for Baltica does an adequately determined apparent polar wander path (APWP) exist for this time interval. For Tarim and Siberia, the data are scarce and mostly unreliable for the mid-Paleozoic. Siberia, for instance, has good Cambrian and Ordovician results followed by a single reliable latest Devonian pole [29], in turn followed by well-established Late Permian–Early Triassic results. The gaps in this path are obviously very large, being partially and incompletely filled by a set of old results obtained without full demagnetization and principal component analysis. Following the usual procedure, reference paleolatitudes have been calculated from two APWP versions for Siberia [30,31] for a common point at 42.5°N, 73.0°E (Fig. 7a). It comes as no surprise that the reference paleolatitude values, recalculated from different versions of Siberia's APWP [30,31], agree only in the Cambrian–Ordovician and around the Permian–Triassic boundary, because for the times in between, different data selection from among the poorly determined poles and varying mathematical methods produce very different results (Fig. 7a). The only reliable latest Devonian result from Siberia [29] was published after the compilation of the above-mentioned APWPs. It predicts a paleolatitude that deviates considerably from all earlier published data of the same age, illustrating the lack of robustness of Siberia's previous APWP constructs.

A meaningful comparison of the KNTD results can be made with Baltica data. Reference paleolatitudes from two APWP versions for Baltica [30,32] were calculated for a common point at 42.5°N, 73.0°E (Fig. 7b). The two reference plots agree reasonably well, despite the difference in approaches: one APWP [30] was calculated by averaging the data for non-overlapping time windows, whereas the other one [32] is based on spline fitting of unit poles.

Paleomagnetic data from the KNTD match both reference paleolatitude plots from Baltica quite well (Fig. 7b). In fact, the observed KNTD values fit each curve better than the curves agree with each other.

The probability that nine observed KNTD values show a good overall agreement with the reference data from Baltica, just by chance, is negligible. In other words, it is unlikely that two units could move independently for ca. 200 My in such a way that the agreement of the observed paleolatitudes and extrapolated reference values is purely coincidental. We argue, therefore, that Baltica and the KNTD had to move coherently since the Late Ordovician to the end of the Permian. Even if a plate boundary existed at times between the two blocks, either its activity could not have lasted for long, or the relative velocity across this plate boundary had to be very low, in order for the relative latitudinal motion of these two blocks to remain within the error limits of the paleomagnetic data. Applying Occam's razor, one could even assume that Baltica and the KNTD, as the backbone of Kazakhstan, moved as a single plate during much of the Ordovician–Permian interval. But strictly speaking, it cannot have been a "true" lithospheric plate, which has to be rigid by definition. Following Gordon [33], the plate tectonic situation can be described as having a rigid continental interior (Baltica) bounded by a wide and diffuse boundary that contains the KNTD as a microcontinent and possibly one or more marginal oceanic basins in between. For brevity, we use the term "quasi-plate" in what follows below.

5.3. Comparison with published paleogeographic models

Since the Late Ordovician, the KNTD was a vast domain that occupied nearly half of the Kazakhstan territory. We examined the available models of UMB evolution to see how well our inferred Mid-to-Late Paleozoic paleogeography of a Baltica–KNTD "quasi plate" is compatible with these models. Another important constraint is that model-predicted paleolatitude positions of the KNTD should match the observed values.

According to many authors [4,5,11] all blocks in Kazakhstan and Kyrgyzstan had docked to Siberia in the Ordovician–Silurian, forming the composite Siberian–Kazakhstanian continent. Until the middle-Late Carboniferous, this composite continent was separated from Baltica by active divergent as well as convergent boundaries. In other models [6,10], the Kazakhstan continent originated from multiple collisions of Precambrian microcontinents and Early Paleozoic island arcs that, in the Ordovician–Silurian, amalgamated into a continent-sized domain. As in the earlier-described models, the Kazakhstanian continent is separated from Baltica by both divergent and convergent boundaries until the middle-Late Carboniferous and was moving independently from all other plates. Other authors also regard Kazakhstan as an independently moving continental plate [2,9]. As examples of the paleogeographic implications of these scenarios, we note that the distance between the North Tien Shan and the southern Urals' margin of Baltica changes from about 4000 km in the Early Devonian to about 2400 km in the Middle Devonian to about 1700 km in the Late Devonian in the reconstructions of Filippova et al. [6]. For the same three times, the maps of Stampfli and Borel [9] locate Kazakhstan about 6000 km, then 5300 km, and then 3600 km removed from the southern Uralian margin of Baltica, where eventually Kazakhstanian elements will collide. Clearly, the above models do not agree with our observations, neither in terms of predicted paleolatitudes nor in their coherency with the values extrapolated from Baltica, which suggest a more or less constant separation for much of the Paleozoic.

Only one model [1] is approximately compatible with the observed data. The paleolatitudes for the North Tien Shan (NTS in Fig. 8), as read from the palinspastic maps by these authors, generally agree with the reference paleolatitudes for Baltica, as well as with the observed paleomagnetic data (compare Figs. 7b and 8). It is interesting to note that another scenario [7], which also envisages complex deformation of an island arc system between Baltica and Siberia, does not fit the observed paleolatitudes.

However, the reasons for such a good fit between model-based and observed values in the model of Şengör and Natal'in [1] are not self-evident. In their maps, one significant plate boundary is shown between the KNTD and Baltica for the entire Silurian and

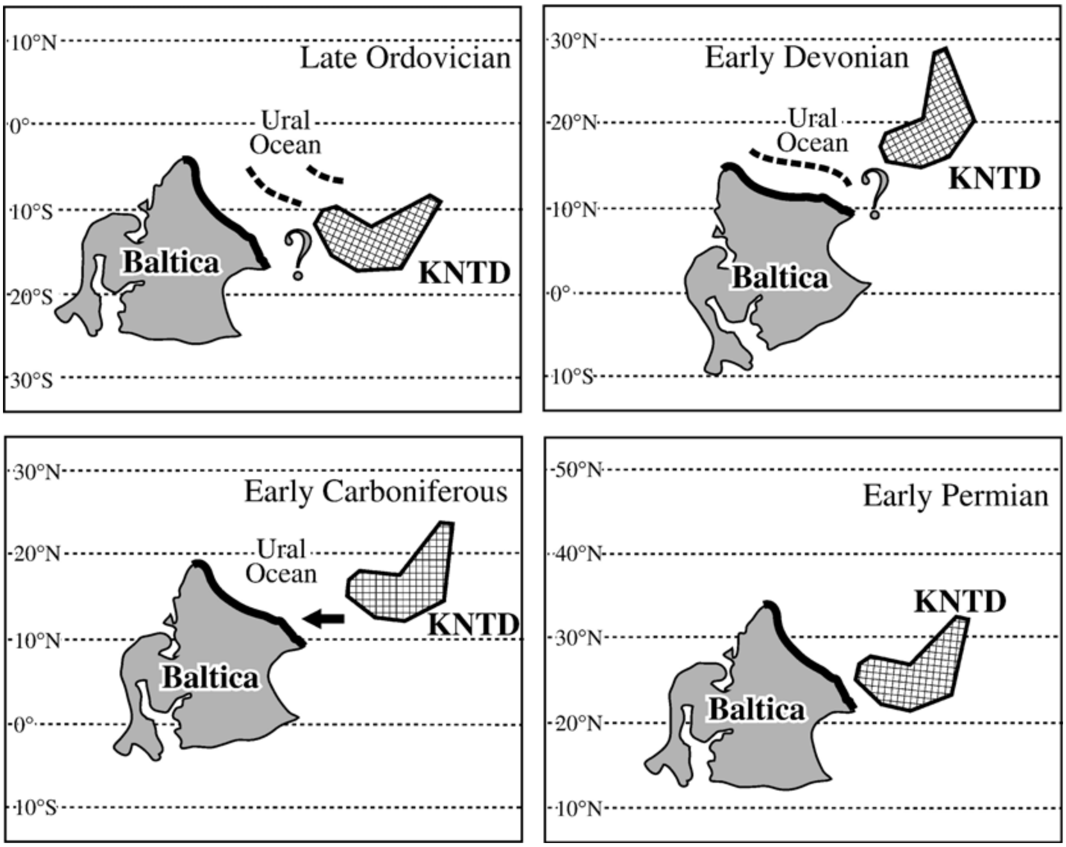

Fig. 9. Cartoons illustrating paleogeographic positions of Baltica and the Kokchetav–North Tien Shan Domain (KNTD) from the Late Ordovician until the Early Permian. The present-day shape of the KNTD is preserved just for better recognition but this does not imply that we know enough about the orientation, subsequent rotations, and internal deformation of this unit. The Uralian margin of Baltica is highlighted with a thick black line. Thick dashed lines represent island arcs that existed within the Uralian ocean (their paleolatitudes and strikes are not constrained by paleomagnetic data and hence are arbitrary). Large question marks denote the area where a mid-Paleozoic basin of fully or partly oceanic nature is postulated to have existed between Baltica and KNTD. The solid arrow in this figure (Early Carboniferous frame) is the inferred direction of convergence between KNTD and Baltica that occurred soon after Early Carboniferous time.

Devonian (see Fig. 8, showing the Mugojar (=also Mugodzhar) Arc and Sakmara–Magnitogorsk marginal sea). Şengör and Natal'in [1] suggested that the Mugojar island arc was located above a southwest-dipping subduction zone and formed, along with the Sakmara–Magnitogorsk back arc basin, the Uralian boundary of Baltica throughout the Silurian and Devonian. The convergence between the North Tien Shan part of the KNTD and SE Baltica appears to have been very large in their model: from their maps we estimate about 3000 km or more of subduction beneath the Mugojar Arc between the Late Ordovician and the Late Devonian. Also, the evidence that the KNTD was already assembled by the end of the Late Ordovician does not easily fit into the scenario of Şengör and Natal'in [1]. It seems that the Kipchak Arc model needs some refinement to remedy these discrepancies.

None of the other models for the Mid-to-Late Paleozoic evolution of the Ural Ocean [2,4–7,9–11] agrees with the paleomagnetic data; the main discrepancy seems to be that nearly all envisage a very wide mid-Paleozoic ocean on the order of several thousands of kilometers as well as long-lived and vigorous mid-Paleozoic plate boundaries between the KNTD and Baltica, which would, if true, render our "quasi-plate" story unlikely.

5.4. Constraints on the KNTD–Baltica paleogeography

We argue that a plausible scenario for the western part of the UMB should simultaneously satisfy several lines of evidence, the most important of which are:

A. In the Eastern Urals, various rocks of oceanic origin, including ophiolites of various ages, numerous island-arc complexes, and deep-sea sediments [34–39,41] indisputably indicate that an oceanic basin existed to the east of Baltica (in present-day coordinates) from the Early Ordovician to the Middle Carboniferous.
B. Although the number of island arcs, let alone their polarities and docking times, are still disputable [39–41], it is clear that these units marked active convergent plate margins to the east of Baltica from the Middle Ordovician to the Carboniferous. The presence of ophiolites indicates that spreading centers existed to the east of Baltica too [2,34,38].
C. Baltica and the KNTD moved coherently since the Late Ordovician in such a way as not to impede the "free" evolution of the components in the Ural Ocean.

The set of cartoons (Fig. 9) illustrates the inferred relative positions of the KNTD and Baltica in a simple, albeit definitely not unique scheme that satisfies the three conditions listed above. We add four comments:

1. The Baltica–KNTD connection may have been a basin with oceanic crust, or an isthmus resembling the Malacca Isthmus of today. What is needed is a lack of vigorously active plate margins throughout most of the Late Ordovician–Permian interval.
2. In its present-day position, the KNTD clearly obstructs any subduction in the South Urals (see Fig. 1a). At the same time, the emplacement of the ophiolites and relicts of island arcs and marginal seas as a consequence of subduction of the Ural Ocean had taken place before mid-Carboniferous time [37,41]. Hence the domain had to arrive in its present-day position after subduction was completed in this area, i.e., in the Late Carboniferous–Early Permian. It is reasonable to assume that both Baltica–KNTD convergence and the cessation of subduction were broadly contemporaneous and may somehow have been related. As the result of this convergence, ophiolite remnants of the Ural Ocean and the relicts of island arcs and marginal seas became placed between Baltica and the KNTD.
3. In order to avoid disrupting the observed coherency in paleolatitudes, Late Paleozoic motion of the KNTD relative to Baltica has to occur nearly along the latitude line at the time of convergence. Naturally, we cannot directly determine the magnitude of convergence with the aid of paleomagnetic data. Regardless, we can constrain it, as a large magnitude would have implied too high velocities and, even more importantly, would disrupt the coherency of older paleolatitudes. It is difficult to give any quantitative estimates, but any Late Paleozoic motion in large excess of 1000 km would be perceptible. This rough estimate stems from the plain fact that the APWP of Baltica was recalculated to the study area in the Tien Shan in its present-day coordinates, and latitude-parallel motion in the Late Carboniferous is not latitude-parallel for older data.
4. Although the clearly recognizable KNTD boomerang is shown in its present-day shape (Figs. 1b and 9), we are not yet sufficiently knowledgeable about the orientation, subsequent rotations, and inner deformation of this unit. It is our hope that many adequate paleomagnetic data will accumulate in the continuing studies of Kazakhstan and Kyrgyzstan, so that rotations can be adequately discussed at some future stage.

6. Conclusions

Our paleomagnetic study of Upper Devonian andesite and basalt flows from the Aral Formation in the North Tien Shan of Kyrgyzstan yields a characteristic and likely primary magnetization. When combined with other reliable paleomagnetic results from the North Tien Shan, a good fit of the observed paleolatitudes with the reference values for Baltica is obvious. Geologic evidence indicates that a large area in Kazakhstan, the Kokchetav–North Tien Shan Domain (KNTD) was consolidated by Late Ordovician time, and we infer that the observed paleolatitudinal agreement can be extrapolated to this entire KNTD. This good fit of the observed and predicted paleolatitudes indicates that Baltica and the KNTD moved coherently during much of the time from the Late Ordovician until the Middle Carboniferous.

Based on this indication, a simple paleogeographic model involving just two main constituents, Baltica and the KNTD, shows that Baltica and the KNTD stayed more or less in the same relative position for some 150 My (Fig. 9a–c). The Ural Ocean closed by mid-Carboniferous time (e.g., [37]). We assume that the KNTD moved to its present-day position relative to Baltica along lines of latitude in Late Carboniferous–Early Permian time. As a result, ophiolite remnants of the Ural Ocean and the relicts of island arcs and marginal seas came to their position between Baltica and the KNTD. The orientation of Baltica in the Carboniferous indicates that the convergence of these two blocks was oblique (Fig. 9c, d).

Thus the main message of our paper is to demonstrate, primarily with the aid of paleomagnetic data, that Kazakhstan units could not constitute the other side of the Ural Ocean. This scenario is, at best, just a skeleton of a full-body model. To further substantiate or refute it, a regional-scale analysis of geological data is required, but this is outside the scope of this paper.

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