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Tectonophysics 377 (2003) 229–247

TECTONOPHYSICS

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Early Paleozoic paleomagnetism of east Kazakhstan: implications for paleolatitudinal drift of tectonic elements within the Ural–Mongol belt☆

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Received 15 November 2002; accepted 2 September 2003

Abstract

Conflicting paleogeographic reconstructions of the Ural–Mongol fold belt have been developed over the past decade; very few of them, however, have been based on paleomagnetic data, which still remain scarce. The Chingiz Range in northeastern Kazakhstan provides an opportunity to evaluate the tectonic evolution of the central part of this belt through extensive paleomagnetic studies. In this paper, we report the results from Upper Cambrian andesites and Lower Ordovician tuffaceous sandstones within the Chingiz Range. A high-temperature component (HTC), decaying to the origin, is isolated from Upper Cambrian rocks at eight sites with an easterly and low-intermediate upward direction. This component passes the tilt test and is likely primary. A HTC is also isolated from Lower Ordovician rocks at 11 sites. These site means exhibit a shallow-inclination girdle distribution within the southeast quadrant, likely due to net rotations within the complex structure studied. The inclination-only tilt test is positive, and the best grouping of data is observed at 100% untilting. Also included in our paleolatitudinal analyses are new middle and late Paleozoic paleolatitudes from nearby parts of the Chingiz Range as well as published paleomagnetic data from central and east Kazakhstan. We favor normal polarity of the early Paleozoic results of this paper and conclude that the study area moved northward throughout the Paleozoic. The observed paleolatitudes generally fit the Siberian reference data and hence indicate coherent latitudinal motion of the Boshekul–Chingiz tectonic zone and the Siberian plate.

Keywords: East Kazakhstan; Early Paleozoic; Paleomagnetism; Paleolatitudes; Ural–Mongol fold belt

1. Introduction

Published syntheses describing the Paleozoic tectonic evolution of the Ural–Mongol fold belt, which separates the European (Baltica), Siberian (Siberia), and Tarim cratons (Fig. 1a), as well as the mosaic of island arc complexes, accretionary wedges, and ophiolites that comprise present-day east–central Kazakhstan (Fig. 1b), are rather controversial. Much of the ambiguity surrounding existing models is due to the scarcity of reliable paleomagnetic data and to the complex structural geometries observed in the

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☆ Refers to doi:10.1016/j.tecto.2003.09.013.

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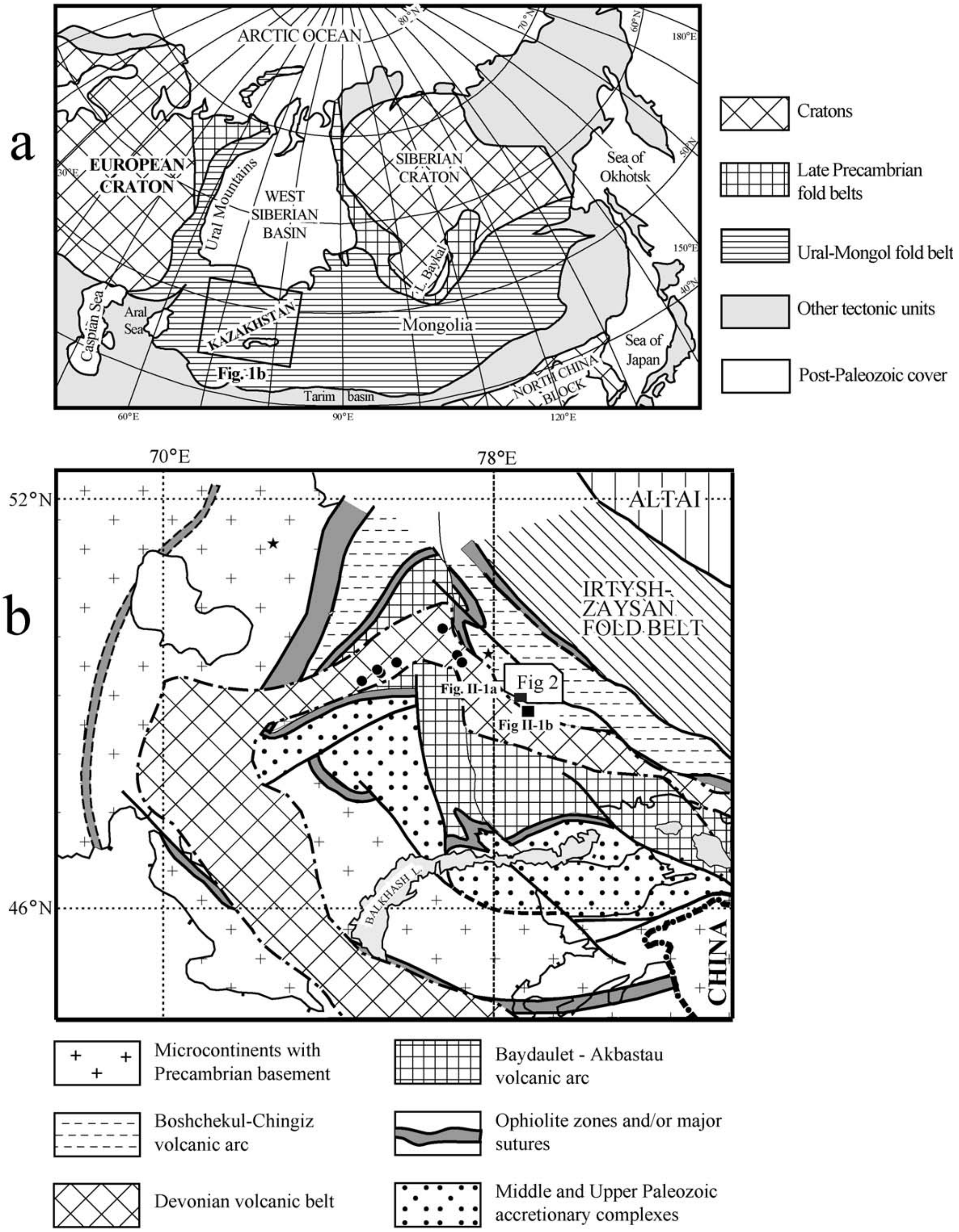
doi:10.1016/j.tecto.2003.09.003


a
ARCTIC OCEAN
80°N
70°N
60°N
50°N
40°N
180°E
150°E
30°E
EUROPEAN CRATON
Ural Mountains
WEST SIBERIAN BASIN
SIBERIAN CRATON
L. Baykal
Sea of Okhotsk
Caspian Sea
Aral Sea
KAZAKHSTAN
Mongolia
Fig. 1b
Tarim basin
NORTH CHINA BLOCK
Sea of Japan
60°E
90°E
120°E
Cratons
Late Precambrian fold belts
Ural-Mongol fold belt
Other tectonic units
Post-Paleozoic cover
b
70°E
78°E
52°N
46°N
ALTAI
IRTYSH-ZAYSAN FOLD BELT
Fig 2
Fig. II-1a
Fig II-1b
BALKHASH L.
CHINA
Microcontinents with Precambrian basement
Boshchekul-Chingiz volcanic arc
Devonian volcanic belt
Baydaulet - Akbastau volcanic arc
Ophiolite zones and/or major sutures
Middle and Upper Paleozoic accretionary complexes

field. Several hypotheses concerning the Paleozoic evolution of these complexes have been generated over the past decade. The two leading reconstructions are contrasting views inferring the Paleozoic paleogeographic positions and tectonic environments associated with the complexes that constitute present-day Kazakhstan and northern Kyrgyzstan (Didenko et al., 1994; Sengör and Natal'in, 1996).

The Didenko et al. (1994) model characterizes the amalgamation of the central Ural–Mongol fold belt as a mosaic of exotic, and mostly unrelated volcanic arc terranes and microcontinents that moved at low to moderate northerly latitudes throughout the Paleozoic. The Didenko et al. (1994) model and others (Zonenshain et al., 1990; Mossakovsky et al., 1993; Dobretsov et al., 1995) suggest that the first-order amalgamation of present-day Kazakhstan occurred by the latest Silurian. In contrast, the original model of Sengör et al. (1993), followed by the more extensive interpretation of Sengör and Natal'in (1996), suggests the existence of a continuous, north–south trending, over 5500 km long volcanic arc system, coined the Kipchak Arc. This arc is hypothesized to have been connected to Siberia, in the north, and Baltica in the south, with a significant intervening ocean. The Kipchak Arc is interpreted as originating in the southern hemisphere during the early Paleozoic, followed by northward drift at the same time as the Siberian and Baltica cratons moved north throughout the rest of the Paleozoic.

Paleomagnetic investigations of the Boshekul–Chingiz region (Fig. 1b) can provide constraints for early Paleozoic latitudinal positions of island arc complexes and accretionary wedges associated with the amalgamation of Kazakhstan. These data will also facilitate reconstructions characterizing the tectonic framework and paleogeographic positions of these tectonic "slivers" throughout early Paleozoic time. In this study, we test the existing hypotheses and suggest a paleolatitudinally plausible solution, for early Paleozoic time. This will in turn set the stage for a model of the middle–late Paleozoic deformation of the area, as discussed in the companion paper (Levashova et al., 2003).

Our study focuses on the Upper Cambrian–Lower Ordovician rocks of the Boshekul–Chingiz volcanic arc (Boshchekul–Tarbagatay unit of Sengör and Natal'in, 1996). The Boshekul–Chingiz volcanic arc, BC, is best exposed in the central Chingiz Range of eastern Kazakhstan (Fig. 2). The BC comprises a subduction-related volcano-sedimentary complex that accumulated between the Middle Cambrian and the Middle Silurian (Esenov and Shlygin, 1972; Khromykh, 1986; Yakubchuk and Degtyarev, 1998). A peculiar feature of the BC volcanic suite is the overwhelming dominance of andesite, with only minor occurrences of acid volcanics in the Late Cambrian. Evidence for less evolved magmatic activity, including basaltic flows and gabbroic intrusions, is absent throughout the early Paleozoic until the Early Silurian.

2. Geologic setting

The central Chingiz Range (Fig. 2) primarily consists of lower and middle Paleozoic volcano-sedimentary complexes of island arc affinity (Borisenok et al., 1989). The oldest rocks in this region are lower Middle Cambrian (Amgan stage) intermediate volcanics and volcaniclastic sediments with intercalated limestone lenses. These units are intruded by coeval granites and together these are overlain, unconformably, by upper Middle Cambrian (Mayan stage) to Lower Ordovician rocks.

Two Upper Cambrian–Lower Ordovician complexes are recognized in the central part of the Chingiz Range (Fig. 2). The Tortkuduk series (Upper Cambrian volcanics in Fig. 2) is characterized by andesitic lava with associated tuffs and rhyolites (Esenov and Shlygin, 1972) and is overlain by Upper Arenigian–Lower Llanvirnian siliceous and terrigenous sediments (Nikitin, 1972; Orlova and Kurkovskaya, 1993). The sec-

Fig. 1. (a) Location of the Ural–Mongol fold belt within Eurasia and (b) main Paleozoic tectonic units of eastern Kazakhstan (simplified after Avdeev and Kovalev, 1989; Yakubchuk, 1990; Zamaletdinov and Osmonbetov, 1988). The Irtysh–Zaisan fold belt and Altai domain are not discussed in this paper and are shown for completeness only. Thick solid lines denote major faults (dashed where inferred). The boundaries of the Devonian volcanic belt are shown as thick dash-dot lines. Thin solid lines bound the outcrops of Paleozoic and Precambrian rocks. The open polygon labeled Fig. 2 refers to the detailed site location map of this paper. Small full rectangles labeled Fig. II-1a and II-1b refer to the corresponding detailed location maps of the paleomagnetic studies of the companion paper (Levashova et al., 2003). Small solid circles and stars are Devonian sampling localities from Grishin et al. (1997) and Burtman et al. (1998), respectively.

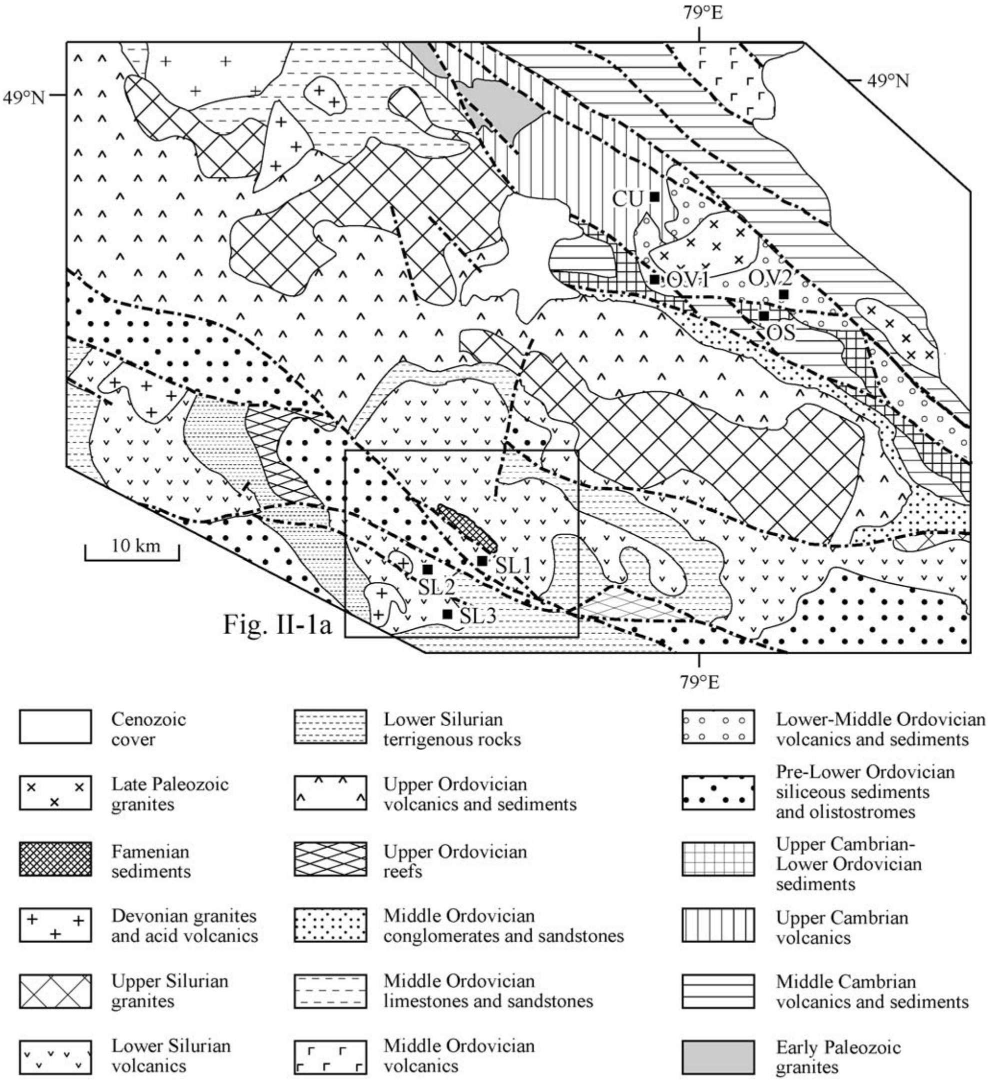


Fig. 2. Geological map of the central Chingiz Range (simplified from Bespalov and Kostenko (1979)). Thick dash-dot lines represent faults; thin lines denote lithologic contacts. Sampling localities are denoted as solid squares and are labeled as defined in the text. The rectangle labeled Fig. II-1a refers to the corresponding Fig. 1(a) in the companion paper (Levashova et al., this 2003).

ond complex is distributed to the east and southeast. Its basal units are Upper Cambrian black cherts. Lower Ordovician volcaniclastic and terrigenous sandstones conformably overlie the basal members of this series. Conglomerates locally overly these Lower Ordovician units. This primarily sedimentary complex is thought to represent a backarc or forearc basin (Degtyarev, 1999a).

By late Early Ordovician time, a set of granitic plutons intruded the Middle Cambrian–Lower Ordovician country rock. This whole sequence, both intrusions and host rock, was thrusted and folded in the Middle Ordovician, most likely in the Llanvirnian. Llandeilian–Caradocian rocks cover the Middle Cambrian–Lower Ordovician series (Degtyarev, 1999b) with an angular unconformity.

The Middle Ordovician units are characterized by andesite flows with local intercalations of limestone in the lower half and by volcaniclastic and terrigenous sediments in the upper one. Upper Ordovician (Caradocian–Ashgillian) rocks unconformably cover all older complexes and are represented by terrigenous sandstones, intermediate volcanics, and volcaniclastic sediments. Upper Ordovician units are conformably overlain by Silurian terrigenous sandstones (Nikitin, 1972). The uppermost part of the BC series includes voluminous basaltic-andesite flows with intercalated redbed members of late Llandoverian–Wenlockian age (Bandaletov, 1969). Upper Silurian granitic plutons were emplaced into the Upper Ordovician–Lower Silurian complex (Kayupov, 1977). In the study area, Famennian to Lower Carboniferous sediments unconformably overlie lower Middle Paleozoic rocks. In other parts of the Chingiz Range and in adjacent tectonic units, a major angular unconformity of Late Silurian age is observed.

3. Sampling and methods

We sampled Upper Cambrian and Lower Ordovician rocks within the BC (Fig. 2; localities CU, OV1, OV2, and OS). The ages of these formations are based on different groups of fossils, mainly trilobites and conodonts, from sedimentary intercalations in these rocks (Degtyarev, 1999b). Porphyric andesites and intercalated red sandstones were collected from 14 sites (112 samples) in the Tortkuduk series (locality CU). Both lithologies, as well as 23 clasts from an intra-formational conglomerate, were collected from both limbs of a NW–SE trending anticline. Lower Ordovician (lower Arenigian) volcanics were sampled at 11 sites (98 samples) at two localities OV1 and OV2 (Fig. 2). All sites are within andesitic lava and tuff units of island arc affinity (Yakubchuk and Degtyarev, 1998). We collected a total of 110 samples of Lower Ordovician (Arenigian) tuffaceous sandstones and siltstones, from 13 sites, distributed over a complex anticline (locality OS; Fig. 2).

Between five and fifteen 2.5-cm-diameter cores, collected with a portable gasoline-powered drill, or hand samples were taken from each site. Both cores and hand samples were oriented with a magnetic compass and corrected for the regional magnetic declination. At all localities, a sufficient number of sedimentary units were found to obtain bedding attitudes for each paleomagnetic site.

At the University of Michigan paleomagnetic laboratory, cylindrical specimens of dimensions 2.2 × 2.5 cm were prepared from cores or hand samples prior to treatment in a magnetically shielded room. Specimens were stepwise thermally demagnetized over the range of 50–680 °C utilizing an Analytical Services TD-48 thermal demagnetizer and measured with a 2G Enterprises cryogenic magnetometer.

At the paleomagnetic laboratory of the Geologic Institute, Russian Academy of Sciences in Moscow, cubic specimens of 8 cm^3 volume were cut from hand blocks. Specimens were stepwise demagnetized in 15–20 increments, up to 685 °C in a homemade oven with internal residual fields of about 10 nT and measured with a JR-4 spinner magnetometer with a noise level of 0.1 mA m^{-1}.

Demagnetization results were plotted on orthogonal vector diagrams (Zijderveld, 1967), and linear trajectories were used to determine directions of magnetic components by a least-squares fit comprising three measurements or more (Kirschvink, 1980). Site-mean directions were computed either using direct observations (isolated components) or combining them with remagnetization circles (McFadden and McElhinny, 1988). Paleomagnetic software written by Randy Enkin, Stanislav V. Shipunov, Trond Torsvik, and Jean-Pascal Cogné was used in the analysis of paleomagnetic data.

4. Results

4.1. Lower Ordovician volcanics

After removal of an unstable component, sometimes accounting for the larger part of the NRM, at 200–300 °C, many samples of volcanic rocks did not reveal a consistent demagnetization pattern. At the same time, other samples yielded perfect rectilinear demagnetization trajectories from room temperature up to well above 600 °C (Fig. 3b), but the corresponding component directions are random within a given site. Only at three sites from locality OV2 could a consistent remanent magnetization component, showing rectilinear decay to the origin, be isolated

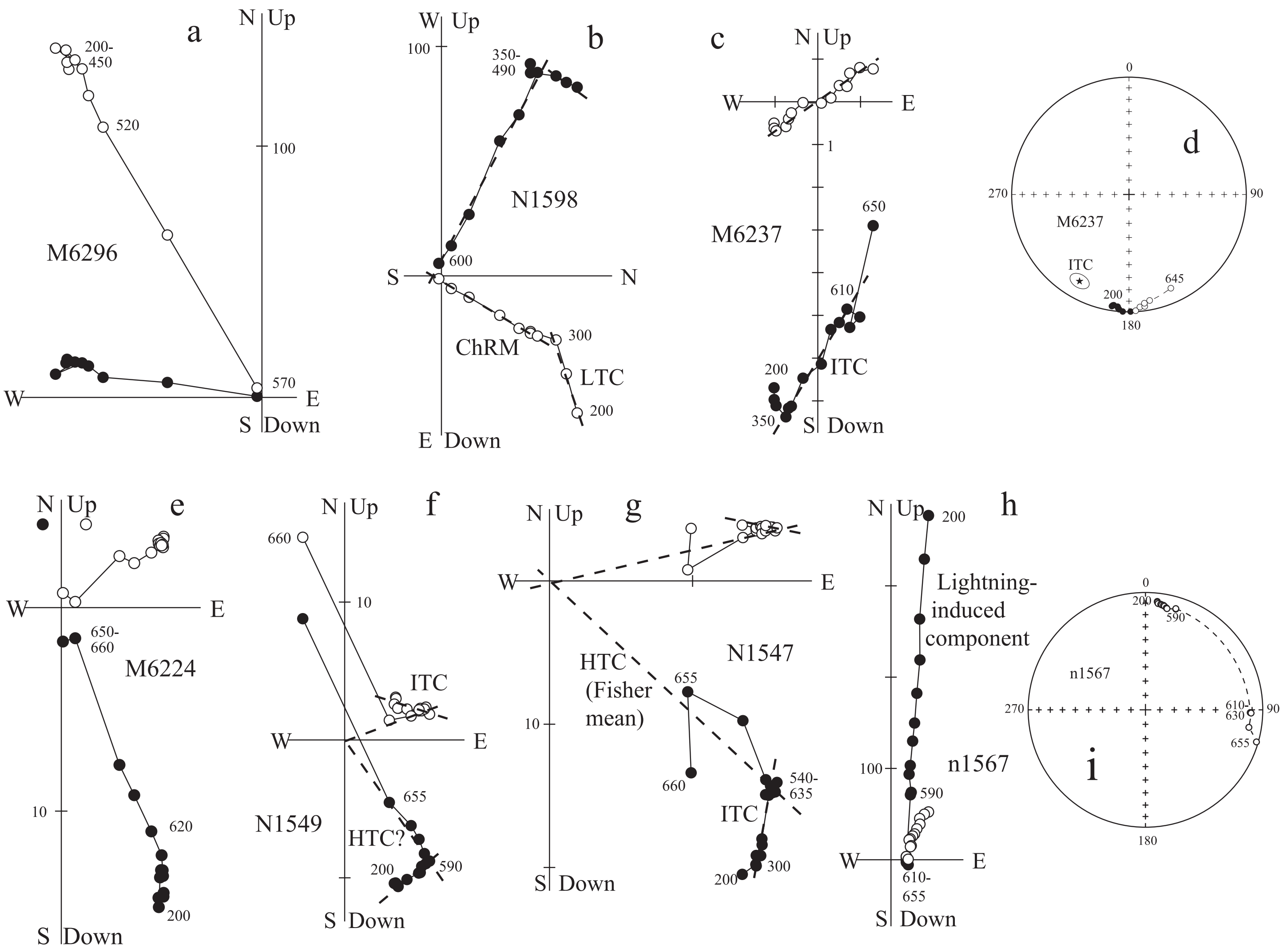


Fig. 3. Representative thermal demagnetization plots and stereoplots of Lower Ordovician rocks from the Chingiz Range: volcanics (a, b) in geographic coordinates and sediments (c–i) in stratigraphic coordinates. Full (open) dots represent vector endpoints projected onto the horizontal (vertical) plane on orthogonal plots. Full (open) symbols and solid (dashed) lines are projected onto lower (upper) hemisphere on stereoplots. Temperature steps are in degrees Celsius. Magnetization intensities are in mA m^{-1}. Thick dashed lines denote isolated components labeled as in the text (shown only on some plots). For clarity, NRM points are omitted from most plots.

(Fig. 3a). This component, generally removed below 570 °C, is called the intermediate-temperature component (ITC) in Table 1. Its three site means are best grouped in situ (Table 1; Fig. 4a,b), thus indicating a postfolding origin of this component.

At both localities OV1 and OV2, sampling could be done only at higher elevations in the generally mature relief, although the very crests were avoided. Despite this, the presence of perfectly single-component, yet randomly directed, remanences indicates that many samples were lightning-struck (e.g., Miller et al., 2000). Very strong drops of NRM intensity at low demagnetization temperatures may result from penetrative weathering due to long exposure times. Tentatively, we interpret the high scatter at most sites to reflect the combined effects of lightning and mineral alteration.

4.2. Lower Ordovician sediments

A low temperature component (LTC) was isolated from more than three samples at only two sites but was observed at other sites as well. Its directions are close to the present-day field in situ and diverge upon tilt correction; hence, this remanence is either a viscous overprint or related to weathering.

Table 1
Paleomagnetic results from Lower Ordovician volcanics and sediments of the Chingiz Range

Site	N_0/N	A/d	Geographic coordinates				Stratigraphic coordinates			
			D (°)	I (°)	k	α_{95}	D (°)	I (°)	k	α_{95}
Intermediate-temperature component (ITC)—volcanic units										
OV2-6	13/8	248/51*	286.5	−76.7	19	13.0	55.1	−48.3	18	13.4
OV2-8	10/9	314/51	241.5	−66.3	13	14.6	165.0	−41.8	13	14.6
OV2-9	7/6	245/76*	209.8	−45.1	28	6.0	101.6	−47.0	6	28.4
Mean	(4/3)		231.4	−65.5	14	34.7	108.7	−55.3	5	61.3
Intermediate-temperature component (ITC)—sedimentary units										
OS1	10/3	36/42*	250.4	−56.9	27	24.3	235.2	−18.3	14	34.9
OS2	10/6	7/61	246.6	−61.2	17	16.7	212.5	−11.8	20	15.3
OS3	8/8	15/74	246.3	−50.0	27	10.9	225.7	10.4	30	10.3
OS4	7/5	19/65	264.1	−54.6	13	21.7	231.0	−7.1	13	22.5
OS5	9/5	347/85	264.1	−49.2	16	19.6	208.4	−8.4	16	19.6
OS10	9/7	227/37*	235.5	−36.6	34	10.8	249.8	−72.7	25	12.7
Mean	(13/6)		250.5	−51.9	53	9.3	224.1	−17.1	7	26.6
ITC	(9)		245.9	−56.6	25	10.5	207.2	−38.6	< 3	40.0
High-temperature component (HTC)—sedimentary units										
OS1	10/10	3/29*	137.4	−54.8	14	14.2	154.3	−30.8	21	11.3
OS2	10/10	8/61	128.1	−66.4	28	9.4	167.3	−15.7	32	8.8
OS3	8/7	14/72*	145.2	−73.9	9	23.6	181.9	−7.2	28	13.3
OS4	7/6	19/65*	135.5	−61.2	41	11.4	172.9	−10.1	153	5.8
OS5	9/8	347/85	57.9	−67.2	52	8.1	144.7	−16.5	54	7.9
OS6	6/5	26/81*	97.3	−34.6	50	12.4	144.1	−16.1	158	6.9
OS7	5/5	13/78*	87.0	−40.5	56	11.8	142.4	−20.5	124	7.9
OS8	9/7	239/104*	196.1	−20.7	24	12.2	110.2	−35.9	40	9.4
OS9	14/10	182/82	109.0	4.3	79	5.7	98.5	−16.5	65	6.3
OS12	8/8	327/42	105.3	−69.8	57	7.8	131.3	−31.9	47	8.6
OS13	9/7	344/44*	120.6	−72.4	26	12.5	150.3	−32.8	18	15.0
Mean	(13/11)		120.4	−57.2	6	20.0	146.3	−23.1	10	14.8
INC	(13/11)		–	−51.8	5	22.3	–	−21.3	29	6.3

Sites are labeled as in text. Mean directions are calculated from site means (Fisher, 1953); ITC: overall mean of overprint data from volcanics and sediments; INC: inclination-only statistics (McFadden and Reid, 1982); N_0/N, the number of samples (sites) studied/accepted; A/d, average dip direction/dip angle (calculated for the accepted samples; $d>90°$ for the beds in overturned position); D, declination; I, inclination; k, precision parameter (Fisher, 1953); α_{95}, radius of confidence circle (in °).

* Bedding attitudes are variable at these sites.

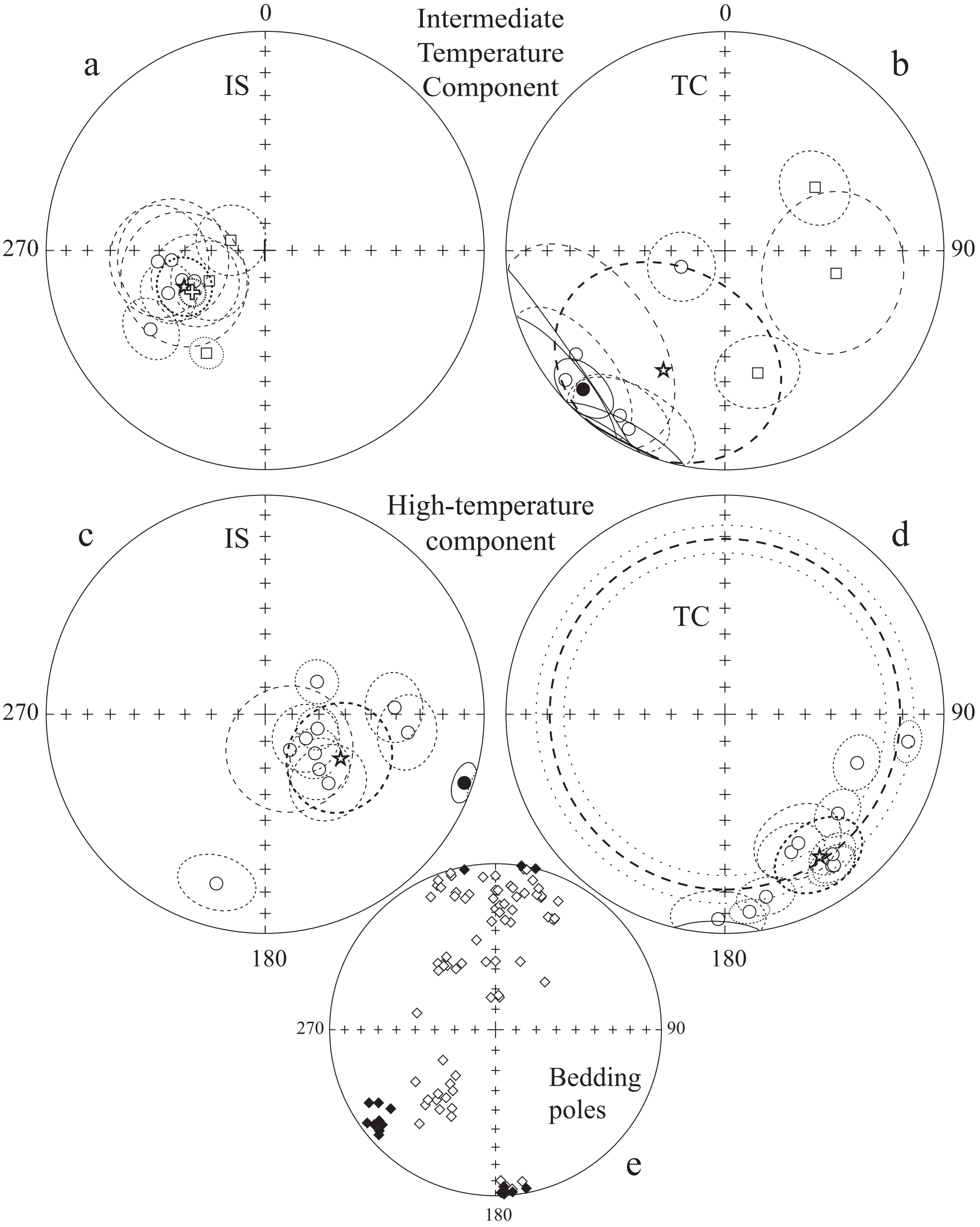


Fig. 4. Stereoplots of intermediate- (a, b) and high-temperature component (c, d) site-mean directions with confidence circles (thin lines) in Lower Ordovician volcanics (squares) and sediments (circles) from the Chingiz Range in situ (a,c) and after tilt correction (b,d). Stars are overall mean directions of these remanences with confidence circles (thick lines). Cross in (a) is the expected Permian Eurasian reference direction for this locality with confidence circle (thick dotted line). Thick and thin dotted lines in (d) denote mean inclination and its confidence limits, respectively, computed with the aid of inclination-only statistics (McFadden and Reid, 1982). (e) Distribution of all bedding poles measured in sediments from locality OS. Solid (open) symbols and solid (dashed and dotted) lines are projected onto lower (upper) hemisphere.

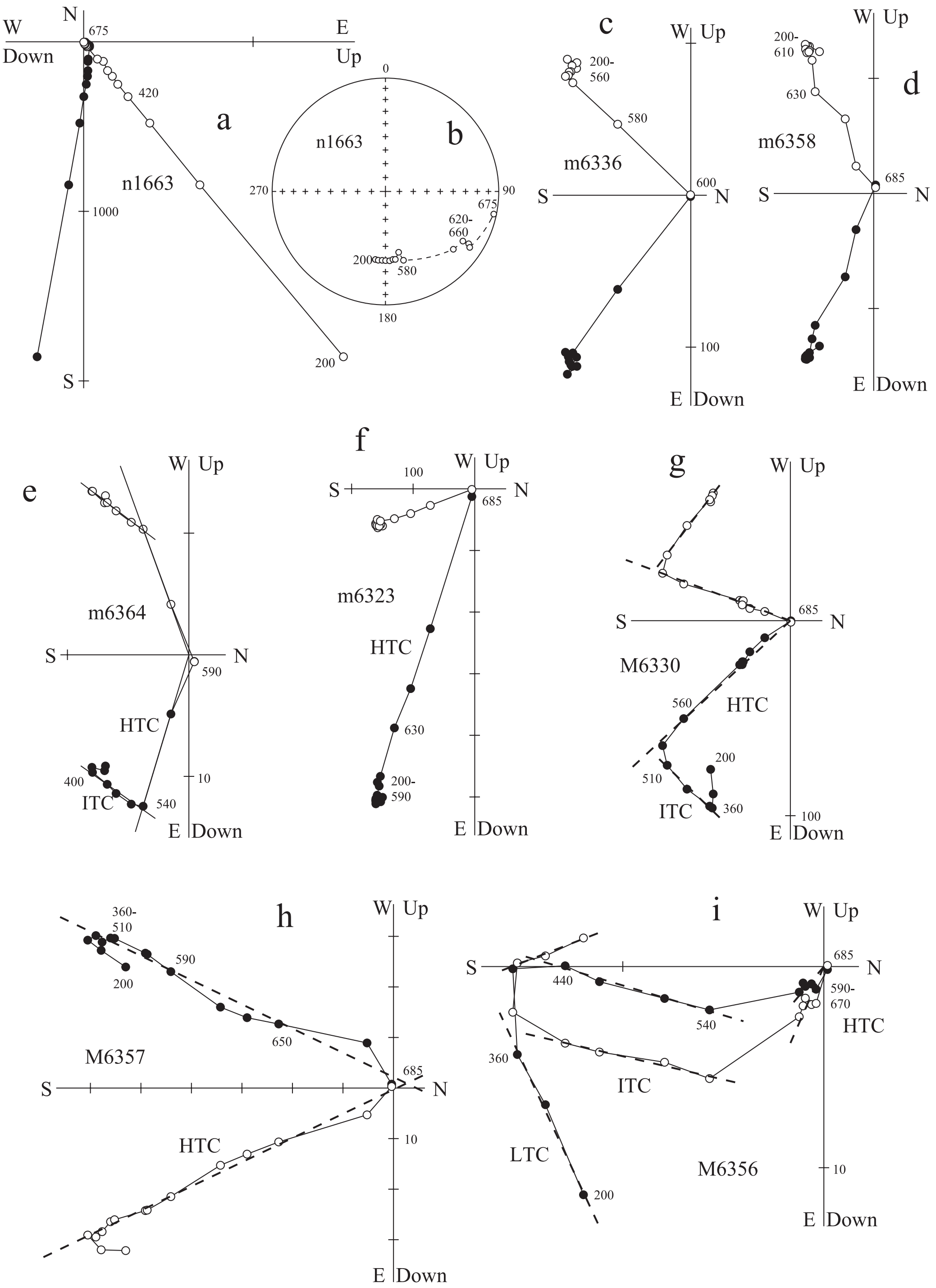


Fig. 5. Representative thermal demagnetization plots and stereoplots of Upper Cambrian host rocks (a–e) and clasts from an intra-formational conglomerate (f–i) in stratigraphic coordinates. Notation as in Fig. 3.

In many samples, a well-defined intermediate component persists over a wide range from 300 °C to more than 600 °C; sometimes, it is the only component. This intermediate-temperature component (ITC) does not decay to the origin and displays remagnetization circles on the stereonet (Fig. 3c,d), thus indicating that a high-temperature component (HTC) is also present. Acquisition of spurious remanences above 600 °C, however, prevented complete demagnetization of several samples. As a result, just an initial part of the HTC trajectory was observed in some samples (Fig. 3f), while the HTC was fully determined from quite a few other samples (Fig. 3e). In still other samples, the remanence stabilized (as clustered vector endpoints), both in intensity and direction, after ITC removal (Fig. 3g; 540–635 °C), but the final decay to the origin could not be observed because of sudden (and spurious) magnetization changes. At two sites, many samples were clearly affected by lightning strikes; luckily, some of them displayed remagnetization circles (Fig. 3h,i), which could be used further on. Directly isolated HTC directions and remagnetization circles were preferably used to calculate HTC site-mean vectors (McFadden and McElhinny, 1988); for samples where the two previous types of data could not be obtained, Fisher statistics was used to determine directions by averaging the clustered endpoints of the interval 540–635 °C.

The ITC site-mean directions cluster better in situ than in tilt-corrected coordinates, and a postfolding age of this component is evident (Table 1; Fig. 4a,b). Its overall mean agrees rather well with the OV2 results, and these data are combined. The fold test is negative for the combined set, and the overprint mean coincides with the Eurasian Permian reference directions well within the error limits of the data (Fig. 4a). Tentatively, overprinting may be connected with the emplacement of large granite intrusions of Permian age in the area studied (Fig. 2).

The HTC directions have declinations in the SE quadrant and shallow, mostly negative, inclinations; a component of opposite polarity was found in just one sample. Clustering of the HTC site-mean directions is rather poor in both coordinate systems (Table 1; Fig. 4c,d). On the other hand, tilt-corrected site-mean inclinations are similar, while the declinations define a girdle distribution (Fig. 4d). The inclination-only tilt test (McFadden and Reid, 1982) is positive and the best grouping is observed at 100% untilting. It should be stressed that the studied structure is neither a cylindrical fold with plunging axis nor a conical fold (Fig. 4e), and parts of the structure are likely to have undergone complex net rotations. We attribute the strongly planar distribution of the entire set to the complex character of deformation and hence conclude that the HTC in Lower Ordovician sediments is pre-deformational. Major deformation is constrained to have occurred during the Middle Ordovician (Degtyarev,

Table 2
Paleomagnetic results from Upper Cambrian volcanics of the Chingiz Range

Site	N_0/N	A/d	Geographic coordinates				Stratigraphic coordinates			
			D (°)	I (°)	k	α_{95}	D (°)	I (°)	k	α_{95}
CU1	8/7	241/78	200.2	−30.2	8	23.0	120.6	−45.9	8	23.0
CU2	10/9	241/78	213.4	−60.5	9	18.0	80.5	−35.9	9	18.0
CU4	8/6	241/78	173.9	−20.8	46	10.1	132.1	−27.7	46	10.1
CU5*	8/6	241/78	165.2	−49.9	6	32.3	100.2	−20.3	6	32.3
CU6*	7/3	17/45	83.3	−15.6	8	46.1	101.5	−27.7	8	46.1
CU8	7/4	17/45	76.2	−22.4	16	15.5	102.3	−37.2	16	15.5
CU9	8/6	17/45	89.0	−14.6	19	23.2	104.9	−23.0	19	23.2
CU10	7/6	17/45	81.3	−31.3	49	10.0	114.8	−39.0	49	10.0
CU11	7/6	17/45	84.9	−22.8	15	18.0	109.2	−31.4	15	17.7
CU12	6/5	16/50	79.0	−22.8	45	11.5	108.0	−34.7	45	11.5
Mean	(14/8)		110.6	−40.1	3	38.6	109.1	−35.2	33	9.8
$F_{(2,12)}=3.89$				$f=53.08$				$f=0.33$		
CONGL	23/18		161.9	−26.8	2.7	26.6	123.8	−14.6	2.5	27.7

Sites are labeled as in text. CONGL, HTC mean direction in the clasts from conglomerate; F, the 95% critical value of F-statistics with the numbers of degrees of freedom in parentheses; f, calculated value of the same statistics; Other notation as in Table 1.

* Excluded from overall mean calculation because of large α_{95} values.

1999b); therefore, it is likely that the magnetization observed is primary.

4.3. Upper Cambrian units

Upper Cambrian volcanics and associated sediments were sampled from both slopes of a small range; although the range crest was avoided, several samples from this collection, during thermal cleaning, exhibit characteristics that can be attributed to lightning-induced magnetization. These observations include convex up geometry of intensity curves, high natural remanent magnetization (NRM) values of 10 A m^{-1} or greater, and random directions. Samples with demagnetization trajectories that miss the origin of the diagrams (Fig. 5a,b) display great circle paths at the final steps of thermal cleaning, and these remagnetization circles were used further on. Apart from the lightning-affected samples, many volcanics show univectorial decay to the origin (Fig. 5c,d), while relatively weak overprints were observed at low to intermediate temperatures in others (Fig. 5e). Grouping of the LTC component, in situ, is coincident with the present-day field, while ITC vectors in some, but not all, samples are close to the late Paleozoic overprint directions, which were identified also in Lower Ordovician rocks (Fig. 4a).

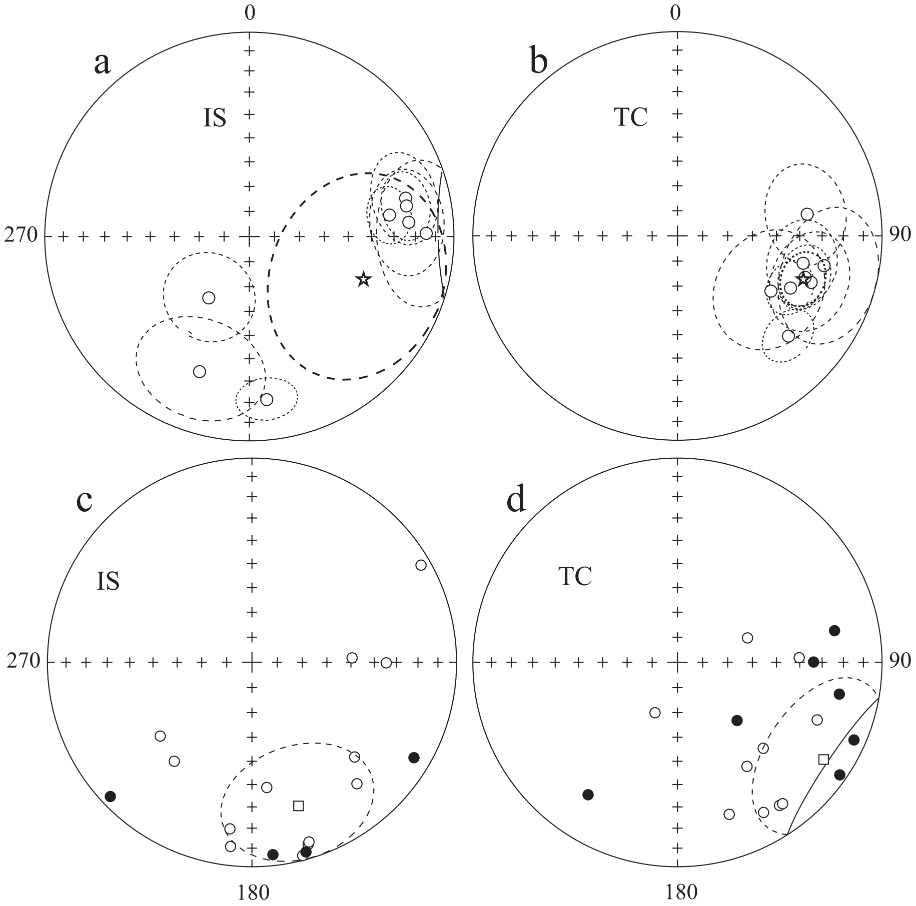


Fig. 6. (a, b) Stereoplots of the HTC site-mean directions (circles) in Upper Cambrian volcanics in situ (a) and after tilt correction (b). Star, the mean direction of the HTC in host-rocks with its confidence circle (thick line). (c, d) Stereoplots of HTC directions (circles) in clasts from Upper Cambrian conglomerate from the Chingiz Range in situ (c) and after tilt correction (d). Square, mean ChRM direction with associated confidence circle. Other notation as in Fig. 4.

HTC directions, such as shown in Fig. 5c–e, are of the same polarity in all samples. The HTC site means are based mostly on directly isolated components, with a few remagnetization circles used if acquisition of spurious remanences prevented complete demagnetization. These directions form two distinct clusters in situ, which converge into a tight one upon tilt correction (Table 2; Fig. 6a,b), providing a positive tilt test (McFadden and Jones, 1981).

Some andesite samples from two conglomerate sites contain only one component up to well above 600 °C (Fig. 5f), while two or even three components are present in others (Fig. 5g–i); the HTC can be confidently isolated from 18 samples out of 23 studied. Despite considerable scatter, HTC directions are not random in either coordinate system (Table 2; Fig. 6c,d); note also that the tilt-corrected HTC mean from the clasts is similar to the host rock data within the error limits (Fig. 6b). This pattern can indicate a complete remagnetization of all Upper Cambrian rocks; because of the positive tilt test, this remagnetization must have been acquired prior to folding, which took place in the Middle Ordovician. However, there is another possible explanation for the lack of randomness in the clast data set. The intra-formational conglomerate studied consists of angular to rounded andesite debris within a matrix of the same composition. In the field, a gradual transition from massive andesite flows to these conglomerate-like units was observed. It is possible that the "conglomerate" is actually an agglomerate, indicating a "hot" depositional nature. In this depositional environment lava debris could have been displaced during final stages of cooling after the HTC magnetization had already been acquired. This displacement would not have been of a magnitude to completely randomize the HTC vectors observed, but would have sufficed to increase the data scatter.

The HTC in Upper Cambrian rocks is prefolding and hence not younger than the end of the Early Ordovician; despite the ambiguous conglomerate data, we favor the interpretation that this remanence is primary.

5. Interpretation

The main objective of this study is to provide a paleomagnetic test of the different hypotheses concerning the early Paleozoic tectonic evolution of the central Ural–Mongol fold belt. The disparate views of Sengör and Natal'in (1996) and Didenko et al. (1994) portray early Paleozoic models placing the BC in different paleogeographic positions and geodynamic settings. Didenko et al. (1994) have inferred a low northerly paleolatitude (~ 15°N) during Early Ordovician time, without any paleogeographic connection to either Siberia or Baltica (Fig. 7a). In contrast, Sengör and Natal'in (1996) place the BC at intermediate southerly paleolatitudes during Late Cambrian time (~ 30°S) and propose that this region is a duplexed member of an extensive volcanic arc that, during the early Paleozoic, was situated between the Siberian and Baltica cratons and reached low southern latitudes by Middle Ordovician time (Fig. 7b). These hypotheses not only show variable location of the BC, but also require different paleolatitudinal displacement histories and predict different origins.

Our new paleomagnetic data can be used to test paleogeographic models for the BC for Paleozoic times. The Late Cambrian ($-35.2 \pm 9.8°$) and Early Ordovician ($-21.3 \pm 6.3°$) mean inclinations correspond to paleolatitudes of $19.4 \pm 6.5°$ and $12.2 \pm 3.6°$, respectively. Given the southeasterly declinations of both these results, it is logical to infer that they are of the same polarity, although it is not known whether this polarity was normal or reversed. As a consequence, it is also not a priori clear whether these early Paleozoic paleolatitudes were northerly or southerly. We also include two new middle Paleozoic results from the companion paper into our analysis (Levashova et al., 2003), which add an Early Silurian (Wenlockian) paleolatitude of $1.4 \pm 4.1°$ and a Middle Devonian (Givetian) one of $30.2 \pm 10.7°$. Lastly, we include a paleolatitude of $32.2 \pm 3.2°$ derived from Permian volcanics in a more easterly part of the Chingiz Range (Levashova et al., 2003).

The polarity of the Permian result is straightforward and places the BC in northern mid-latitudes. The Middle Devonian paleolatitude is almost certainly northerly as well, as the opposite option creates large difficulties for the tectonic evolution of the entire Ural–Mongol belt and would require ultra-fast velocities for the BC in post-Givetian time. The Wenlockian result indicates that the study area straddled the equator within error limits; its polarity choice is therefore irrelevant for the paleolatitudinal evolution-

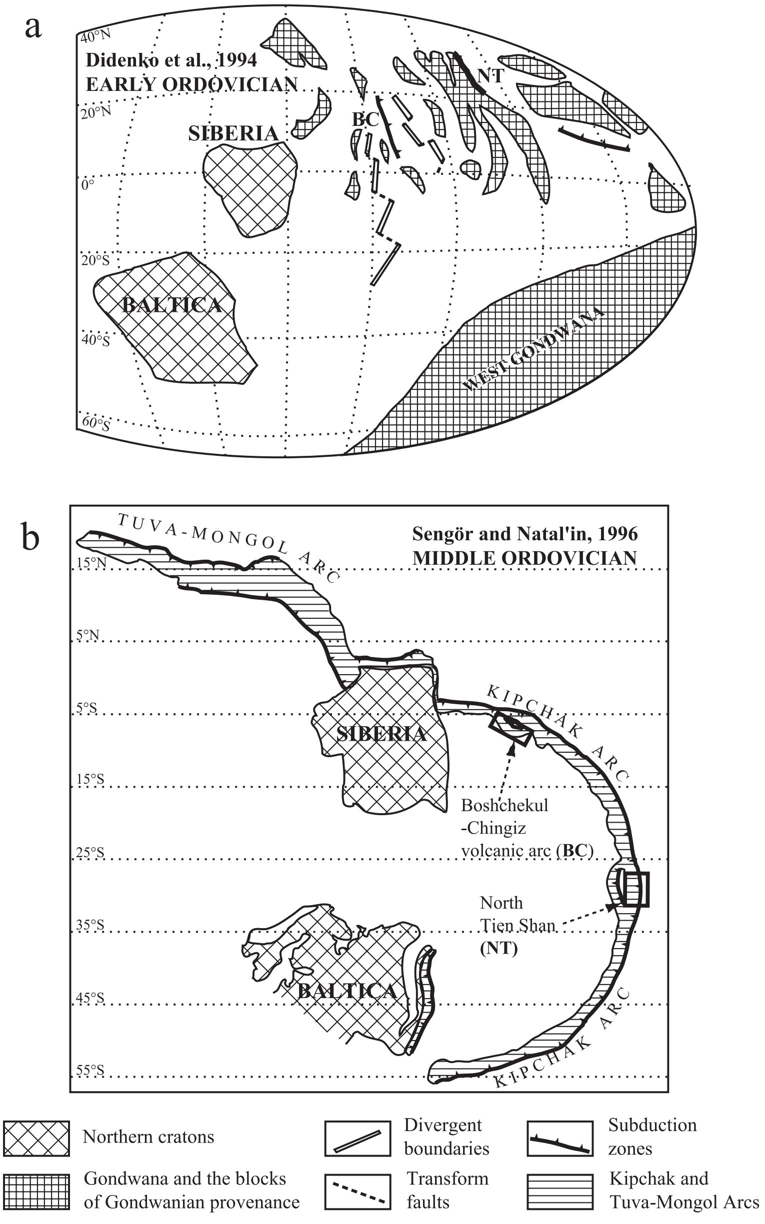
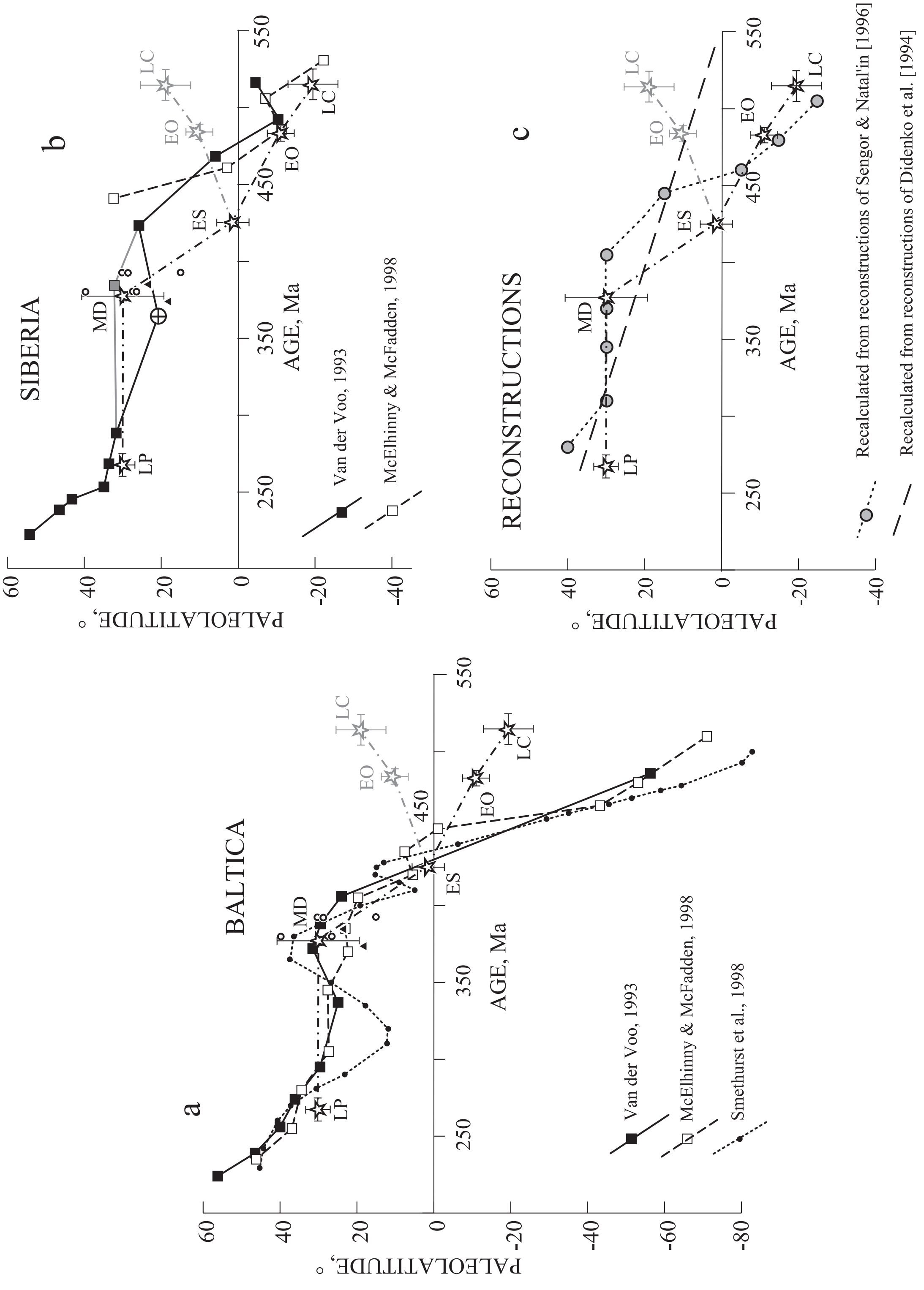


Fig. 7. Palinspastic reconstructions of the Ural–Mongol belt: (a) after Didenko et al. (1994), depicting Early Ordovician time; BC—Boshekul–Chingiz volcanic arc, NT—North Tien Shan block; (b) after Sengör and Natal'in (1996), depicting Middle Ordovician time. Both reconstructions are simplified. For clarity, only major units pertinent to this study are shown and are labeled as they are referred to in the text.

ary scenario, although this choice will certainly play a role in the discussion of rotations as indicated by the declinations (Levashova et al., 2003). However, the polarity option for the two early Paleozoic results allows for two competing drift scenarios. Assuming normal polarity, the paleolatitudes indicate a southern-hemisphere position in the early Paleozoic and require a rather steady northward translation of the BC throughout the Paleozoic (Fig. 8). A reversed-polarity scenario would imply a northerly paleolatitude posi-


a
BALTICA
b
SIBERIA
c
RECONSTRUCTIONS
PALEOLATITUDE, °
AGE, Ma
60
40
20
0
-20
-40
-60
-80
250
350
450
550
LP
MD
ES
EO
LC
Van der Voo, 1993
McElhinny & McFadden, 1998
Smethurst et al., 1998
Recalculated from reconstructions of Sengor & Natal'in [1996]
Recalculated from reconstructions of Didenko et al. [1994]

tion and requires a southward translation during the early Paleozoic; it also would imply a reversal in the motion of BC sometime during the Silurian (Fig. 8).

Both scenarios are plausible. The first one implies a movement of BC in general accord with those of Siberia, which shows steadfast northward motion throughout the Paleozoic, albeit with variable velocities (e.g., Torsvik et al., 1996). Instead, the second scenario requires a southward drift of the BC from the Late Cambrian to the Early Silurian that is completely independent of, and opposite to, the movements of the nearby (?) cratons of Baltica and Siberia. In favor of the second scenario is that the Arenigian is thought to be largely, if not entirely, an interval of reversed polarity (Khramov et al., 1982; Torsvik and Trench, 1991; Gallet and Pavlov, 1996; Pavlov and Gallet, 1998).

For our subsequent analysis, the above results from the BC are compared with reference paleolatitudes, which can either be estimated from the palinspastic reconstructions of the Ural–Mongol belt or, more conventionally, calculated from the apparent polar wander paths (APWPs) of adjacent major cratonic blocks, i.e., Baltica and Siberia. We used the reconstructions of Sengör and Natal'in (1996) and Didenko et al. (1994) as the end-members of the models proposed thus far.

Several APWPs have been constructed for Baltica during the last decade (Van der Voo, 1993; Pechersky and Didenko, 1995; Smethurst et al., 1998; McElhinny and McFadden, 2000, and others). Although they are based on different selection criteria and statistical treatments, these paths show a general agreement. Some, albeit limited, additions of newer paleomagnetic data for Baltica may account for the differences in the APWPs and, hence, in the corresponding paleolatitude plots (Fig. 8a). To first approximation, our results show good agreement with these plots for the Early Silurian–Late Permian interval. In contrast, the observed early Paleozoic paleolatitudes differ from the predicted ones for both polarity options; the magnitude of inferred poleward motion of the BC is much less than that expected for Baltica for Cambro-Ordovician times (Fig. 8a).

All published Siberian APWPs result in rather similar paleolatitude predictions for the BC in the early Paleozoic (Fig. 8b), despite the steadily growing database for this interval (e.g., Gallet and Pavlov, 1996; Pavlov and Gallet, 1998). In contrast, the reference values diverge greatly in the middle Paleozoic and Carboniferous; in particular, a recent Siberian APWP of McElhinny and McFadden (2000) predicts paleolatitudes up to 50°N and higher for the study area, and these are higher by more than 20° than those predicted by other APWPs (e.g., Van der Voo, 1993; Smethurst et al., 1998). This discrepancy, however, is not surprising because the middle–late Paleozoic Siberian data used by McElhinny and McFadden (2000) are decades old and are suspected to be unreliable. These suspicions are confirmed by geological data (Scotese and McKerrow, 1990; Pedder and Oliver, 1990) that point to much lower paleolatitudes for Siberia than those deduced from the older paleomagnetic data. Also, the APWP of McElhinny and McFadden (2000) predicts paleolatitudes that are too high by about 20° compared to observed values for some blocks near the southern margin of Siberia, which are thought to have been geologically linked to the Siberian craton in the middle Paleozoic (Bachtadse et al., 2000 and references therein). Finally, Kravchinsky et al. (2002) have just obtained a Late Devonian–Early Carboniferous pole, which differs from all previously available data for Siberia. So, for this paper, we replaced the Devonian pole of Van der Voo (1993) by this new result (Fig. 8b) and did not include the Silurian and younger reference APWP of McElhinny and McFadden (2000). For our purposes, the uncertainties in the APWPs for Siberia allow us to reach only qualitative conclusions.

Our results show an acceptable agreement with the predictions extrapolated from Siberia for the early Paleozoic, but they deviate in the Early Silurian and

Fig. 8. Plots of paleolatitudes versus age for observed and reference data. Stars, observed paleolatitudes for the Chingiz Range with associated error bars. LC: Late Cambrian, EO: Early Ordovician, ES: Early Silurian, MD: Middle Devonian, LP: Late Permian (age uncertainties for MD and ES are smaller than symbols). Ages are assigned according to the DNAG time scale after Palmer (1983). For LC and EO, black (lightly shaded) symbols and lines correspond to normal (reversed) polarities of these results as discussed in the text. Reference paleolatitudes are calculated for a common point at 48.9°N, 79.0°E from different APWPs for (a) Baltica and (b) Siberia and (c) palinspastic reconstructions of Sengör and Natal'in (1996) and Didenko et al. (1994). Small open circles and solid triangles in (a) and (b) are Devonian paleolatitudes from Grishin et al. (1997) and Burtman et al. (1998), respectively.

converge again for the Middle Devonian–Late Permian interval (Fig. 8b). The Early Silurian discrepancy might have some tectonic explanation. However, we would like to point out that all Silurian results from Siberia are old and, at the very least, of suspected quality. Moreover, several attempts to get more reliable data for this interval have failed because Silurian rocks, even at previously studied localities, are found to be either completely remagnetized, presumably during the emplacement of Permo-Triassic flood basalts, or they reveal no stable components altogether (V.E. Pavlov, personal communication). So it appears to be likely that the Early Silurian discrepancy is due to low reliability of the Siberian data set.

Our analysis shows that the Devonian–Permian segments of both Baltica and Siberia reference paleolatitude plots do not differ for the Chingiz; at least two APWPs from the available sets give predicted paleolatitudes that coincide with our results within the error limits. The Early Silurian paleolatitude agrees better with Baltica, but the reliability of the Siberian data, as already noted, is very doubtful.

We next turn to the two early Paleozoic results, which differ from Baltica predictions for either choice of polarity. Assuming the reversed polarity option, these two paleolatitudes from the BC differ from the Siberian reference plot as well. Instead, they show rather good agreement with the Siberian curve for the normal polarity option. Although not indisputable, this agreement, and the fact that all tectonic elements surrounding the study area show northward drift, makes us prefer the latter option below.

Besides an examination of the predictions from reference APWPs, we have also used tectonic models of the Paleozoic amalgamation of Kazakhstan for a comparison with our observations (Fig. 8c). This comparison shows that the reversed polarity option results in serious disagreement with the positions and motion of the BC suggested by Sengör and Natal'in (1996). Comparison with the Didenko et al. (1994) model exhibits only minor disagreement with respect to latitudinal position of the BC for the reversed polarity option (Fig. 8c). However, this model suggests northward drift of the Chingiz during the Paleozoic, whereas a reversed-polarity interpretation of our data calls for a southward drift of the BC from the Late Cambrian to the Early Silurian. Hence we conclude that an apparent agreement of the early Paleozoic paleolatitudes with the Didenko et al. (1994) model is fortuitous.

Conversely, the normal polarity option is in disagreement with the Didenko et al. (1994) model, whereas it provides a rather good correlation of the BC paleolatitudinal positions with the Sengör and Natal'in (1996) model during the early Paleozoic (Fig. 8c). The Early Silurian paleolatitude supports this correlation by the general sense of Chingiz motion but differs considerably from the predicted value. We recall, though, that the position of the Kipchak Arc of Sengör and Natal'in (1996) is tied to the positions of Siberia and Baltica, which in turn have been based on (older) paleomagnetic data by these authors. If, as we just argued, the APWP for Siberia is in error, the model should—and can—be modified accordingly (alas, not in this paper).

Unfortunately, we cannot get more support for our conclusions from the few previously published paleomagnetic results because of their low or disputable reliability. Several results from Ordovician and Early Silurian ophiolite complexes of central Kazakhstan (Fig. 1b) have been used to suggest that these rocks were originally at low northerly latitudes, between the equator and 20°N (Turmanidze et al., 1991; Grishin et al., 1991). These collections were mostly heated in a few steps up to 540 °C and revealed very scattered remanence directions at the highest temperatures used. Consequently, the mean directions are based mainly on "remagnetization great circles"; however, these were drawn to connect only the last two vector endpoints (usually 500 and 540 °C); more rigorous principal component analysis (Kirschvink, 1980) was rarely used. We do not think that these data are reliable enough to be incorporated in our interpretation.

Our Middle Devonian result (Levashova et al., 2003) is clearly of preliminary nature. Several Devonian paleomagnetic results were reported from central and east Kazakhstan (Grishin et al., 1997; Burtman et al., 1998), and we tried to reinforce our interpretation by combining all results. The corresponding paleolatitudes, however, are rather scattered (Fig. 8a,b; small open circles and full triangles); our evaluation of these data is that their reliability is not high. Clearly, new reliable middle Paleozoic and Carboniferous results are needed.

At this point in time, though, we think that the generally good agreement of the BC paleolatitudes with the Siberian reference values looks rather convincing and, hence, that BC motion was mainly governed by the kinematics of the Siberian plate. Within the framework of the model of Sengör and Natal'in (1996), the BC is treated as a peri-Siberian segment of the huge Kipchak Arc; hence, we can state, with the above-discussed reservations, that this model is compatible with available paleomagnetic data.

So far, we discussed only paleomagnetic data from the northeastern part of Kazakhstan, which supposedly constituted the peri-Siberian part of the Kipchak Arc. Recently, a set of Ordovician and Carboniferous paleomagnetic results (Bazhenov et al., 2003) was obtained in south Kazakhstan and north Kyrgyzstan, in the North Tien Shan tectonic zone, which was placed in the central part of the same Kipchak Arc and thus closer to Baltica (Fig. 7b). Resolving polarity ambiguities for the Ordovician results by assuming steady northward drift (just like in this paper), Bazhenov et al. (2003) found that the paleolatitudes for the North Tien Shan generally match the expected values for Baltica and differ from the Siberian data. Hence, the available paleomagnetic data from the two distant segments of the hypothetical Kipchak Arc generally agree with the kinematics of the craton closest to each of them.

Despite numerous uncertainties about the different APWP versions for Baltica and Siberia, the paleolatitude predictions agree too well with the observed middle–late Paleozoic paleolatitudes from the North Tien Shan and BC to be a coincidence. It is also well known that the Ural Ocean existed between Baltica and Kazakhstan sensu lato during the same interval as indicated by numerous island arc complexes and deep-sea sediments of various ages in the modern Ural Mountains (Fig. 1a). This ocean is thought to have closed not earlier than the end of Carboniferous or even later (Puchkov, 1993, 1997; Alvarez-Marrón et al., 2000). Close agreement between the observed paleolatitudes and the reference values for Baltica, Siberia and Kazakhstan greatly narrows the north–south extent of this ocean. However, a rather large difference in Devonian latitudes has been reported for both sides of the Ural Ocean (Burtman et al., 2000). A resolution of the paleogeography of the Ural Ocean will require further study.

Conclusions that can be drawn from an analysis of the declinations of all the Paleozoic results from the Chingiz area and the North Tien Shan Zone will be discussed in the companion paper (Levashova et al., 2003).

6. Conclusions

We have isolated prefolding paleomagnetic components from Upper Cambrian and Lower Ordovician rocks of the Chingiz Range in eastern Kazakhstan. Notwithstanding an ambiguous conglomerate test for Cambrian volcanics and a large range of declinations in the Ordovician tuffaceous sediments, both components are most likely primary and were acquired in geomagnetic fields of the same polarity. These results are combined with middle and late Paleozoic data from other parts of the Chingiz Range (Levashova et al., 2003; Levashova et al., 2003) and allow us to evaluate paleolatitudinal displacements of this area over most of the Paleozoic. Comparison with the reference latitudes for Siberia and Baltica shows that the Chingiz area moved coherently with Siberia; a misfit of Silurian predictions and observations can be attributed to the low reliability of Siberian reference poles. When compared with the models of the tectonic evolution of the Ural–Mongol belt, our paleomagnetic data show good correlation with the hypothesized kinematics of the Kipchak Arc (Sengör et al., 1993; Sengör and Natal'in, 1996) and disagree with other models. This correlation is further corroborated by paleomagnetic data from the North Tien Shan Range in south Kazakhstan and north Kyrgyzstan (Bazhenov et al., 2003), which also show good correspondence with the kinematics of its segment of this arc. Therefore, available paleomagnetic data from the central part of the Ural–Mongol belt generally support the model suggested by Sengör and colleagues. Our data, however, come from only two segments of the Kipchak Arc and do not provide as complete a coverage of Paleozoic time as would ultimately be desirable; clearly, a lot of work still awaits geologists and paleomagnetists before a thoroughly documented kinematic model of the Ural–Mongol belt will be available.

Acknowledgements

We thank Nina Dvorova for extensive help with paleomagnetic measurements. We would also like to thank the Scientific Station of the Institute for High Temperatures (IVTAN) in Bishkek, Kyrgyzstan, for immeasurable logistical support during our field works in Kyrgyzia and Kazakhstan. Helpful comments from Ben van der Pluijm, Josep M. Parés, and Konstantine Statagin greatly improved the contents of the manuscript, as did constructive reviews by Vadim Kravchinsky, an anonymous reviewer and Editor J. P. Burg. This research has been funded by the United States National Science Foundation through a grant from the Earth Sciences division (EAR 9909231-RVDV), through grants issued by the Russian Basic Research Fund (Bazhenov, Degtyarev and Levashova; nos. 00-05-64148, 00-05-64149, and 00-0564646), and through grant support from the University of Michigan Scott Turner Fund (Collins).

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