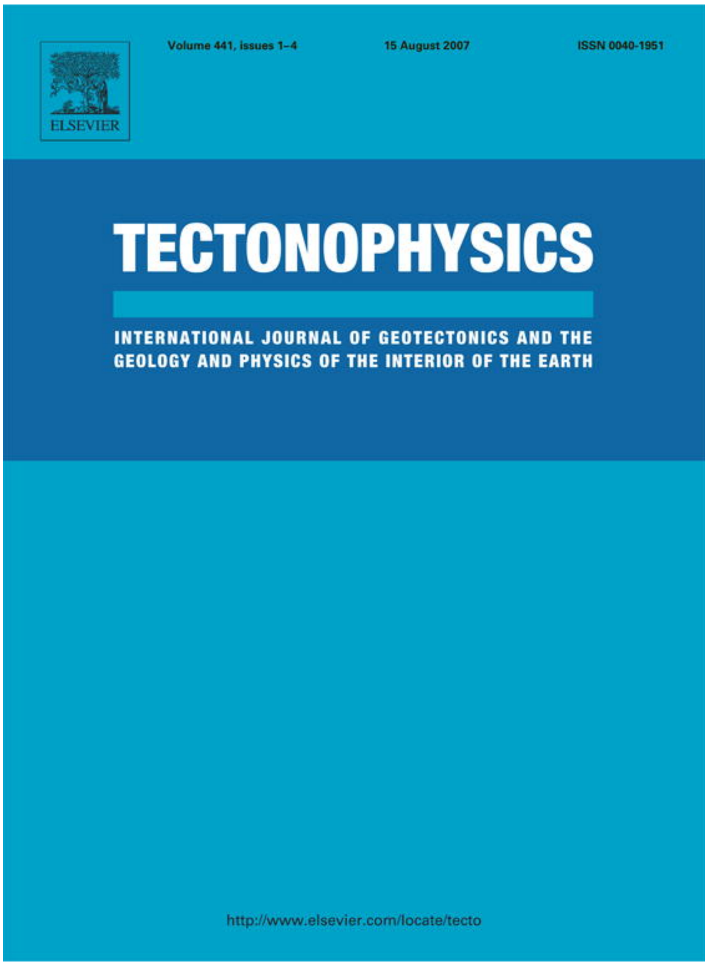
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Paleomagnetic constraints on the paleogeography and oroclinal bending of the Devonian volcanic arc in Kazakhstan

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Abstract

A prominent feature of the central part of the Ural–Mongol orogenic belt is a series of concentric horse-shoe shaped volcanic arcs, with the youngest arc on the inside. This structure was long-suspected to be an orocline, but unequivocal evidence for this was lacking, mainly because paleomagnetic results of suitable age from this area remained sparse, but also because their interpretation was not straightforward due to a long history of deformations associated with the protracted late Paleozoic assembly of Asia.

Our paleomagnetic study of Middle Devonian basaltic and andesitic flows in southeastern Kazakhstan revealed two main components of magnetization. The primary nature of a high temperature magnetization (tilt corrected Dec = 286.5, Inc = 46.4, α_{95} = 7.8, k = 29.2, N = 13 sites) is supported by the presence of antipodal directions and a baked-contact test. We also isolated a post-folding overprint with an *in situ* mean direction Dec = 134.9, Inc = −43.0 (α_{95} = 4.9, k = 71.6, N = 13 sites). The age of this overprint can be estimated as Early Permian with a high degree of confidence. The declination of the overprint is seen to be deflected counter-clockwise by 100 ± 6° relative to the 290-Ma reference direction, indicating that the studied locality, similar to many other localities in the region, was affected by late-orogenic rotations. We use the overprint's deflection to correct the declination of the primary Devonian magnetization for these late-orogenic block-rotations.

Declinations from other Silurian and Devonian paleomagnetic results in the subduction-related Devonian volcanic arc of Kazakhstan have been corrected for such rotations wherever the latter are reasonably well documented. Using corrected declinations as passive markers we restored the trend of the volcanic belt to its Devonian configuration. Our analysis indicates that the presently curved belt was nearly straight and NW–SE trending. This ∼1500 km long volcanic belt characterized the northeastern margin of a landmass in today's central Kazakhstan where subduction occurred towards the southwest. Oroclinal bending of this arc took place in the interval between the Middle Devonian and the Late Permian.

Keywords: Paleomagnetism; Kazakhstan; Oroclinal bending; Devonian; Paleogeography

1. Introduction

It is now widely recognized that Central Asia is a composite realm assembled during the Phanerozoic by accretion of various continental blocks, island arc

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fragments, and accretionary complexes (Fig. 1). The assembly mechanism is still disputed for the early Paleozoic, however. Regardless whether authors favored collision of microcontinents that were originally separated by oceanic basins and multiple island arcs (Mossakovsky et al., 1993; Didenko et al., 1994; Dobretsov et al., 1995; Filippova et al., 2001; Windley et al., 2007), or forearc accretion and oroclinal bending of a single, long-lived subduction system (Şengör and Natal'in, 1996), most scientists agree that by the middle Paleozoic several relatively small terranes had amalgamated into a single tectonic unit (often referred to as "Kazakhstania", but the definition of this concept may differ from author to author). Possibly from Early Silurian onwards (Degtyarev and Ryazantsev, 1993) and certainly from Late Silurian to Early Permian time, volcanic arc structures marked one of the margins of the amalgamated block (Bakhtiev, 1987; Zonenshain et al., 1990; Kurchavov, 1994; Skrinnik and Horst, 1995). In their present-day configuration, the Devonian and late Paleozoic volcanic belts are horse-shoe shaped (Fig. 2). The area internal to the strongly curved volcanic structures is dominated by rocks indicative of deeper marine environments, whereas the regions surrounding

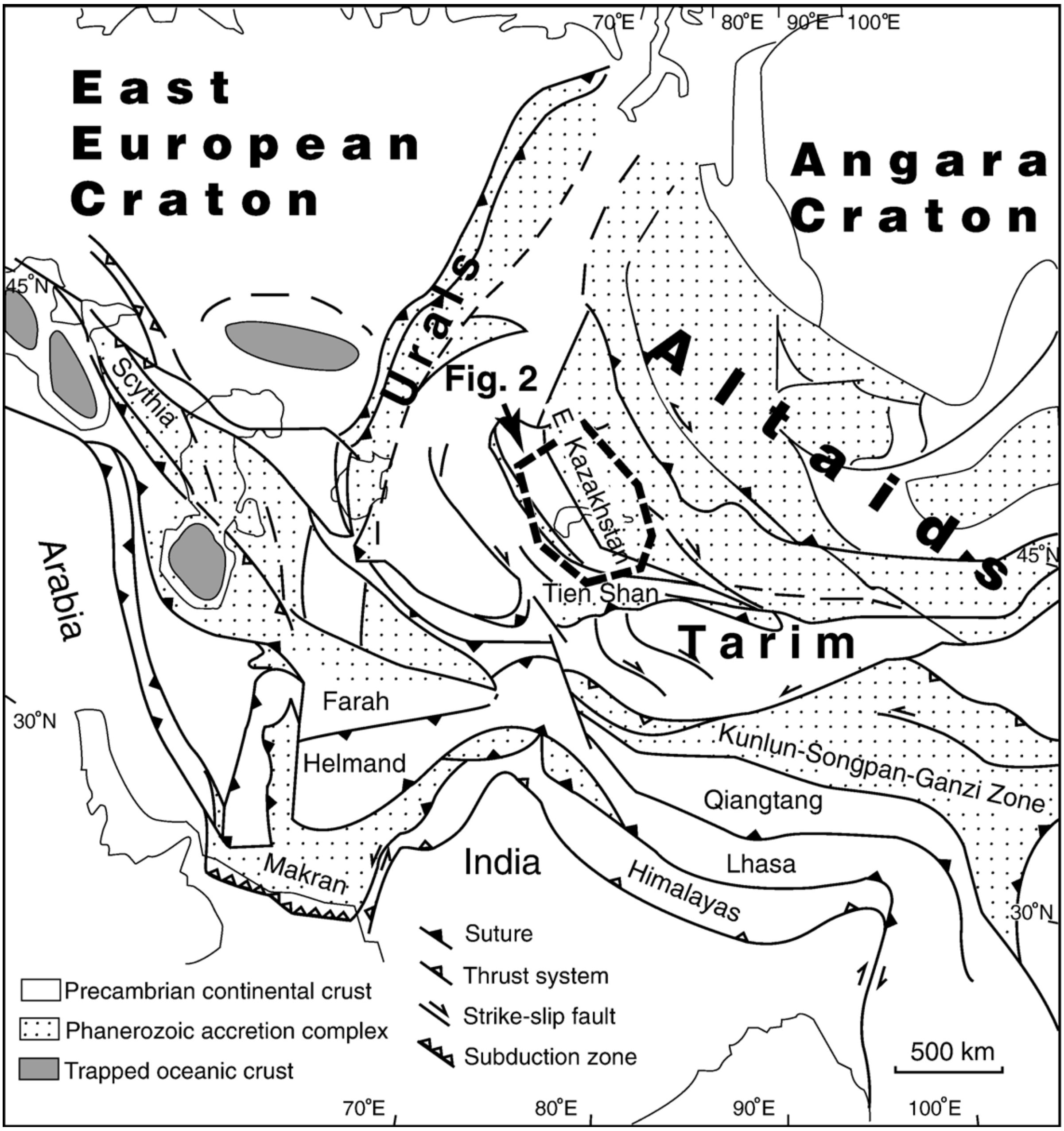

Fig. 1. Schematic map of central Asia, showing the location of the East Kazakhstan study area, wedged in between the Tarim, Baltica and Siberia cratons (modified after Allen et al., 2001).

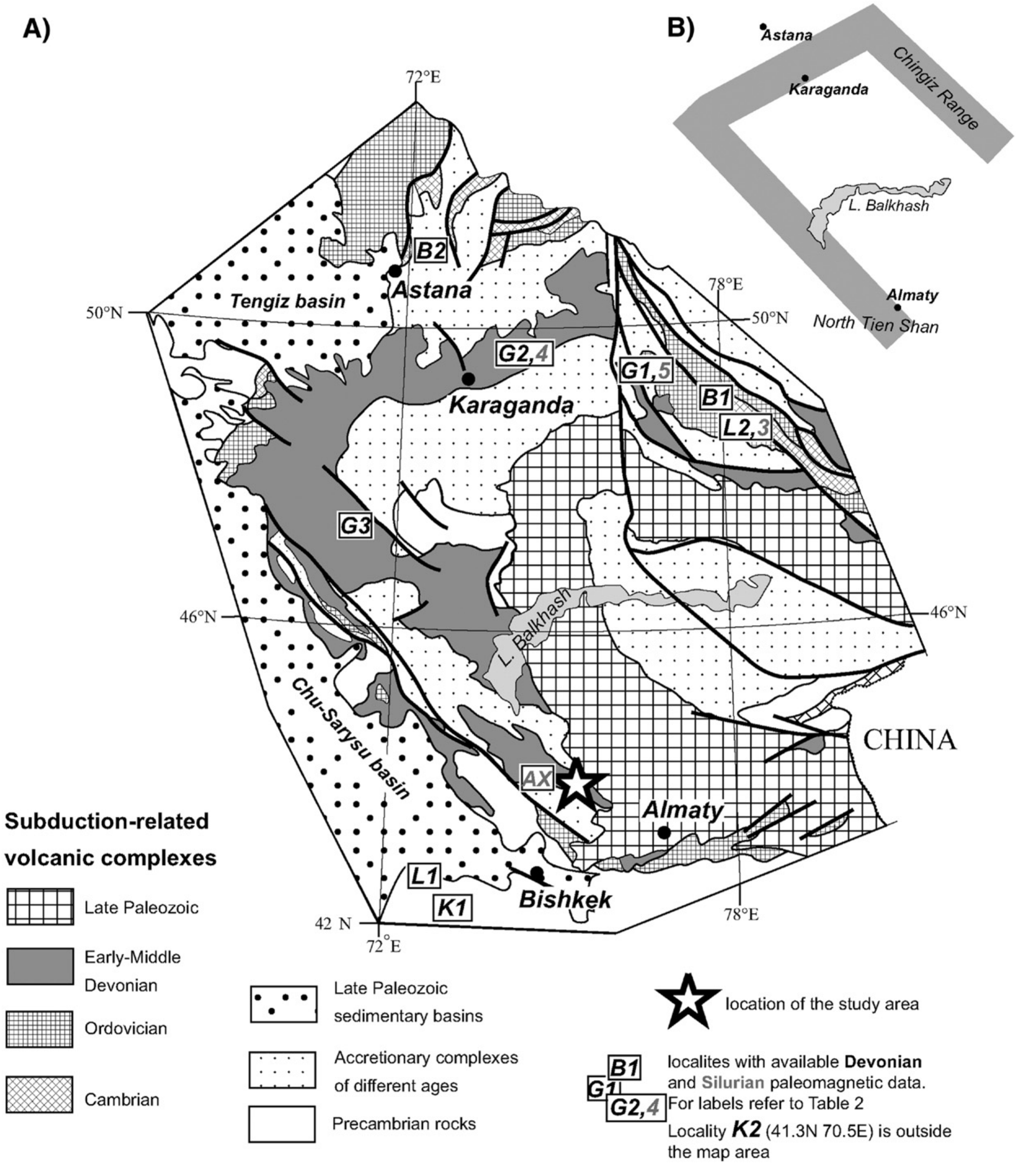

Fig. 2. Paleozoic subduction-related complexes showing strongly curved Devonian and late Paleozoic volcanic belts (A; modified after Degtyarev, 2003), with the North Tien Shan and Chingiz Range at either end, as labeled in (B). The sampling localities of previously published Silurian and Devonian paleomagnetic results (G1-5, L1-3, B1-2, AX) and of this study (star) are indicated.

it were either non-depositional highlands or epicontinental shallow marine and non-marine basins (Zonenshain et al., 1990). Taken at face value, such a distribution implies that subduction was directed outwards from the inner part of the curved structure. This scenario, however, is difficult to reconcile with plate tectonic theory; oroclinal bending of an originally straighter arc was therefore suggested as a possible explanation for the shape of the volcanic belts (Zonenshain et al., 1990; Şengör and Natal'in, 1996; Grishin et al., 1997; Levashova et al., 2003; Van der Voo, 2004).

Currently several paleomagnetic efforts are underway to improve our understanding of the tectonic history of Central Asia, and especially that of the "Kazakhstan orocline" (*e.g.*, Bazhenov et al., 2003; Collins et al., 2003; Levashova et al., 2003; Alexyutin et al., 2005; Van der Voo et al., 2006; Levashova et al., 2007). The declinations of primary magnetization in Ordovician rocks from the Chingiz Range (the northeastern limb of the orocline) and the North Tien Shan (south- to southwestern limb) were found to differ by about 180°, which was interpreted by Levashova et al. (2003) as evidence for oroclinal bending. The Permian results from the same two areas (Van der Voo et al., 2006) show declination differences on the order of 90°. The post-Permian rotations, on the other hand, were attributed to small-scale block rotations within a larger-scale sinistral wrenching zone of deformations in and around the North Tien Shan area. Thus, only about 50% of the total post-Ordovician rotation was attributed to the putative oroclinal bending that presumably happened some time between Ordovican and Late Permian.

To further constrain the timing and mode of the oroclinal bending, we studied Middle Devonian volcanics from the southwestern limb of the Kazakhstan orocline. The declination obtained in the present study will be compared with those for rocks of similar age as well as with the declination pattern of Silurian results from the entire curved volcanic arc structure (Grishin et al., 1997; Levashova et al., 2003; Alexyutin et al., 2005). Declination deviations will be taken as an indication of relative rotations of the limbs.

2. Geological setting

The stratotype locality of the Kurgasholak Formation is located in the southeast of the Chu-Ili region (Fig. 3; GPS location N 44° 07′ 10″, E 74° 47′ 30″). This locality is the only known outcrop of the Middle Devonian volcanics in the region (Abdullin et al., 1980); basaltic extrusive volcanism here occurred along the south–west boundary of the outcrops of Precambrian metamorphic rocks (Abdullin et al., 1980).

The Kurgasholak Formation unconformably overlies the Lower to Middle Devonian Degrez Formation and in turn is unconformably overlain by the Upper Devonian (Famennian) Zhingeldy Formation (Tokmacheva et al., 1974; Senkevich, 1991). The Kurgasholak formation is subdivided into three members. The lower member (~600 m thick) comprises basal pebbly conglomerate, medium- to fine grained sandstones, rare tuffaceous sandstones, two rhyolite flows and occasional beds of limestone. The middle member (~1100 m thick) consists mostly of massive flows of purplish-grey, dark green and brown porphyritic basalt and andesitic basalt with rare feeder-dikes. No occurrence of tuff is known in the sequence. In the majority of the flows the upper oxidized surface is preserved, suggesting short-lived but nearly continuous volcanic activity. The flows are inter-bedded with occasional layers of sandstone and pebbly conglomerates, which contain products of erosion and re-deposition of the contemporary volcanics. The upper member of the formation (~560 m thick) comprises poorly exposed fine- to coarse-grained, cross-bedded, red sandstones and mudstones.

The age assignment of Middle Devonian for the Kurgasholak Formation is based on stratigraphic position as well as on fossil plants collected from sandstones of the lower member: *Cooksonia (?) degrezensis* Senk., *Taeniocrada cf. langi* Stockm., T. *cf. dubia* Kr. et W., *Lidasimophyton akkermensis* Senk., *Protolepidodendron schrianum* Kr., *Protopteridium cf. hostimense* Kr. The plant assemblage does not allow for a more precise age estimate within the Middle Devonian (Tokmacheva et al., 1974).

The sampling area is located in a zone (called Stepnyak–North Tien Shan) that by Devonian time was incorporated into the Kokchetav–North Tien Shan Domain (KNTD) according to Windley et al. (2007, Fig. 6). This domain is approximately the same as the "Kazakhstan–Kyrghyz" block of Filippova et al. (2001). These scientists argued that this block was probably not rigid, but that it did act as a coherent paleogeographic unit in post-Ordovician times, and that an Early Devonian arc system developed on its eastern side, as illustrated in Fig. 2, accommodating west- or southwest-dipping subduction (in present-day coordinates).

3. Field and laboratory methods

For this study, we collected volcanics of the middle member of the Kurgasholak Formation at the type locality for this formation (see Fig. 3). In total, we sampled 18 volcanic sites, each representing a cooling unit, and one layer of an intra-formational conglomerate (16 clasts, site m9476 in Table 1). Sample labels start with a capital letter (A, or M), followed by sample number, whereas sites are marked with a lower-case letter and the number of the first sample collected.

Paleo-horizontal of the volcanic flows in the sampled sections and the younging direction of the section were

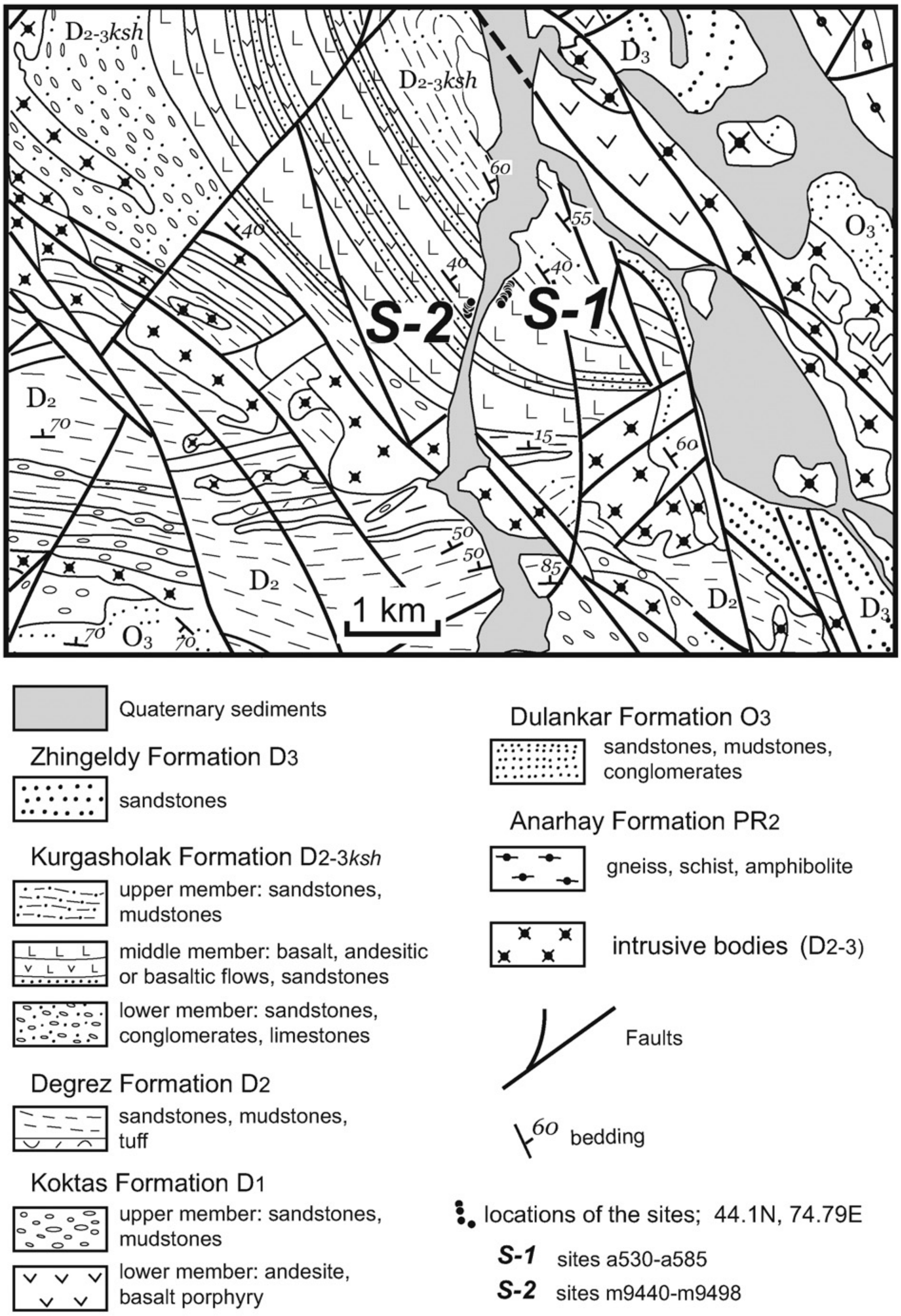

Fig. 3. The sampled sections of the middle member of the Kurgasholak Formation at N 44° 07′ 10″, E 74° 47′ 30″, are shown on a geological map from Abdullin et al. (1980).

determined from oxidized flow-tops and the intra-formational conglomerate bed. Bedding attitudes show some variation from bottom to top of the sampled section; see Table 1, which contains the strikes and dips of the sites, listed in stratigraphic order. Samples were collected as oriented blocks; a magnetic compass with inclinometer was used for the orientation of the samples. A lack of deflection of the magnetic compass needle by the basalts demonstrated that magnetic intensities did not significantly affect orientation readings.

In the laboratory, cubic specimens with ~20 mm side dimensions were cut from the block samples, yielding,

Table 1
Site-mean and formation-mean directions of the components isolated from the Kurgasholak Formation

Site	Bedding	cmp	*m*/*n*	Geographic				Stratigraphic	
				Dec	Inc	α_{95}	*k*	Dec	Inc
a530	343/30	a	(1g2s)/7	86.5	−17.4	12.0	80.5	91.8	−46.3
		c	(6g1s)/7	126.2	−48.5	12.7	47.8	166.3	−57.9
a537	343/30	a	(2g4s)/6	86.6	−15.6	7.0	100.0	91.5	−44.5
		c	(2g1s)/6	119.7	−38.0	12.2	282.5	147.4	−53.5
a543	340/35	a	(1g4s)/6	81.5	−13.2	8.2	72.5	86.6	−47.2
		c	1s/6	139.2	−49.9			182.7	−49.3
a549	338/37	a	(3g2s)/6	89.4	−21.2	9.5	100.8	103.6	−54.2
		c	(2g4s)/6	127.0	−50.7	6.8	107.4	178.7	−54.5
a555	335/40	a	4s/5	78.2	−13.2	8.4	119.4	86.0	−51.6
a561	332/45	a	1s/6	89.1	−18.4			111.1	−55.1
		c	(4g2s)/6	127.3	−38.6	11.4	43.8	168.5	−42.2
a568	332/45	c	2hd/5	143.3	−43.4	15.3	270.0	181.6	−34.3
a573	332/45	c	3g*/6	127.9	−51.9	6.8	676.8	185.9	−47.3
a579	328/45	a	(5g1s)/6	75.8	−15.2	21.7	16.8	90.4	−56.6
a585	328/45	a	(2g4s)/6	80.4	−18.0	8.0	76.4	99.9	−57.2
		c	1hd/6	133.6	−45.7			177.5	−39.0
m9498	320/40	b	5g*/6	284.9	5.5	10.3	72.9	295.2	26.2
m9492	320/40	b	5s/6	286.3	11.8	6.9	122.6	300.7	30.4
m9476 cgl.	320/40	b	(2g13s)/16	285.5	18.9	6.4	37.0	305.5	36.3
m9470	320/40	c	(4g1s)/6	133.0	−41.8	19.7	24.0	165.9	−34.7
m9464	320/40	c	5s/6	138.5	−37.4	13.9	31.2	165.2	−28.6
m9458	320/40	c	6s/6	134.8	−34.6	5.2	166.0	160.6	−28.9
m9452	320/40	a	(1g3s)/5	95.4	−12.9	10.3	64.4	111.2	−37.7
		c	(4g1s)/5	153.8	−31.2	10.3	86.0	170.5	−15.4
m9446	320/40	a	5g*/6	103.6	−31.5	18.6	22.6	135.7	−46.5
		c	(4g2s)/6	145.4	−42.2	15.7	38.0	173.3	−28.0
Mean a+b	*In situ*		*N*=13	*90.9*	*−16.6*	6.3	44.5		
	After TC		*N*=13			7.8	29.2	106.5	−46.4
Mean c	*In situ*		*N*=13	134.9	−43.0	4.9	71.6		
	After TC		*N*=13			7.6	30.4	*171.1*	*−39.9*
Anomalous (an) directions (not used)									
a568	332/45	an	(3g2s)/5	*218.1*	*17.2*	14.0	46.9	*198.5*	*55.8*
a573	332/45	an	(1g5s)/6	*174.9*	*−52.3*	9.0	61.0	*204.3*	*−23.0*
a579	328/45	an	(4g2s)/6	*55.7*	*−3.4*	12.1	33.9	*54.5*	*−48.4*
m9440	290/40	an	4s/6	*346.7*	*58.5*	17.6	28.2	*2.0*	*21.9*
m9476 cgl.	320/40	an	(8g3s)/16	*218.4*	*−40.2*	13.2	13.9	*221.2*	*−0.8*

Legend and explanation for Table 1: Bedding measurements are given as the strike and dip angle (down dip to the right (clockwise) of strike). Components (cmp) labeled as in the text. *m* indicates number of samples used in the statistical analysis: g—great circle, s—stable endpoint, hd—intersection point of two great circles (Hoffman and Day, 1978); *n*—number of samples demagnetized; *N*=number of sites. *indicates sites that showed only trends that did not reach a stable endpoint. In such cases, a site-mean direction of the nearest site with a stable endpoint estimate for the particular component was used as an anchor in the great circle analysis. TC=tectonic correction. Dec and Inc are the declination and inclination of the site-mean direction (in °); α_{95} is the radius of the 95% confidence cone about the mean direction in °; *k* is the Fisher (1953) concentration parameter. Directions (Dec/Inc values) in italics are not used in the interpretation of the results.

on average, 2 specimens per sample. Measurements of natural remanent magnetization (NRM) were performed in the University of Michigan paleomagnetic laboratory. The remanent intensities and directions were measured with a three-axis 2G superconducting magnetometer. Alternating field demagnetization of a few pilot specimens failed to isolate components of magnetization successfully. The bulk of the specimens were therefore thermally demagnetized in an ASC TD-48 demagnetizer. Both demagnetization and measurement were done in a magnetically shielded room with a rest field <200 nT. Results of the demagnetization treatments have been plotted in orthogonal vector endpoint diagrams (Zijderveld, 1967) and in stereonets. For calculation of the magnetization directions, principal component analysis (PCA, Kirschvink, 1980) was used on linear segments of the Zijderveld plots; in cases where stable endpoints were not obtained, so that successive endpoints were seen moving as trends along great circle paths, a combined analysis of remagnetization circles and direct observations (McFadden and McElhinny, 1988) was used.

4. Results

NRM intensities of the studied samples range from 0.2 to 11 A/m. Demagnetization diagrams (Fig. 4) show a wide range of behavior. Apart from a low-temperature overprint generally removed at ~200 °C, specimens revealed a number of discrete directions that have been divided into *a*-, *b*-, and *c*-components. The site-mean directions of the intermediate- and high-temperature components and their associated statistical parameters are listed in Table 1 together with the formation mean directions.

The first-removed low-temperature components are tightly clustered (with a mean of dec/inc = 6.4°/62.7°, k = 42, α_{95} = 5.4°, N = 18 site means) around the present-

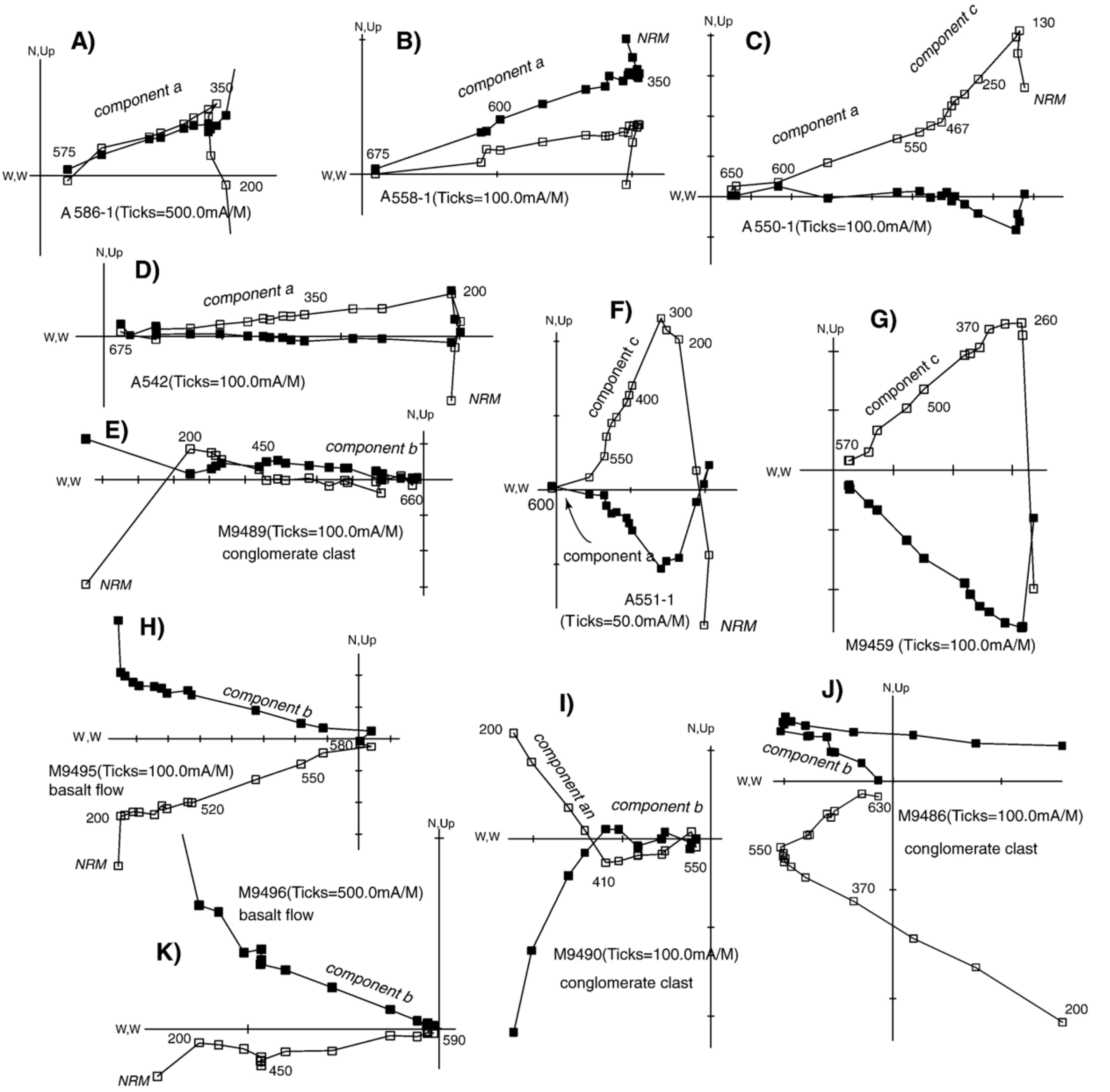

Fig. 4. Orthogonal demagnetization diagrams (Zijderveld, 1967) in geographic coordinates. Sample numbers correspond to similarly numbered sites (see Table 1). Components, as labeled (*a*, *b*, *c* or *an*), are discussed in the text. Open (closed) symbols correspond to magnetization end-points projected onto the east–west vertical (horizontal) plane. Tickmarks denote intensities as labeled in mA/m.

day geomagnetic field direction, which is dec/inc = 5.4°/63.8° in 2005. These components are readily interpreted as of recent and most likely viscous origin and have no significance for the tectonics of the area. Even so, the good clustering of these directions testifies to the accuracy and coherency of the field-orientations of our samples.

4.1. The a- and b-components

The high temperature *a*-component, easterly and shallow up in geographic coordinates, was isolated in 10 out of 18 sampling sites. This component was usually removed between 500 and 580 °C, although in samples collected from the upper oxidized part of the flows, the magnetization could persist up to 675 °C with no significant change in direction from 350 to 470 °C to >650 °C (Fig. 4A–D), suggesting that magnetite and hematite contribute similarly to the higher-temperature remanence (*a*-) directions. In some samples, the *a*-component was readily identified even though it appeared to co-exist with a lower-temperature component (which we will call *c*), as can be seen for instance in Fig. 4C. In yet other samples, *a* and *c* appear to co-exist, but an insufficient number of steps is available to determine the *a*-component by PCA (*e.g.*, Fig. 4F). In several demagnetization experiments the trajectory of the data-points did not reach a stable direction, indicating overlapping temperature spectra of two or more components. In these cases, the McFadden and McElhinny (1988) great-circle technique was used to estimate the directions of the various components.

A high-temperature *b*-component, westerly and shallow down in geographic coordinates (Fig. 4H, K), was found in three sites and its remanence unblocks in the same range as the *a*-component in the other sites, *i.e.*, between 250–475 °C and ~600 °C. Two of these sites are successive volcanic flows (sites m9492 and m9498; Table 1); the third one is a conglomerate bed just below these flows (Figs. 4E, I–J, 5). The mean magnetization direction of the overlying flow (star in Fig. 5) agrees well with the characteristic directions of the conglomeratic clasts, suggesting that in all likelihood the magnetization of each individual clast represents more or less the same spot reading of the geomagnetic field. Thus, it appears that the characteristic magnetization of the conglomerate clasts is a thermoremanent magnetization (TRM) acquired during the emplacement of, and heating by, the overlying flow.

The *a*- and *b*-directions are approximately antipodal; with a deviation $\gamma = 18.9°$, it could be argued that they pass the McFadden and McElhinny (1990) reversal test,

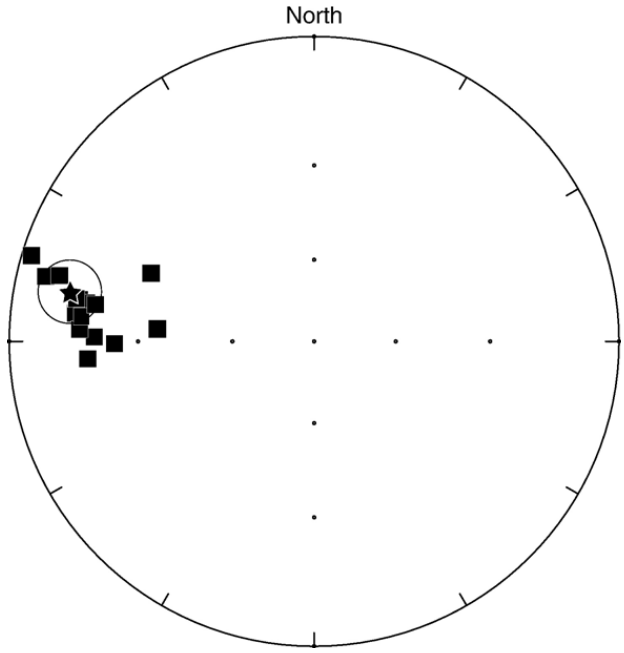

Fig. 5. The site-mean *b*-direction of a basalt flow (site m9492; star) and *b*-component directions (filled squares), which have been obtained from clasts in the underlying, baked conglomerate of site m9476, and which have been interpreted as a thermo-remanent magnetization. Lower-hemisphere equal-angle projection.

but not much significance can be given to this because of the limited number of site-means with a westerly/shallow downward *b*-direction, which, moreover, probably represents only a spot reading of the geomagnetic field. However, the very presence of a dual-polarity remanence (*a*- and *b*-components) as well as evidence for the baking of the conglomerate during the emplacement of the overlying flow suggest that the high temperature ($a+b$) magnetization is of primary nature. The tilt corrected mean direction of the combined $a+b$ site-mean components is $D = 106.5°$; $I = -46.4°$ ($\alpha_{95} = 7.8°$; $k = 29.2$ for $N = 13$ site-means out of 19 sites collected). Because during Devonian time, the North Tien Shan and adjacent Kazakhstan were clearly situated in the northern hemisphere (*e.g.* Bazhenov et al., 2003; Levashova et al., 2007), the normal-polarity direction in the study area should be pointing downward. The upward pointing direction, therefore, corresponds to that of a reversed-polarity field; the normal polarity direction of the primary magnetization of the Kurgasholak Formation is $D = 286.5°$; $I = +46.4°$.

4.2. The c-component

The *c*-component is south-easterly and intermediate-up in geographic coordinates; it was isolated in 13 sites out of the total of 19 sites. The 6 other sites often revealed the possible presence of a *c*-component, but its direction could not be determined with any accuracy. The *c*-component generally unblocks between ~250 and 580 °C and is usually revealed as an intermediate-temperature component co-existing with the *a*-component (Fig. 4C, F). In five sites (a568, a573, m9470, m9464, m9458) it was found as the only characteristic direction (*e.g.* Fig. 4G), but in two of these sites it co-existed with anomalous lower-temperature (*an*) components that have no coherence and no statistical significance (see Table 1).

Very often the *c*-component directions can be seen to contribute to a great-circle ("mixing") trend in the stereonet or in curved trajectories of the demagnetization diagrams, and it seems clear in many cases that overlap with *a*-components can be held responsible. In these cases, as mentioned, we used the McFadden and McElhinny (1988) technique to estimate the directions of the components. But this raises the critical question whether the mean inclination and declination of the intermediate-temperature *c*-component are accurately determined, given that many of the great circles run more or less parallel between the more easterly *a*-component and the southeasterly *c*-component. To document that the *c*-directions are indeed well constrained, we next examine Fig. 6.

In the common occurrence that the *a*- and *c*-components are being removed simultaneously (Fig. 6A, example of site a537), the great-circles run more or less parallel to each other roughly along lines of equal inclination in the south- to southeastern part of the stereonet. This means that for this site, the inclination is reasonably well defined, but the declination is not well constrained. In contrast, the samples shown in Fig. 6C do not appear to contain the *a*-component, but instead show great-circles that connect low-temperature, viscous (present-day) magnetization directions with the southeasterly and upward *c*-directions. In these cases the great-circles define the declination reasonably well, but the inclination less so. In Fig. 6B, the sample illustrates the co-existence and overlapping unblocking temperatures, first of the present-day field (PDF) and c component, and subsequently of the *a* and the *c*-component; however, the unblocking temperature spectra of the PDF and *a* components do not appear to overlap. Thus, the directions define two great circles and the well-constrained intersection of these two (gray star in upper hemisphere) corresponds to the (*c*-) component in common to both.

Combining the effects of the great-circles shown in Fig. 6A–C, one can see that their intersections, the stable endpoints of a few samples (stars in Fig. 6A), and the clear vectorial separation of the trends in Fig. 6B, allow us to state with confidence that the mean *in-situ* *c*-direction with dec/inc = 135°/−43° is well constrained.

Although the small range of variation in the bedding attitudes at our sampling locality does not allow for a statistically significant fold test for the $a+b$ components, site-mean directions of the *c*-component group much better in geographic coordinates with the concentration parameter k decreasing from 71.6 to 30.4 upon unfolding (Table 1, Fig. 7B). The k-ratio of 2.36 ($N=13$) is statistically significant at the 95% confidence level, indicating a post-folding origin of this magnetization.

4.3. Anomalous directions of magnetization

Here we discuss briefly the five site-means that have been labeled anomalous in Table 1 and which are shown in Fig. 7C. These site-means are listed because they correspond to magnetizations that unblocked at intermediate-to-high temperatures. One site-mean (m9440) clearly corresponds to the direction of the present-day field (PDF); it is not anomalous in that sense, but is different from all other sites in that this PDF-component persists up to higher temperatures. The shallow northeasterly direction of site a579 can readily be explained as due to simultaneous removal of PDF and an *a*-component, whereas the southwesterly and up intermediate-temperature directions of the conglomerate site (m9476) fall between those of the *b*- and the *c*-components. We note, however, that great-circle trends are lacking to document the suspicions that these directions are due to simultaneous removal of two directions.

The anomalous components of sites a568 and a573 are removed at intermediate-temperatures. Although these directions co-exist with *c*-components (see Table 1), they do not seem to correspond to any mixing trends. We can only speculate as to what imparted these magnetizations; perhaps these directions reflect transient geomagnetic fields during excursions.

5. Discussion

5.1. Results summary and ages of magnetization

We conclude that the high-temperature, dual-polarity remanence (*a*- and *b*-components) with the tilt-corrected mean direction dec/inc = 286.5°/+46.4°, represents a valuable characteristic magnetization direction for the Kurgasholak Formation. The primary (Middle Devonian) age of this remanence is indicated by the normal polarity interval found in-between reversed flow sequences below and above the conglomerate and by

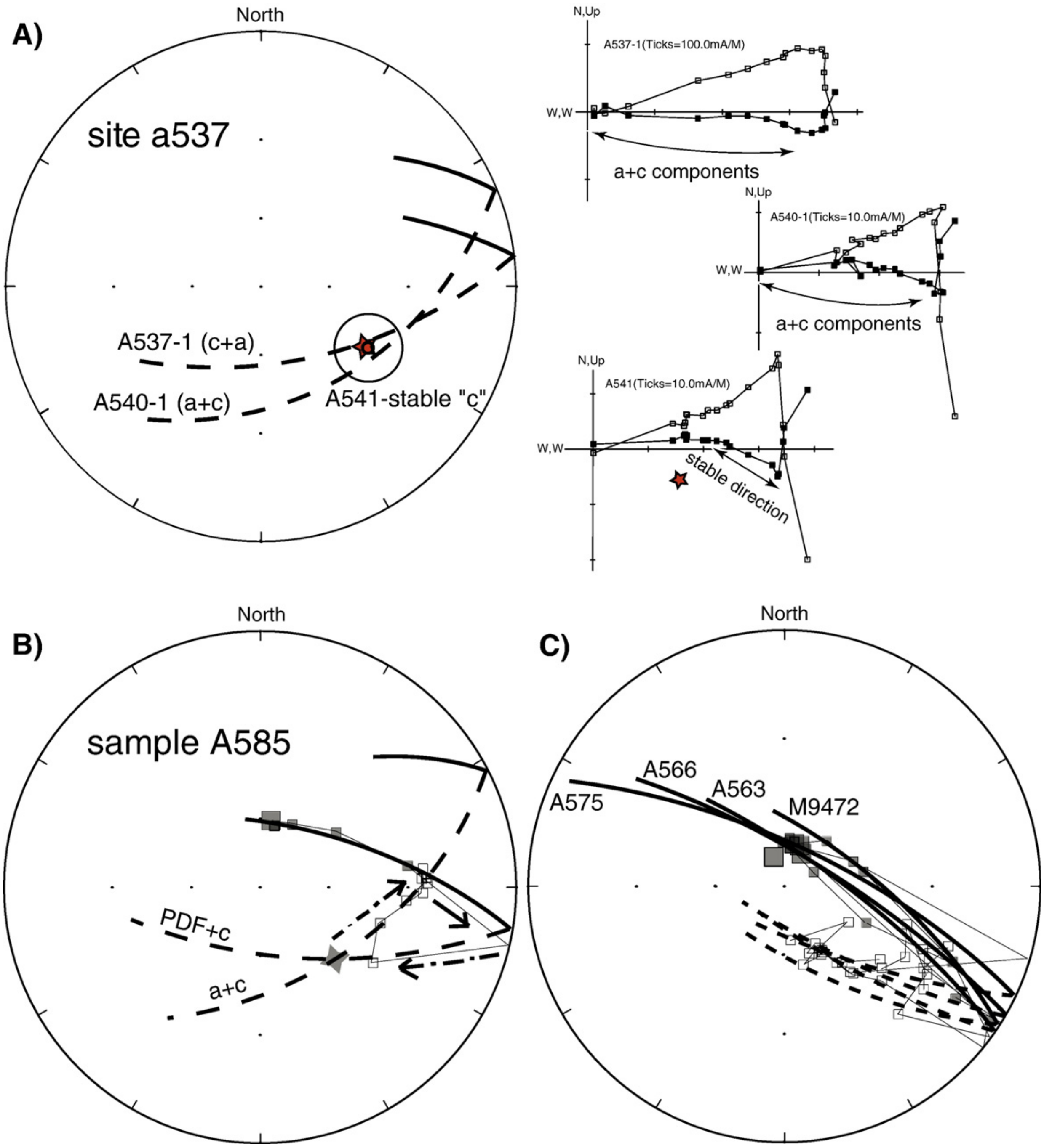

Fig. 6. Examples of great-circles used in constraining the *c*-component directions as discussed in the text. Lower-hemisphere projections are represented by solid lines and filled symbols, upper hemisphere results are shown as dashed lines and open symbols. The stars in (A) represent what we believe to be a fairly accurate isolation of the *c*-component without contamination by the higher-temperature *a*-component. In (B), the three arrows indicate the trends in the progressive locations of the magnetization end-points during thermal demagnetization, which illustrate, first, simultaneous removal of the present-day field (PDF) and *c*-component and then, the simultaneous removal of the *c*-component and the *a*-component. The intersection in (B) is therefore the direction of *c* (gray star, upper hemisphere).

the evidence for the baking of this conglomerate by the overlying volcanic flow (the baked contact test).

The *in-situ* inclination of the *a*-component is significantly lower than those from rocks of Devonian or any younger age in the area (Lyons et al., 2002; Bazhenov et al., 2003; Van der Voo et al., 2006), suggesting that the tilt correction is needed in order for the result to reflect the ancient magnetic field. This, in turn, implies that the magnetization is older than the folding and also, therefore, older than the post-folding *c*-component, which makes sense given the relative unblocking temperatures.

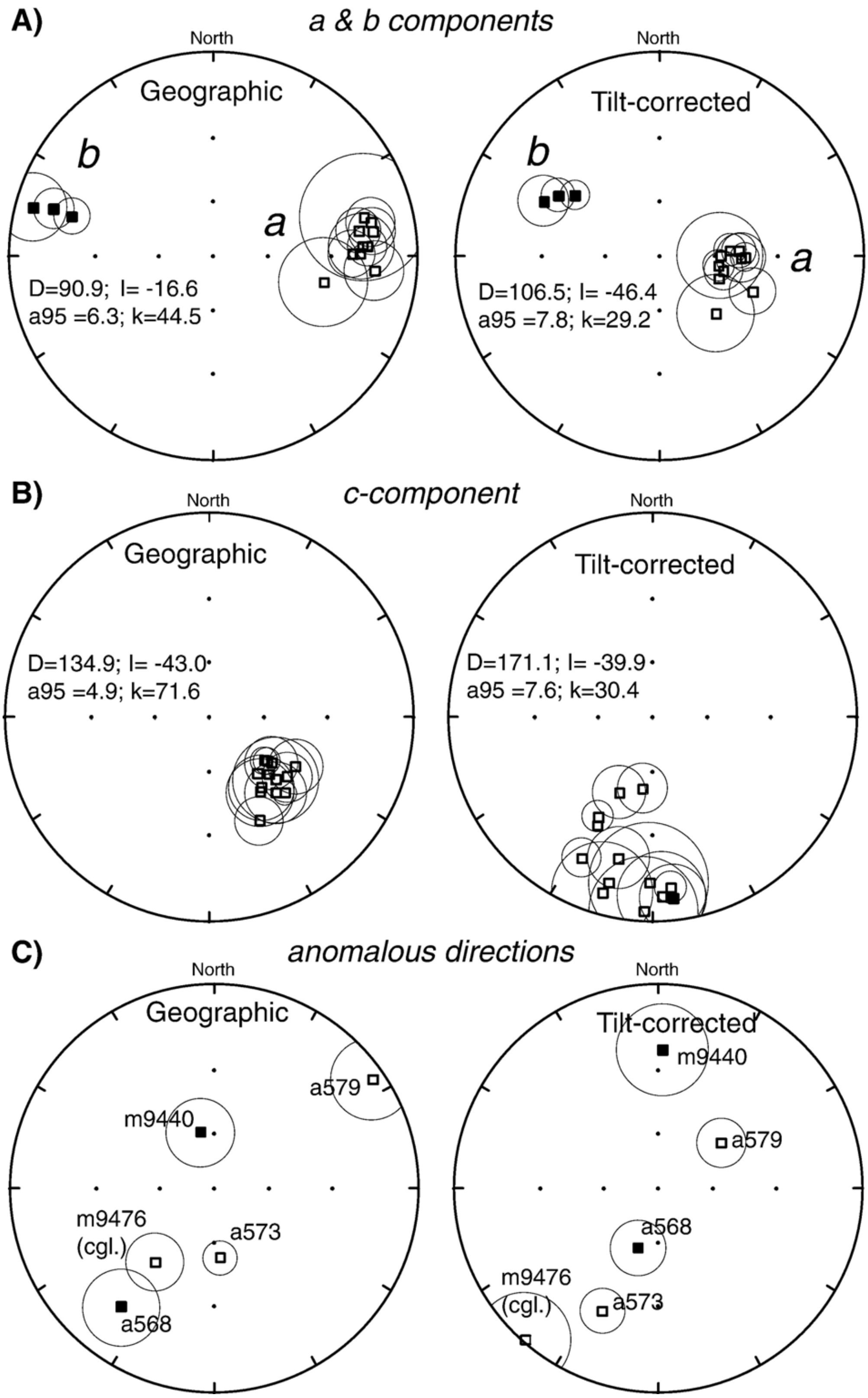

Fig. 7. Equal-angle stereoplots of the various component site-means isolated in the Kurgasholak Formation (as also listed in Table 1). Open (closed) symbols represent upper (lower) hemisphere projections.

We also derive support for our arguments that the $a+b$ remanence is of Middle Devonian age from a comparison with Late Devonian paleomagnetic directions from the Aral Formation (Levashova et al., 2007) some 250 km to the SW of our locality (Fig. 8). Tilts of the Aral and Kurgasholak are very different, suggesting

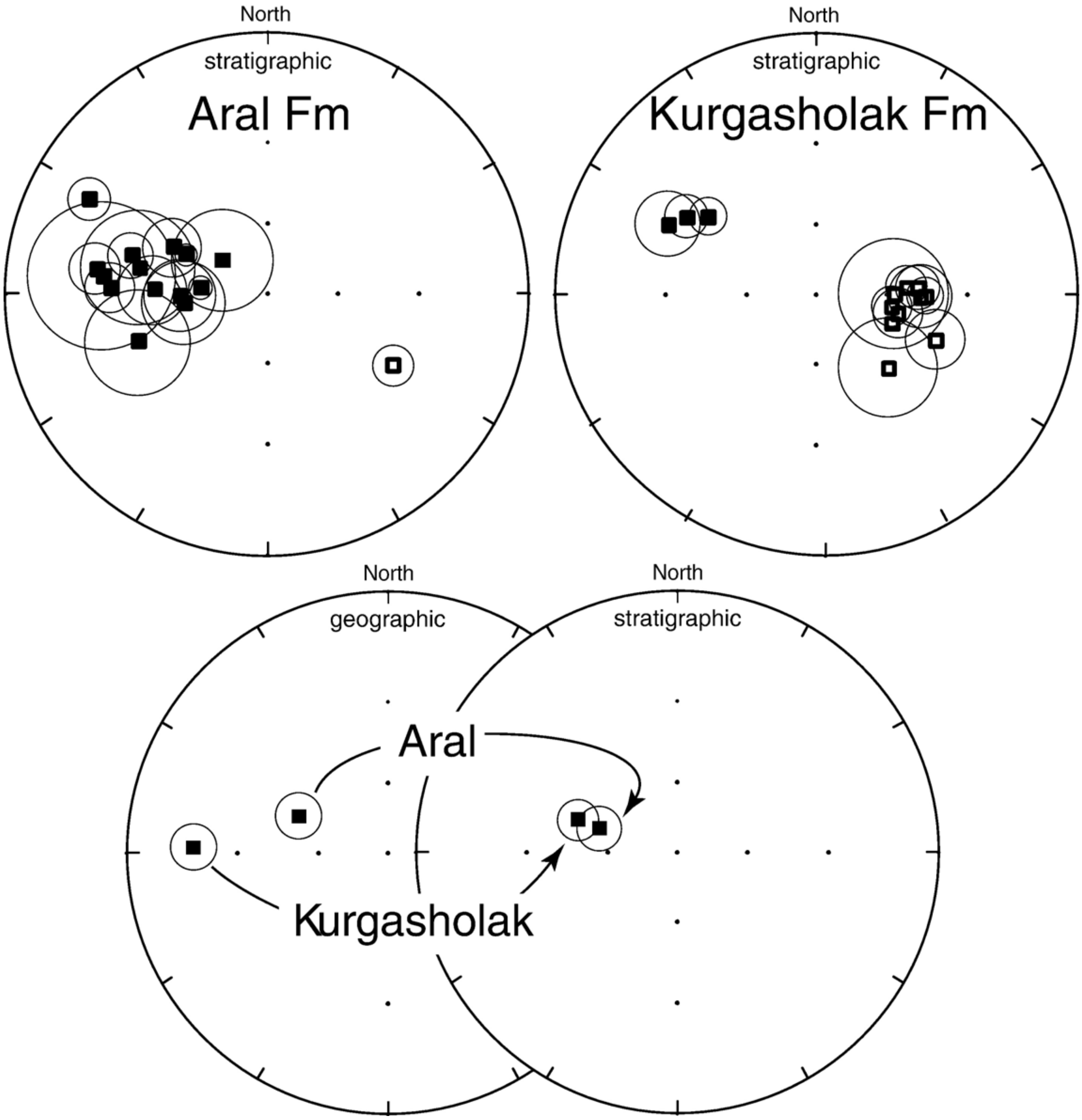

Fig. 8. Stereoplots showing the tilt-corrected primary site-mean directions of magnetization obtained from the Late Devonian Aral Formation (Levashova et al., 2007) and the Middle Devonian results of this study, with the third plot showing the difference in tilt-correction effects.

that the remanences are both pre-folding and of approximately the same, presumably primary, age.

The *c*-component has a statistically significant negative fold-test, yielding better grouping in geographic coordinates with a southeasterly, intermediate-upward *in situ* mean direction (dec/inc = 134.9°/−43.0°). Eastern Kazakhstan rocks have often revealed similar overprint components, sometimes pre-folding, sometimes post-folding, depending on the age of deformation. These overprints seem to be associated with the “Pan-Asian thermal event” (Coleman, 1989) — widespread and pervasive intrusions of A-type (anorogenic) granites of late Paleozoic age that affected almost all the area of Kazakhstan (Yakubchuk, 1997). In almost all cases, the magnetizations are of reversed polarity and usually show upward inclinations of 40–60°. Fig. 9 illustrates that these inclinations are characteristic of the late Paleozoic reference directions. In Fig. 9 these directions are calculated for the area by extrapolation from Baltica, but it must be noted that using Siberian or Tarim’s late Paleozoic poles as reference poles yields very similar inclination predictions. It must also be noted that the paleolatitudes of Kazakhstan are, without exception, higher than 40° N for the entire Mesozoic and Cenozoic,

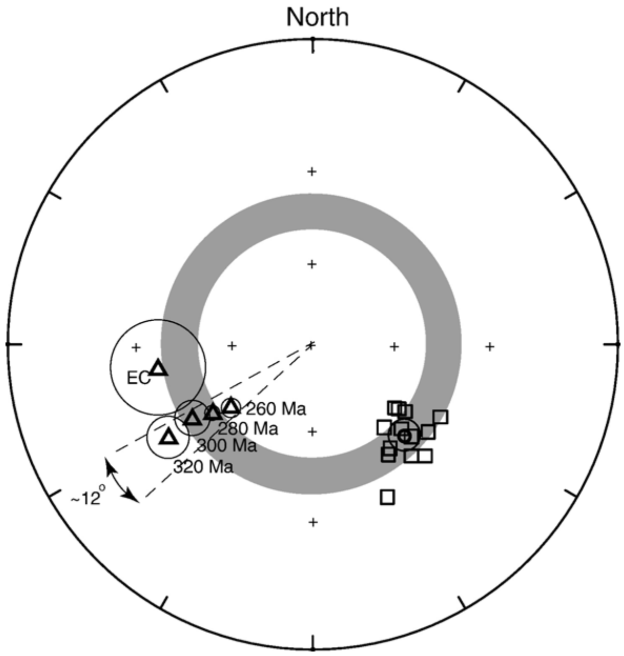

Fig. 9. Equal-angle stereoplot of the reference and the *c*-component directions. Reference directions are the triangles with associated 95% confidence circles and age in Ma (EC is the early Carboniferous direction (360–320 Ma)). They are calculated by extrapolation from the APWP of Baltica (Torsvik et al., 2001; Van der Voo, 1993). Open squares represent site means of the *c*-component directions, with the full dot (upper hemisphere projection) showing their mean (Table 1). The concentric circle around this mean represents its 95% confidence limit. The shaded band marks the range of the *c*-component inclinations for comparison with the reference directions and their ages.

as can be seen by examining Scotese's (2000) paleogeographic maps; this indicates that the observed paleolatitude of 25 ± 5° N from the *c*-component implies a pre-Mesozoic age of the magnetization. All-in-all, this leads us to argue for a Permian age for the *c*-component.

5.2. General pre-amble to an analysis of rotations in the Devonian volcanic arc

Despite some recent accomplishments, primary paleomagnetic results from Kazakhstan and Kyrgyzstan remain sparse and frequently defy a unique interpretation. While the inclination data provide consistent paleolatitude estimates for the area of interest to this study, such as the Chingiz Range and North Tien Shan limbs of the curved Devonian orocline illustrated in Fig. 2B (Bazhenov et al., 2003; Collins et al., 2003; Alexyutin et al., 2005; Levashova et al., 2007), an unambiguous interpretation of declination data from this region is hampered by the multiple episodes of wrench faulting and transpressional deformation during the protracted late Paleozoic assembly of this part of Asia. The repeated episodes of strike strip motions along the abundant east–west and northwest–southeast fault systems in the region are well documented (Allen et al., 2001; Natal'in and Şengör, 2005; Van der Voo et al., 2006). Such strike–slip faulting is frequently associated with vertical-axis rotations which cause a deviation in paleomagnetic declinations. Bazhenov et al. (1993) and Van der Voo et al. (2006) discussed the complex patterns of late-orogenic, Late Permian–Early Triassic rotations in Kyrgyzstan and eastern Kazakhstan. In the Chingiz Range (the northeastern limb of the orocline) the rotations are generally clockwise and small, whereas in the North Tien Shan and adjacent areas the rotations are usually large, on the order of 90°, and predominantly counter-clockwise. But importantly, exceptions to the latter pattern do occur in some restricted localities of the North Tien Shan and vicinity where rotations are minor (Alexyutin et al., 2005; McCausland et al., 2005). Late orogenic rotations of larger magnitude, obviously, must be considered in making tectonic reconstructions for earlier times. In the next section we will briefly discuss the paleomagnetic data available for Silurian and Devonian volcanic rocks in the oroclinal belt of Kazakhstan, and we will also describe estimates for the declination corrections that may restore rock units to their pre-Late Permian orientation.

5.3. Previously published Silurian and Devonian paleomagnetic data and their corrected pre-Late Permian declinations

Available paleomagnetic results from rocks of Silurian and Devonian age from localities in or close to the Devonian volcanic belt are listed in Table 2. Primary magnetizations of Devonian age have been obtained by us from the Aral and Kurgasholak formations, with westerly and intermediate downward dual-polarity magnetizations in both formations (dec = 280–287°); the localities of these two formations are shown as L2 and a star in Fig. 2. Klishevich and Khramov (1993) presented Devonian results from two localities (K1 and K2) in the North Tien Shan. Their results passed fold and reversals tests and are considered reliable. Only one other Devonian and one Silurian result have been derived from this southwestern limb of the putative orocline: G3 (Grishin et al., 1997) and AX (Alexyutin et al., 2005). The latter is of Silurian to Early Devonian age and the magnetization is demonstrably pre-Middle Devonian owing to a positive fold test; this result is clearly reliable. In contrast, the G3 result cannot be qualified as reliable; moreover, the information

Table 2
Summary of published Siluro–Devonian paleomagnetic data from the Devonian volcanic belt of the Kazakhstan orocline

Label-limb	Reference	Estim. Paleolat. $\pm\Delta\lambda$	Dec $\pm\Delta D$	Correction value $R\pm\Delta R$	Corrected mid-Paleozoic declination
Devonian results					
A-SW	This study	+28±10	287±11	100±6 cw	27±13
L1-SW	Levashova et al. (2007)	+36±13	286±15	~90 cw	~16
L2-NE	Levashova et al. (2003)	+30±17	172±19	~0	~172±19
K1-SW	Klishevich and Khramov (1993)	+21±8	334±9	~49±18	~23±20
K2-SW	Klishevich and Khramov (1993)	+19±5	309±6	~73±37	~22±37
G1-NE	Grishin et al. (1997)	+29±12	168±14	13±31 cw	181±34
G2-NW	Grishin et al. (1997)	+23±11	111±13	~0	~111±13
G3-SW	Grishin et al. (1997)	*+33±17*	*139±20*	*28±20 cw*	Not used
B1-NE	Burtman et al. (1998)	*+24±7*	*52±8*	Not avail.	Not used
B2-NW	Burtman et al. (1998)	*+17±8*	*50±10*	Not avail.	Not used
Silurian results					
AX-SW	Alexyutin et al. (2005)	+12±9	347±14	~0	~347±14
L3-NE	Levashova et al. (2003)	−1±7	217±13	~0	~217±13
G4-NW	Grishin et al. (1997)	+13±7	124±10	~0	~124±10
G5-NE	Grishin et al. (1997)	+6±7	144±13	14±3 cw	158±13

Labels are the same as those described in the text and used in Figs. 2 and 10; limb (NE, NW or SW) denotes one of the three branches of the strongly curved Devonian volcanic belt and its putative oroclinal model. Estimated paleolatitude is given as + (−) for northern (southern) hemisphere, respectively, together with its 95% uncertainty ($\pm\Delta\lambda$)*. Declination uncertainties are labeled $\pm\Delta D$*. The Correction value (R, see text for further description) restores a locality's orientation to its pre-Permian value, by correcting for rotations that occurred during the Permian and Early Triassic (Van der Voo et al., 2006). The Correction value (R) has uncertainties $\pm\Delta R$*. "Not used" (with declinations in italics) indicates that the data were of insufficient quality to be used in reconstructions (see Background-data Table A1).
*: $\Delta\lambda$ is calculated from dp, the meridional semi-axis of the oval of 95% confidence around the paleopole; $\Delta D=\alpha_{95}/\cos I$. Rotations: R is the difference in the declinations of the observed and reference directions, with uncertainties ΔR calculated according to the technique of Debiche and Watson (1995). The confidence level for the corrected mid-Paleozoic declinations is calculated as $(\Delta D^2+\Delta R^2)^{1/2}$. Correction values for G1 and G3 are taken directly from the paper, whereas that for G5 was calculated by us.

available in the publication is not always complete. We have analyzed the three relevant Devonian paleomagnetic results from the Grishin et al. (1997) study and in a Background data Table A1 we list the seven reliability criteria of Van der Voo (1993) and enumerate how well the G1–G3 results meet these criteria. The G3 result meets only one or two of the seven criteria, and consequently cannot be considered as reliable. A negative conglomerate test and an inconclusive foldtest also argue strongly against the use of this result. Thus, we did not include G3 in our analysis.

The NE limb has yielded five results, two of which (L3, G5) are of Silurian age. The Devonian L2 result published by some of us in 2003 (Levashova et al., 2003) is in need of substantiation as we have maintained from the beginning, but the formation seems to have some promise; work in progress has given us some confidence that the result will eventually meet minimum reliability (*i.e.*, $Q>3$). The Silurian G5 result meets minimum reliability criteria ($Q=3$ or perhaps 4), and L3 is of good quality as well. Both have therefore been included in the analysis, and so has the more marginal ($Q>3$?) Devonian result (G1) from Grishin et al. (1997).

The two results published by Burtman et al. (1998), on the other hand, have not been included in our analysis. These authors reported a dual polarity, pre-folding remanence from two Middle Devonian localities (B1, B2, Table 2). The directions of the magnetization, however, match closely the expected Late Paleozoic overprint direction in both declination and inclination. Thus, we think it likely that these rocks were remagnetized prior to the Middle Carboniferous to Early Permian folding episode that affected the sampled localities.

The third (NW) limb of the orocline connects the SW and NE limbs in the pattern shown in Fig. 2B. It has yielded two useable results (G2, G4), one each of Devonian and of Silurian age. These results meet minimum reliability criteria ($Q>3$ in both cases), and have been included in the analysis. The reliability of G4, in particular, is attested to by a positive fold-test on a syn-sedimentary slump structure.

In summary, Table 2 provides us with eleven declinations distributed over all three limbs of the orocline that can be analyzed for rotations. The Silurian and Devonian data sets are of mixed quality, but as we will see, the results of the two groups do not contradict each other. Our next step is to use our knowledge of the sense and magnitude of Late Permian–Early Triassic rotations to restore the declinations to their pre-Late Permian orientations.

The deflection of the "*c*-component" of this study (that we consider to be an overprint of Permian age) relative to the reference direction indicates that the sampling locality underwent a counter-clockwise rotation of about 100°, similar sense rotations are common in the region (*e.g.* Van der Voo et al., 2006). The much less plausible choice of the alternative option, a rotation of 260° clockwise, will, of course, result in the same corrected value of the Devonian declination. The uncertainties of this and other rotations have been calculated by the method of Debiche and Watson (1995) and are included in Table 2 (labeled ΔR). As a reference direction for the calculation of rotations in the study area we chose the 290 Ma pole. It should be noted that while the reference inclinations for the study area steadily increase with younging age during the Late Paleozoic, the declinations show relatively minor changes (Fig. 9). Thus, somewhat imprecise dating of the *c*-component will not significantly affect the reference declination and, consequently, the estimate of the rotations.

Rotating the primary Devonian direction clockwise by 100° (or counter-clockwise by 260°), we restore the declination of the primary $a+b$ component to its pre-Late Permian bearing of 27±13°.

For the Aral result no estimate of any late Paleozoic rotation is available from the rocks themselves, but considering that their locality is within the same shear-zone as our study area (Van der Voo et al., 2006), it is reasonable to expect that the Aral-Formation sampling area was also affected by a counterclockwise (ccw) rotation of considerable magnitude. If this rotation was of the order of 90° ccw (Van der Voo et al., 2006), then the corrected Devonian declination turns into a northerly direction, not unlike that of the corrected declination from this study. Even if the rotation was only some 60° ccw, the restored declination of 340° is northerly.

Klishevich and Khramov (1993) reported the presence of secondary overprints in some of their samples in addition to the primary Devonian K1 and K2

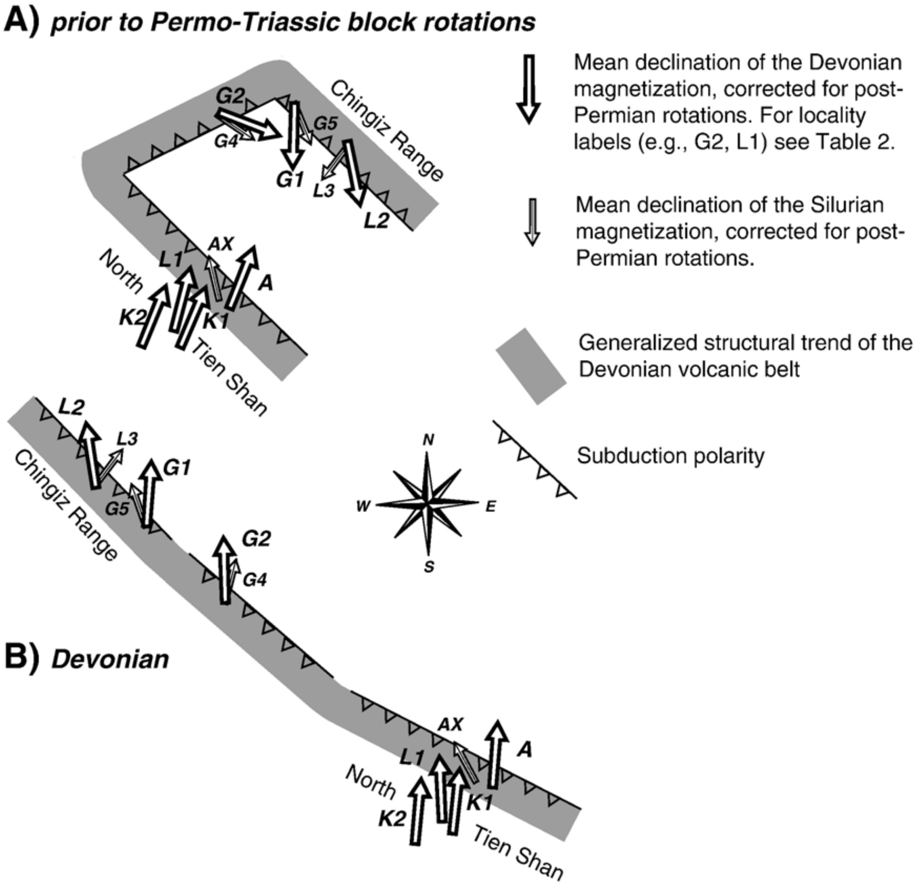

Fig. 10. Cartoon illustrating the relationship between the structural trends and the declinations of the primary Silurian and Devonian magnetizations for the time prior to Permo-Triassic small-block rotations (A) and for the inferred Devonian (B) configuration of the belt. For locations of the schematically represented limbs of the orocline and the sampling localities of the different studies, see Fig. 2 and Table 2.

magnetizations. The directions of these secondary components are described as being "similar to that of the primary magnetization of the Permian rocks in the sampling regions". However, no explicit information about the direction of this component was provided in the publication. Thus, we used an average of several published Late Permian results to correct the declinations for late Paleozoic rotations (Van der Voo et al., 2006). These results come from localities closest to the K1 and K2 sampling sites. Restored to their pre-Late Permian bearings, the Devonian declinations of both sites are ~20 NE.

In the NE and NW limbs of the orocline, the later rotations are generally negligibly small, which is concluded from overprints of late Paleozoic age that agree well with the coeval reference declination. The Devonian declinations in the Chingiz Range (NE limb) thus remain southerly (172 and 181°), whereas the Devonian declination in the NW limb is of the order of 110°.

The Silurian results show the same pattern as the Devonian (Table 2) with a northerly (347°) declination in the Kendyktas block, where no appreciable late Paleozoic rotation is observed (Alexyutin et al., 2005; McCausland et al., 2005; Van der Voo, 2006), whereas the declinations are roughly southerly (144° and 217°) in the Chingiz Range and east-southeasterly (about 124°) in the third (NW) limb.

5.4. Unbending the orocline

The corrected declinations of the Devonian and Silurian magnetizations are plotted in Fig. 10A within the structural trends of the strongly curved Devonian volcanic belt. In general, there is a good correlation between the change in the structural trend and the change in declination. This correlation suggests that the present-day curvature of the belt is, indeed, the result of oroclinal bending of an originally much straighter belt. One can test, to first approximation, whether the initial Devonian configuration of the belt was linear, by using the declinations as passive markers and aligning them all roughly parallel (Fig. 10B).

We realize, of course, that Fig. 10 reduces an exceedingly complex geological situation to three straight bands and a set of seemingly precise directions (arrows). Nevertheless, recognizing that the figure is a simplification, it usefully illustrates that a ~1500 km-long active volcanic arc trended approximately northwest-southeast in Devonian times. The subduction responsible for the volcanism was towards the southwest. The consistent inclination data from all segments indicate that the arc, which delineated the northeastern margin of the KNTD ("Kazakhstania") landmass, was situated at a ~30° northerly paleolatitude (see also Levashova et al., 2007). We note that the results of Klishevich and Khramov (1993) have shallower inclinations than all the other (volcanic) Devonian results, possibly due to inclination shallowing in the K1–K2 sedimentary formations.

6. Conclusions

Our paleomagnetic study of the Middle Devonian rocks (Kurgasholak Fm) from the southern limb of a long curved belt of the Devonian volcanics in Kazakhstan revealed two meaningful components of magnetization:

1) a high-temperature, dual-polarity remanence (*a*- and *b*-components) with a mean direction dec/inc = 286.5°/+46.4° and pole position 30.3° N, 355.4° E. We interpret this remanence as a primary Middle Devonian magnetization based on reversals and a baked contact test.
2) a secondary magnetization (*c*-component) with an *in situ* mean dec/inc = 134.9°/−43.0° and pole position 48.9° N, 332.2° E. This post-folding component is younger than the $a+b$ remanence and likely represents a Permian (~290 Ma) overprint, as evidenced by a good agreement of the *c*-component inclination with the reference inclination for this age and as consistent with observations of similar overprints in other formations in this area of Kazakhstan. The declination of the *c*-component, however, is deflected counter-clockwise by about 100° relative to the reference direction. This deflection indicates that the studied locality was affected by late-orogenic small-block rotations within a shear-zone of deformations, as suggested by Van der Voo et al. (2006). Using the sense and magnitude of this deflection, we corrected for these late-orogenic rotations, and thereby restored the declination of the primary Devonian magnetization to a north-northeasterly pre-Late Permian value.

Our corrected declination combined with several other published paleomagnetic directions of Devonian and Silurian age shows a good correlation with the structural trends of the curved Devonian volcanic belt, suggesting that the curvature is, indeed, a result of oroclinal bending.

Using corrected declinations as passive markers, we restored the belt to its Devonian configuration. Our reconstruction suggests that in the Devonian the "Kazakhstania" (Kokchetav-North Tien Shan (KNTD)) landmass was situated at about 30° N paleolatitude. The eastern margin of the landmass was delineated by a nearly straight, northwest-southeast trending, ~1500 km long volcanic arc. The subduction responsible for the volcanism was towards the southwest. The bending of this volcanic arc into its present horse-shoe shape took place sometime between Middle Devonian and the Late Permian. This ~180° post-Devonian bending of Kazakhstania provides additional geometrical constraints on the changing positions of Baltica, Siberia and Tarim during final stages of their convergence, which should be taken into consideration by tectonic models dealing with the amalgamation of Eurasia.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tecto.2007.04.008.

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