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Kazakhstan and the Altai in the Devonian: Paleomagnetic Evidence

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Abstract—The paleomagnetism of Middle Devonian and Frasnian sedimentary and volcanic rocks of Kazakhstan and the Altai Mountains was studied. New paleomagnetic data were obtained in the northeastern part of Central Kazakhstan within the Ermentau–Chingiz–Tarbagatai tectonic unit and near the southwestern margin of the Altai block in the Rudny Altai zone. Based on the paleomagnetic evidence obtained, in the Middle Devonian, the Chingiz–Tarbagatai margin of the Kazakhstan–Kyrgyz block trended nearly E–W, and the active margin of the Altai trended NE–SW. In the Middle–Late Devonian, the northern (in Devonian reference frame) marginal zone of the Kazakhstan–Kyrgyz block was located at a latitude of 21.3° ± 3.6°, and the southeastern margin of the Altai block had a latitude of 31.7° ± 4.1°. In the present-day structure, these blocks are separated by the Irtysh–Zaisan tectonic zone less than 300 km wide. In Devonian time, the distance between them along the ancient meridian was in the range 650–1650 km.

INTRODUCTION

In the Middle Devonian, Kazakhstan and the Altai were sialic blocks whose basement was made up of Early Paleozoic and older rocks. In Devonian time, volcanic rocks of calc-alkaline composition and molasses formed on this basement.

In the present-day structure, the Kazakhstan and Altai blocks are separated by the Irtysh–Zaisan tectonic zone, which is an amalgamation of rocks of Middle Paleozoic oceanic margins, an ensimatic island arc (or arcs), and fragments of oceanic crust. At present, this zone is less than 300 km wide and trends NW–SE (Fig. 1).

In the northeastern Irtysh–Zaisan zone, the accretionary wedge contains a subduction-related mélange and sediments likely derived from a deep-sea trench, which are of Famennian–Tournaisian age [12, 19]. Further southwest, there are rocks of the Devonian–Carboniferous Zharma–Saur volcanic arc, which probably had an oceanic basement. Presumably, within the Irtysh–Zaisan ocean, in the Devonian, there were two or three subduction zones, which plunged towards the Altai, the Zharma–Saur arc, and Kazakhstan, initiating volcanism on their territories [10, 15, 17]. It should be noted that the subduction of Irtysh–Zaisan oceanic crust beneath the Kazakhstan block is unlikely. There are no conclusive arguments for such a model, and major-element studies of Devonian volcanics in the Chingiz–Tarbagatai zone [3, 13, 14] do not confirm that the magmatism has a northeasterly polarity, which is assumed in model. It is more likely that this tectonic zone, which at present is adjacent to rocks of the Irtysh–Zaisan paleocean, is located in a block offset along a strike-slip fault [9, 26].

We undertook a paleomagnetic study of Devonian rocks in Kazakhstan and the Altai in the hope of determining the mutual position of these sialic blocks and the distance between them in Devonian time.

STUDY OBJECTS

Kazakhstan. In Kazakhstan, we studied Devonian rocks in two areas within the Ermentau–Chingiz–Tarbagatai tectonic unit. Devonian volcanic and terrigenous deposits unconformably rest on subjacent deposits.

In the Ermentau zone, conglomerates at the base of the Devonian section give way upsection to sandstones and siltstones. These deposits are more than 2 km thick. This is a redbed rhythmic sequence with occasional cross-bedded units and desiccation fissures. The lower part of this sequence (Chadrinskaya Formation) contains Givetian floras, and the upper part, Late Devonian floras. These deposits conformably pass upsection into sandstones and limestones with Famennian brachiopods [21]. In the Ermentau Range, in the Keregetas Mountains (51.5° N, 72.6° E), at the limbs of the Tumsuk syncline, we studied siltstones and fine-grained sandstones from a Givetian–Frasnian sequence (Fig. 1, E).

The second area studied (Fig. 1, K) lies in the Chingiz–Tarbagatai zone at the limbs of the Kainar syncline (in the Kenasu and Ul'ken-Sarymet mountains: 49.1° N, 77.5° E). Here, Silurian rocks are unconformably overlain by a thick sequence of sand- and silt-sized tuffaceous rocks and lavas of acid and intermediate composition, constituting the Kaidaul' Formation. The latter contains Devonian floras and is overlain by sandstones, cherts, and limestones with Givetian and Frasnian flora [16]. We studied lavas and tuffstones

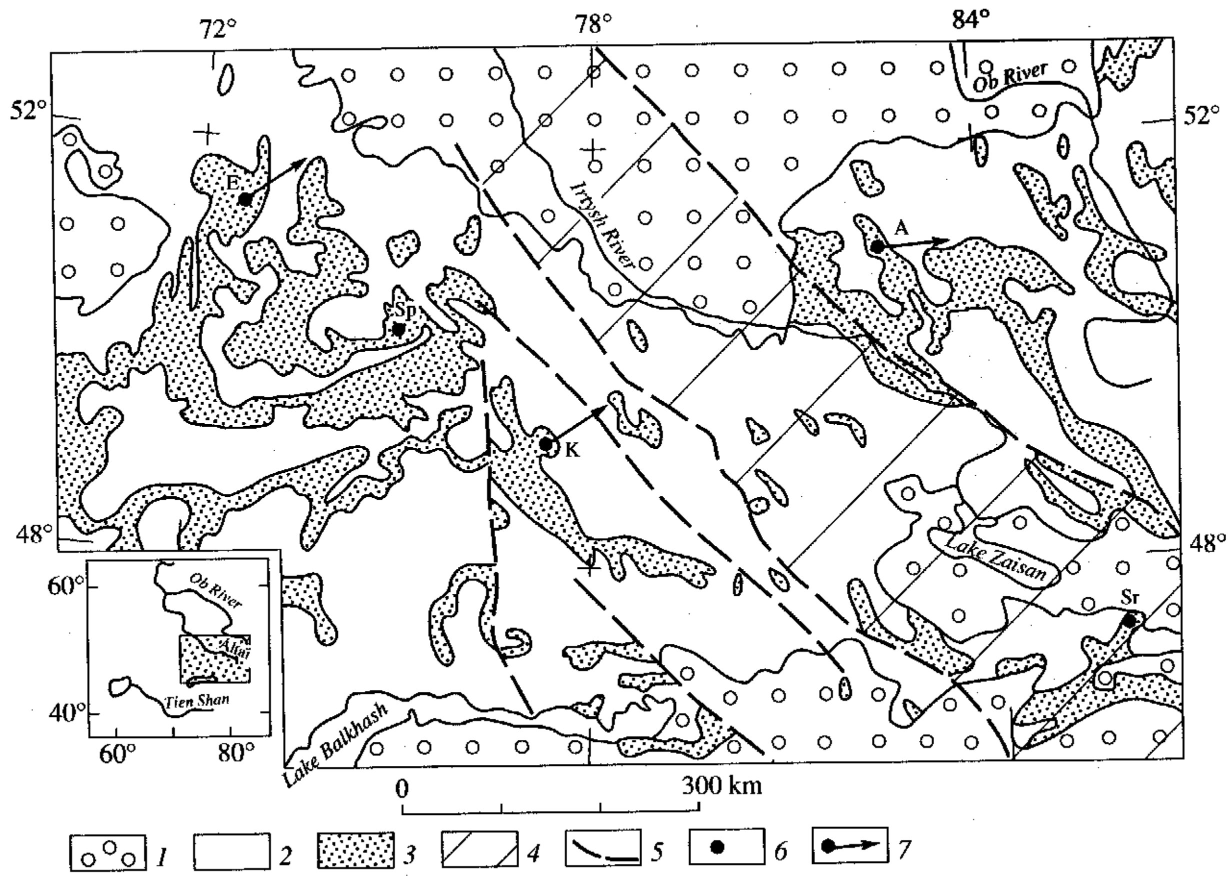

Fig. 1. Location of sampling sites. (*1*) Cenozoic; (2) Mesozoic, Paleozoic, and Precambrian, except Devonian; (*3*) Devonian deposits; (*4*) Irtysh–Zaisan tectonic zone; (*5*) main Late Paleozoic strike-slip faults; (*6–7*) areas in which reliable paleomagnetic data were obtained from Devonian rocks: (*6*) in [6, 7]; (*7*) in this work: A = Rudny Altai, K = Kainar, E = Ermentau, Sp = Spasskaya zone, Sr = Saur Range.

from the Kaidaul' Formation and sandstones, siltstones, and cherts from Givetian–Frasnian deposits.

Altai. In the Altai Mountains, we studied Middle and Upper Devonian rocks from the Alei anticlinorium and Rudny Altai tectonic zone. The Middle Devonian deposits unconformably overlie metamorphosed Lower Paleozoic rocks. The sequence consists of acid and intermediate volcanic rocks that alternate with sedimentary rocks. The deposits are very thick and are divided into formations.

At the northeastern limb of the Alei anticlinorium (Fig. 1, A), we studied rocks from three areas. In the Uba–Maralikha interfluvial area, near the village of Verkhneubinskoe (50.5° N, 82.5° E), massive lavas of the Talovka Formation contain a member consisting of marls and sandstones; these marls were studied by us. The rocks make up a faulted homocline with a dip angle of 20° to 60°. The Talovka Formation contains scanty Devonian faunas [1], overlies rocks with Eifelian brachiopods and corals, and is overlain by deposits with Upper Givetian brachiopods. Further northwest, near the village of Shipunovskoe (51.0° N, 82.3° E), we studied siltstones and fine-grained sandstones of the Shipunovskoe Formation, which is known to contain Upper Givetian brachiopods [1]. The rocks exhibit graded bedding and make up a homocline, whose dip angle varies from 10° to 40°. In the town of Zmeinogorsk (51.1° N, 81.1° E), in the homoclinal section, we studied bedded limestones of the Losishinskaya Formation, which is abundant in Eifelian flora [1, 18].

At the southwestern limb of the Alei anticlinorium in the Talovka River valley (50.5° N, 81.8° E), near the village of Rossypnoe (Mikhailovskoe), in the homoclinal section, we studied fine-grained and silty tuffites of the Snegirevskaya Formation, in which Famennian brachiopods were found [18].

LABORATORY STUDY OF PALEOMAGNETIC SAMPLES

The paleomagnetic hand samples collected were cut into cubes 2.0 cm on a side. Two cubes from each hand sample were put to stepwise demagnetization in a thermal unit covered by a two-layer μ-metal screen. The remanent field in the thermal unit was less than 20 nT. To determine the effect of the remanent field on the results obtained during heating, two cubes from each hand sample were placed in the thermal unit with opposite orientation along the X and Z axes. The heating steps were varied from 100°C in the low-temperature range to 30–10° closer to the Curie points for magnetite and hematite and were determined after the leading collection was preheated. Remanent magnetization was measured on a JR-4 magnetometer placed within Helmholtz coils in order to decrease the laboratory field; before transferring the cubes from the thermal unit to the measuring instrument, they were placed into a μ-metal container.

The components of natural remanent magnetization (NRM) were identified by analyzing Zijderveld temperature plots with programs that were kindly provided by R. Enkin. Components that coincided for the pair of cubes were accepted for further processing. Fold, consistency, and correlation tests were employed [24, 26, 27].

RESULTS OF PALEOMAGNETIC STUDIES

Kazakhstan. In the Ermentau area, results were obtained on 18 large samples collected from two limbs of the syncline. The NRM varies from 20 to 2500 mA/m. The component interpreted was identified in the temperature range from 350–400 to 530–570°C (B124, Figs. 2, 3), occasionally, in the range 250–660°C (see B126, Figs. 2, 3), and is related mainly to magnetite. More rarely, it could be identified in the temperature range 600–660°C, which is typical of hematite (see 8286, Figs. 2, 3). The polarity is reversed in 16 samples and normal in two. On the stereogram, the projections of the directions of the NRM components in the stratigraphic reference frame make up a visible cluster (with a consistency ratio of 13.8), which, in the geographic reference frame, is divided in two with an overall internal consistency of 5.1 (Fig. 4). The mean directions are given in Table 1. The test results (Table 2) indicate that magnetization had formed prior to folding.

In the Kainar area, results were obtained on 40 samples. The NRM varies from 1 to 140 mA/m (sedimentary rocks) and from 10 to 25 000 mA/m (andesites); the magnetization of acid lavas varies from 10 to 110 mA/m. The component interpreted is mainly distinguishable in sedimentary rocks in the temperature range from 300–350 to 530–630°C; in andesite, from 300–470 to 500–570°C for magnetite (titanomagnetite?) and from 500–600 to 670°C for hematite; and in acid lavas, within the range 350–530°C (magnetite) and from 470–500 to 600–630°C (magnetite and hematite?). Thirty samples are magnetized reversely and ten are magnetized normally. Reversed polarity was identified in all rock types, and normal polarity was found in andesites; both magnetite and hematite can be its carrier (see Figs. 2, 3). On the stereogram, the projections of the NRM components in the stratigraphic reference frame make up a cluster (with a consistency ratio of 12.2), which, in the geographic frame, has a consistency ratio of 4.1. The test results suggest that the magnetization predates folding. The reversal test was also positive: the differences between the mean directions of normal and reversed polarity are equal to 144° in the geographic reference frame, and 171° in the stratigraphic reference frame (Fig. 4).

Altai. In the Altai, results were obtained on 38 samples. The rocks are weakly magnetic, with the NRM varying from 0.3 to 7.0 mA/m. The NRM component interpreted was identified in the temperature range from 300–350 to 500–570°C and is related to magnetite (Figs. 2, 3). All rocks studied (except for a single case) are magnetized reversely (Fig. 4, Table 1). The test results (Table 2) indicate that the magnetization component identified is older than folding.

Thus, for all study areas, it was possible to ascertain the direction of the prefolding NRM component. Folding in this region occurred in the Middle Carboniferous–Early Permian [4]. A comparison of the inclinations obtained with reference inclinations relative to the paleomagnetic poles of Eastern Europe and Siberia taking the determination errors into account provides no additional constraints on the age of the magnetization. The possible upper age limit is set by the presence of samples with normal polarity, whereas the presence of samples with both normal and reversed polarity is evidence in favor of a primary origin for the NRM component in the Devonian. Another argument for primary magnetization is the coincidence of paleomagnetic directions in rocks of different origin with those in various magnetic minerals.

Table 3 presents the paleolatitudes for Kazakhstan and the Altai Mountains calculated from the paleomagnetic inclinations obtained.

Published data. In the Late Paleozoic, the Middle Paleozoic Kazakhstan–Kyrgyz sialic block underwent complex tectonic deformations, including strike-slip faulting and rotation of tectonic blocks [2, 10, 20, 22, 28]. Reliable paleomagnetic determinations are insufficient to decipher the kinematics of internal deformations in this complex region. It is only possible to compare paleomagnetic inclinations.

In the northern and central Tien Shan in Middle–Upper Devonian terrigenous and terrigenous-carbonate rocks in three areas, Burtman *et al.* [5] identified the prefolding, probably primary, magnetite component. Its average inclination ($I = 39° \pm 1.5°$) corresponds to paleomagnetic inclinations determined in Kazakhstan rocks of the same age. Within the same Tien Shan territory at eight localities, Lower Devonian rocks were studied [11]. The average paleomagnetic inclination calculated ($I = 36° \pm 13°$) from these data agrees with our determinations from Middle–Upper Devonian rocks.

In central Kazakhstan, the paleomagnetic direction was isolated from Lower–Middle Devonian volcanic rocks collected in the Karaganda raion from the Spasskaya tectonic zone (see Sp in Fig. 1). These were used to identify the prefolding normal–reversed magnetite component probably of primary origin [6]. The

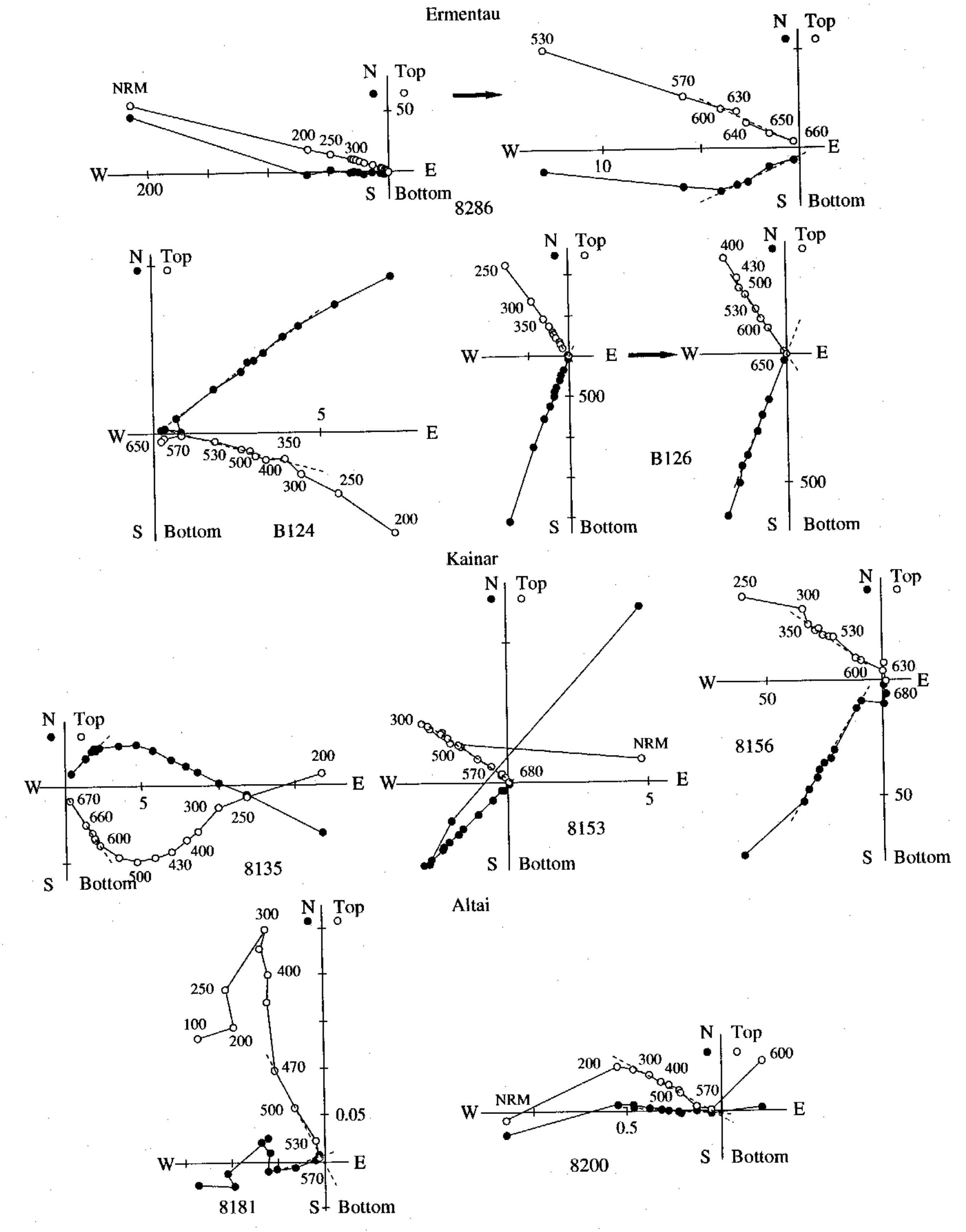

Fig. 2. Zijderveld temperature plots. Magnetization intensity in mA/m; dashed line represents the component interpreted.

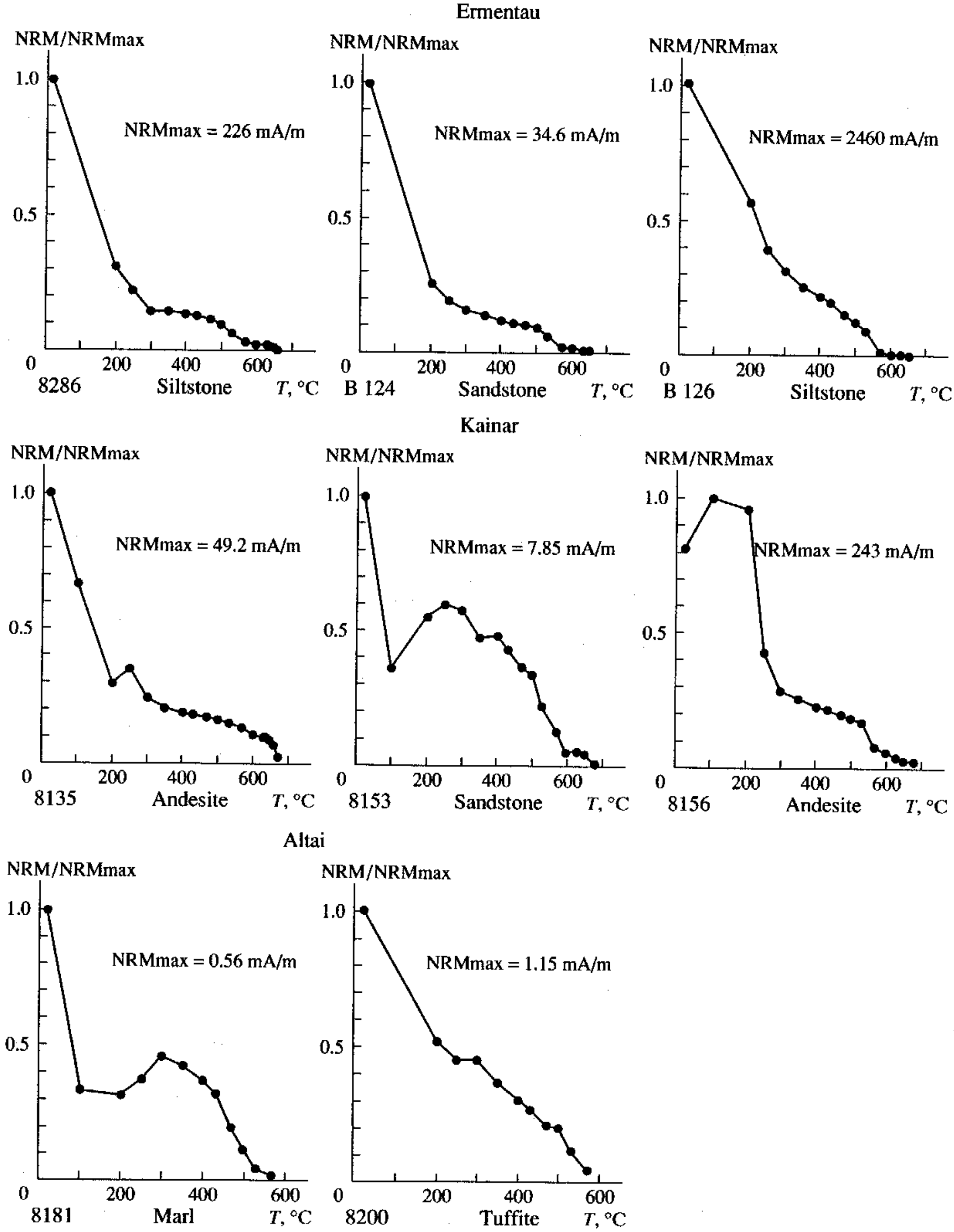

Fig. 3. Thermal cleaning curves.

paleomagnetic inclination obtained (I = 40° ± 10°) corresponds to our determination of the inclination in Middle Devonian and Frasnian rocks from the Chingiz–Tarbagatai tectonic zone.

The Sauskii Range (see Sr in Fig. 1) is situated within the Irtysh–Zaisan tectonic zone. Here, Givetian and Frasnian lavas and tuffs were studied [7]. They formed in the Zharma–Saur island arc, which probably

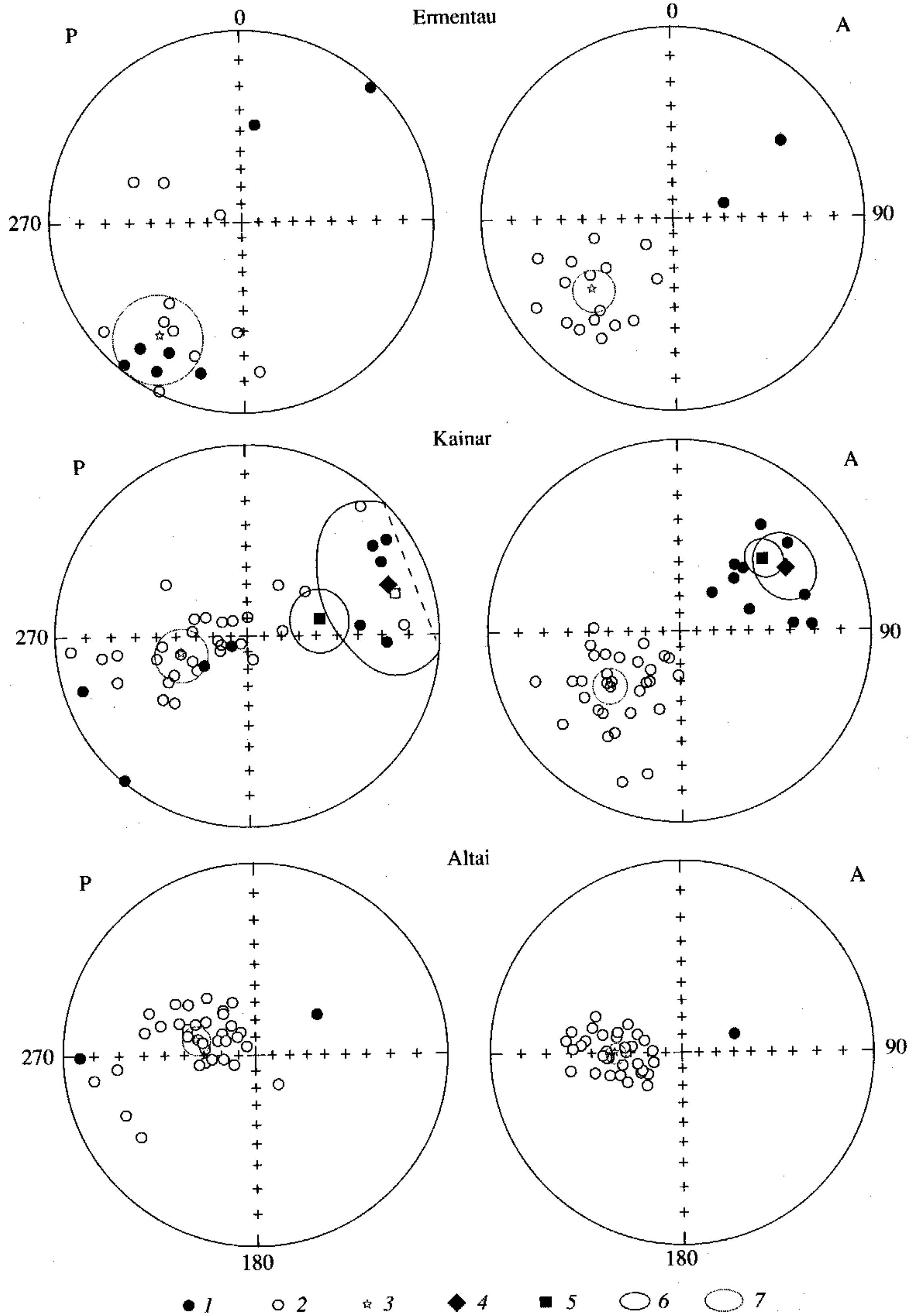

Fig. 4. Projections of paleomagnetic vectors on stereograms in geographic (P) and stratigraphic (A) reference frames. (*1*) Lower hemisphere projections; (*2*) upper hemisphere projections; (*3*) mean directions for the areas; (*4–5*): mean directions for normally (*4*) and (*5*) (reversed direction) reversely magnetized rocks in the Kainar area; (*6–7*), confidence ellipsoids of the mean directions of normal (*6*) and reversed (*7*) polarity.

Table 1. Paleomagnetic data

Area	Average dips, °	N/n	D°	I°	k	α_{95}	D°	I°	k	α_{95}
			geographic reference frame				stratigraphic reference frame			
Ermentau	Dip 145, ∠55; Dip 0, ∠60	43/18	216	−17	5.1	14.7	230	−31	13.8	8.9
Kainar	Dip 30, ∠60; Dip 260, ∠30	97/40	254	−50	4.1	11.0	232	−41	12.2	6.4
Kazakh-stan	(Ermentau + Kainar)[1]	140/58	239	−41	3.7	9.4	231	−38	12.4	5.2
Altai	Dip 15, ∠20; Dip 70, ∠30; Dip 200, ∠30	70/38	285	−55	9.4	7.4	269	−51	25.5	4.5

Note: N is the total number of hand samples; n is the number of hand samples included in the statistics; D° is the declination; I° is the inclination; α_{95} and k are the radius of the confidence ellipsoid (in degrees) and internal consistency ratio, respectively, as determined from Fisher statistics.

[1] The mean direction was calculated from the directions of the NRM components of the hand samples.

Table 2. Paleomagnetic test results

Area	Test								Unfolding at k_{max} in %
	consistency ratio			correlation			unfolding		
	Fp	Fcr	Fa	R_sP	R_scr	R_sa	S	Scr	
Ermentau	24.05	3.29	**0.72**	0.678	0.64	**0.32**	**2.69**	1.77	**100**
Kainar	43.35	3.12	**1.24**	0.871	0.442	**0.285**	**2.97**	1.45	**95**
Kazakhstan	41.83	2.45	**1.43**	11.93	2.66	**1.81**	**3.39**	1.36	**100**
Altai	21.60	2.50	**1.12**	0.733	0.448	**0.383**	**2.73**	1.47	**100**

Note: $S = k_{max}/k_{min}$; F and R_s are selected statistic values (p = in geographic reference frame; a = in stratigraphic reference frame; cr = critical value); the tests of consistency and correlation are positive (magnetization predates folding) when Fa and R_sa are less than the critical values; the fold test is positive at S > Scr; data of positive tests are set in bold type.

Table 3. Calculated paleolatitudes

Region	I°	α_{95}°	φ°	δφ°	Δφ°	δΔφ°
Kazakhstan	37.9	5.2	21.3	±3.65	10.4	±4.4
Altai	51.0	4.5	31.7	±4.1		

Note: I° is the inclination of the mean NRM vector in stratigraphic reference frame; α_{95}° is the radius of the confidence ellipsoid; φ° and δφ° are the paleolatitude and its determination error, respectively; Δφ° and δΔφ° are the difference in paleolatitudes and its determination error [25].

rested on a mafic basement. In these rocks, the prefolding N–R magnetite component probably of primary origin was identified. The paleomagnetic inclination (I = 51° ± 8°) is close to that obtained by us for Rudny Altai, corresponding to the mutual position of these tectonic zones.

Conclusions. The paleomagnetism of Middle Devonian and Frasnian sedimentary and volcanic rocks of Kazakhstan and the Altai Mountains was studied. The rocks underwent the necessary laboratory investigations, and the data obtained were subjected to paleomagnetic tests. As a result, it was possible to reliably determine the parameters of prefolding magnetization, which is probably of primary origin (Table 1). The new data are very precise and agree with published results from paleomagnetic studies of Devonian rocks in other parts of the region. All this indicates that the paleomagnetic evidence obtained is fit for paleotectonic reconstructions.

MODERN PALEOTECTONIC RECONSTRUCTIONS IN LIGHT OF THE NEW PALEOMAGNETIC EVIDENCE

The new paleomagnetic data were obtained in the northeastern part of the Middle Devonian Kazakhstan–Kyrgyz sialic block and near the southwestern margin of the Altai block. In the present-day structure, these blocks are separated by the Irtysh–Zaisan tectonic zone less than 300 km wide. The paleomagnetic data were used to determine the orientation of these tectonic unit in the Middle–Late Devonian and calculate the paleolatitudes. We obtained the following parameters that define the position of the units.

(a) The northern (in Devonian geographic coordinates) marginal zone of the Kazakhstan–Kyrgyz sialic block trended nearly E–W.

(b) This marginal zone (Chingiz–Tarbagatai zone) had a latitude $21.3° \pm 3.6°$.

(c) The active margin of the Altai sialic block trended NE–SW.

(d) This marginal zone (Rudny Altai) was located at a latitude of $31.7° \pm 4.1°$.

(e) The distance between the Chingiz–Tarbagatai and Rudny Altai zones along the ancient meridian was $10.4° \pm 4.4°$, i.e., 1150 ± 500 km.

Let us compare the results obtained with the position of the units we studied in the Devonian reconstructions for Central Asia proposed in recent years. The reconstruction in [10] corresponds to the parameters (c) and (e); the geodynamic reconstructions in [8, 17] correspond to the parameters (c), (d), and (e); the paleotectonic reconstructions in [23, 28] correspond to the parameters (a), (b), and (e); and the palinspastic reconstruction in [6] corresponds to the parameters (c) and (d) and does not correspond to the remaining parameters.

We are far from suggesting that paleomagnetic data can replace tectonic analysis and provide a criterion for selecting a geodynamic model. At the same time, this model must agree with the results of paleomagnetic studies. Most of the aforementioned models can be corrected by taking the new paleomagnetic evidence into account.

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