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Structural Evolution of Central Asia to the North of Tibet: A Synthesis of Paleomagnetic and Geological Data

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Abstract—A paleomagnetic study of Paleogene basalts from the Tien Shan was carried out to evaluate a crustal shortening to the north of Tibet during the India–Eurasia collision. The mean inclination of the prefolding and, presumably, primary magnetization component in the basalts was found to be close to the early Cenozoic reference values as recalculated from the paleomagnetic polar wander path analysis for Eurasia. A comparison of the published measured and expected (reference) paleomagnetic inclination values for the last 270 Ma (Late Permian to Quaternary) suggests that the Permo-Triassic data on the Tien Shan and adjacent structures are consistent with the data on Eurasia within the uncertainty limits, whereas most Cretaceous and Paleogene inclinations in sedimentary rocks are shallower than the expected values, especially concerning the Cenozoic data. The nontectonic origin of Cretaceous and Paleogene shallowed inclinations is argued, so that the total crustal shortening, including the effect of collision, lies well within the paleomagnetic data uncertainty limits and, most probably, does not exceed a few hundred kilometers. An analysis of Cretaceous and Paleogene declinations to the north of Tibet showed that the systematic large-scale rotations took place only near the Pamirs in connection with the Pamir wedge indentation. The Late Cenozoic rotation zone was bounded by the Talas–Fergana Fault; no Alpine rotations occurred east of this fault as far as Qaidam. Because the significant crustal shortening and extensively developed rotations are inevitable for a large-scale lateral extrusion, this mechanism cannot explain the structural pattern of Central Asia north of Tibet. This means that the India–Eurasia convergence for a distance of 2500 km during the last 50 Ma was almost completely accommodated within Tibet and the Himalayas. It has been shown that the insignificant Alpine displacements along faults in the Tien Shan were not accompanied by rotation, whereas the Permo-Triassic strike-slip displacements amounted to several tens of kilometers and were systematically accompanied by counterclockwise rotation through angles up to 90°. Thus, the Tien Shan structural pattern arose from the Late Paleozoic left-slip movements, whereas the Alpine compression just selectively rejuvenated some older faults.

INTODUCTION

Most researchers admit the contribution of the India–Eurasia collision in the creation of the present-day structural pattern of Asia, but the general agreement ends here. The convergence of these continents since the beginning of the collision is estimated at 2500 km [57 among others], but researchers disagree completely as to where and how exactly the convergence was accommodated [51, 58, 59, 77, 79]. Geological [62, 67, 68] and paleomagnetic [61, 75] data east and southeast of Tibet fit well with the model of lateral extrusion from the collision zone. Some authors employ this mechanism to explain the development of Alpine structures in Asia north of Tibet and extend its effect as far as to Lake Baikal [38, 66] or even to the Sea of Okhotsk [74].

The proposed India–Eurasia convergence accommodation mechanisms imply different scales and types of strike-slip movements in Central Asia. The lateral extrusion mechanism, for instance, supposes that such movements have a large amplitude. Firstly, the lateral extrusion implies a significant crustal shortening north of Tibet (hereafter this term means Tibet proper and the Kunlun, for the sake of brevity). Secondly, the lateral extrusion is inevitably associated with intense deformations and/or large-scale shearing of the initially consolidated continental crust, most probably accompanied by block rotations. Therefore, a paleomagnetic analysis enables one to verify various models of the structural evolution of Central Asia: general shortening can be deduced from paleolatitude analysis and the magnitude, sign, and areal extent of rotation, from paleomagnetic declination analysis. Note that it is impossible to estimate in quantitative terms the extent of shortening and the spatial distribution of rotation zones accompanying the lateral extrusion because of the complexity of deformations in such a process; however, a qualitative consistence must be fulfilled: large-scale extrusion requires significant strike-slip displacements and appreciable rotations over large areas.

The Tien Shan is an ideal test area for such investigations. If the effect of lateral extrusion was significant here, this mechanism can really be regarded as a far-ranging one. On the contrary, if lateral extrusion did not

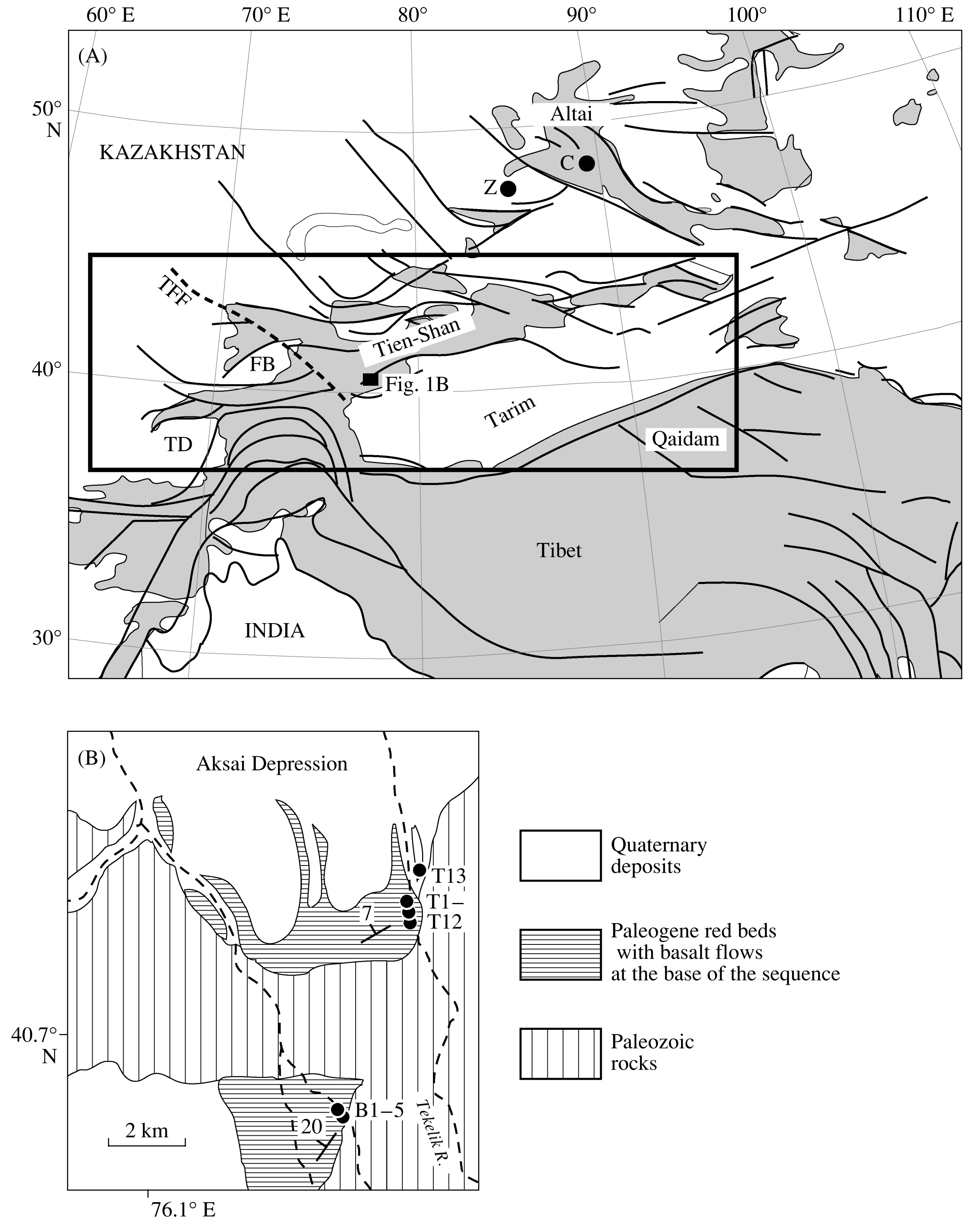

Fig. 1. (A) Schematic structural map of Central Asia and (B) schematic geological map of the study area. Panel A: Solid lines are major faults; dashed line is the Talas–Fergana Fault (TFF) (modified after [38]); FB—Fergana Basin, TD—Tajik Depression. Circles indicate paleomagnetic sampling sites in Cenozoic sequences in the Zaisan (Z) and Chu (C) depressions [71]. The rectangle indicates the area discussed in this article. Panel B: Filled circles indicate Paleogene basalt sampling sites.

play a significant role in the structural evolution of the Tien Shan, the latter must behave as a barrier for the northern parts of Eurasia merely due to its geographical position (Fig. 1A). This paper presents new paleomagnetic data on the Cenozoic rocks from the central Tien Shan and the results of paleolatitude and rotation angle analysis together with an estimation of displacements along faults of various ages for the whole Tien Shan and adjacent areas during the last ~270 Ma.

GEOLOGICAL BACKGROUND

The sector of Asia north of Tibet discussed in this paper (Fig. 1a) consists of structures with different Paleozoic tectonic histories. By the mid-Permian, however, all oceans in this region closed [4], and, as commonly assumed, it became a part of the Eurasian plate, occasionally involved in younger intraplate movements [24]. The Triassic occurs here locally, whereas Jurassic and younger deposits rest upon the Paleozoic and Triassic rocks with a sharp angular unconformity. Numerous relatively small basins originated in the region almost simultaneously at the Triassic–Jurassic boundary and then were filled with Jurassic clastic sediments. Early Cretaceous rocks in the region are absent (Central Tien Shan) or consist of lagoonal and coastal red beds and less abundant marine sediments (Tajik and Fergana depressions and the western Tarim). During the Late Cretaceous and Paleogene, a shallow-water sea existed in the western and southwestern parts of the region. The Cretaceous is absent east of the Talas–Fergana Fault, where the Paleozoic basement is unconformably overlain by the Paleocene–Eocene clastics and carbonates of the Kokturpas Formation, with locally developed basalt flows at the base. In the Oligocene and early Miocene the sea retreated, and the whole Tien Shan became an area of clastic sedimentation with an upsection increase in the proportion of conglomerates. This trend and the fission-track timing of the uplift episodes [64] testify to the differentiated vertical movements during the Miocene. No regional angular unconformities are recorded in the Tien Shan from the Jurassic to the Miocene; the bulk of the deformations took place in the late Miocene and especially in the Pliocene and Quaternary [15]. The intensity of Alpine deformation reveals wide lateral variations. The broad anticlines in Tarim are usually buried beneath the recent sediments. The zones of steep folds in the Tien Shan alternate with weakly deformed areas without any marked northward waning of folding. Most of the Alpine folds, reverse and thrust faults in the Tien Shan are E–W trending. The fault vergence is generally oriented toward foredeeps, i.e., to the Tarim Basin in the south and to the Chu and Ili basins, in the north.

PALEOMAGNETIC ANALYSIS

Most Cenozoic paleomagnetic data on Central Asia were obtained from sedimentary rocks, red beds in particular, except for one basalt flow in the northern Tien Shan [69]. As is well known [19 and others], magnetic inclination in sediments is sometimes shallowed. This can be reliably assessed from the studies of igneous rocks, but only when (a) it is possible to establish the initial position of these rocks and (b) the rocks were formed long enough for an averaging of secular geomagnetic field variations. The Paleocene basic igneous rocks identified in a number of localities in the Tien Shan [7, 9] are represented either by minor intrusions that do not meet both conditions (a) and (b) or by isolated thin basalt flows that do not meet requirement (b). Luckily, a basalt flow series with a total thickness of about 80 m was found in the southern Aksai Depression near the China–Kyrgyzstan boundary (Fig. 1B). Three K–Ar datings of the basalts yielded 50–74 Ma [8] unlike other basalts from Kyrgyzstan, which are dated around 50 Ma, although with a certain scattering of results [7].

In the studied Section T, the number of lava flows is no less than 5 [9]. Section B at a distance of 10 km from the former contains lava varieties unknown in Section T. Consequently, the number of studied flows is wittingly more than 5, but it is difficult to correlate flows between the sections and to count the exact number of flows. A total of 101 basalt samples were collected from 18 sites. Lavas differ in strike and dip azimuths and angles, but are flat-lying in both sections.

An unstable magnetization component was removed by heating up to 200–300°C. After that, the main component of reversed polarity falling into the origin of coordinates in Zijderveld diagrams was determined in almost all cases; the complete demagnetization of samples in the interval of 570–600°C suggests that magnetite is the main magnetization source (Figs. 2A and 2B). The directions of this component are well grouped in each point, and the fold test [54] indicates its prefolding origin (Figs. 2C and 2D; Table 1). The average inclination of this component ($I = -54.0 \pm 3.8°$) is small but statistically significant and shallower by $7.9 \pm 4.8°$ than the reference value for 50 Ma derived from the recalculation of the Eurasian polar wander path [31]. The difference becomes statistically insignificant when compared with reference inclination values at 60 and 70 Ma, which fits into the age determination uncertainty (Table 2). (See [30] for a more detailed description of these results and interpretation).

VARIOUS ESTIMATES OF CRUSTAL SHORTENING TO THE NORTH OF TIBET

The crustal shortening resulting from Alpine deformations was estimated using various techniques. The pre-Alpine base levels were investigated along a system of profiles in various parts of the Tien Shan, and shortening was estimated everywhere as only a few percent [22]. The most typical are the results from five trans-Tien Shan profiles, where the shortening varies between 10 and 50 km; of that, the shortening between

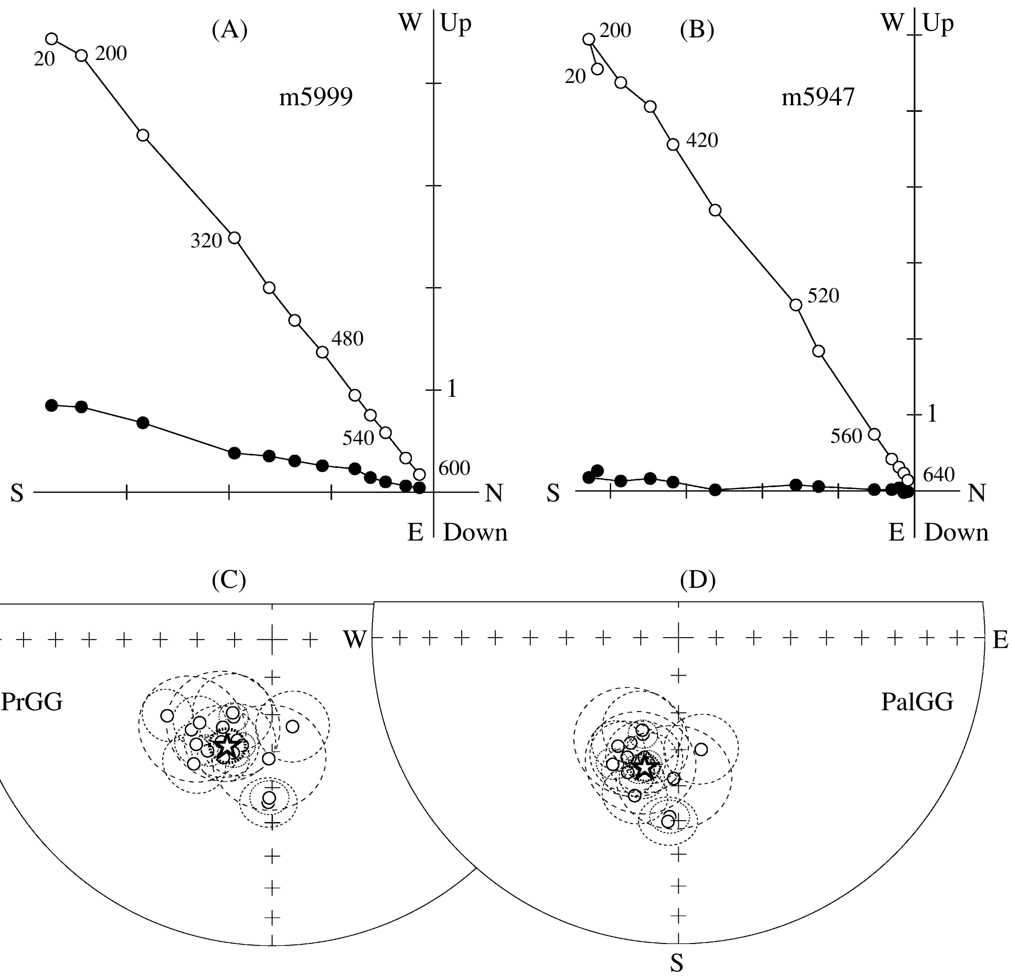

Fig. 2. (A and B) results of thermal demagnetization and (C and D) stereograms of site-mean directions of the main magnetization component in the Paleogene basalts from the Central Tien Shan in the present-day geographic (C) and paleogeographic (D) grids. Panels A and B: Filled (open) circles indicate the projections onto a horizontal (vertical) plane in a paleogeographic grid; temperature is given in degrees Celsius and magnetization, in mA/m. Panels C and D: Circles indicate site-mean directions with confidence circles (fine dashed lines); asterisk and dotted line indicate the common mean direction and its confidence circle; all data are projected onto the upper hemisphere. PrGG and PalGG are the present-day geographic and paleogeographic grids, respectively.

Tarim and Kazakhstan along three profiles ranges from 24 to 39 km. We believe, however, that this method yields only the minimum possible shortening value.

Investigations using the Global Positioning System (GPS) suggest that the velocity of convergence between Tarim and Kazakhstan is 12 ± 1 mm/yr [23]. The general shortening was estimated at 70–90 km on the assumption that this process began approximately 10 Ma ago and was proceeding at an approximately constant rate [32]. Other authors estimate the upper limit of the Tien Shan shortening at 200 km [25]. To summarize, Tarim–Eurasia convergence during the Late Cenozoic did not exceed 200 km based on geological and geophysical data.

As is well known, the convergence of blocks can be reliably established from geological data, whereas the extent of convergence is estimated much less reliably, and then only its minimum value. This accounts for the frequent attempts to determine the extent of crustal shortening between India and Eurasia from paleomagnetic data [40, 45, 50]. Because the most important deformations in Central Asia occurred in the late Cenozoic, the Cretaceous and/or Cenozoic data were usually employed. But, as mentioned above, all oceanic basins north of Tibet closed by mid-Permian time at the latest [4] and, hence, pre-Cretaceous paleomagnetic data can also be employed. The Cretaceous and Cenozoic data on Central Asia were analyzed with reference to Eurasia's polar wander path for the last 200 Ma [31], and the Permo-Triassic data, with reference to a less detailed curve [73].

For the Late Permian and Triassic inclinations in the Tien Shan (Fig. 3A), the differences between the measured and expected Eurasian values are insignificant and random (Figs. 3B and 4, nos. 32–39; Table 2). Moreover, there are no appreciable differences between

Table 1. Results of paleomagnetic study of the Paleogene basalts from the Tien Shan

Site	N	PrGG		PalGG			
		D°	I°	D°	I°	c	$\alpha_{95°}$
T1	6/3	214.7	–63.1	204.3	–59.1	70	14.8
T2	5/5	172.1	–66.2	168.5	–59.4	65	9.6
T3	5/5	211.8	–67.0	200.2	–62.5	399	3.8
T4	6/5	204.1	–57.9	196.8	–53.0	369	4.0
T5	6/6	204.3	–61.5	196.0	–56.6	47	9.8
T6	6/6	186.8	–58.1	181.9	–52.0	22	14.5
T7	6/6	215.4	–55.4	207.5	–51.6	251	4.2
T8	6/6	211.6	–59.4	203.0	–55.1	48	9.7
T9	5/5	201.1	–60.6	193.5	–55.4	505	3.4
T10	5/5	207.7	–55.7	200.6	–51.1	133	6.7
T11	5/5	186.2	–47.2	182.8	–41.1	253	4.8
T12	7/7	186.5	–45.7	183.2	–39.7	74	7.1
T13	7/6	213.7	–67.8	201.4	–63.5	42	10.4
All T	(13/13)	200.5	–59.6	193.3	–54.3	69	5.0
B1	5/4	239.2	–55.1	209.1	–56.7	126	6.8
B2	5/5	226.9	–57.5	196.9	–54.6	43	14.1
B3	4/3	221.1	–55.2	194.6	–50.8	469	5.7
B4	6/6	217.3	–50.3	195.5	–45.5	70	8.1
B5	6/6	227.3	–60.5	193.3	–56.7	92	7.0
All B	(5/5)	225.9	–56.0	197.6	–53.0	180	5.7
CA	(19/19)	208.1	–59.1			56	4.6
				194.6	–54.0	85	3.8
F(2, 32) = 3.3		f = 8.75		f = 0.4			

Note: Sampling site locations are shown in Fig. 1A; (CA) common average; (N) number of samples (sites) studied/used; (PrGG) present-day geographic and (PalGG) paleogeographic grids; (D) declination; (I) inclination; (c) concentration [46]; (α_{95}) radius of confidence circle; (F) critical value of F distribution at 95% confidence level (numbers in parentheses are the degrees of freedom); (f) calculated value of this statistics.

the data on the northern and southern margins of the Tien Shan (cf. nos. 38, 39 and 33, 34 in Figs. 3B and 4 and Table 2); nor does the inclination in the Permian rocks of southern Tarim differ from the Eurasian reference value (Table 2, no. 40). Thus, the displacement of the Tien Shan and Tarim relative to Eurasia from the Late Permian to the present day are well within the data uncertainty. It is impossible to define the limits, but a northward displacement of even 500 km would change the difference between measured and reference values considerably (see dashed line in Fig. 3B). Consequently, the convergence between the Tien Shan and Eurasia from the Late Permian to Recent is much less than this value.

Most Cretaceous inclinations are shallower than the reference values by 10°–20° (Fig. 4, nos. 24, 25, and 27–31; Table 2), and this gave grounds to infer a significant crustal shortening to the north of Tibet [45, 50, and others]. However, Paleogene inclinations in the Tien Shan and adjacent areas are 20°–30° shallower than the reference values (Fig. 4, nos. 5–15; Table 2); nevertheless, no attempts were made to interpret this difference in tectonic terms, probably because of the extremely large displacements obtained. Indeed, the direct conversion of inclinations into paleolatitudes suggests that Central Asia was a part of the Eurasian plate during the Permian and Triassic, and the total extension north of the Tien Shan in the Cretaceous and Paleogene attained more than 2000 km by the end of the Paleogene.

This interpretation, however, contradicts many paleomagnetic and geological data, which can be summarized as follows:

(1) All the data on the Cretaceous were obtained from sedimentary rocks, red beds mostly, where inclinations can be shallowed. Moreover, the special works established a significant shallowing in the Lower Cretaceous red beds from northern Tarim [65];

Table 2. Measured and expected paleomagnetic directions and kinematic parameters for Central Asia

No.	Age	D_m°	I_m°	D_r°	I_r°	F° ± ΔF°	R° ± ΔR	References
1	N_2(2.5)	349	43	0	59	16 ± 2	11 ± 2	[35]
2	N_1(20)	25	29	11	60	31 ± 6	–14 ± 10	[44]
3	N_1(20)	358	40	10	60	20 ± 7	12 ± 10	[60, 76]
4	O–N_1(21)	10	39	11	60	21 ± 6	1 ± 10	[37]
5	O(30)	343	36	10	57	21 ± 8	27 ± 12	[69]
6	O(30)	2	49	10	59	10 ± 7	8 ± 12	[69]
7	O–N(30)	336	33	9	54	21 ± 11	33 ± 15	[70]
8	O–N(30)	349	35	9	54	19 ± 11	20 ± 15	[70]
9	O–N(30)	336	30	9	53	23 ± 11	33 ± 14	[70]
10	O–N(30)	317	34	9	54	20 ± 10	52 ± 13	[70]
11	O–N(30)	3	30	9	53	23 ± 8	6 ± 11	[34]
12	O(30)	18	37	10	55	18 ± 6	–8 ± 10	[60, 76]
13	E–O(40)	5	37	15	60	23 ± 11	10 ± 17	[69]
14	E(40)	13	50	16	64	14 ± 8	3 ± 16	[36]
15	E(50)	4	24	11	58	34 ± 8	7 ± 10	[60, 76]
16	E(50)	15	54	11	61	7 ± 5	–4 ± 9	[30]
16a	Pa(60)	15	54	11	56	2 ± 5	–4 ± 9	[30]
17	Pa(62)	28	30	11	53	23 ± 11	–17 ± 14	[47]
18	K_2(80)	16	39	6	53	14 ± 9	–10 ± 14	[53]
19S	K_2(90)	350	56	11	56	0 ± 6	21 ± 11	[26]
20S	K_2(90)	357	58	10	55	–3 ± 6	13 ± 10	[26]
21S	K_2(90)	6	49	10	53	4 ± 4	4 ± 6	[29]
22S	K_2(90)	2	52	10	54	2 ± 4	8 ± 8	[29]
23S	K_2(90)	356	49	10	53	4 ± 4	14 ± 6	[29]
24	K(105)	10	38	11	57	19 ± 22	1 ± 46	[37]
25	K(109)	18	40	9	59	19 ± 9	–9 ± 16	[39]
26	K(113)	32	50	12	55	5 ± 9	–20 ± 14	[49]
27	K_1(120)	356	42	14	52	10 ± 6	18 ± 9	[26]
28	K_1(120)	6	37	12	48	11 ± 6	6 ± 7	[29]
29	K(125)	16	29	17	56	27 ± 8	1 ± 10	[65]
30	K_1(129)	22	42	14	56	14 ± 9	–8 ± 14	[53]
31	K(129)	13	49	15	58	9 ± 7	2 ± 13	[36]
32	$T_{2–3}$(230)	355	70	55	63	–7 ± 6	60 ± 16	[28]
33	P_l–T_1(250)	22	55	55	58	3 ± 5	33 ± 9	[55]
34	P_l(255)	8	48	48	47	–1 ± 5	41 ± 6	[28]
35	P_l(255)	350	56	50	50	–6 ± 5	60 ± 8	[3]
36	P_l(255)	358	58	51	52	–6 ± 6	53 ± 11	[3]
37	P_l(255)	28	50	52	54	4 ± 4	24 ± 7	[52]
38	P_l(255)	343	62	57	61	–1 ± 4	74 ± 8	[63]
39	P_l(255)	7	59	58	62	3 ± 7	51 ± 10	[56]
40*	P(270)	30	52	52	51	–1 ± 7	22 ± 11	[47]

Note: # Modern dipole field was used for reference; * reference value was derived from interpolation between the Early and Late Permian data [47]; No. is the site number; geological age of rocks: P—Permian, T—Triassic, K—Cretaceous, Pa—Paleocene, E—Eocene, and O—Oligocene; age in Ma is given in parentheses. D and I are the declination and inclination of paleomagnetic directions; m and r in subscript indicate measured and reference data; F (shallowing) is the difference between the reference and measured inclination values with a measurement uncertainty of ΔF; R (rotation) is the difference between the reference and measured declination values with a measurement uncertainty of ΔR; negative (positive) values of this parameter correspond to clockwise (counterclockwise) rotation. Measurement uncertainties were calculated according to [41].

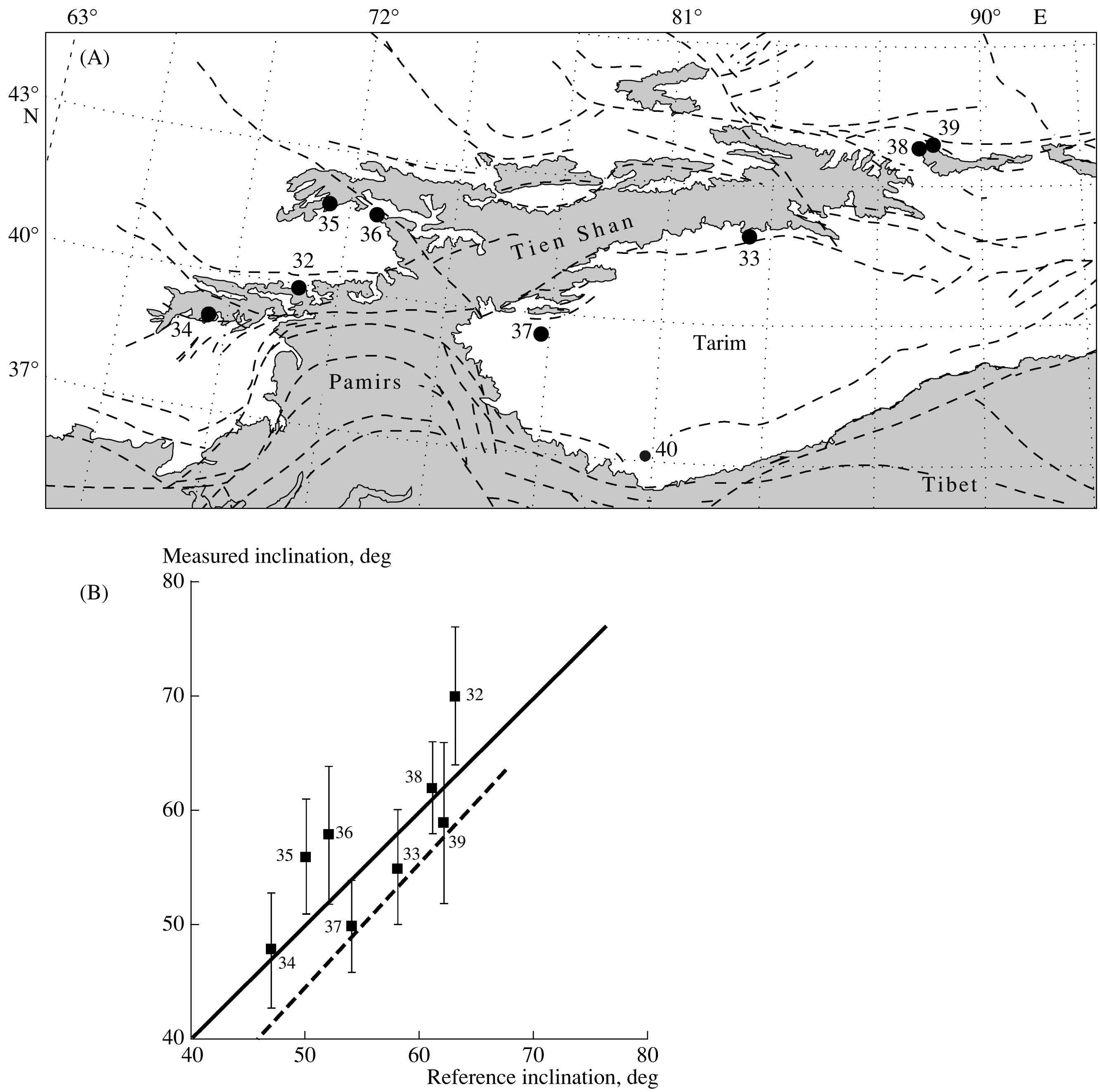

Fig. 3. (A) Paleomagnetic sampling sites in the Upper Permian and Triassic sequences in the Tien Shan and (B) measured *versus* reference inclinations for the Late Permian and Triassic data for the Tien Shan. Panel A: Filled circles are numbered as in Table 2; gray-colored regions are areas with elevations above 2000 m; dashed lines are faults (modified after [38]). Panel B: Vertical lines are uncertainty limits; theoretical graphs in the absence of lateral displacement (solid line) and for the general northward displacement of the Tien Shan by 500 km during the last 270 Ma (dashed line). Site 40 in southern Tarim [47] is shown in Fig. 3A but not employed for quantitative analysis (Fig. 3B) because of insufficiently precise timing (Permian, unspecified).

(2) The inclinations of the secondary component of Late Cretaceous age in the Lower Cretaceous red beds of the Tajik Depression [29] and the Fergana Depression [26] coincide with the Eurasian reference values (Fig. 4, nos. 19–23; Table 2);

(3) The inclination in the Paleogene and Cretaceous basalts of the Tien Shan is much steeper than in sedimentary rocks and is almost equal to the reference values (Fig. 4, nos. 16 and 26; Table 2);

(4) The consolidated continental crust in Central Asia wittingly existed in the Late Cretaceous, and large-scale movements in the region must be accompanied by deformations. The age of all Cenozoic deformations north of Tibet are less than 10 Ma. Hence, the

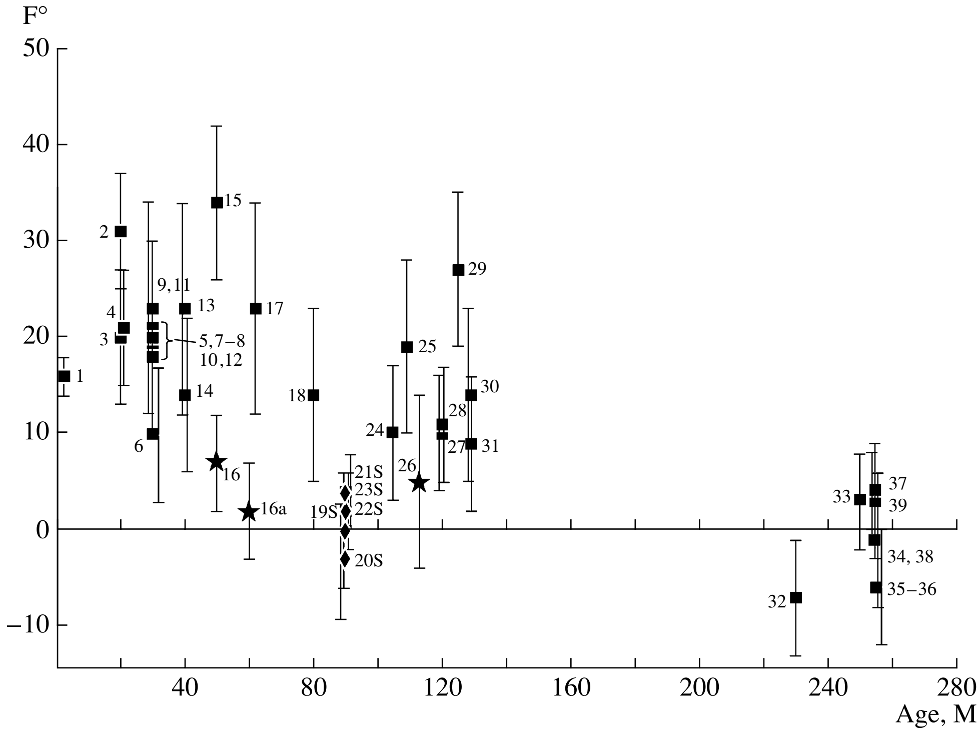

Fig. 4. Parameter F (difference between the Eurasian reference and measured inclinations) *versus* age. Data are numbered as in Table 2. F values for the primary (secondary) magnetization components are indicated by circles (rhombs); in the latter case, numbers are supplemented by the letter S. Asterisks indicate the results on basalts. For the Paleogene basalts from the Tien Shan, F was calculated for two ages, 50 and 60 Ma (16 and 16a). Vertical lines are uncertainty intervals for parameter F.

northward movements could only occur during the Late Cenozoic [48], and the velocity of the Tarim movement would be much more than 15 cm/yr. This is greater by an order of magnitude than the velocities of movements inside continents, along the Talas–Fergana Fault for example [33], and more than the velocity of India–Eurasia convergence;

(5) Inclinations of 30° less than the reference values were detected in the Pliocene deposits from northern Tarim [35], thus implying even higher velocities;

(6) Geological evidence for the enormous extensions north of the Tien Shan in the Cretaceous and Paleogene is completely lacking;

(7) All the large-scale movements deduced from Cretaceous and Paleogene data would destroy the preexisted, particularly, pre-Permian geological links in the Tien Shan and adjacent areas. For example, in compliance with the Cretaceous paleomagnetic data on Tarim, one has to tear the Tien Shan apart in the middle: its western half would remain intact, while the eastern, near-Tarim part, would be offset several hundred kilometers to the south [50].

The discrepancies between the geological and paleomagnetic data disappear if we admit the shallowing of inclination in the Cretaceous and Cenozoic sedimentary rocks. This hypothesis was discussed earlier [40 among others] but was rejected for the following reasons. Firstly, the shallowing of inclinations in the Central Asian red beds is refuted by good consistence of regional data [40, 50]. But this argument is not convincing, because most results were obtained from similar red beds, where the same distorting factor might affect all of the measurements. So, whereas the Cretaceous paleolatitudes are still attributed to crustal shortening between Eurasia and Tibet [50], other mechanisms are attracted to the interpretation of the Paleogene data [34, 40] despite the same regional consistence.

The second argument against the shallowing of inclinations is the absence of significant magnetic anisotropy (anisotropic magnetic susceptibility –AMS) [34, 40]. But the low AMS in red beds can be controlled by other factors, such as a small admixture of clastic magnetite, which hardly will affect the paleomagnetic directions but contributes much to the AMS value. In any case, inclinations in the Lower Cretaceous red beds from northern Tarim are strongly shallowed, while AMS is not higher than a few percent [65].

Thus, the low AMS values and the regionally consistent inclinations in red beds DO NOT imply that the inclinations are not shallowed. On the contrary, some facts, such as the coincidence of measured and expected inclinations in basalts along with the much shallower inclinations in coeval sediments, provide direct evidence in support of this phenomenon (Table 2). Consequently, the inclinations of magnetic components in the Creta-

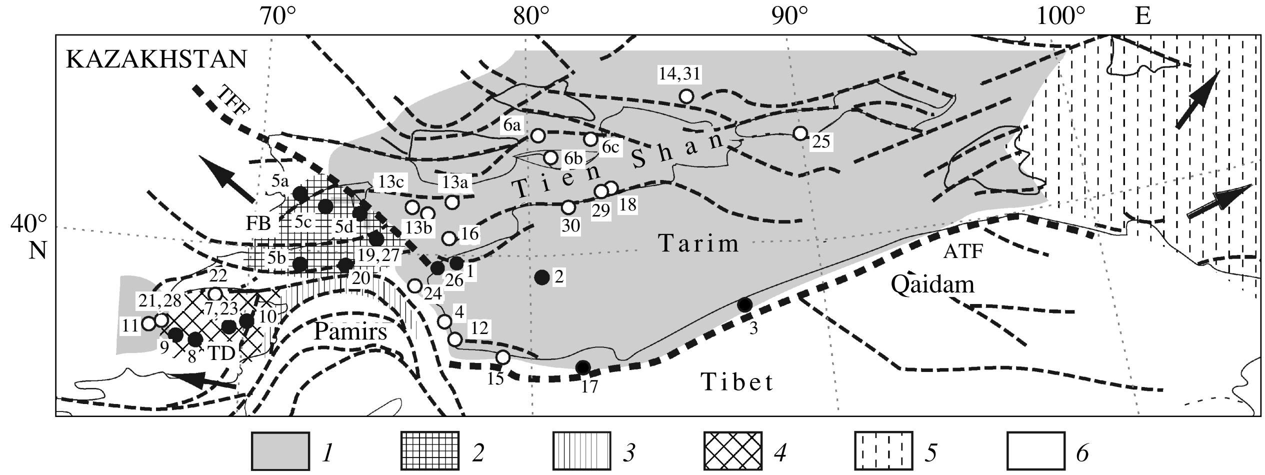

Fig. 5. A scheme of Alpine rotations in Central Asia to the north of Tibet. Filled circles indicate the sites with significant rotation and open circles, the absence of rotation. Sites are numbered as in Table 2; for sites 5, 6, and 13 (Fergana, Issyk Kul, and Naryn depressions), circles indicate particular studied sections (with additional letters after numbers; data on these sections are not included in Table 2 for the sake of brevity). Arrows indicate the inferred direction of lateral extrusion. Dashed lines are Talas–Fergana (TFF) and Altyn Tagh (ATF) faults. (*1*) Absent or insignificant and unsystematic rotation; (*2*) counterclockwise rotation of rigid blocks; (*3*) secondary bend of the outer zone of the Pamirs; differential (*4*) counterclockwise and (*5*) clockwise rotations; (*6*) data are not available (Kazakhstan and Turan platforms) or not discussed in this paper (Tibet).

ceous and Cenozoic red beds cannot be employed directly for an estimation of horizontal movements in Central Asia. The other data suggest that crustal shortening within Tarim and the Tien Shan and their displacements relative to Eurasia from the Permian to the Recent fall within the limits of paleomagnetic data uncertainty and are most probably much shorter than 500 km.

ANALYSIS OF PALEOMAGNETIC DECLINATIONS

Paleomagnetic data for the Permian, Mesozoic, and Cenozoic of the study area were analyzed using only the data obtained from full progressive demagnetization and component analysis. Rotation angles were determined as the difference between the expected [31, 73] and measured declinations, and uncertainties were estimated according to [41].

The Cretaceous and Cenozoic rotation angles for the same areas differ within the accuracy of the estimation technique throughout the entire region. All rotations were therefore post-Paleogene and most probably occurred during the last 10 Ma along with the main deformation [15].

The oroclinal bend of the Outer Pamirs Zone was formed in the Late Cenozoic, when the Pamir wedge indented northward [2]; paleomagnetic declinations are thus northwesterly in the southwest of the zone and easterly and northeasterly, in the east. The paleomagnetic data supporting this conclusion do not comply with present-day standards, but a resampling of the Paleogene [70] and Cretaceous [29] rocks from the southern part of the zone confirmed the previous interpretation. Declinations are strongly scattered in the eastern part of the arc [37] but are generally NE- and E-oriented, at about 50° on average, indicating a significant clockwise rotation consistent with less reliable data on the Transalai Range [2]. The secondary origin of the Pamir arc is additionally supported by paleomagnetic data on the Late Paleozoic in the North Pamirs [27].

Significant differential counterclockwise rotations were also revealed in the Tajik Depression (Fig. 5), where the rotation angle gradually decreases away from the Pamirs [70]. The anticlockwise rotation of the Fergana depression and surrounding mountains through some 20° also was detected [26, 29]. Looking at a map (Fig. 5), one can suggest that the rotations were induced by the indentation of the Pamirs and the westward and northwestward extrusion of the surrounding structures.

The overwhelming majority of paleomagnetic declinations east of the Talas–Fergana Fault coincide with reference values within the uncertainty limits (Fig. 5; Table 2). In the rare cases of statistically significant rotation angles (Fig. 5; Table 2), they are not systematic and small in value; in all probability, they are of local importance, e.g., in the center of Tarim (Fig. 5, no. 2), or are related to the movements along the Altyn Tagh (nos. 3 and 17) or the Talas–Fergana (nos. 1 and 26) faults. Another Alpine rotation domain is located near the northeastern and eastern margins of Tibet [43, 61]. In the Zaisan Depression (Z in Fig. 1A) north of the Tien Shan, rotations were not detected; farther northeast, rotations were noticed in the Chu Depression in the Altai (C in Fig. 1A) [71], but their regional significance is questionable. Thus, no Alpine rotations took place over much of Central Asia north of Tibet (Fig. 5). It should be emphasized that this statement does not

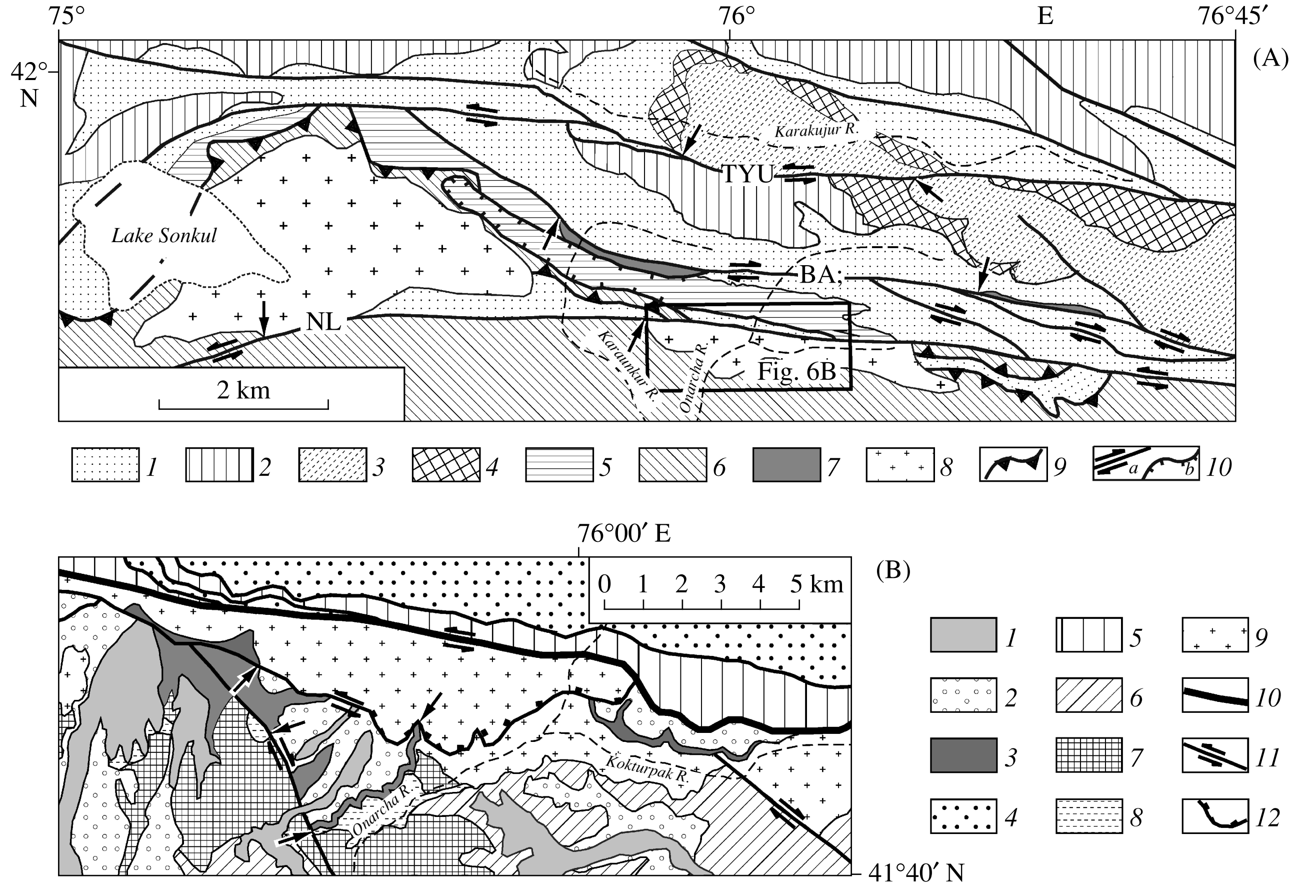

Fig. 6. (A) Scheme of the Late Paleozoic tectonics in the eastern Sonkul area and (B) Late Cenozoic rejuvenation of the Late Paleozoic fault (Nikolaev Line). Panel A: (*1, 2*) Caledonian complex: (*1*) Riphean and Lower Paleozoic stratified rocks, (*2*) Early–Middle Ordovician granitoids; (*3*) Late Ordovician–Silurian granitoids; (*4*) Late Ordovician–Silurian zonal metamorphic complex; (*5–8*) Hercynian complex: (*5*) autochthon, (*6*) allochthon, (*7*) neoautochthon, (*8*) Middle Carboniferous granitoids; (*9*) nappes; (*10a*) strike-slip faults and (*10b*) conjugate thrust faults. Faults (letters on map): TYU—Tyulek, BA—Baidulla, NL—Nikolaev line. Panel B: (*1*) Upper Pliocene–Quaternary sediments of the Sharpyldak Formation; (*2*) Oligocene–Miocene sedimentary rocks of the Shamsy Formation; (*3*) Paleocene–Eocene sedimentary rocks of the Kokturpak Formation; (*4, 5*) Paleozoic North Tien Shan complex: (*4*) Upper Devonian–Lower Carboniferous Sonkul gray-colored terrigenous sequence, (*5*) Cambrian–Ordovician rocks of the Karagyr Formation; (*6, 7*) Middle Tien Shan Paleozoic complex: (*6*) Middle Devonian–Lower Carboniferous Kavak carbonate sequence, (*7*) Middle–Upper Ordovician Ichkebash Formation; (*8*) Early Permian leucocratic granite of the Adyrtor complex; (*9*) Middle Carboniferous granite and granodiorite of the Sonkul Complex; (*10–12*) Late Cenozoic and rejuvenated Paleozoic faults: (*10*) Nikolaev Line, (*11*) strike-slip faults, (*12*) thrust faults. Double arrows in both panels indicate the conjugate sites, for which separation (offset) was determined.

depend on possible dating and/or declination measurement errors, because all reference declinations in the study area coincide within the limits of 5°.

To summarize, the Alpine rotations are confined either to the Pamirs indentation or to the areas east of Tibet, where rotations are attributed to the lateral extrusion [43, 61]. The absence of rotations in the Tien Shan and Tarim, on the contrary, militates against lateral extrusion north of Tibet. This is supported by inclination analysis, which testifies to the small extent of crustal shortening over the last 270 Ma. Neotectonic measurements also indicate a purely compressive stresses and minor lateral shortening of the Earth's crust over much of the Tien Shan [23, 32].

Thus, no lateral extrusion of structures took place in the Tien Shan or adjacent areas, except where the process was local and small-scale. As mentioned above, the Tien Shan, due to its geographical position, was a barrier for further northward propagation of extrusive stresses. It is very unlikely that the Tien Shan and Tarim could move for considerable distances as a single rigid body, because this would inevitably destroy older structural connections between the Tien Shan and Kazakhstan. Hence, a significant extrusion north of the Tien Shan was also unlikely. The total crustal shortening in the Tien Shan was less than paleomagnetic data uncertainties and did not exceed 200 km from geological evidence [25]. This estimate is less than 10% of the total crustal shortening of 2500 km between India and Eur-

Table 3. Alpine and pre-Alpine lateral displacements along strike-slip faults in the Tien Shan

No.	Fault	Sense of displacement	Displacement		Reference
			P–Cz	Cz	
1	Chilik–Kemin (northern)	Left-lateral	20 km (190 km*)	15 m**	[1, 6]
2	Chilik–Kemin (southern)	Left-lateral	?	3–4 km (300 m**)	[16, 21]
3	Toguzbulak	Left-lateral	?	0.7 km	[16]
4	Shamsy	Left-lateral	?	2.5 km	[16]
5	Beshtash–Terek	Right-lateral	17 km	?	[10]
6	Tyulek	Left-lateral	20 km	4 km	[16, 18]
7	Baidulla	Right-lateral	32 km	?	
8	Nikolaev Line	Left-lateral	60 km	~8@ km	[17], this work
9	Atbashi–Inylchek	Left-lateral	Great#	?	[4]
10	Akbeit	Left-lateral	?	6 km	[5]
11	Kipchak	Left-lateral	80 km	?	[20]

Note: * Displacement may amount to 190 km (L.I. Skrinnik, unpublished);
** Late Quaternary displacement;
@ Strictly speaking, the Cenozoic displacement shown in Fig. 6B is 5 km, and the remainder (3 km) was calculated beyond the figure limits;
# The displacement was not determined exactly, but it should be great judging from the wide development of horizontal S-folds associated with the fault. P is Permian and Cz is Cenozoic. Question mark indicates that data are not available.

asia. This implies that much of the shortening was accommodated within Tibet and the Himalayas. Note that Late Cenozoic displacements of several hundred kilometers were proved for the Altyn-Tagh Fault and conjugate structures [78]. Most likely, this fault precisely defined the northern boundary of the zone that accommodates the crustal shortening.

WERE THERE SIGNIFICANT ROTATIONS IN THE TIEN SHAN AND WHEN?

Based on the structural patterns, first of all, on the fault systems, some authors regard the Alpine structure of the Tien Shan as a result of lateral extrusion accompanied by large-scale rotations [11, 12, 72]. As has been shown above, no Late Cenozoic rotations are documented east of the Talas–Fergana Fault. At the same time, significant rotations in this region were deduced from the Permo-Triassic paleomagnetic data, because all declinations of this age exhibit counterclockwise rotation through various angles [3]. The largest rotations are obviously confined to the central Tien Shan, where rotation angles are as high as 80°–90° against less than 20° on the periphery of the belt. These rotations occurred from the latest Permian to the Triassic. As has been demonstrated earlier [3], the rotated Permo-Triassic declinations could not be explained by the rotation of the belt as a whole and are related to the rotations within the lift-slip zone extending approximately parallel to the present-day trend of the Tien Shan. The weak point in this model is a lack of geological evidence despite the obvious signs of strike-slip movements in local areas [4, 10]. This is related to the limited outcropping of the Upper Permian and especially Triassic rocks in the region and to the scarcity of structural data on the Late Paleozoic and Early Mesozoic deformations.

Thus, we witness a paradox: significant late Alpine rotations are suggested in the Tien Shan east of the Talas–Fergana Fault from geological data but not supported by paleomagnetic data, and on the contrary, the Permo-Triassic rotations through up to 90° in the Tien Shan [3] are reliably established from paleomagnetic data but lack structural evidence. It should be emphasized that the absence of Late Cenozoic rotations does not imply the absence of rotations through less than ±10° that fall within the common limits of paleomagnetic data uncertainty or are related to local deformations such as the plunging of fold axes. We are speaking about rotations through 30°–60° inferred by some authors [12].

The late Alpine rotations [12] were suggested from the analysis of Alpine structures. As regards the paleomagnetic data employed, magnetization predated the folding and, as indicated by some facts, may be primary; consequently, the rocks acquired magnetization before any Alpine deformation. This means that no major Alpine rotations took place over much of the region and the obvious rotation-related geometry of some structures requires an explanation.

We analyzed displacements along faults in the Central Tien Shan (Fig. 6; Table 3) east of the Talas–Fergana Fault. The offset of Middle Carboniferous conglomerates suggests that the Baidulla Fault is a right-slip fault with a strike separation of 32 km (Fig. 6a). The age of movements is confirmed by a series of Late Paleozoic intermediate and acid dikes and minor bodies that fill the tension gashes along the Baidulla Fault

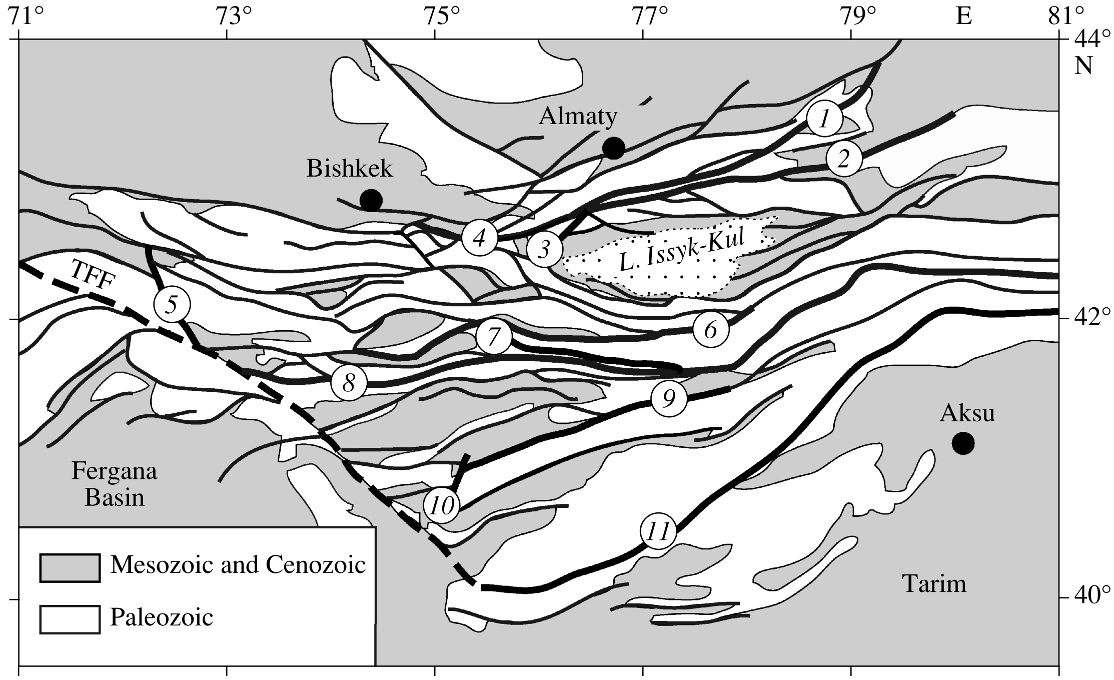

Fig. 7. Major faults of the central Tien Shan; solid lines indicate faults with established strike-slip displacements numbered as in Table 3; fine solid lines are other faults; dashed line indicates the Talas–Fergana Fault (TFF).

proper and its second-order feather joints. The Late Paleozoic left-slip displacement of 60 km along the Nikolaev Line has been established from the strike separation of the Middle Carboniferous Sonkul granitic pluton and the metamorphics of the Lesser Naryn complex (Fig. 6A), whereas the Cenozoic offset for 8 km was identified from the strike-slip duplex separation (Fig. 6B). And finally, the Late Paleozoic offset for 20 km and the Cenozoic offset for 4 km along the Tyulek Fault were determined from the displacements of the zonal metamorphic complex and the strike-slip duplex, respectively [16, 18]. Unfortunately, the strike-slip movements for at least one time interval were established for a very small number of faults (Fig. 7; Table 3). Nevertheless, the available data suggest that the Alpine strike-slip displacements are always no greater than one or two kilometers and cannot account for the significant rotations of large structures. The older (most probably Permo-Triassic) displacements for several tens of kilometers (Table 3), on the contrary, may well be responsible for the large rotations established from the Permo-Triassic paleomagnetic data [3].

The seeming controversy between structural [11, 12, 72] and paleomagnetic data vanishes away if we assume much of the present-day structural pattern, the fault system in particular, to be of Permo-Triassic rather than Alpine age and a result of left-lateral strike-slip deformation. All researchers agree that the Alpine compressive stresses actually affected the Tien Shan. This is supported by the thrusting of Meso-Cenozoic sequences over the Paleozoic rocks reported from many localities. Ancient faults of an E–W orientation were to be rejuvenated first, and the faults of this orientation should arise from precisely Permo-Triassic shearing. The suggestion that the neotectonic uplifts and depressions were inherited from the Paleozoic structural pattern was proposed as far back as the 1950s [13, 14, 42], but an attempt to purposefully compare the Late Paleozoic and neotectonic structural patterns was made only recently [16]. However, the evidence is still insufficient… .

CONCLUSIONS

The paleomagnetic data of the Paleogene basalts from the Tien Shan have shown that the inclinations of prefolding and, in all probability, primary magnetization in these rocks are close to the Early Cenozoic reference values as derived from Eurasian APW paths. Geological data suggest that the consolidated continental crust to the north of Tibet was formed by the mid-Permian, and this makes it possible to compare the measured paleomagnetic data with reference values from the Late Permian to the Recent, that is, for approximately the last 270 Ma. The Permo-Triassic data on the Tien Shan and adjacent structures are consistent with data on Eurasia within the uncertainty limits, and this testifies to the absence of significant convergence between Tarim and Eurasia. On the contrary, much of the Cretaceous and Paleogene inclinations in sedimentary rocks are shallower than the reference values. Geological and paleomagnetic data suggest that the Cretaceous and Paleogene low-angle inclinations are not of tectonic origin and, hence, the total crustal shortening north of Tibet, including the effect of collision, falls within the limits of paleomagnetic data uncertainty and most probably does not exceed a few hundred kilometers.

The Cretaceous and Paleogene declinations to the north of Tibet suggests that significant systematic rotations occurred only close to the Pamirs in connection with its indentation. The area of Late Cenozoic rotations was bounded by the Talas–Fergana Fault: no rotations are recorded east of this fault as far as to Qaidam. Because the appreciable crustal shortening and widespread rotations are the necessary attributes of the large-scale lateral extrusion [68, etc.], this mechanism can hardly be responsible for the formation of the Central Asian structural grain north of Tibet. This implies that the India–Eurasia convergence over 2500 km during the last 50 Ma was almost completely accommodated within the Himalayas and Tibet.

These conclusions come in conflict with the results obtained by researchers who attributed the Alpine structural pattern of the Tien Shan to the lateral extrusion and suppose the occurrence of large-scale rotations here [11, 12, 72]. However, as has been shown above, the real Alpine displacements were fairly small and not accompanied by rotation. The Permo-Triassic strike-slip movements, on the contrary, amounted to several tens of kilometers with rotation through angles up to 90°, always counterclockwise. These facts allowed us to offer the hypothesis that the structural pattern of the Tien Shan was created by the Late Paleozoic left-slip movements, and the Alpine compressive stresses only selectively rejuvenated some of these faults.

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