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Late Paleozoic Deformations of the Tien Shan

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Abstract—Tectonic structure of the Tien Shan was formed in the Late Paleozoic as a result of collision of sialic blocks. Composite multistage deformations were the consequence of the interaction of these blocks. Paleomagnetic and geologic studies show that during the Permian, a sinistral shear zone existed on the larger part of the Tien Shan. Within this zone, a counterclockwise rotation of rock masses occurred. It was realized through plastic deformation and longitudinal horizontal tectonic flow. Within the shear zone, a major extension zone marked by alkaline magmatism came into existence. The zone of sinistral shear stresses was formed as a result of oblique collision of the Kara Kum and Tien Shan continental blocks. After collision in the Carboniferous, the Kara Kum block with the Tarim massif moved along the Tien Shan block initiating sinistral shear stresses in its crust.

Tectonic structure of the Tien Shan was formed in the Late Paleozoic as a result of collision of three sialic blocks (Fig. 1). Block boundaries are now the Turkestan and the southern Hissar oceanic sutures. Composite multistage deformations were the consequence of the interaction of these blocks.

After the Kazakhstan–Kyrgyz, Alai–Tarim, and Kara Kum sialic blocks collided in the Carboniferous, a composite continent was formed on the site of the Tien Shan and Tarim. At this place, in the Late Carboniferous and Permian, subaerial volcanic rocks (collisional and rift-related), terrigenous continental, and shallow-water marine deposits accumulated. Only in the remnant marine basins near the Turkestan collisional suture (in the eastern Fergana and in the Dzhamandavan Range), pelagic turbidites continued to form until the Asselian. Before the beginning of the Artinskian, marine sedimentation ceased throughout the Tien Shan.

This paper discusses kinematics and dynamics of the Late Paleozoic deformations on the basis of paleomagnetic and magmatic data for the Permian deposits of the Tien Shan.

PALEOMAGNETISM OF THE PERMIAN ROCKS

We studied paleomagnetism of the Permian rocks in the western and central Tien Shan. We also used published data acquired in the eastern (Chinese) Tien Shan, in northern Dzungaria, and on the Tarim platform (table).

Western Tien Shan. In the Hissar Range, volcanic rocks of the Luchoba Formation and terrigenous deposits of the Khanaka Formation were studied. The Luchoba Formation was studied in the valleys of the Varzob and Khanaka rivers (A in Fig. 2). It overlies unconformably

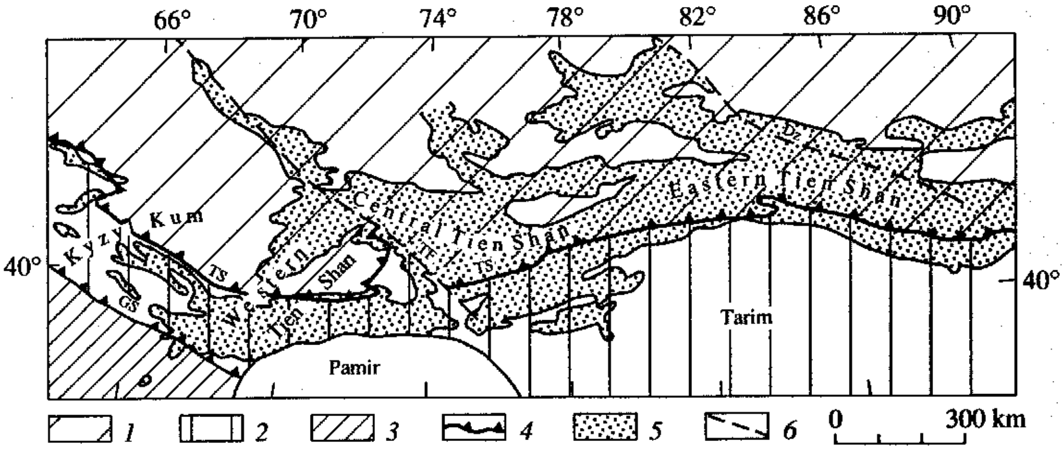

Fig. 1. Paleozoic sialic blocks in the Tien Shan structure. (*1*) Kazakhstan–Kyrgyz; (*2*) Alai–Tarim; (*3*) Kara Kum; (*4*) sutures (TS = Turkestan, GS = South Hissar); (*5*) Paleozoic rocks; (*6*) main shears (TF = Talas–Fergana, Dz = Dzungaria).

Permian paleomagnetism of the Tien Shan

Point in Figs. 2, 3	Age		I, deg	D, deg	a_{95}, deg	RE, deg	Σ, deg	RT, deg	c	δ, deg	Reference
	of rocks	of magnetization									
A	P_1	a	39	325	5	51	86 ± 5	31	–	66 ± 13	[26]
B	P_1	b	48	8	4	49	41 ± 6	31	–	23 ± 13	[26]
C	P_1	a	41	327	4	52	85 ± 4	31	+	54 ± 13	[6]
D	P	b	43	36	3	52	16 ± 4	–	–	–	[27]
E	P	b	46	55	4	56	1 ± 4	–	–	–	[23]
F	P	a	48	343	6	56	73 ± 8	34	–	51 ± 15	[23]
G	P	b	49	33	4	55	22 ± 5	33	–	0 ± 14	[23]
H	C	a	50	48	5	61	13 ± 7	–	–	–	[39]
I	P_2	b	62	343	4	57	74 ± 8	38	–	55 ± 16	[35]
J	P_2	b	59	7	6	58	51 ± 10	38	–	31 ± 18	[33]
K	P_2	b	55	19	7	55	36 ± 9	36	–	17 ± 17	[32]
L	P	a	50	28	5	52	24 ± 7	–	–	–	[31]
M	P_1	a	58	32	3	56	24 ± 5	–	–	–	[36]
N	P_1	a	44	42	10	56	14 ± 11	–	–	–	[24]
O	P_1	a	41	34	6	56	22 ± 5	–	–	–	[24]
P	P	a	43	354	5	55	61 ± 6	33	–	39 ± 14	[25]
R	P_1	a	41	295	10	53	118 ± 11	33	+	88 ± 17	[25]
R	P Kun–Ufi	b	58	0	4	53	53 ± 8	33	+	23 ± 14	[25]
S	P_1	a	36	299	6	53	114 ± 7	32	+	83 ± 14	[25]
T	P_1	a	48	312	6	53	101 ± 8	32	+	70 ± 15	[25]
T	P Kun–Ufi	b	57	350	5	53	63 ± 9	32	+	32 ± 15	[25]
U	P_1	a	61	302	6	53	111 ± 10	31	+	79 ± 16	[25]
U	P Kun–Ufi	b	55	350	8	53	63 ± 13	32	+	32 ± 17	[25]
V	P_1	a	54	325	4	53	88 ± 6	32	+	57 ± 14	[25]
W	P	a	40	292	6	53	121 ± 7	31	+	89 ± 14	[25]

Note: I, D, paleomagnetic inclination and declination; a_{95}, radius of confidence circle; RE, paleomeridian direction relative to the Permian European pole [38]; Σ, counterclockwise rotation angle of paleomagnetic declination relative to the Permian European pole; RT, paleomeridian direction relative to the Permian Tarim pole determined on the basis of data acquired at localities L–O (Fig. 2); c, correction for rotation of the Western Tien Shan in the Cenozoic (c = 10°); δ, counterclockwise rotation angle of paleomagetic declination relative to the Permian Tarim pole corrected for "c." This angle reflects rotation of paleomagnetic declination within shear zone of the Tien Shan relative to the "frame" in the Late Permian–Early Mezozoic; a and b, see text.

the deposits with Late Carboniferous brachiopods. The formation contains fossil plants that existed in the Late Carboniferous and Early Permian. The rocks of the Khanaka Formation were studied in the valley of the Khanaka River (B in Fig. 2). This formation contains fragments of rocks of the Luchoba Formation and some Early Permian flora [15, 16]; the formation might also contain some Upper Permian deposits.

At the northern foothills of the Alai Range (Guzan Mts.) (V in Fig. 2), tuffaceous rocks of the Burgana Formation were examined, and their Asselian age was determined based on foraminifers. In the Gal'chabashi Mts. (W in Fig. 2), terrigenous deposits with foraminifers of Asselian age and terrigenous redstone rocks (Gal'chabashi Formation) overlaying them with minor angular unconformity were studied. The latter contains Permian flora [15].

In the Chatkal Range, our studies also covered two localities. In the Gavasai River–Koksarek River interfluve (U, Fig. 2), volcanic deposits of the Shurabsai and Ravash formations were studied. The lower section of the Shurabsai Formation is composed of sedimentary rocks with Asselian and Sakmarian foraminifers and Early Permian flora [15]. In the upper volcanic part of the sequence, some Early Permian plant fossils were also collected [3]. The Ravash Formation overlies, with a hiatus, the Shurabsai Formation and is overlain with angular unconformaty by deposits with Kazanian flora of the Upper Permian.

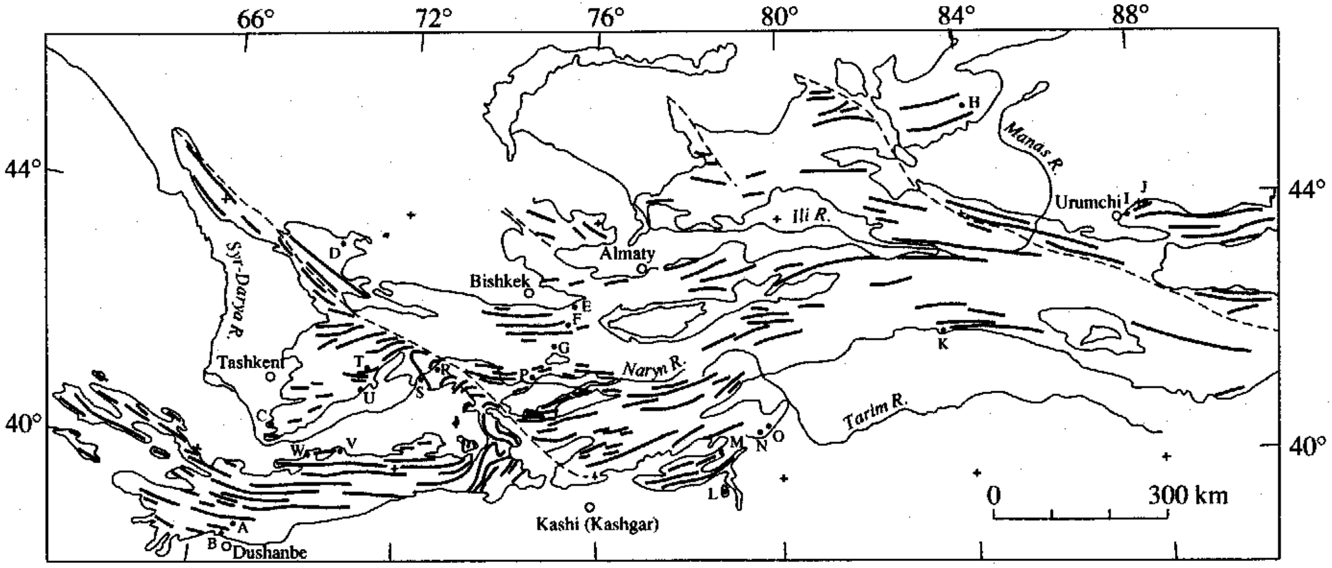

Fig. 2. Axes of Late Paleozoic F_2 folds (heavy lines) and localities of paleomagnetic studies of Permian rocks (A–W) in the Tien Shan. Areas of Paleozoic rocks are showed by thin line.

In the Chatkal Range, no fossils were reported from rocks of the Ravash Formation; in the Kurama Range, the latter contains flora suggesting a Kungurian–Ufimian age for the sequence [15]. In the Kassan graben (T, Fig. 2), we studied rocks of the Shurabsai Formation and varicolored tuffaceous deposits that overlie them with a break and are correlatable with lower horizons of the Ravash Formation.

In the Baubashata Mts., in the valley of the Karasu River (R, Fig. 2), terrigenous rocks of the upper section of the Kelemata Formation and of the Karasu Formation were examined. The Kelemata Formation unconformably overlies Asselian limestones and contains fragments of limestones with Sakmarian foraminifers. Upsection, the Kelemata Formation is conformably overlain by the Karasu Formation, which contains fossils of the Kungurian–Ufimian age [15]. The rocks of the Kelemata Formation were also studied in the valley of the Sarybel' River (S, Fig. 2).

During the 1960s–1980s, in the western Tien Shan different investigators carried out paleomagnetic studies of Paleozoic rocks without complete magnetic cleaning or component analysis. We do not use these data for tectonic constructions because they are not sufficiently reliable.

The central Tien Shan occupies the area from the Bol'shoi Karatau Range and Fergana Range in the west to the Khan Tengri massif in the east. In the northwestern part of this area, at the foothills of the Malyi Karatau Range near Lake Tuzkul' (D, Fig. 2), terrigenous deposits of the Tuzkul' Formation were studied. They contain plant fossils, suggesting a Kungurian–Ufimian age of the rocks [27]. Farther southeast on the Moldotau (P, Fig. 2), Sonkel'tau (G, Fig. 2), and Kyrgyz ranges (F, E, Fig. 2), volcanic rocks of the Ashul'kator Formation were examined. The formation unconformably overlies deposits with Late Carboniferous flora. On the Kyrgyz Range, it contains spores and pollen of Permian age [3]; on the Moldotau Range, plant fossils of Sakmarian–Artinskian age [15]; in the more southern areas, at the base of the formation, Early Permian foraminifers are found [4]. The upper age limit of these deposits might correspond to the Late Permian.

Our collection of Permian rocks from the western and central Tien Shan was put to paleomagnetic study, including stepwise thermal cleaning (10–17 steps) to 680°C, and to component analysis. These studies are described in [23, 25–27], and the results are given in the table. In the studied collections, magnetization is older than any deformations and may have originated when the rocks were formed. The only exception is the Guzan area (V, Fig. 2), where magnetization was formed during the Permian folding.

Eastern Tien Shan and Tarim platform. Near the southern border of the eastern Tien Shan (K, Fig. 2), paleomagnetic data were obtained for terrigenous rocks of the Tatarian Stage of the Upper Permian [32]; near its northern border, (I, J, Fig. 2) Upper Permian volcanic and terrigenous rocks were studied [33, 35]. To the north of the eastern Tien Shan, in Carboniferous rocks of northern Dzungaria (H, Fig. 2) the synfold paleomagnetic component was separated, which might be Permian [39]. At the northern margin of the Tarim platform in the zone of the Kelpin (Kepin) deformations, limestones with Early Permian fauna (M–O, Fig. 2) were studied and at one locality (L, Fig. 2) basaltic dikes intruding these deposits [24, 31, 36] were examined.

Discussion. An analysis of paleomagnetic declinations allows us to draw the following conclusions,

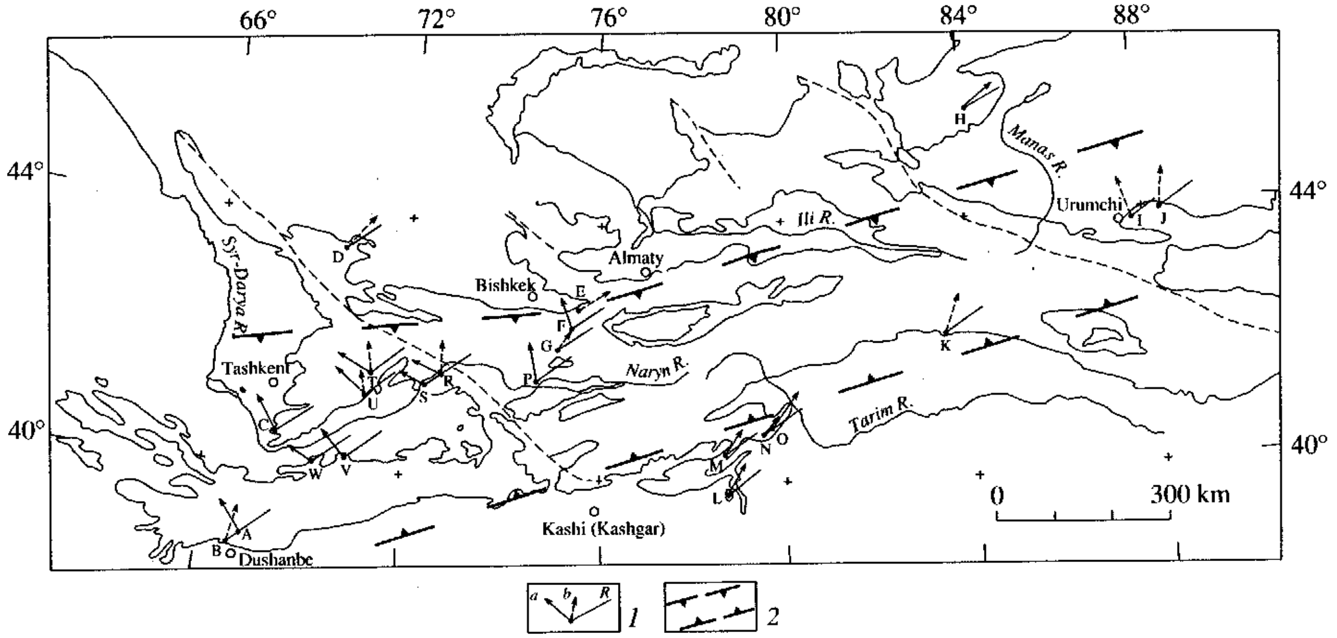

Fig. 3. Declination of remanent magnetization in Permian rocks of the Tien Shan. (*1*) Paleomagnetic declinations: directions *a* are Early Permian, Artinskian inclusive, and age interval of the *b* directions includes the Kungurian and the Late Permian; *R*, direction of the Early Permian paleomeridian, calculated on the basis of the European pole [38]; (*2*) zone where paleomagnetic declinations were rotated relative to the European paleomeridian through an angle greater than 25°.

which must be taken into account while studying tectonic deformations.

(1) All paleomagnetic declinations were rotated counterclockwise relative to the Permian paleomagnetic pole determined by the European data [38]. In the northern peripheral part of the Tien Shan (point D, Fig. 3), in northern Dzungaria (point H), and on the Tarim platform (points L–O), the rotation angle equals 15°–25° or less (point E). In the inner part of the Tien Shan, this angle is considerably larger and in places exceeds 100° (points R, S, T, U, W). Two regions are distinctly separated: the "frame," where the rotation angle does not exceed 25°, and the inner zone, where paleomagnetic declinations were rotated through larger angles. This zone is nearly 300 km wide and continues along the Tien Shan from the city of Dushanbe in the west to the city of Urumchi in the east (Fig. 3).

(2) The paleomagnetic directions obtained can be divided into two age groups (table, Fig. 3). Group *a* is Early Permian, Artinskian inclusive in age, and group *b* spans an age interval from the Kungurian to the Late Permian. The majority of paleomagnetic results are reliably referred to one or another age group; in some cases (points G, H, E, L), age group was determined arbitrarily. The studies carried out in northern Fergana (points R, T, U) showed that the group *a* Early Permian paleomagnetic declinations were rotated counterclockwise relative to the group *b* declinations through an angle of 45°–65° (Fig. 3, table). Consequently, rotation through that angle occurred in the Early Permian, in the Artinskian–Kungurian time. Data obtained for the Hissar Range (points A, B), where the Permian paleomagnetic directions of various ages are also distinguished, confirm this conclusion and allow us to expand it over most of the western Tien Shan. The remaining part of the rotation falls on the Late Permian and later time.

(3) The total rotation of paleomagnetic vectors (Σ in the table) consists of several components. We may distinguish the β *component*—rotation of all paleomagnetic vectors (including the "frame") through 15°–25° relative to the Permian European paleomeridian, and the ¥ *component*—rotation in the inner regions of the Tien Shan relative to the "frame." The β component is the background rotation recorded throughout the study area, and ¥ component is the rotation in the inner zone minus the background rotation.

In order to define the inner deformations of the Tien Shan, we will consider rotation of paleomagnetic declinations relative to the Permian magnetic pole, as calculated on the basis of results from the "frame" rock study. This pole (here named Tarim) is determined by data received at localities L–O (Fig. 2) at the margin of the Tarim platform. It has coordinates: 61.0°N, 177.3°E (a_{95} = 9.2°; accuracy C = 101). Angle between the paleomeridian corresponding to this pole and magnetic declination determines the value of the ¥ component of rotation in each point.

The ¥ component is also heterogeneous. It reflects rotation that occurred from the Early Permian until present. The paleomagnetic study of the Paleogene rocks shows that, since the Paleogene, the area of the

Fergana block of the western Tien Shan, where localities R–W (Fig. 2) occur, rotated counterclockwise relative to the central Tien Shan [2, 37]. The rotation angle for the Fergana block since the Paleogene according to these data is in the range 10°–30°. The rotation of the Fergana block is compensated for by crustal thickening in the Chatkal area, where the crust is as thick as 60 km [19, 21]. The correlation between these two phenomena (block rotation and compensatory thickening of the crust) limits the rotation angle of the Fergana block in the post-Paleogene time to 10° [2]. Introducing this correction for the Cenozoic rotation (c = 10°), we determined the δ component, which reflects rotation of paleomagnetic vectors in the Permian or in the Permian–Early Mesozoic relative to the Tarim pole (table).

(4) The origin of the background rotation (β component) may be different. In the Permian, sialic blocks (mostly fragments of former island arcs) that make up the earth's crust in Kazakhstan and Tien Shan continued to move relative to each other and to Europe and Siberia [22, 34]. These displacements may have been accompanied by rotation of blocks and of their amalgamations. The β component might reflect these processes. In our case, the entire region was rotated as a unit. It is possible, however, that the background rotation is caused by inner regional reasons, which also account for the δ component of rotation. Specifically, within the "frame" at the northern periphery of the Tien Shan and on the deformed margin of the Tarim platform, the same processes (which will be discussed below) as within the shear zone, although on a lesser scale, took place. In this case, the inner zone and its "frame" will only differ in the intensity of similar-type deformations. Solution of this problem depends on the still scarce paleomagnetic data for areas adjacent to the Tien Shan.

While analyzing the processes within the Tien Shan, this problem is of little importance. At the same time, the mentioned uncertainty in the position of the Permian paleomagnetic pole for the Tien Shan reduces the precision of spatial positioning of the region on paleotectonic reconstruction. In the reconstruction presented below (Fig. 6), we preferred the first variant of the solution of this problem and oriented the reconstruction with respect to the Tarim pole. To position the reconstruction relative to the European pole (if the second variant is preferred), it is necessary to rotate it counterclockwise through 20°.

ALKALINE MAGMATISM AND STRESS FIELD IN THE PERMIAN

Paleomagnetic studies showed that in the Permian most of the Tien Shan was occupied by a zone in which counterclockwise mass rotation occurred. This indicates that a sinistral shear stress field governed.

The Permian period differs from the previous and following ones in featuring widespread alkaline magmatic rocks (Fig. 4), which may be considered an indicator of tensional conditions in the earth's crust. Let us determine the boundaries and some features of the inner structure of this extension area based on distribution and intensity of the alkaline magmatism.

Western Tien Shan. In the western Tien Shan, alkaline magmatic rocks are most widespread on the Alai, Chatkal, and Kurama ranges.

On the Alai Range (5, Fig. 4), the numerous alkaline intrusions are united in three magmatic complexes [11]. The Alai complex is found at the watershed of the range. It is composed of alkaline syenites and nepheline syenites (phase 1) and granosyenites, alkaline granites, syenites, and quartz syenites (phase 2). These rocks intrude deposits of different age to the Early Permian inclusive. Intrusions of the Zardala complex occur on the northern slope of the range. Three emplacement phases are recognized: gabbro and monzonite (phase I), alkaline syenite, monzonite, and essexite (phase II), and nepheline syenites (phase III). The youngest deposits cut by these intrusions are Late Carboniferous. In the eastern part of the Alai Range, the Kichikalai magmatic complex is identified. It is composed of granodiorites, syenito-diorites, and monzonites, cutting the Early Permian rocks.

To the west and southwest of the Alai Range, the Permian alkaline intrusions abruptly decrease in volume and size. Small bodies of alkaline magmatic rocks are found on the Karategin (3, Fig. 4), Turkestan (4), Zeravshan (1), and Hissar ranges (2). On the south slope of the Hissar Range, alkaline lavas of Early Permian age are also found: trachyandesites occur among felsic volcanic rocks of the Luchoba Formation, and trachyandesibasalts, trachyandesites, and their tuffs occur intercalated in the Khanaka Formation [15].

On the Chatkal (7, Fig. 4) and Kurama ranges (6) Permian volcanic rocks are widespread (the Oyasai, Shurabsai, Ravash, and Kyzylnura formations). Their thickness exceeds 5 km. In these formations, trachybasalts, trachyandesites, trachytes, trachyrhyolites, and their tuffs alternate with felsic and intermediate volcanic rocks. In the lower part of the sequence, alkaline rocks account for 50% of the thickness; in the middle part, for 80%; and in the upper part, their amount decreases. In the lower part of the volcanic sequence, Asselian foraminifers are found, in the middle part, vertebrate and flora fossils of Permian age occur, and in the upper part, plant fossils dating to the Late Permian and Early Triassic were collected [18]. Volcanic rocks are accompanied by alkaline subvolcanic bodies and intrusions. Among the intrusions, monzonites and syenites prevail, whose formation occurred in several phases.

In the northern part of the study area, on the western spurs of the Talas Range (8, Fig. 4), volcanic rocks of the Daubaba Formation with a considerable proportion of trachybasalts and trachyandesites are present [12]. This formation contains spores and pollen of Permian age [1].

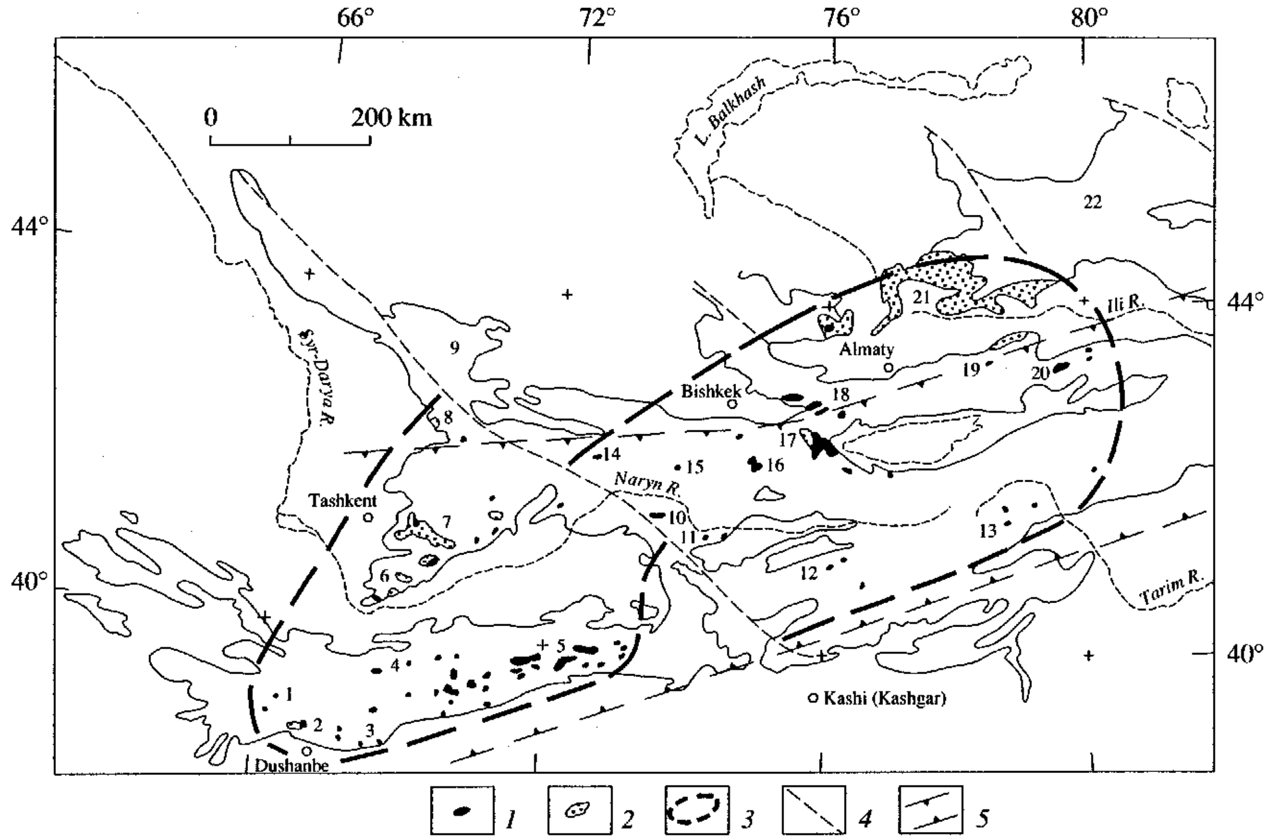

Fig. 4. Permian alkaline magmatism in the Tien Shan. (*1*) Alkaline intrusions; (*2*) alkaline volcanic rocks; (*3*) area of the alkaline magmatism; (*4*) main shears; (*5*) zone of intense shear stresses based on rotation of Permian paleomagnetic vectors. Numbers 1–22 in the figure are explained in text.

Central Tien Shan. In the northwestern part of this region, Permian alkaline rocks are known to occur on the Talas Range (14, Fig. 4), where they form the Kurgan complex of minor intrusions and dikes. The trachytes, trachyandesites, syenites, and alkaline syenites were emplaced in six phases [11]. Farther north, on the Malyi Karatau Range (9, Fig. 4), similar rocks are absent.

Further south on the Takhtalyk Range (10, Fig. 4) and Akshiirak Range (11), alkaline rocks compose the Shamator magmatic complex. It shows two emplacement phases and is composed of essexites and monzonites (phase I) and syenites (phase II). On the Akshiirak Range, the monzonites intrude Upper Carboniferous deposites. K–Ar radiometric determinations on biotite date this complex to the Permian [11].

On the Susamyr (15, Fig. 4), Dzhumgol (16), and Kyrgyz ranges, intrusions of the Ortotokoi complex occur. This complex is composed of four magmatic phases [11]: syenites and nepheline syenites (I and II), syeno-diorites (III), and granosyenites (phase IV). These rocks intrude Upper Carboniferous deposits. In the eastern part of the Kyrgyz Range (17, Fig. 4) and south and east of this area, on the Kungei (18, Fig. 4) and Zailiiskii ranges (19), Permian volcanic–terrigenous deposits of the Ashulkator Formation occur. It shows trachybasalts, trachytandesites, and trachytes occurring among felsic and intermediate rocks [4]. These deposits are cut by intrusions of the Kokmoinok complex that shows two emplacement phases: monzonites and syeno-diorites, and granosyenites [11].

Further east in the Ketmen' Range (20, Fig. 4), an alkaline intrusive complex comprising granosyenites, syenites, syeno-diorites, and monzonites is present. The intrusions cut Lower Permian deposits. North of the Ili River, at the western foothils of the Borokhoro Range (21, Fig. 4), only rare layers of trachyandesites of the Zheldykora Formation [1] are found among volcanic–terrigenous sequence with Permian flora. Further north on the Dzungaria Range (22, Fig. 4), no Late Paleozoic alkaline rocks are known to occur.

In the southern part of the central Tien Shan, on the Atbashi (12, Fig. 4) and Kokshaal ranges (13), intrusions of the Surtekin complex are present. They consist of essexites, monzonites, shonkinites, and syenites. In the Atbashi Range, four intrusive phases are determined [7]. The youngest deposits intruded by these rocks are Late Carboniferous–Early Permian.

Eastern Tien Shan. In the eastern (Chinese) Tien Shan, alkaline rocks are absent everywhere. Only in the southwestern part of this area small bodies of alkaline gabbro, supposedly Cenozoic in age [30], occur.

Conclusions. The area where the Permian alkaline magmatic rocks occur includes the western and central Tien Shan. Farther west (in the Kyzyl Kum) and east (in the eastern Tien Shan), the alkaline magmatism is not exhibited. It manifested itself most intensely on the Alai, Chatkal, and Kurama ranges in the western Tien Shan. In the northern part of the Tien Shan orogen, the Permian alkaline magmatism wanes, and is absent in the northern peripheral ranges (Kazakhstan and Dzungaria).The southern limit of the Permian alkaline magmatism coincides with the boundary between the Tien Shan Paleozoides and the Tarim platform, the Pamirs, and the Kara Kum block.

The alkaline magmatic rocks formed over a long period of time. This is confirmed by the great thickness of volcanic sequences and polyphase character of the alkaline intrusions. At the same time, neither stratigraphic data nor radiometric determinations allow constraining this magmatism within the Permian period or determining its absolute duration.

Alkaline magmatism is considered an indicator of extension conditions in the earth's crust. On the basis of the data presented, we arrive at the conclusion that on the site of the western and central Tien Shan a wide extension zone existed in the Permian. It did not cover the Kyzyl Kum or eastern Tien Shan, or the northern peripheral areas of the mountain country. Taking into account the intensity of the alkaline magmatism, we may conclude that the eastern half of the western Tien Shan experienced the greatest extension.

LATE PALEOZOIC DEFORMATIONS OF THE TIEN SHAN

The Late Paleozoic deformations of the Tien Shan are due to the interaction of sialic blocks—Kazakhstan–Kyrgyz, Alai–Tarim, and Kara Kum. The deformations began in the Moscovian Age as a result of the closure of oceanic basins (first the Turkestan Ocean and then the South Hissar Ocean) that previously separated the sialic blocks. The colliding sialic blocks were deformed, and a fold system emerged. Its formation was a long-term process that continued into the terminal Paleozoic. In this process, we can distinguish several stages [9, 28, 29]. The first two deformational stages terminated at the beginning of the Permian. They will be briefly described in order to give a complete picture. The conclusions obtained through the analysis of the alkaline magmatism apply to the processes that occurred since the beginning of the Early Permian and paleomagnetic data apply to those since the end of the Artinskian or since the Kungurian Age.

Stage D_1. The first result of the convergence and subsequent collision between the Tarim–Alai and Kazakhstan–Kyrgyz sialic blocks was the formation of a nappe system. This process began at the margin of the closing Turkestan ocean and then migrated onto the continental slope and shelf of the Tarim–Alai continental block. Most nappes were formed in the Moscovian; in places, however, this process continued into the end of the Carboniferous or the beginning of the Permian.

Stage D_2. At this stage, thrust sheets, the autochthon, and rocks of magmatic arcs, forearc basins, and intraarc sediment basins were folded into F_2 folds associated with overthrusts and reverse faults. The F_2 folds trend conformably with the suture of the Turkestan Ocean. The age of the D_2 deformation is Late Carboniferous and Early Permian.

Stage D_3 includes the Early Permian and a part of the Late Permian. The transition from stage D_2 to stage D_3 is due to a change in the stress field. The F_2 folds originated at the previous deformational stage under compression at right angles to the fold axes. At stage D_3, folds F_2 were folded into a sinistral horizontal flexure that formed in a shear stress field (Fig. 5).

The paleomagnetic studies allow us to determine the limits of the zone where paleomagnetic vectors are rotated counterclockwise relative to the "frame." The limits of the field of intense sinistral stresses were thus determined. The zone of these stresses and ensuing deformations extends along the Tien Shan and is nearly 300 km wide (Fig. 3).

The Fergana horizontal flexure is located within the sinistral shear zone and was studied by paleomagnetic method [13, 14]. In the rocks of the Moscovian and younger stages of the Carboniferous system, the low-temperature prefold (?) magnetization component is recognized whose declination within the horizontal flexure reveals a dependence on the trend of F_2 folds. Unfortunately, the incomplete cleaning of the collection and the peculiarities of treatment of paleomagnetic data and presentation of results render the conclusions based on these data unreliable.

Localities R and S of our study are within the closing limb of the Fergana horizontal flexure (Fig. 2). As the flexure formed, this limb rotated counterclockwise through a large angle, possibly greater than 90° (Fig. 3). Early Permian magnetic declinations at localities R and S differ slightly from those at localities A, C, V, and W outside the horizontal flexure. Paleomagnetic component *a* at localities R and S is Artinskian in age. Consequently, the upper age limit for emergence of the horizontal flexure is Artinskian. The lower age limit is set by the age of deformed deposits and coincides with the Early Permian.

In the Permian, an area of crustal extension recorded by alkaline magmatism came into existence (Figs. 4, 5). This area fits well into the stress system within the shear zone. In similar conditions, strong extension commonly results in sag, termed pull-apart depression. The area of alkaline magmatism came into being on the site of and succeeded such a depression. This can be explained by the fact that it occurs above collision zones and involves a relatively small amount of extension.

At the same time, as it was shown above, the extension was more intense in the eastern half of the western Tien Shan. In the same area, the rotation angles determined from paleomagnetic data were maximum.

Thus, in the Permian, over most of the Tien Shan there existed a sinistral shear zone where rock masses rotated counterclockwise. Rotation was realized through plastic deformations (the formation of the Fergana horizontal flexure) and, probably, through longitudinal horizontal tectonic flow that encompassed the entire shear zone. This tectonic flow may have caused the counterclockwise rotation of the Permian paleomagnetic vectors, which is not reflected in the megastructure of the study area. The reason for this rotation of paleomagnetic vectors must be rotation of tectonic blocks.

Thus, the D_3 stage falls into two epochs, with distinctive deformation styles. In the early epoch (D_3a, Sakmarian–Artinskian), plastic deformation prevailed, and later (epoch D_3b), longitudinal tectonic flow did. Against the background of these processes, the shear zone became the site of an extension area with alkaline magmatism. The stress field during stage D_3 did not change, and these epochs may have partially overlapped one another.

Of interest are the results of magma source reconstruction for the Late Paleozoic magmatism of the Chatkal–Kurama area based on the K_2O content variation in the magmatic rocks [17]. The magma source region was an inclined zone that in the Early Permian rotated counterclockwise around a vertical axis.

Most likely, the sinistral shear stress zone arose, as the Kara Kum block collided obliquely with the already amalgamated Tien Shan continental block (Fig. 6). After collision in the Late Carboniferous, the Kara Kum block was translated along the boundary of the Tien Shan block, initiating sinistral shear stresses in its crust.

The rotation angles of declinations of the Early Permian magnetization in the western Tien Shan are larger than in the central Tien Shan. This effect is partially explained by the rotation of the western Tien Shan in the post-Paleogene time. However, this effect considered, the tendency (see table) for rotation angles to be larger in the western part of the Permian shear zone than in the eastern part remains unchanged. This seems natural, if we accept the hypothesis that the shear stresses resulted from interaction of the Kara Kum and Tien Shan sialic blocks. Their collision occurred in the west (in present geographical coordinates). Then, the Kara Kum block, moving along the boundary of the Tien Shan block, entrained the Tarim massif, which split off of the Tien Shan and was transported to the east (Fig. 6). The sinistral shear and associated horizontal flexures were discovered on the Kokshaal and Sarydzhaz ranges at the boundary between the Tien Shan and the Tarim massif [5, 20]. According to this model, shear stresses propagated from west to east, and the stress field in the west must have originated earlier, existed longer, and must have been more intense.

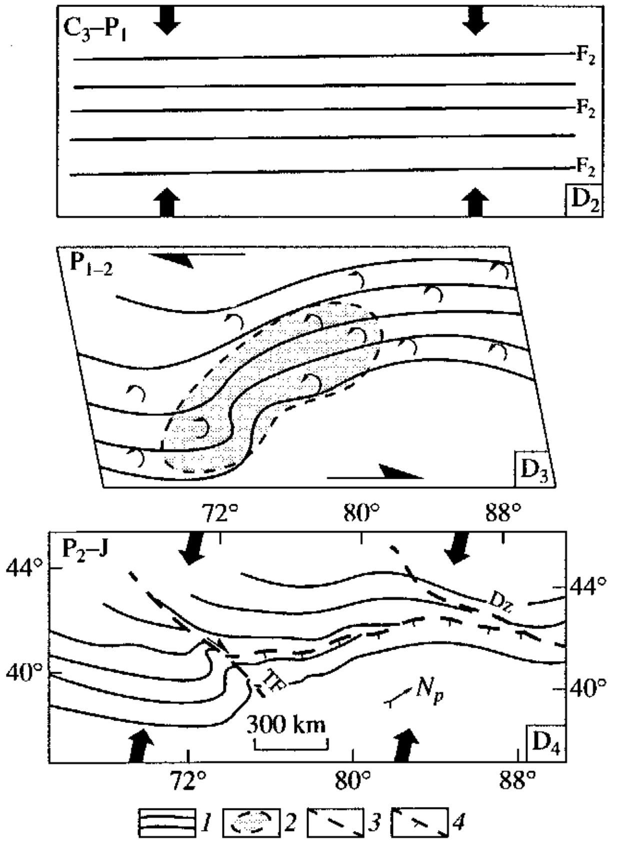

Fig. 5. Scheme of formation of the Late Paleozoic Tien Shan structure at the D_2–D_4 stages (plan view). (*1*) Strike of the F_2 folds; (*2*) area of the Permian alkaline magmatism; (*3*) main shears (TF = Talas–Fergana, Dz = Dzungaria); (*4*) main thrust faults. Stress system is shown by large arrows; rotation direction, by round arrows. N_p, direction of the Permian magnetic pole.

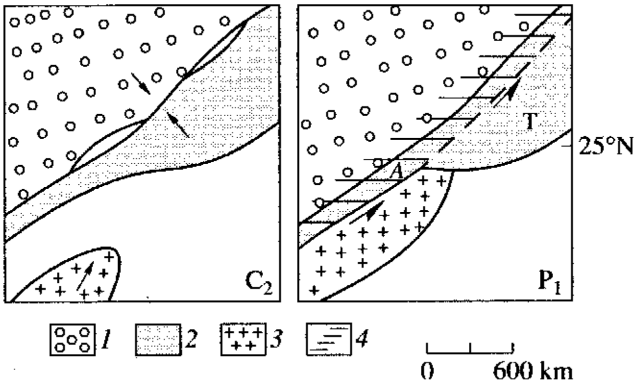

Fig. 6. Scheme of interaction of Paleozoic sialic blocks. (*1*–*3*) Sialic blocks: (*1*) Kazakhstan–Kyrgyz, (*2*) Alai–Tarim (A = Alai, T = Tarim), (*3*) Kara Kum; (*4*) zone of shear stresses and strains.

Stage D_4. At this stage, all the previously formed structures were cut by diagonal shears and thrust faults, the latter involving horizontal and vertical drag folds. The bends of the Fergana horizontal flexures converged, and the flexure was compressed and folded [8–10, 29]. The D_4 faults affect structural forms of all the preceeding deformation stages and deposits to the Late Permian inclusive (Ufimian–Kazanian).

The D_4 deformations were due to compression stresses directed almost across the fold system. The stress field may have had a transpressional nature, involving both compressional and sinistral shear elements. The existence of sinistral shear is evidenced by the counterclockwise rotation of the magnetic declinations measured for Triassic rocks [26, 32].

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REFERENCES

1. Afonichev, N.A. and Vlasov, N.G., *Prilozheniya k geologicheskoi karte Kazakhstana i Srednei Azii masshtaba 1 : 1 500 000* (Appendix to the Geological Map of Kazakhstan and Central Asia to the Scale 1 : 1 500 000), Leningrad: VSEGEI, 1984.
2. Bazhenov, M.L., Burtman, V.S., Cobbold, P.R., Perroud, E., Sadybakasov, I., Thomas, J.-Ch., and Chauvin, A., Paleomagnetism of Tertiary Deposits and Alpine Kinematics of the Tien Shan, *Geotektonika*, 1993, no. 6, pp. 50–62.
3. Bel'govskii, G.L., Permian System, in *Geologia SSSR. Kirgizskaya SSR* (Geology of the USSR. Kyrgyz SSR). Moscow: Nedra, 1972, vol. 25, book 1, pp. 190–200.
4. Bel'govskii, G.L., Biske, G.S., Vlasov, N.G., Voitovich, I.I., Kotel'nikov, V.I., Khristov, E.V., and Yagovkin, A.V., Permian System, in *Stratifitsirovannye i intruzivnye obrazovaniya Kirgizii* (Stratified and Intrusive Formations of Kirgizia), Frunze: Ilim, 1982, vol. 1, pp. 314–324.
5. Biske, Yu.S., Late Paleozoic Collision of the Tarim and Kyrgyz–Kazakhstan Paleocontinents, *Geotektonika*, 1995, no. 1, pp. 31–39.
6. Bol'shakov, A.S., Solodovnikov, G.M., and Vinogragov, Yu.K., Intensity of the Early Permian Geomagnetic Field, *Izv. Akad. Nauk SSSR, Ser. Fiz. Zemli*, 1989, no. 7, pp. 70–77.
7. Burov, V.G., Purkin, M.M., Khristov, E.V., and Khristova, M.P., The Surtekin Intrusion of Alkaline Rocks, *Zap. Vses. Mineral. O-va*, 1965, no. 5, pp. 39–49.
8. Burtman, V.S., *Talaso-Ferganskii sdvig* (The Talas–Fergana Shear), Moscow: Nauka, 1964.
9. Burtman, V.S., *Strukturnaya evolyutsiya paleozoiskikh skladchatykh sistem* (Structional Evolution of Paleozoic Fold Systems), Moscow: Nauka, 1976.
10. Burtman, V.S., Structional Evolution of the Variscides of the Tien Shan, *27 Mezhdunarodnyi geologicheskii kongress, Moskva. Putevoditel' ekskursii "Tektonika varistsid Tyan'-Shanya" po Kirgizskoi SSR* (27th IGC, Moscow. Excursion Guide Book "Tectonics of the Tien Shan Variscides" for Kirgiz SSR), Frunze: Kyrgyzstan, 1984, pp. 36–43.
11. Ges', M.D., Garetskaya, E.N., Izraileva, R.M., and Leskov, S.A., Permian Intrusive Rocks, in *Stratifitsirovannye i intruzivnye obrazovaniya Kirgizii* (Stratified and Intrusive Formations of Kirgizia), Frunze: Ilim, 1982, vol. 2, pp. 128–181.
12. Klishevich, V.L., *Ob"yasnitel'naya zapiska k geologicheskoi karte SSSR masshtaba 1 : 1 000 000. List K-42, 43* (Explanatory Note to the Geologic Map of the USSR, Scale 1 : 1 000 000. Quadrangle K-42, 43), St. Petersburg: VSEGEI, 1992.
13. Klishevich, V.L., Klishevich, I.A., Rzhevskii, Yu.S., and Khramov, A.N., On the Question of the Fergana Sigmoid, *Dokl. Akad. Nauk SSSR*, 1986, vol. 286, no. 2, pp. 402–405.
14. Klishevich, V.L., Rzhevskii, Yu.S., Khramov, A.N., Talashmanov, Yu.A., and Krylova, T.N., Late Variscan Horizontal Deformations of the Fergana Sector, *Vestn. Leningr. Univ., Ser. 7: Geol., Geogr.*, 1989, no. 1, pp. 3–10.
15. Masumov, A.S., Upper Paleozoic of the Central and Western Tien Shan, *Abstract of Doctoral (Geol.–Mineral.) Dissertation*, Moscow: Moscow State Univ., 1994.
16. Masumov, A.S., Borisov, O.M., and Bensh, F.R., *Verkhnii paleozoi Sredinnogo i Yuzhnogo Tyan'-Shanya* (Upper Paleozoic of the Central and Southern Tien Shan), Tashkent: Fan, 1978.
17. Mukhin, P.A., Distribution of the Normalized K_2O Content in the Volcanic Rocks of the Chatkal–Kurama Area as an Indicator of the Subduction Process in the Late Paleozoic, in *Geologiya, geodinamika i metallogeniya Srednei Azii* (Geology, Geodynamics and Metallogeny of Central Asia), Tashkent: SAIGIMS, 1990, pp. 58–63.
18. Tulyaganov, Kh.T., Yudalevich, Z.A., Korzhaev, V.P., Kim, O.I., Yaskovich, B.V., Kozlov, S.A., and Poniklenko, I.A., *Karta magmaticheskikh kompleksov Uzbekskoi SSR (opisanie)* (Map of Magmatic Complexes of the Uzbek SSR (Description)), Tashkent: Fan, 1984.
19. Ulomov, V.I., *Dinamika zemnoi kory Srednei Azii i prognoz zemletryasenii* (Dynamics of the Earth's Crust of Central Asia and Earthquake Prediction), Tashkent: Fan, 1974.
20. Khristov, E.V., Collisional Structures of the Area of the Sarydzhaz Syntax, in *Tektonika, geodinamika i metallogeniya Uralo-Tyan'shan'skoi skladchatoi sistemy* (Tectonics, Geodynamics, and Metallogeny of the Urals–Tien Shan Fold System), Sverdlovsk, 1989, pp. 154–155.
21. Chernovskii, B.A., *Glubinnoe stroenie, osobennosti orogennoi tektoniki i metallogenii Chatkalo-Kuraminskogo regiona* (Deep Structure, Peculiarities of the Orogenic Tectonics, and Metallogeny of the Chatkal–Kurama Region), Tashkent: Fan, 1991.
22. Şengör, A.M.D., Natal'in, B.A., and Burtman, V.S., Tectonic Evolution of the Altaides, *Geol. Geofiz.*, 1994, vol. 35, no. 7/8, pp. 41–58.
23. Audibert, M. and Bazhenov, M.L., Permian Paleomagnetism of the North Tien Shan: Tectonic Implications, *Tectonics*, 1992, vol. 11, pp. 1057–1070.
24. Bai, Y., Chen, G., Sun, Q., Li, Y., Dong Y., and Sun, D., Paleozoic Polar Wander Path for the Tarim Platform and Its Tectonic Significance, *Tectonophysics*, 1987, vol. 139, pp. 145–153.

25. Bazhenov, M.L., Burtman, V.S., Dvorova, A.V., and Klishevich, V.L., Permian Paleomagnetism of the Tien Shan: The Succession and Style of Tectonic Deformation, *Tectonophysics*, (in press).

26. Bazhenov, M.L., Chauvin, A., Audibert, M., and Levashova, N.M., Permian and Triassic Paleomagnetism of the Southwestern Tien Shan: Timing and Mode of Tectonic Rotations, *Earth Planet. Sci. Lett.*, 1993, vol. 118, pp. 195–212.

27. Bazhenov, M.L., Klishevich, V.L., and Tselmovich, V.A., Paleomagnetism of Permian Red Beds from South Kazakhstan: DRM Inclination Error or CRM Shallowed Directions?, *Geophys. J. Int.*, 1995, vol. 120, pp. 445–452.

28. Burtman, V.S., The Structural Geology of Variscan Tien Shan, USSR, *Am. J. Sci.*, 1975, vol. 275A, pp. 157–186.

29. Burtman, V.S., Faults of Middle Asia, *Am. J. Sci.*, 1980, vol. 280, pp. 725–744.

30. Chen, Z., *Geological Map of Xinjiang Uygur Autonomous Region (China) in Scale 1 : 2 000 000*, Explanatary Notes, Beijing, 1985.

31. Li, Y.P., McWilliams, M., Cox, A., Sharps, R., Li, Y.A., Gao, Z., Zhang, Z., and Zhai, Y., Late Permian Paleomagnetic Pole from Dykes of the Tarim Craton, *Geology*, 1988, vol. 16, pp. 275–278.

32. McFadden, P.L., Ma, X., McElhinny, M.W., and Zhang, Z., Permo-Triassic Magnetostratigraphy in China: Northern Tarim, *Earth Planet. Sci. Lett.*, 1988, vol. 87, pp. 152–160.

33. Nie, S., Van der Voo, R., Li, M., and Rowley, D.B., Paleomagnetism of Late Paleozoic Rocks in the Tien Shan, Northwestern China, *Tectonics*, 1993, vol. 12, no. 2, pp. 568–579.

34. Şengör, A.M.C., Natalin, B.A., and Burtman, V.S., Evolution of the Altaid Tectonic Collage and Paleozoic Crustal Growth in Eurasia, *Nature*, 1993, vol. 364, no. 6435, pp. 299–307.

35. Sharps, R., Li, Y., and McWilliams, M. Paleomagnetic Inverstigation of Upper Permian Sediments in the South Junggar Basin, China, *J. Geophys. Res.*, 1992, vol. 92, pp. 1753–1765.

36. Sharps, R., McWilliams, M., Li, Y., Cox, A., Zhang, Z., Zhai, Y., Gao, Z., Li, Y.A., and Li, Q., Permian Paleomagnetism of the Tarim Block, Nortwestern China, *Earth Planet. Sci. Lett.*, 1989, vol. 92, pp. 275–291.

37. Thomas, J.Ch., Perroud, H., Cobbold, P.R., Bazhenov, M.L., Burtman, V.S., Chauvin, A., and Sadybocasov, I., Paleomagnetic Study of Tertiary Formations from the Kirghiz Tien Shan and Its Tectonic Implications, *J. Geophys. Res.*, 1993, vol. 98, pp. 9571–9589.

38. Van der Voo, R., Phanerozoic Paleomagnetic Poles from Europe and North America and Comparison with Continental Reconstructions, *Rev. Geophys.*, 1990, vol. 28, pp. 167–206.

39. Zhao, X., Coe, R.S., Zhou, Y., Wu, H., and Wong, J., New Paleomagnetic Results from Northern China: Collision and Suturing with Siberia and Kazakhstan, *Tectonophysics*, 1990, vol. 181, pp. 43–81.