

GEOCHEMISTRY

## <sup>40</sup>Ar/<sup>39</sup>Ar Dating of the Stage of Transform-Shear Deformation in Evolution of the Early Caledonides in Western Sangilen, Southeastern Tuva

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In paleotectonic reconstructions of the Central Asian Foldbelt (CAFB), special attention is paid to the Early Paleozoic processes of the formation and breakdown of orogenic edifices. In this regard, the results of geological and isotopic studies of the southern framework of the Siberian Craton attract interest, because they provide chronological links between accretion and collision, on the one hand, and reactivation of magmatic processes, on the other [1–10, 12, 14]. In line with these investigations, we investigated the scale and duration of the evolution of the CAFB that underwent all evolution stages ranging from Late Vendian subduction and accretion to Cambrian collision and the Ordovician stage of transform-shear deformation in the Sangilen region, an Early Caledonian fragment of CAFB in southeastern Tuva [8]. The *PTdt* model proposed in this work illustrates periods of origination and reactivation of the main tectonic deformation of the region: the Agardag suture zone and the Erzin and Kokmolgarga shear zones. These and related deformations of the lower rank compose the West Sangilen strike-slip system, the evolution of which led to fragmentation of crust into large tectonic blocks (Tannuol, Mugur–Chinchilig, and Erzin–Naryn) (Fig. 1).

This study, a logical continuation of the investigations mentioned above, is devoted to the most complicated structure, the Mugur–Chinchilig Block (Fig. 1). The blocks include fragments of the Mugur metasedimentary complex, which is characterized by different grades of metamorphism ranging from the moderate-pressure amphibolite facies (andalusite–sillimanite assemblages,  $M_2$ ) in the west to the high-pressure epidote–amphibolite facies (staurolite–kyanite assemblages,  $M_1$ ) in the east [8, 13, 15].

The differently metamorphosed fragments were juxtaposed at the same erosion level during regional transtension 480–430 Ma ago [8], when the left-lateral kinematics of tectonic movements promoted fragmentation of the Mugur–Chinchilig Block with pulling apart and exhumation of its fragments.

The dynamics of the West Sangilen shear system, including the conjugate near-meridional and near-latitude faults, controlled not only the intensity and character of crustal mass fragmentation but also the emplacement of considerable volumes of basic and silicic melts. The emplacement of the Bashkymugur gabbro–monzodiorite massif is the most striking manifestation of these events. Data on the age of this massif are as follows (Fig. 1):  $464.6 \pm 5.7$  Ma (U–Pb zircon dating [15]),  $465 \pm 1.2$  Ma (Ar/Ar biotite dating [13]), and  $464 \pm 5$  Ma (Rb–Sr whole-rock dating [14]).

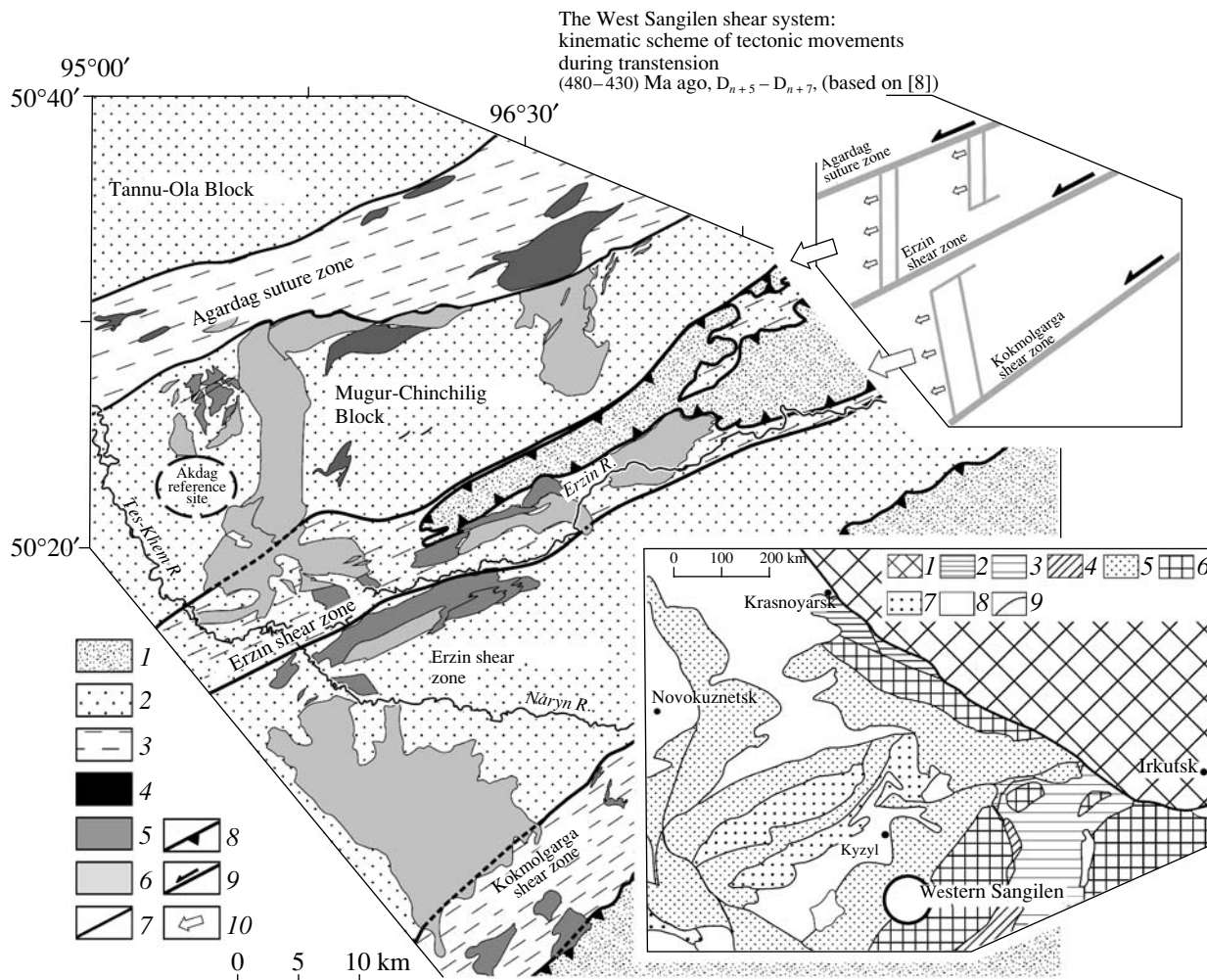
Despite the long-term study of the western Sangilen region [1, 2, 5, 8, 10, 11, 13–15], the scale of tectonomagmatic transformations during the transform-shear deformation (480–430 Ma ago) remains an open issue: were these processes confined to large shear zones (Agardag, Erzin, and others) or were these processes combined with destruction of tectonic blocks, their heating, and deformation of metamorphic rocks?

This problem can be solved either by large-scale structural–petrological studies or by comprehensive examination of a particular reference site located in the central sector of the tectonic block. The latter version makes it possible to exclude the influence of deformations of different stages within the shear zones (Agardag and Erzin) and decrease the thermal influence of large magmatic massifs (Bashkymugur, Ukhadag, and others).

We gave preference to the second approach. We carried out detailed structural, petrological, and isotopic studies at the Akdag reference site within the Mugur–Chinchilig Block.

This site is situated west of the Bashkymugur gabbro–monzodiorite massif between the Agardag suture zone and the Erzin shear zone (Figs. 1, 2).

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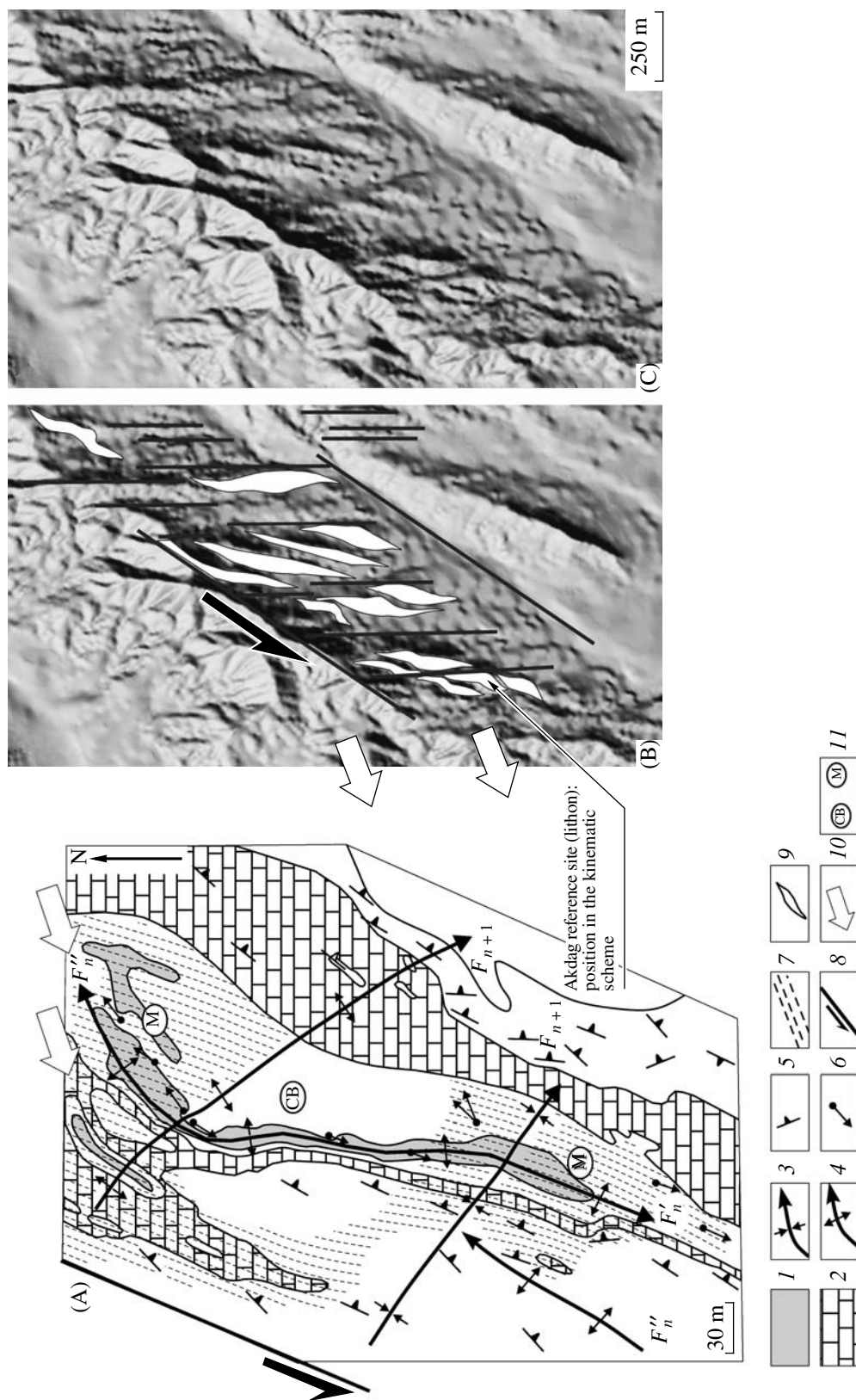
**Fig. 1.** Tectonic and kinematic schemes of the West Sangilen shear system, western Sangilen, southeastern Tuva (based on [8]). The figure clearly demonstrates that the older (570–490 Ma) magmatic massifs are related to shear zones; the younger (490–430 Ma) massifs, to the zones of fragmentation and extension of tectonic blocks of the pull-apart type. (1) Thrust sheets; (2) tectonic blocks; (3) shear zones; (4–6) magmatic bodies and massifs of different ages: (4) 570–525 Ma, (5) 525–490 Ma, (6) 490–430 Ma; (7) faults; (8) nappes; (9) kinematics of tectonic movements; (10) direction of extension. Inset map demonstrates the geological position of western Sangilen (based on [2]): (1) Siberian Craton; (2) Upper Riphean rift-related complexes; (3–5) island-arc complexes: (3) Late Riphean, (4) Vendian, (5) Cambrian; (6) terranes with the Early Caledonian remobilization of crust; (7) Late Cambrian–Silurian orogenic molasses and sedimentary basins; (8) Middle Paleozoic–Early Mesozoic geological complexes; (9) main faults.

The Akdag site and its framework are composed of sedimentary rocks (Mugur Complex), which were metamorphosed under conditions of the epidote–amphibolite facies. Biotite and garnet–biotite gneisses and amphibolites prevail here. High-alumina metapelites with andalusite, sillimanite, and cordierite are widespread. Thin units of quartzite and carbonate–terrigenous rocks are noted. The metamorphic rocks were subject to criss-cross folding and transformation into numerous conjugate sigmoid structures (Fig. 2A) during the early collisional deformation (stage  $D_{n+1}$  [8], 535–525 Ma ago).

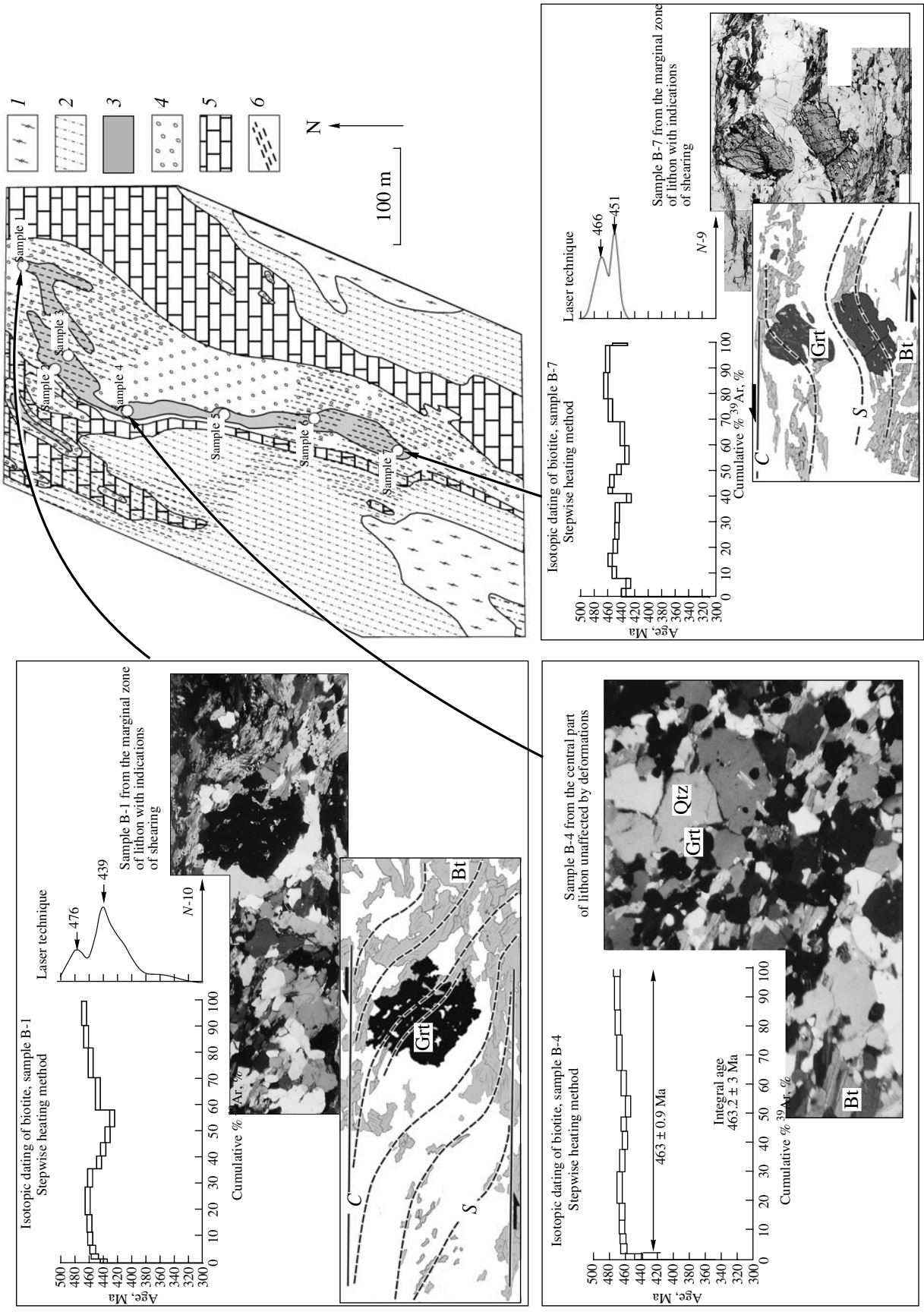
To elucidate the internal fragmentation of the Mugur–Chinchilig Block, we compiled a shaded relief model of its western part, the Akdag site inclusive (Fig. 2B), which clearly demonstrates the en echelon system of NE- and NS-striking lineaments (Figs. 2B, 2C).

Fieldworks revealed that separate blocks represent rigid, undeformed, or slightly deformed lithons divided by zones of volumetric shear flow (Figs. 2, 3). The blocks are displaced relative to one another without a break in integrity of the lithological units, and the macrotextures of S-type rotation complicate the older criss-cross folding (Fig. 2A). Such a collage of rigid blocks appeared in the viscoelastic matrix as a result of left-lateral transtensional deformation (Figs. 2A, 2B).

The Akdag lithon revealed during the decoding of blocks was subject to transtension (Figs. 2, 3). To characterize the synkinematic alteration of rocks, we took the oriented samples from the same unit of garnet–biotite gneiss (Fig. 3). The comprehensive comparative analysis of these samples allowed us to synchronize



**Fig. 2.** Kinematic scheme of tectonic movements responsible for fragmentation of metamorphic rocks in the western Mugur-Chinchilig Block, right bank of the Turlashkin River: (A) Structural-kinematic scheme showing superposition of the left-lateral strike-slip faulting ( $463.6 \pm 0.9$  Ma) upon cross folding ( $F_n/F_{n+1}$ ) in the Akdag reference site. (B) Shaded relief model and kinematic scheme of transension of metamorphic rocks based on this model. (C) Shaded relief model of the right bank of the Turlashkin River. (1, 2) Key lithological units: (1) garnet-biotite schists, (2) carbonate-terrigenous rocks; (3, 4) folds: (3) synform, (4) antiform; (5) strike-and-dip symbols; (6) plunging of microfolds hinges; (7) zones of viscous and brittle-ductile mylonitization related to shear motions; (8) faults and kinematic elements of deformation; (9) fragments of blocks (lithons); (10) direction of extension of tectonic fragments; (11) fields of rocks with variable competence; (M) shear deformation of rocks; (CB) competent (rigid) rock zones without indications of shear flow.



**Fig. 3.** Results of  $^{40}\text{Ar}/^{39}\text{Ar}$  isotopic dating of blastomylonites (samples B-1 and B-7) and rocks taken beyond the zone of viscoelastic shear flow (sample B-4). Akdag reference site, right bank of the Tarylshkin River, western Sangilen, southeastern Tuva. (1) Andalusite–sillimanite metasediment, (2) amphibolite, (3) garnet–biotite gneiss, (4) quartzite, (5) carbonate–terrigenous rock, (6) blastomylonite.

Results of  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of biotite with stepwise heating, Akdag reference site, southern Sangilen, southeastern Tuva

Ord. no.	$T, ^\circ\text{C}$	$t, \text{min}$	$^{40}\text{Ar}, 10^{-9} \text{ncm}^3$	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}/^{39}\text{Ar}$	$\Sigma^{39}\text{Ar}, \%$	Age, Ma ( $\pm 1\sigma$ )
Sample B-1, $J = 0.003057 \pm 0.000028$								
1	450	20	5.44	98.56	7.998	0.9468	0.2	$223.3 \pm 80.3$
2	550	20	5.96	116.17	3.645	0.0905	0.3	$332.6 \pm 39.9$
3	600	20	50.5	98.3	0.44	0.0413	2	$438.3 \pm 4.9$
4	625	20	59.25	96.86	0.364	0.0249	3.9	$450.7 \pm 4.9$
5	650	20	101.78	96.56	0.214	0.0212	7.2	$453.5 \pm 3.9$
6	675	20	149.99	96.26	0.18	0.0232	12.2	$457.1 \pm 3.5$
7	700	20	201.79	96.14	0.199	0.0211	18.8	$458.0 \pm 3.4$
8	750	20	321.36	95.93	0.128	0.0142	29.4	$460.6 \pm 3.3$
9	800	20	208.77	95.35	0.158	0.013	36.3	$457.3 \pm 3.4$
10	850	20	142.98	93.06	0.135	0.0078	41.1	$444.8 \pm 3.4$
11	900	20	149.22	92.64	0.167	0.0055	46.2	$439.1 \pm 3.7$
12	950	20	172.18	90.7	0.191	0.0072	52.2	$433.1 \pm 3.3$
13	1000	20	180.77	88.85	0.14	0.0098	58.7	$426.7 \pm 3.3$
14	1050	20	362.04	93.09	0.167	0.0104	71	$446.6 \pm 3.3$
15	1100	20	339.46	95.31	0.175	0.0081	82.2	$456.3 \pm 3.3$
16	1150	20	261.65	96.44	0.16	0.0116	90.8	$462.5 \pm 3.3$
17	1200	20	284.1	97.55	0.174	0.0239	100	$465.1 \pm 3.4$
Sample B-4, $J = 0.002981 \pm 0.000024$								
1	450	20	5.58	233.27	0.323	0.7838	0.1	$8.9 \pm 127.7$
2	550	20	12.84	106.73	0.066	0.0993	0.4	$374.5 \pm 25.9$
3	600	20	78.35	102.93	0.034	0.0323	2.4	$443.1 \pm 4.9$
4	625	20	129.97	101.83	0.029	0.0139	5.8	$461.2 \pm 3.9$
5	650	20	130.8	100.74	0.029	0.0093	9.2	$462.4 \pm 3.6$
6	675	20	175.75	99.96	0.029	0.0057	13.8	$463.5 \pm 3.4$
7	700	20	219.81	99.95	0.028	0.0058	19.6	$463.4 \pm 3.4$
8	750	20	406.39	99.43	0.027	0.0016	30.4	$466.4 \pm 3.3$
9	800	20	290.37	99.16	0.028	0.0034	38.1	$463.0 \pm 3.3$
10	850	20	230.15	98.71	0.028	0.0046	44.3	$459.7 \pm 3.3$
11	900	20	186.39	98.93	0.028	0.0041	49.2	$461.3 \pm 3.4$
12	950	20	265.96	97.81	0.028	0.0045	56.4	$456.1 \pm 3.2$
13	1000	20	326.69	98.7	0.027	0.0032	65.1	$461.4 \pm 3.3$
14	1050	20	459.44	99.78	0.027	0.0026	77.3	$466.6 \pm 3.2$
15	1100	20	326.42	100.27	0.027	0.0028	85.8	$468.4 \pm 3.3$
16	1150	20	436.2	100.44	0.027	0.0029	97.3	$469.0 \pm 3.2$
17	1200	20	104.46	102.04	0.029	0.008	100	$469.4 \pm 4.0$
Sample B-7, $J = 0.002902 \pm 0.000024$								
1	450	20	10.05	238.04	0.141	0.5318	0.1	$380.4 \pm 59.9$
2	550	20	42.72	81	0.059	0.0522	0.7	$314.3 \pm 5.8$
3	600	20	269.58	99.67	0.038	0.0191	4	$435.3 \pm 3.1$
4	625	20	305.93	95.74	0.034	0.0116	7.9	$428.3 \pm 3.4$
5	650	20	388.39	101.69	0.034	0.0146	12.6	$449.0 \pm 3.2$
6	675	20	423.48	100.99	0.033	0.0071	17.7	$455.1 \pm 3.1$
7	700	20	445.38	98.43	0.032	0.0047	23.3	$447.6 \pm 3.2$
8	725	20	520.05	97.58	0.032	0.0037	29.8	$445.4 \pm 3.1$
9	750	20	621.88	97.43	0.032	0.0037	37.6	$444.7 \pm 3.1$
10	775	20	273.34	94.7	0.034	0.0086	41.2	$427.5 \pm 3.4$
11	800	20	200.56	101.37	0.033	0.0083	43.6	$455.2 \pm 3.2$
12	850	20	402.77	99.9	0.031	0.0054	48.5	$452.7 \pm 3.1$
13	900	20	328.98	98.01	0.032	0.0078	52.6	$442.2 \pm 3.2$
14	950	20	561.14	94.53	0.032	0.0057	59.9	$430.4 \pm 3.0$
15	1000	20	732.46	95.96	0.031	0.0048	69.3	$437.4 \pm 3.2$
16	1050	20	736.12	100.07	0.032	0.0043	78.3	$454.8 \pm 3.1$
17	1100	20	843.54	101.04	0.031	0.002	88.5	$461.5 \pm 3.1$
18	1150	20	867.98	100.52	0.031	0.0025	99.1	$458.7 \pm 3.2$
19	1200	20	74.95	100.69	0.047	0.0183	100	$440.5 \pm 11.0$

Note: ( $J$ ) Parameter characterizing the neutron flow.

stages of mineralization and left-lateral shearing and to estimate the age of tectonic movements.

It was established that the chemical composition of garnet–biotite gneiss remains unaltered when passing from the center of the rigid block to the zone of viscoelastic deformations, whereas the texture of rocks changes drastically. Indications of shear flow are absent within the rigid block (Figs. 3, 4) and appear only in its framework as the snowball texture of garnet, extension structures of the S/C type, and other attributes testifying to synkinematic mineralization (Fig. 3, samples B-1, B-7).

The microprobe results show that the composition of biotite in all samples is virtually identical (deviations are up to 3%). This fact may indicate that shearing did not affect the chemical composition of biotite or (and this is more probable) that biotite was recrystallized at the final syntectonic thermal stage. In any case, biotite crystallized at the same *PT* parameters irrespective of the sample location.

The microprobe analysis of garnet crystals yielded their similar compositions and comparable profiles of MnO, MgO, CaO, and FeO distribution in both marginal zones of the competent lithon affected by shearing and its central sector.

The  $^{40}\text{Ar}/^{39}\text{Ar}$  dating was performed by stepwise heating of biotite samples from both zones of volumetric shear flow and zones unaltered by shearing (Fig. 3; table). Spectra of samples B-4 and B-5 from the latter zone shows a plateau corresponding to the age of  $462.9 \pm 3.2$  and  $463.6 \pm 3.2$  Ma. Series of similar-age spectra with troughs recorded in their central segments are characteristic of the deformed samples (Fig. 3, samples B-1, B-7). Study of these plates using the laser evaporation technique (ruby laser,  $\lambda = 694$  nm, resolution 50–100  $\mu\text{m}$ ) revealed a binary age distribution with maximums at 470 and 440–450 Ma (Fig. 3). Younger ages are characteristic of smaller grains, whose isotopic system could have been rejuvenated as a result of the superimposed low-temperature heating. Therefore, we suggest that the troughs in age spectra may be explained by the preferential concentration of the middle sector of the spectra with Ar released from small imperfect biotite grains. The maximal formation of such grains in vacuum is shifted toward lower temperatures. The grain size inhomogeneity and the increase in the amount of defects in biotite are typical of its growth under conditions of volumetric shear flow [11].

Because the *PT* conditions of metamorphism, compositions of rocks, and compositions of minerals (biotite and garnet) are similar in both the rigid blocks and shear zones, the plateau ages also correspond to both the last, short-term heating of volcanosedimentary rocks of the Mugur Complex [12] and shear deformations that were synchronous with metamorphism.

It is noteworthy that the age of  $463.2 \pm 3.2$  Ma coincides with the timing of the large Bashkymugur gabbro–monzodiorite massif situated east of the Akdag site. This massif yielded the following age values:

$465.0 \pm 3.8$  Ma (Ar/Ar biotite dating [13]),  $464 \pm 5$  Ma (Rb–Sr datings of plagioclase, amphibole, orthopyroxene, clinopyroxene, biotite, and whole-rock samples [14]), and  $464.6 \pm 5.7$  Ma (U–Pb zircon dating [15]). The injection of synplutonic mingling dikes into local extension cracks is related to the same time:  $468.6 \pm 12.0$  and  $467 \pm 21$  Ma (Rb–Sr dating of whole-rock samples) and  $462.5 \pm 1.0$  Ma (Ar/Ar biotite dating) [2].

Thus, our investigations demonstrated that the Sangilen Highland underwent intense shearing  $\sim 465$  Ma ago that provoked fragmentation of the Mugur–Chinchilig Block and destruction of the integrity of its separate parts. High permeability of the Earth's crust during this period promoted the emplacement of magmatic rocks of different compositions into upper levels of the Earth's crust. The Bashkymugur gabbro–monzodiorite massif, the largest in western Sangilen, is an example.

The tectonic movements were characterized by left-lateral strike-slip kinematics. In terms of the intensity of maximal values, they corresponded to transtension of the region at 480–430 Ma [8].

Destruction of integrity and exhumation of fragments of the Mugur–Chinchilig Block fostered its high permeability and additional heating, which are probably related to the emplacement of the Bashkymugur gabbro–monzodiorite massif.

The metasedimentary rocks of the Mugur Complex were heated under conditions of epidote–amphibolite facies at moderate pressures (andalusite–cordierite assemblage). However, metamorphism might have been limited by local recrystallization of rocks due to the extremely inhomogeneous permeability of rocks controlled by shearing.

The data obtained allow us to interpret tectonic conditions and mechanism of large-scale magmatism in the Tuva–Mongolia segment of the CAFB  $455 \pm 8$  Ma ago [2] as a result of transtension recorded in the Early Caledonides of western Sangilen.

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