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Postcollisional magmatism in the South Tien Shan Variscan Orogenic Belt, Kyrgyzstan: Evidence for high-temperature and high-pressure collision

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Received 3 January 2006; received in revised form 7 August 2006; accepted 23 August 2006

Abstract

The South Tien Shan Collisional belt consists of two segments divided by the largest in the Central Asia Talas-Fergan diagonal dextral strike-slip fault. The narrow eastern (Kokshal) segment, where the Late Carboniferous collision was followed by continental subduction of the Precambrian Tarim platform beneath the Caledonian Kazakh continent, is characterized by overthickened (60–65 km) crust and ultrahigh-pressure (coesite eclogite) regional metamorphism. The Permian postcollisional magmatism is represented there by a small volume of relatively ‘cool’ two-mica peraluminous leucogranites, moderate volumes of K-rich calc-alkaline (transitional from I- to S-type) granites and several large plutons of A-type rapakivi granites. The latest could have formed by a two-step process involving: (1) syncollisional submergence of the Tarim platform granulitic basement into the mantle accompanied by considerable heating of the source rocks, (2) ‘rapid’ postcollisional exhumation accompanied by decompression and extensive high-degree of melting. In the western (Alay) segment, which is much wider, the collision was not followed by continental subduction. The thickness of crust decreases westward dramatically (from 60 to 45 km). The Alay segment is characterized by the high-temperature/low-pressure regional metamorphism and significant volume of Permian shoshonitic/ultrapotassic magmatism, connected with postcollisional strike-slip tectonics. The shoshonitic magmatism is indicative of lithosphere delamination and input of mantle-derived melts and heat into the crust. In contrast to the Kokshal segment, the postcollisional granitic magmatism in the Alay segment is represented by relatively ‘hot’ cordierite- and sillimanite-bearing strongly peraluminous (S-type) granites, locally rooted in the high-temperature/low-pressure metamorphic rocks and large volume of calc-alkaline (I-type) granitoides of mixed (crust-mantle) origin.

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Keywords: Granites; Plate collision; Tien Shan; Kyrgyzstan

1. Introduction

There is significant diversity among the continental collision orogenic belts. They are distinguished mainly by the thickness of continental crust, type of regional metamorphism and proportion of mantle/crust-derived melts in collision-related magmatism. According to the concept of a

‘duality of orogens’ introduced by Zwart (1967) and developed by Sylwester (1998), two contrasting types of collisional orogens are distinguished: high-pressure as opposed to high-temperature collisional orogens. A full spectrum of transitional orogens exists between those contrast types. In high-pressure orogens (Alps and Himalayas) with crust extremely thickened by thrust stacking to more than ~50 km, high and ultrahigh-pressure regional metamorphism preceded granitoid magmatism (Scharer et al., 1986; von Blanckenburg, 1992; Gebauer et al., 1997). Syncollisional in situ radiogenic heating is the main source for crustal anatexis, which may have resulted from postcollision

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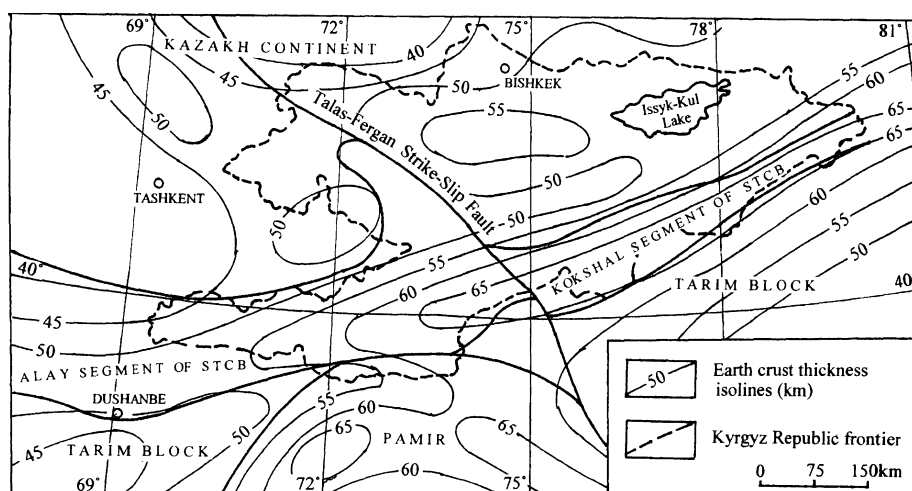


Fig. 1. Map showing the thickness of continental crust in the South Tien Shan collisional belt and adjoining territories (modified after [Sabitova, 1989](#)).

decompression melting along some of the deep-rooted thrusts ([Sylwester, 1998](#)), though fluid focusing along crustal shear zones ([Strong and Hanmer, 1981](#)) and advection or conduction of mantle-derived heat into lower crust ([Wickham and Oxburgh, 1987](#)) may also contribute.

In high-temperature orogens (European Hercynides, Lachlan in Australia), the newly formed continental crust is comparatively thin (less than 50 km) and large volumes of peraluminous (S-type) granites are associated with postcollisional high-temperature/low-pressure metamorphism ([Sylwester, 1998](#)), which typically can not be produced by in situ radiogenic heating in <50 km thick crust ([Thompson and Connolly, 1995](#)). Unlike high-pressure collisional orogens, S-type granites of high-temperature collisional belts are associated with large volumes of contemporaneous calc-alkaline (I-type) postcollisional granites that exhibit evidence for interaction with mantle-derived magmas ([Sylwester, 1998](#); [Bonin, 2004](#)). The chemical and mineralogical composition of peraluminous granites is also evidence of mantle-derived heat contribution. In high-pressure orogens, peraluminous granites are represented by a 'cool' (<875 °C) two-mica variety that occurs where thick continental crust is crosscut by major shear thrust zones, while in high-temperature orogens, they manifest themselves as 'hot' (>875 °C) cordierite–sillimanite varieties locally rooted in high-grade metamorphic rocks ([Sylwester, 1998](#); [Barbarin, 1999](#)).

The above-mentioned orogens are not of the same age (Caledonian, Hercynian, and Alpine) and do not refer to the same continents. Therefore, an alternative possibility is that different granitoids can also be related to distinct structural levels of a continental collision-related orogenic belt ([Barbarin, 1999](#)). The Himalayas may represent the upper level, while the Lachlan belt will be indicative of the lower one.

In this connection, the South Tien Shan Hercynian collisional belt (STCB) provides an opportunity to check that hypothesis. The belt consists of two segments divided by

the Talas-Fergan diagonal dextral strike-slip fault ([Fig. 1](#)), the largest in Central Asia. All available geological, geophysical and petrological data below suggest that the eastern (Kokshal) segment of STCB may represent a high-pressure collision orogen, while the western (Alay) segment is related to a high-temperature one. In each of those segments collision-related magmatism has some distinct peculiarities. In this article, the generalized petrological, geochemical and isotopic data concerning collision-related granitoids from both segments of STCB are presented and compared.

2. Geological setting

The South Tien Shan collisional belt, being the south-central portion of the huge Central Asian folding belt, formed as a result of Late Paleozoic collision of the Post-caledonian Kazakh continent with the Precambrian Tarim block ([Bakirov et al., 1989](#); [Byske, 1996](#); [Gao et al., 1998](#); [Chen et al., 1999](#)). Before the collisional event, the Kazakh continent to the north (in present-day coordinates) and Tarim to the south had been divided by the Turkestan Ocean. According to [Burtman \(1997\)](#), the northern margin of the Turkestan Ocean was active from the Ordovician until Early Devonian, passive or transform in the Middle and Late Devonian and most of the Early Carboniferous and active again in Serpukhovian time and Late Carboniferous. In contrast, the southern Tarim margin remained passive throughout this time interval.

Along its extent, the Turkestan Ocean closing suture is marked by ophiolitic mélange outcrops ([Fig. 2](#)). In some of those outcrops, subduction-related high-pressure/low-temperature (blueschist facies) metamorphism was preserved ([Bakirov et al., 1989](#)). The K–Ar age of glaucophane from the Atbashy blueschists is 360 ± 10 Ma ([Zamaletdinov, 1994](#)). The ophiolitic mélanges and blueschists are also widespread along that suture in the eastern Chinese part of STCB. Those blueschists occur as small blocks, lenses or

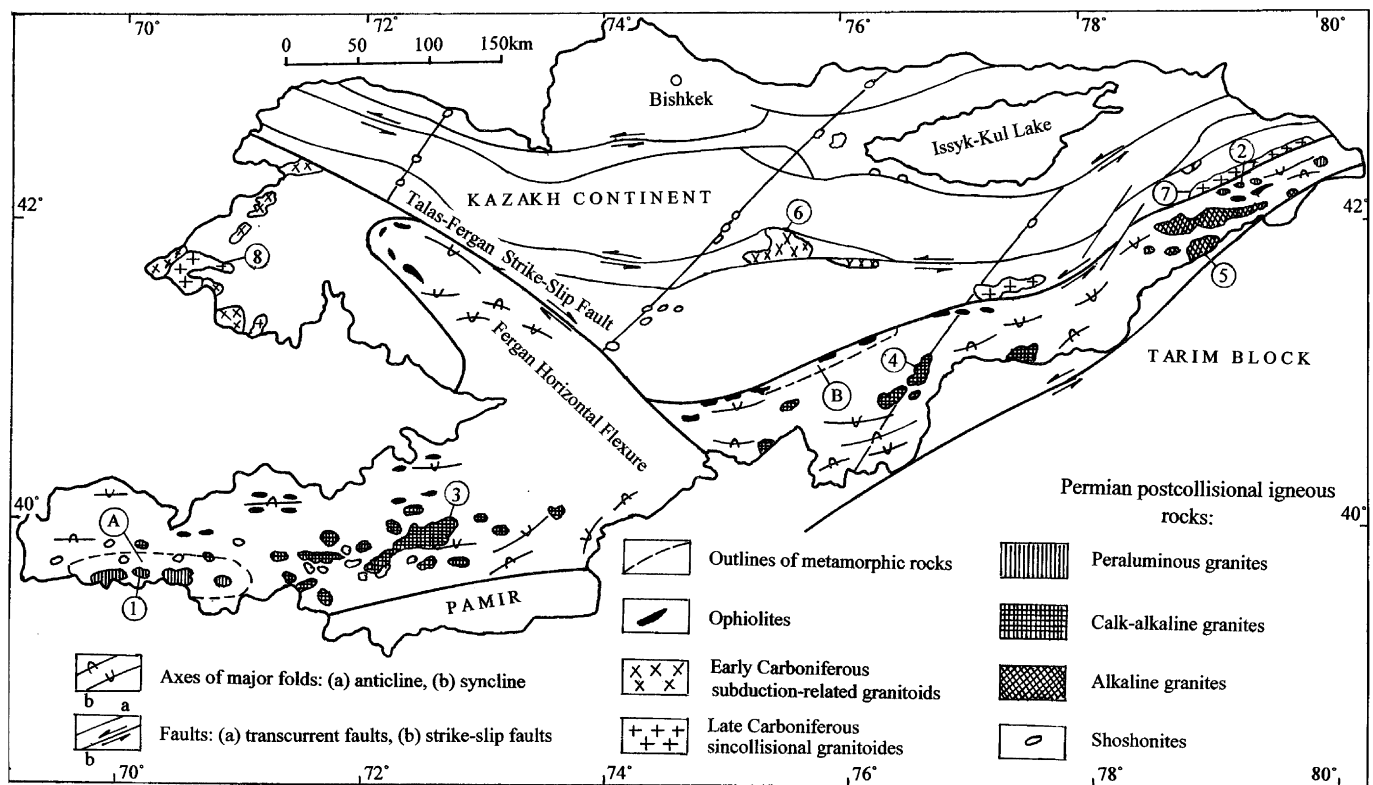


Fig. 2. Sketch geological map showing the location of the Late Paleozoic granitoids and shoshonites in the Kyrgyz parts of the South Tien Shan collisional belt and Kazakh continent. Names of metamorphic complexes: (A) the Turkestan high-temperature/low-pressure metamorphism, (B) the Atbashi high- and ultrahigh-pressure metamorphism. Names of major granitoid plutons: 1, Karavshy; 2, Inylchek; 3, Karakazyk; 4, Mydrym; 5, Jangart; 6, Sonkul; 7, Terety; 8, Akbulak. The majority of shoshonitic bodies are not to scale.

sheets in greenschist facies country rocks (Gao et al., 1999). The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of glaucophane from the Changawuzi ophiolites is 350.89 ± 1.96 Ma (Chen et al., 1999). The subduction-related (Andean type) magmatism on the southern active margin of the Kazakhstan continent started in Serpukhovian time and ceased due to the continental collision in the Late Carboniferous (Ges and Seliverstov, 1995). The magmatic arc occurs north of the suture and consists of abundant andesites and dacites and their diorite, monzodiorite and granodiorite plutonic counterparts (Ges and Seliverstov, 1995). The Rb–Sr isochron age of the Sonkul gabbro-monzodiorite-granodiorite pluton (Fig. 2) is 326 ± 6 Ma (Solomovich, 1996).

The Turkestan Ocean closed in the Moskovian of the Late Carboniferous and small remnants of deep-water basins existed close to the suture until the Early Permian (Byske, 1996). The Late Carboniferous sincollisinal magmatism, like the subduction-related one, occurs north of the suture and is represented by plentiful dacite lavas and large tonalite-granodiorite-granite plutons. The K–Ar age of biotite from the largest sincollisinal granitoid plutons of the Terekty and Akbulak (Fig. 2) is in range of 290–316 Ma (Ges et al., 1982).

The Permian period corresponds to the postcollisional stage of Tien Shan geological development. In the Early Permian, the thrust and fold structures of STCB were deformed into the Fergan sinistral horizontal flexure (Fig. 2), thus marking a transition from compression to

strike-slip tectonics (Bazhenov et al., 1999). The significant sinistral-type displacements along sublatitudinal faults inside STCB were described for the first time by Porshniyakov (1983). Then it was established that lithosphere-scale sinistral displacements of Permian age are common in the Tien Shan and the adjoining territories (Allen et al., 1995; Natal'in and Sengor, 2005) and those displacements are a consequence of oblique collision between the Tarim and Kazakh continents (Byske, 1996; Chen et al., 1999). According to paleomagnetic data (Bazhenov et al., 1999), the Permian sinistral shear zone, which is about 300 km wide, is traced along the Tien Shan fold belt for 2500 km. The evaluated amplitude of the Permian horizontal displacement along the major sublatitudinal faults in Tien Shan extends for tens of kilometres (Bazhenov and Mikolaichuk, 2004).

Unlike the sincollisinal magmatism, the Permian postcollisional magmatic domain connected with strike-slip tectonics, is much wider. Besides STCB, that domain also includes a significant portion of the Kazakh continent and is characterized by a variety of chemical compositions. In addition to different types of granites, which are the main subject of this article, the Permian domain includes various mantle-derived alkali rocks (Solomovich, 1987; Bazhenov et al., 1999). The shoshonitic/ultrapotassic volcanics and their shallow level plutonic counterparts prevail significantly among those alkali rocks. The K–Ar ages of many

shoshonites are in the range of 268–296 Ma (Ges et al., 1982). The connection between shoshonites and strike-slip tectonics is well established on the adjoining STCB territory of the Kazakh continent to the east of the Talas-Fergan strike-slip fault. While some shoshonites are directly controlled by major sublatitudinal sinistral strike-slip faults, the bulk of them occur along NE transcurrent faults (Fig. 2). Such a distribution of shoshonites is easy to explain, because being inside of wide sinistral shear zone those NE faults were exposed to tension.

The Talas-Fergan strike-slip fault of Late Permian–Early Jurassic age (Burtman, 1980) divides STCB into two segments. The narrow eastern (Kokshal) segment is characterized by overthickened (60–65 km) crust, while in the western (Alay) segment, which is much wider, the thickness of continental crust decreases westward dramatically from 65 to 45 km (Fig. 1). That distinction of STCB segments is believed to be evoked by the difference in style of continental collision in each segment. The overthickened crust of the Kokshal segment probably resulted from subduction of the Tarim continental crust beneath the Kazakh continent (Byske, 1996; Chen et al., 1999; Solomovich and Trifonov, 2002), while in the Alay segment, collision was not followed by continental subduction. Instead, sedimentary cover of the Tarim platform was incorporated into the nappe structure of STCB (Burtman, 1997).

In the Kokshal segment, the descent of continental crust to considerable depths (~100 km or more), at least locally, is confirmed by the presence of ultrahigh-pressure metamorphism (UHPM). It is currently suggested that UHPM (coesite eclogite facies) results from deep subduction of continental crust, which incorporates mantle eclogite from the upper plate, in an intracontinental subduction zone. The following rapid postcollisional exhumation is driven by buoyancy propulsion due to the considerable difference in density between crust and mantle (Liou et al., 2004; Janak et al., 2006). The Atbashy blueshist metamorphism hosts an allochthonous sheet 400 m thick (the Choloktor suite established by Bakirov (1978)), which is composed of pelitic and siliceous schists alternating with thin coesite eclogitic layers. Eclogites preserve prograde and retrograde paths with a peak metamorphic condition at 660 °C and 2.5 GPa. Coesite eclogites yielded a Rb–Sr isochron age of 270 ± 3 Ma (Tagiri et al., 1995). In the Chinese portion of STCB numerous outcrops of coesite eclogites conjugated with blueshists form a 200 km long belt. According to SHRIMP-analyses of zircon from those eclogites, the age of UHPM is younger than 310 ± 5 Ma (Zhang et al., 2002), which is close to dates by Tagiri et al. (1995) and supports the Early Permian metamorphism proposed by Chen et al. (1999).

The Alay segment of STCB lacks UHPM. Instead, it hosts high-temperature/low-pressure Turkestan metamorphism (Fig. 2). The core of Turkestan zoned metamorphism consists of migmatites (Bakirov, 1978), which contain relics of the granulite facies (Nenakhov et al., 1992). The distinction between two segments of STCB is also emphasized by the distribution of mantle-derived shoshonites. To the west of the Talas-Fergan strike-slip fault, shoshonites occur solely

inside the Alay segment of STCB, while to the east of that fault shoshonites spread significantly north of the suture (Fig. 2). The Kokshal segment therefore lacks shoshonites.

Unlike the Late Carboniferous syncollisional granites, the Permian postcollisional granites occur mainly within STCB. On the basis of geographic location, intrusive relations and petrological and geochemical arguments, the Permian granites from STCB can be classified into five intrusive complexes that represent three main petrochemical types of granites: peraluminous, calc-alkaline and alkaline.

3. Peraluminous granites

Peraluminous granites form two intrusive units: the Karavshy migmatite–granite complex in the Alay segment and Inylchek leucogranite complex in the Kokshal segment.

3.1. The Karavshy migmatite–granite complex

The Karavshuy complex consists of four small to medium size bodies (total area ~220 km²), which form the latitudinal strike chain in the core of the Turkestan high temperature–low pressure zoned metamorphism (Fig. 2). The autochthonous and semi-autochthonous granite bodies are situated inside the sillimanite isograd, where extensive anatexis migmatization occurred (Bakirov, 1978). The country rocks are predominantly Silurian and Devonian quartz-muscovite-biotite metapelites and meta-graywackes with minor marbles. The dominant structural feature of the metasedimentary rocks is east trending, steeply dipping foliation. The granite bodies are isometric with rounded shapes. They are usually surrounded by wide zones of migmatites. The contacts of granites with country rocks are gradual. However, in some places, granite offshoots crosscut the country rocks obliquely and contain angular xenoliths of the latter. The granite plutons host numerous mica-rich enclaves of sillimanite and garnet-bearing metasedimentary rocks, which are common for S-type granites rooted in high-grade metamorphism and usually are considered as restites (Chappel et al., 1987), while the mafic microgranular enclaves are sparse. The numerous rare-element pegmatites containing lepidolite, spodumene, beryl, pollucite, cassiterite and rubellite occur in the migmatitic field surrounding granites. A core of plutons usually consists of granite, which gradually grades into granodiorite outwards. In some places, however, granites cut through granodiorites. Granodiorites and granites are occasionally protoclastic and have a faint secondary foliation. Those features suggest the synkinematic formation of rocks. However, K–Ar ages of biotite (259–267 Ma) (Nenakhov et al., 1992) suggest a postcollisional setting.

Granodiorites are medium-grained and porphyritic, whereas granites are medium- to fine-grade and equigranular. The major mafic mineral of both rocks is biotite. The presence of highly aluminous primary phases such as muscovite, cordierite, sillimanite, tourmaline and garnet (Table 1) is a distinctive feature of those rocks. Both granodiorites and

Table 1
Petrography compositions of the Permian granitoides from the South Tien Shan

Complex	Karavshy		Inylchek				Karakazyk					Mydrym		Jangart	
Description	Grd	Bi-gr	Grd	Bi-gr	TM-lcgr	LM-lcgr	Gb	Q-dr	Q-mzdr	Grd	Mzgr	Amf-gr	Bi-lcgr	Rpk	Has-gr
<i>Major minerals in volume percentage</i>															
Quartz	15–25	25–30	20–25	23–29	32–35	33–37	–	5–10	10–15	20–23	25–35	24–32	28–35	15–30	23–28
K-feldspar	15–40	30–40	15–25	48–50	35–40	35–38	–	3–5	10–30	23–27	30–35	35–60	45–55	40–60	43–53
Plagioclase	30–50	25–30	45–50	15–18	25–28	25–27	48–52	55–60	30–40	40–42	28–32	10–30	15–20	15–25	16–21
Clinopyroxene	–	–	<1	–	–	–	35–45	4–8	0–5	–	–	–	–	–	–
Amphibole	–	–	<1	–	–	–	3–8	25–30	8–20	2–6	0–2	3–5	0–1	2–7	0.5–3.5
Biotite	15–20	3–8	10–15	5–9	2–5	–	1–3	2–4	10–22	5–10	5–8	2–6	2–5	5–10	4–6
Muscovite	0–2	1–3	–	<1	2–5	4–5	–	–	–	–	–	–	0–1	–	–
<i>Accessory minerals</i>															
Apatite	xxx	xx	xxx	xxx	xxx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
Zircon	x	xx	x	xx	xx	xx	–	–	xx	xxx	xxx	xxx	xx	xxx	xxx
Monazite	–	x	–	x	xx	xx	–	–	–	–	–	–	–	–	–
Sillimanite	xxx	xx	–	–	–	–	–	–	–	–	–	–	–	–	–
Cordierite	xx	x	–	–	–	–	–	–	–	–	–	–	–	–	–
Garnet	xx	xx	x	–	xx	x	–	–	–	–	–	–	–	–	–
Tourmaline	xxx	xxx	xx	xxx	xxx	xxx	–	–	–	–	–	x	x	–	x
Allanite	–	–	x	x	–	–	–	x	xx	xx	xx	xx	–	xx	xxx
Titanite	–	–	x	x	–	–	xxx	xxx	xxx	xxx	xxx	xxx	x	x	x
Ilmenite	x	x	x	x	x	x	–	–	–	–	–	–	–	xx	xx
Magnetite	–	–	–	–	–	–	xxx	xxx	xxx	xx	xx	xx	x	xxx	xx

Grd, granodiorite; Bi-gr, biotite granite; TM-lcgr, two-mica leucogranite; LM-lcgr, Li-mica leucogranite; Gb, gabbro; Q-dr, quartz diorite; Q-mzdr, quartz monzodiorite; Amf-gr, amphibole-biotite granite; Bi-lcgr, biotite leucogranite; Rpk, rapakivi granite; Has-gr, hastingsite granite; –, absent; x, rare; xx, common; xxx, abundant.

granites are strongly peraluminous ($A/CNK \geq 1.1$), normative corundum being greater than 1% CIPW corundum. The high value of K_2O/Na_2O ratio, low CaO content (Table 2) and relatively high initial $^{87}Sr/^{86}Sr$ ratios ($Sr_0 = 0.708–0.710$) (Nenakhov et al., 1992) are also typical for the Karavshy granitoides. The above geological and petrological characteristics of the Karavshy granites are similar to S-type granites, according to Chappell and White (1974) and cordierite-bearing peraluminous granites (CPG) after Barbarin (1999).

The increase in Rb, Pb, Sn, Ta concentrations (Table 2) and decrease in K/Rb, La/Yb, Eu/Eu* ratios toward more silica rocks suggest that the variation of chemical composition in granites may be caused by fractionation of plagioclase, biotite and accessory phases, mostly monazite and zircon. Both $Al_2O_3/(MgO + FeO_{tot})$ vs. $CaO/(MgO + FeO_{tot})$ and Rb/Ba vs. Rb/Sr diagrams (Figs. 3 and 4) indicate that the metagreywacks are the most likely source rocks for melts that crystallized to form Karavshy granites.

3.2. The Inylchek leucogranite complex

Intrusives of the Inylchek complex are exposed in the narrowest part of STCB (Fig. 2), which is known as the Saryjaz syntaxis (Khristov, 1989). The complex includes six small shallow level granite bodies (total area about 40 km²), which form the chain along the transcurrent shear zone, intersecting the fold structure obliquely (Trifonov and Solomovich, 1993). The granites cut through and metamorphose the Devonian volcanic and sedimentary rocks, which make up the upper most thrust sheet package in the Saryjaz syntaxis (Byske, 1996). The granite Rb–Sr isochron age (268 ± 8 Ma) corresponds to the Permian (Solomovich and

Trifonov, 2002). The enclaves in granites are scarce and represented by angular xenoliths of country rocks, while the miarolitic cavities filled by tourmaline pegmatite are common. The Inylchek complex was formed by consecutive emplacement of three intrusive phases: (1) biotite granodiorites; (2) coarse-grained porphyritic biotite granites; (3) medium-grained two-mica leucogranites and Li-mica leucogranites. The two-mica leucogranites dominate. They comprise up to 70% of granite outcrops. Two-mica leucogranites are equigranular or slightly porphyritic with miarolitic fabric. They consist of quartz, perthitic microcline, albite-oligoclase, biotite and muscovite (Table 1). Towards the apical parts of intrusives, two-mica leucogranites grade into microcline-albite Li-mica leucogranites containing protolithionite and zinnwaldite (Baybulatov et al., 1983). Besides the minerals listed in Table 1, they also contain topaz, cassiterite, columbite, thorite, cyrtolite and xenotime. The dyke suite of leucogranites is mainly represented by quartz-topaz keratophyre (Trifonov and Solomovich, 1982), which is similar to ongonite described by Kovalenko and Kovalenko (1976).

All of the Inylchek granites are peraluminous, poor in Ca and Sr and rich in K and lithophile trace elements such as Li, Rb, Cs, Be, Sn, Nb, Ta, HREE, B, F (Table 2), the concentrations of which increase in successive intrusive phases and reach a maximum in Li-mica leucogranites and ongonites. The above petrological and geochemical characteristics of the Inylchek granites, together with high initial $^{87}Sr/^{86}Sr$ ratio ($Sr_0 = 0.7099 \pm 0.0023$) (Solomovich and Trifonov, 2002), are similar to muscovite-bearing peraluminous granites (MPG) after Barbarin (1999). Just as in the case of the Karavshy granites, the

Table 2
Major (wt%) and trace element (ppm) concentration of granitic rocks from South Tien Shan

Complex	Karavshy		Inylchek			Karakazyk					Mydrym				Jangart		
Description	Grd	Bi-gr	Grd	Bi-gr	TM-lcgr	LM-lcgr	Ong	Gb	Q-mzdr	Grd	Mzgr	Am-gr	Bi-lcgr	Vg	Rpk-qsy	Rpk-gr	Has-gr
SiO ₂	64.72	72.58	67.42	71.29	74.22	74.2	70.24	52.61	61.32	66.08	71.28	71.37	74.55	55.42	64.99	68.18	71.81
TiO ₂	0.53	0.29	0.35	0.23	0.13	0.07	0.04	0.66	0.59	0.45	0.21	0.26	0.11	0.84	0.52	0.53	0.24
Al ₂ O ₃	16.42	14.08	16.55	14.08	13.65	13.75	15.36	14.52	15.96	15.46	14.35	13.23	13.02	14.63	15.39	14.07	13.09
Fe ₂ O ₃ ^t	5.53	1.68	3.68	2.65	1.47	1.68	1.61	8.33	6.02	4.34	2.27	3.13	1.96	7.21	5.73	4.79	3.18
MnO	0.08	0.04	0.05	0.04	0.03	0.04	0.06	0.16	0.17	0.08	0.06	0.06	0.04	0.15	0.09	0.07	0.05
MgO	1.68	0.72	1.12	0.35	0.11	0.12	0.09	7.94	2.89	1.68	0.76	0.24	0.07	8.34	0.51	0.27	0.21
CaO	2.72	1.19	2.61	1.51	0.77	0.72	0.85	10.53	5.57	4.15	2.58	1.62	0.65	6.23	2.79	2.09	1.25
Na ₂ O	3.12	2.72	3.05	3.23	3.62	4.03	4.66	1.79	2.85	3.01	3.33	3.75	3.85	2.31	3.96	3.49	3.92
K ₂ O	4.08	5.52	4.03	5.22	5.09	4.54	3.29	1.59	3.11	3.85	4.56	5.09	4.92	3.21	5.25	5.35	5.01
P ₂ O ₅	0.18	0.15	0.07	0.16	0.04	0.03	0.06	0.16	0.12	0.11	0.06	0.06	0.05	0.35	0.19	0.18	0.05
L.O.I.	0.82	0.29	0.61	0.85	0.63	0.66	2.89	1.22	0.54	0.31	0.22	0.48	0.33	1.38	0.35	0.51	0.57
Total	99.88	99.26	99.54	99.61	99.76	99.84	99.15	99.51	99.14	99.52	99.68	99.29	99.55	100.07	99.77	99.53	99.38
A/CNK	1.14	1.12	1.16	1.03	1.05	1.08	1.19	0.61	0.88	0.93	0.94	0.91	1.01	0.78	0.89	0.91	0.93
Li	82	105	63	108	296	579	2560	12	32	38	35	70	49		26	38	48
Rb	185	270	209	340	440	979	1970	44	110	175	205	200	235	125	222	227	278
Sr	353	145	345	144	72	20	32	540	480	425	246	165	119	570	167	172	76
Ba	1320	915	670	477	328	45	83	590	1370	1200	1250	620	341	1530	1307	1333	529
Sn	11	12	5.7	17.5	29	47	190	5.1	6	4	4.6	8.5	9.3		11	14	8.7
Pb	33	40	26	42	52	44	63	15	24	45	41	30	38		55	36	25
Nb	24	16		41	87	66.2	41.2		17	18					68	78	71
Ta	1.8	3.6		4.6	13.5	18.3	25.4		1.2	1.7					7	13	5.7
Zr	230	170	210	247	134	169	110		175	110	152	198	225		335	470	710
Hf	6.6	4.2		8.1	5.5	9.5	6		6	6	5.3				4.6	6.5	14.2
Ni	14	7.5	14	6.7	3.3	1.6	1.2	76	8	7	8	19	8	86	33	27	17
Cr	22	12	36	16	9.3	7.6	7	125	102	20	14	29	20	155	40	61	29
Be	7.1	5.4	4.4	6.8	8.4	10.2	7.9	1.3	5.2	6.5	4.1	4.2	5.8		2.6	2.9	2.8
B			15	31	82	115	166					22	25		26	25	35
F (wt%)	0.12	0.11	0.09	0.25	0.41	0.65	2.66					0.09	0.11		0.31	0.23	0.3
La				63	18	18		21	41	46	25				122	114	89
Ce				87	32	36		38	64	62	43				224	232	168
Sm				10	8	7.5		3.5	4.8	5.3	3.5				16	12	11
Eu				0.84	0.19	0.08		1.2	1.1	0.9	0.3				2.1	1.8	0.9
Gd				8.2	6.6	8.4		3.4	4	3.8	4.4				15	12	8.9
Yb				3.4	9.4	6.3		1.8	2.7	2.3	4				4.6	4.9	6.4
Y	13	19		74	67	68		18	20	21	22				67	62	90
N(n)	14(6)	10(5)	3(1)	15(7)	16(8)	18(10)	6(6)	5(3)	36(12)	42(8)	5(3)	15(5)	2(2)	2(2)	4(4)	7(7)	4(4)

Mean contents of elements are represented. Complete data can be found in Trifonov and Solomovich (1982), Baybulatov et al. (1983), Solomovich and Trifonov (1990), Solomovich and Malukova (2000), Solomovich and Trifonov (2002). Fe₂O₃^t is total iron as Fe₂O₃; A/CNK is molar Al₂O₃/(CaO + Na₂O + K₂O); Ong, Ongonite; Vg, Vaugnerite; N(n), sample numbers for major and trace elements accordingly; (rest of symbols as Table 1).

most likely melting source rocks for the Inylchek granites are metagreywacks (Fig. 3). The two-mica leucogranite average composition in the field of clay-rich sources in the Rb/Ba vs. Rb/Sr diagram (Fig. 4) probably reflects Rb-accumulation during fractional crystallization rather than its concentration in the source rocks. The highly differentiated Li-mica leucogranites and ongonites are not plotted because their composition definitely does not reflect the primary melt composition.

Because some collisions may produce hotter peraluminous granites than other collisions, the CaO/Na₂O vs. Al₂O₃/TiO₂ diagram (Fig. 5) was used to evaluate the relative temperatures of the Karavshy and Inylchek granite melts. According to Sylwester (1998), the relative temperatures of strongly peraluminous granite melts are reflected in their Al₂O₃/TiO₂ ratios. Pelite- and psammite-derived granites with low Al₂O₃/TiO₂ ratios were derived at higher temperature than those with high Al₂O₃/TiO₂ ratios. The Karavshy granite average compositions fall along the low

Al₂O₃/TiO₂ (hot) join of the quadrilateral that encompasses the worldwide compositional array of strongly peraluminous granites, whereas the Inylchek granites tend to plot along the high Al₂O₃/TiO₂ (cool) join.

4. Calc-alkaline granites

The calc-alkaline granites also form two intrusive units inside both the Alay and the Kokshal segments of STCB: the Karakazyk diorite–granodiorite and the Mydrym granite complexes, respectively.

4.1. The Karakazyk diorite–granodiorite complex

Numerous plutons of the Karakazyk igneous complex are exposed in the Alay segment of STCB (Fig. 2). The complex consists of 65 intrusive bodies that cover a combined area of about 1200 km². The largest Karakazyk batholith is about

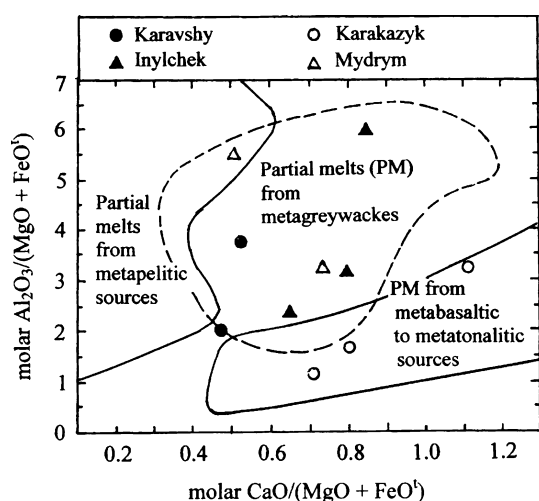


Fig. 3. Molar $\text{Al}_2\text{O}_3/(\text{MgO} + \text{FeO})$ vs. $\text{CaO}/(\text{MgO} + \text{FeO})$ diagram for average compositions of peraluminous and calc-alkaline granitoids from the South Tien Shan collisional belt. Outlined fields denote compositions of partial melts from different sources according to Alther et al. (2000).

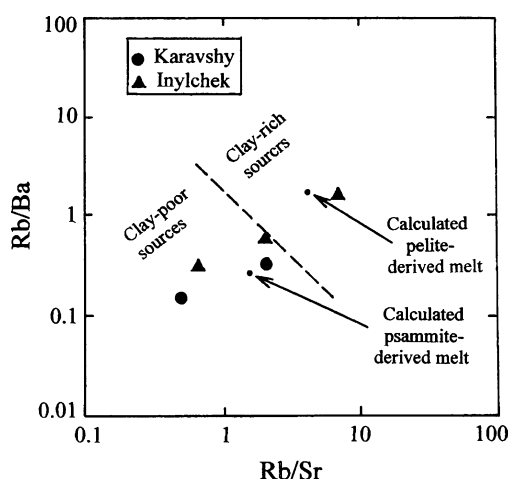


Fig. 4. Rb/Sr vs. Rb/Ba ratios for average compositions of peraluminous granites from the South Tien Shan collisional belt. The dashed line divides strongly peraluminous granites derived mostly from clay-poor sources from those formed mostly from clay-rich source rocks. Also plotted are calculated compositions of pelite- and psammite-derived melts (Sylwester, 1998).

520 km². The granitoids cut through and metamorphose fossil-bearing sediments varying in age from the Silurian to Upper Carboniferous (Byske, 1996). The K–Ar ages of amphiboles from diorites and granodiorites ranges from 259–280 Ma (Nenakhov et al., 1992) or Permian in age. In contrast to the Early Carboniferous subduction-related diorite–granodiorite association, the Karakazyk complex lacks any volcanic counterparts. In some places the Karakazyk granitoids cut the Karavshy S-type granites. The intrusive relations between the Karakazyk granitoids and shoshonites are contradictory. In some cases shoshonites are intrusively emplaced into granitoids, whereas in other cases granitoids cross-cut shoshonites (Nenakhov et al., 1992). The Karakazyk complex was formed by successive emplacement of four intrusive

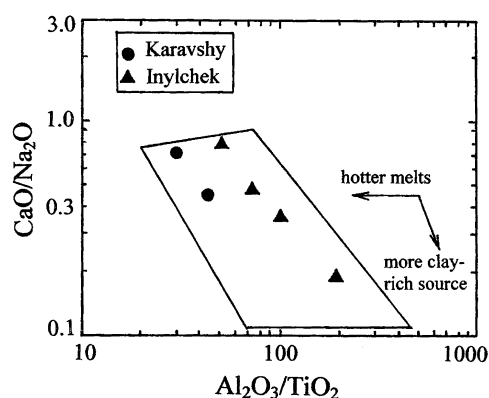


Fig. 5. $\text{CaO}/\text{Na}_2\text{O}$ vs. $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios for average chemical compositions of peraluminous granites from the South Tien Shan collisional belt. The quadrilateral field denotes the worldwide compositional array of strongly peraluminous granites by Sylwester (1998). See text for further explanation.

phases: (1) gabbro and gabbro-diorites; (2) quartz diorites and quartz monzodiorites; (3) granodiorites; (4) monzogranites. The gabbros occur solely as xenoliths among granitoids. The cores of the largest (0.5–1.8 km²) xenoliths usually consist of gabbro, which is gradually replaced by gabbro-diorite towards the margin. The quartz diorites (monzodiorites), granodiorites and monzogranites form composite plutons as well as separate bodies. The proportion of those rocks within composite plutons varies widely. The Karakazyk batholith, for example consists of: gabbro and gabbro-diorites – 2%, quartz diorites and monzodiorites – 58%, granodiorites – 30%, monzogranites – 10% (Nenakhov et al., 1992). The granitoids contain numerous mafic (meladiorite) microgranular enclaves displaying isotropic igneous texture. The mafic enclaves are larger and more abundant in quartz diorites and monzodiorites, whereas in granodiorites and especially monzogranites their number and size decrease.

The fine-grained gabbro exhibits ophitic texture, which is evidence of a shallow level intrusion. Major minerals are plagioclase and clinopyroxene (Table 1). Gabbro-diorite additionally contains quartz, more amphibole and less pyroxene. The quartz diorite and quartz monzodiorite, which grade each into the other, are medium-grained equigranular rocks. The major mafic mineral is amphibole. The quartz monzodiorite contains more K-feldspar, quartz and biotite and less clinopyroxene and plagioclase. The granodiorite is medium-grained and porphyritic. The most typical variety contains 10–20% megacrysts of K-feldspar. The monzogranite of the final intrusion is characterized by equal amounts of plagioclase and K-feldspar. The major mafic mineral is biotite, whereas amphibole is sparse.

The Karakazyk rocks exhibit a high-potassium, calc-alkaline trend (Fig. 6). All of them are metaluminous ($A/\text{CNK} = 0.88\text{--}0.94$) and characterized by relatively high concentrations of K, Mg, Ti, Rb, Sr, Ba and LREE (Table 2) in comparison with the low-K calc-alkaline rocks. No compositional gap is observed between gabbro and granite. On the basis of those features, the Karakazyk rocks were consid-

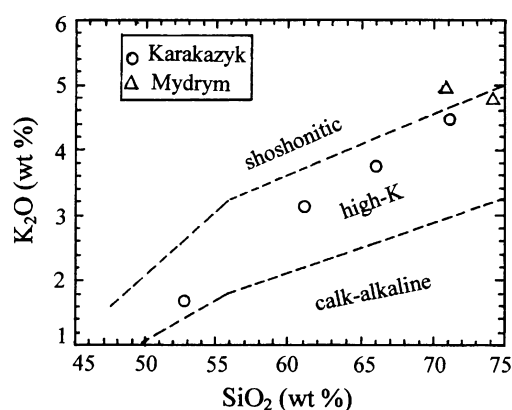


Fig. 6. K_2O vs. SiO_2 nomenclature diagram (Peccerillo and Taylor, 1976) for average compositions of calc-alkaline granitoids from the South Tien Shan collisional belt.

ered cogenetic and variations of their chemical composition were explained by fractional crystallization of mafic magma (Nenakhov et al., 1992). However, Sr-isotope data (Solomovich, 1996) indicate derivation of rocks from different sources. The initial $^{87}Sr/^{86}Sr$ ratios for quartz diorites and granodiorites ($Sr_0 = 0.7052\text{--}0.7057$) are significantly higher compared with gabbro and gabbro-diorites ($Sr_0 = 0.7041\text{--}0.7049$). In cases where fractional crystallization is not primarily responsible for the bimodal character of plutonism, contemporaneous melting of distinct mantle and crustal sources and interaction between mafic and felsic magmas may be a possible alternative (e.g., Zorpi et al., 1991; Petford et al., 1996; Poli et al., 1996; Ferre and Leake, 2001). From that viewpoint, the above-mentioned high concentration of incompatible elements and relatively enriched Sr-isotope signature of the Karakazyk mafic rocks in comparison with depleted asthenospheric mantle suggest an enriched lithospheric mantle source (e.g., Allen, 1991; Janousek et al., 1995; von Blanckenburg et al., 1998; Alther et al., 2000). Alternatively, high values of molar $CaO/(MgO + FeO^t)$ combined with low $Al_2O_3/(MgO + FeO^t)$ ratios suggest an origin for quartz diorites and granodiorites from metabasaltic to metatonalitic, lower-crustal sources (Fig. 3).

The petrological, geochemical and Sr-isotopic characteristics of the Karakazyk complex are similar to collision-related high-K, calc-alkaline, I-type plutonism in the European Variscides, the latter also explained in terms of mantle-crust interaction (Alther et al., 2000; Ferre and Leake, 2001). According the classification proposed by Barbarin (1999), the Karakazyk granitoids are related to the amphibole-rich, calc-alkaline (ACG) type.

4.2. Mydrym granite complex

Plutons of the Mydrym complex occur in the western part of the Kokshal segment of STCB (Fig. 2). The complex consists of seven medium-size bodies with a total area of about 400 km². According to geophysical evidence, more granite plutons are possibly buried under the thick Paleogene–Neogene molassa basin (Baybulatov

et al., 1983). The granites cut through and metamorphose the fossil-bearing sedimentary and volcanic rocks of Devonian and Early Carboniferous age. The K–Ar age of amphibole from granite (282 ± 6 Ma) corresponds to the Early Permian (Solomovich, 1996). All of the Mydrym complex plutons are made up of monotonous coarse-grained, densely porphyritic granites. Megacrysts are represented by K-feldspar. Mafic minerals are amphibole and biotite (Table 1). In some places, these granites are cross-cut by small stocks and sills consisting of fine-grained porphyritic biotite granites. The mafic microgranular enclaves (diameter up to 80 cm) are common in coarse-grained granites. The enclaves are rounded and characterized by isotropic igneous texture, fine-grained rims and acicular hornblende crystals, suggesting rapid cooling in colder granitic magma.

The dyke suite is usually represented by monotonous granite-porphyry. The swarm of parallel melanocratic dykes occurring inside the largest Mydrym pluton (Baybulatov et al., 1983) stands out against that background. The distinctive potassic and magnesian character of those rocks (Table 2) makes them close to vaugnerites, described by Ferre and Leake (2001) in the Corsica batholith. The melanocratic dyke swarm is traced for the distance about 10 km along the regional transcurrent NE fault, which cross-cuts the pluton. One of those dykes occurs in the center of a thick granite-porphyry dyke (dyke in dyke like structure). Numerous K-feldspar megacrysts that cross-cut the sharp contact of vaugnerite with the granite-porphyry host indicates the synplutonic character of vaugnerites (Baybulatov et al., 1983).

The chemical composition of these granites is also metaluminous and exhibits a high-K, calc alkaline trend (Fig. 6). However, in comparison with the Karakazyk I-type granites having the same silica content, they are distinguished by high values of general alkalinity ($K_2O + Na_2O = 8.84$), K_2O/Na_2O ratios and FeO^t but low contents of MgO , CaO , Sr and Ba (Table 2). These Mydrym granitic features together with their higher silica content, presence of tourmaline (Table 1) and relatively high initial Sr-isotopic ratios ($Sr_0 = 0.707\text{--}0.708$) (Solomovich, 1996) make them close to S-type granites. Thus the Mydrym granites have chemical and petrological features that may be considered transitional between I- and S-type granites. The chemical and isotopic characteristics of the Mydrym granites suggest that their parental magma was mostly derived from partial dehydration melting of metagreywackes (Fig. 3), probably slightly modified by input of mantle-derived vaugnerite magma. According to the classification of Barbarin (1999), the Mydrym granites are close to K-rich, K-feldspar porphyritic, calc-alkaline granites (KCG).

5. Alkaline granites

The alkaline (A-type) granites in STCB are represented by only one intrusive complex of the Jangart rapakivi gran-

ites, which occurs within the Saryjaz syntaxis close to the Inylchek leucogranite unit (Fig. 2). The Jangart complex consists of two large plutons and six small satellites, which together occupy an area about 1000 km². The granites cut through large masses of the Tarim platform basement, occurring within Paleozoic sedimentary rocks as well as fossil-bearing sediments varying in age from the Silurian to Upper Carboniferous. Both the Rb–Sr isochron age of 269 ± 21 Ma (Solomovich and Trifonov, 2002) and U–Pb zircon age of 296 ± 4.2 Ma (Mao et al., 2004) corresponds to the Permian. The main intrusive phase of the Jangart complex is represented by coarse-grained rapakivi granite and rapakivi quartz syenite, which grade into one other. The small stocks of medium- to fine-grained hastingsite–biotite granites crosscut the rapakivi. The enclaves within granites consist of metamorphosed country rocks. No mafic microgranular enclaves were found. Both rapakivi granite and quartz syenite are densely porphyritic and occasionally exhibit a trachytoid fabric. In the typical varieties, 30–40% of the K-feldspar megacrysts are surrounded by oligoclase rims 1–2 mm thick, to create a rapakivi-textured mantle. Besides the minerals listed in Table 1, rapakivis contain abundant accessory fluorite. Fayalite and wustite globules with native iron cores are also found in some samples with low quartz content (Jenchuraev and Solomovich, 1979).

The chemical composition of the Jangart rapakivi (Table 2) is close to that of the Fennoscandian Shield (Solomovich and Trifonov, 1990, 2002). In comparison with the calc-alkaline granites of similar SiO₂ content, they are notable for the high alkalinity (Na₂O + K₂O ranges from 8.0 to 9.1 wt%) with K₂O > Na₂O and slightly lower contents of CaO, MgO, and Al₂O₃. All the rocks are metaluminous. The presence of fayalite, wustite, and native iron along with high FeO^t/(FeO^t + MgO) ratios are indicative of low H₂O and O₂ fugacities in the magma, typical of rapakivi granites (Shinkarev and Ivanikov, 1983; Frost et al., 1999). The trace element contents (Table 2) also correspond to those of classical rapakivi. The high concentration of both compatible (Ni, Cr) and incompatible (Rb, Ba, and REE) elements are typical. The fluorine content (0.20–0.35 wt%) is especially high and close to that of rare-metal granite according to Koval (1998). Some geochemical features of the hastingsite–biotite granites, such as lower La/Yb ratios and more pronounced Eu anomalies, are consistent with fractionation of plagioclase and mafic minerals (Solomovich and Trifonov, 2002).

The moderately low initial ⁸⁷Sr/⁸⁶Sr ratio ($Sr_0 = 0.7075 \pm 0.0043$) along with low oxygen and water fugacity, suggest that a radiogenic felsic crustal source is unlikely for the Jangart rapakivi. Taking into account the well known spatial association of rapakivi with ancient platform basement exposures and similarity of their chemical composition to charnokites and enderbites (Collins et al., 1982; Shinkarev and Ivanikov, 1983), the deeply metamorphosed and dehydrated (granulitic) basement of the Tarim platform submerged beneath STCB is considered

the most likely source of the Jangart granites (Solomovich and Trifonov, 2002).

6. Discussion

All available paleontological and isotopic data definitely establish the Permian age of the above-described granitic units. However, because of significant errors of isotope analyses, those data are not reliable enough to specify the age relations between different types of granites as well as between granites and shoshonites, especially as the emplacement ages of those rocks can be very close. For instance, S- and I-types granites in the northern Vosges (European Variscides) were emplaced within the narrow time span of just 6 Ma (Alther et al., 2000). Meanwhile, the age relation between granites and shoshonites is crucial, because the emplacement of extension-related shoshonites marks the transition from syncollisional compression to postcollisional strike-slip tectonics.

The field observations show that the only granites within STCB carrying some traces of foliation are the Karavshy migmatite–granites. However, they also host mafic microgranular enclaves. The evidence is overwhelming that those enclaves represent globules of quenched, mafic magma mingled and modified by exchange with host granitic magma (Clemens, 2003). Therefore, the formation of the Karavshy granites is supposed to begin during the syncollisional stage of thrusting and folding and end at the postcollisional stage of strike-slip and extensional faulting. The tectonic setting of S-type granites within other collisional orogens is also controversial. However, it is now apparent that the large majority of collision-related, strongly peraluminous granites are best described as postcollisional, in that they were emplaced after the climax of crustal thickening (Sylwester, 1998).

I-type granites of the Karakazyk complex crosscut the Karavshy S-type granites and their intrusive phases alternate reciprocally with shoshonites. The postcollisional emplacement of I-type granites within STCB as well as other orogens (Pitcher, 1983; Pearce et al., 1984; Harris et al., 1986; von Blanckenburg, 1992) is undisputable. The postcollisional character of the transitional (I–S) type Mydrym granites is confirmed by the presence of synplutonic vaugnerite dykes and numerous mafic microgranular enclaves.

The Saryjaz syntaxis, where the peraluminous leucogranites of the Inylchek and rapakivi of the Jangart occur, lacks shoshonites and vaugnerites and no mafic microgranular enclaves were found within granites. However, the postcollisional emplacement of those granites is confirmed by their tectonic arrangement. Both leucogranites and rapakivi are discordant with the Paleozoic country rocks and form E–W-striking chains along transcurrent shear zones that crosscut the folded structure obliquely (Trifonov and Solomovich, 1993; Solomovich and Trifonov, 2002).

The postcollisional period of strike-slip tectonics is usually accompanied by lithosphere thinning, delamination

and upwelling of the asthenosphere, which can rise to melting depths. Mantle-derived magma emplaced within the lower crust provides enough heat to enhance crustal anatexis. That mafic magma can be injected into and mix with the crust-derived melt (Sylwester, 1998; Bonin, 2004). However, the ability of the asthenosphere to reach melting depths depends on previous lithosphere thickening. The simulations indicate that mantle melting could be possible if asthenosphere were able to ascend to depths of 50 km or less (e.g., Davies and von Blanckenburg, 1995).

Moderate crustal thickening, high-temperature–low-pressure metamorphism and numerous shoshonitic intrusions in the Alay segment of STCB suggest that asthenospheric upwelling was able to reach shallow mantle depths and produce anatexis inducing mafic magmas. In that way, relatively ‘hot’ cordierite- and sillimanite-bearing peraluminous (S-type) granites of the Karavshy and voluminous calc-alkaline (I-type) granites of the Karakazyk formed. In the Kokshal segment, where extensive syncollisional crustal thickening confirmed by ultra high-pressure metamorphism occurred, postcollisional upwelling of asthenosphere was largely unable to reach depths sufficiently shallow for melting. This is particularly true for the Saryjaz syntaxis, which lacks shoshonites. Syncollisional, in situ, radiogenic heating of overthickened crust followed by postcollisional decompression melting along the deep-rooted shear zone, produced a small volume of relatively ‘cool’, two-mica, peraluminous leucogranites of the Inylchek. In the western, more widened portion of the Kokshal segment, where the mantle manifested itself by the swarm of vougnerite dykes, a moderate volume of calc-alkaline transitional (I–S) type granites of the Mydrym formed.

The high-temperature vs. high-pressure collision hypothesis provides a satisfactory explanation for some distinct peculiarities of postcollisional magmatism in different segments of STCB. However, the origin of alkaline (A-type) rapakivi granites of the Jangart remains poorly understood. On the one hand, the inability of asthenospheric upwelling to reach depths sufficiently shallow for melting beneath the overthickened lithosphere of the Saryjaz syntaxis makes a mantle-derived source (e.g., Eby, 1992; Turner et al., 1992; Bonin, 1998) to be unlikely for the Jangart rapakivi. On the other hand, melting of the refractory low-crustal granulitic source without any significant mantle-derived heat input should also be ruled out.

In contrast to their abundant mid-Proterozoic counterparts, the Phanerozoic rapakivis are very sparse and are never accompanied by anorthosites (Shinkarev and Ivanikov, 1983), which are usually considered to be derivatives of mantle melts that caused the anatexis of the granulitic lower crustal domains (Collins et al., 1982; Christiansen et al., 1983; Clemens et al., 1986; Creaser et al., 1991). In this scenario, the similarity of the chemical composition of rapakivi with charnokites and enderbites (Collins et al., 1982; Shinkarev and Ivanikov, 1983) is evidence of a high-degree of melting of the granulitic source, which was possi-

ble because of high geothermal gradients within the Proterozoic crust and mantle (e.g., Hand et al., 1999). In the Phanerozoic folding belts, the high-degree of melting of a refractory lower-crustal granulitic source is possible only as the result of descent of those source rocks to considerable depths during continental subduction. The Jangart rapakivi granitic melt could have formed by a two-step process involving: (1) syncollisional submersion of the Tarim platform granulitic basement into the mantle accompanied by considerable heating of source rocks, (2) ‘rapid’ postcollisional exhumation followed by decompression and extensive high-degree melting. From this point of view, both coesite eclogites of the Atbashy and rapakivi of the Jangart are consequences of the same continental subduction event.

7. Conclusion

The equal extent of the Mesozoic peneplain preservation in the Tien Shan highland both to the west and to the east of the Talas-Fergan strike-slip fault (Adyshev, 1987) is evidence that the Alay and Kokshal segments represent the single structural level of STCB. Therefore, distinct patterns of regional metamorphism and postcollisional magmatism in those segments are best explained by changes in continental crustal thickness and structure, which in turn were a consequence of different continental collision styles.

Acknowledgement

The author is grateful to Professor Boris Natal'in for critical review and good suggestions.

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