

Hercynian post-collisional A-type granites of the Kokshaal Range, Southern Tien Shan, Kyrgyzstan

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Abstract

The Tien Shan (Tianshan) orogen formed during Late Palaeozoic collision between the Karakum–Tarim continent and the Paleo-Kazakhstan continent, a Caledonian component of the Altaid Collage. The Southern Tien Shan terrane represents an intensely deformed fold and thrust belt formed after the final closure of the Paleo-Turkestan ocean. In the Late Carboniferous–Early Permian the Tien Shan was affected by regionally developed diverse post-collisional magmatism. Post-collisional granites of the Kokshaal Segment (350 × 100 km), the easternmost segment of Southern Tien Shan in Kyrgyzstan, include some 20 post-tectonic intrusions varying in composition from biotite–hornblende rapakivi granite to biotite and topaz-bearing leucogranite. The granites are associated with coeval tholeiitic mafic rocks and with alkaline undersaturated syenites. The granites have a pronounced A-type affinity: they are metaluminous with high concentrations of Na₂O + K₂O, Rb, HFSE and high K₂O/Na₂O and Fe/(Fe + Mg) ratios, and comprise a single geochemical trend explained by fractionation of K-feldspar and hornblende. The U–Pb zircon SIMS ages of the Djangart, Uch-Koshkon, Mudryum and Kok-Kiya intrusions of the Kokshaal are 296 ± 4 Ma, 279 ± 8 Ma, 281 ± 2 Ma and 281 ± 3 Ma, respectively. The oldest age was obtained for rapakivi granites in the eastern part of Kokshaal while the leucogranites in its western part were dated at 280 Ma. This time span closely corresponds to known ages of post-collisional granitoids and related gold deposits of the Tien Shan. The granites have negative initial ϵ_{Nd} values (−1.6 to −6.9 at 280 Ma) and depleted mantle model ages of 1.05–1.43 Ga indicating a mixing of asthenospheric mantle and Precambrian crustal components. Precambrian Mesoproterozoic crust comprises the basement of the Tarim microcontinent underthrust to the north beneath the sedimentary piles of Kokshaal. Mafic rocks associated with the granites may represent juvenile asthenospheric melts underplating the Tarim margin at the post-collisional stage and providing heat for generation of A-type granites from its Precambrian crust. Lithospheric plate-scale strike–slip shear zones that formed in the region subsequent to collision provided suitable conduits for ascending asthenospheric material.

On a regional scale, available Nd data for the Tien Shan show that most Paleozoic felsic rocks originated from Precambrian crustal sources. The Northern Tarim rocks, exposed in the Kokshaal Range, and rocks of the southern Paleo-Kazakhstan margin have similar Proterozoic depleted mantle model ages.

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1. Introduction

The Tien Shan is one of the major Asian mountain systems extending for 3000 km from the Gobi desert in Mongolia to the lowlands of western Uzbekistan. The mountain system formed in the course of Cenozoic collision between India and Asia followed by reformation, uplift and exposure of the older Palaeozoic mobile belts. The Palaeozoic Tien Shan is a part of the giant Central Asian Orogenic Belt (CAOB) (Jahn et al., 2000a,b) also called the Altaid Collage (Sengör et al., 1993). The CAOB formed since the Neoproterozoic by continuous subduction–accretion and final amalgamation in the Late Paleozoic between the Eastern European Craton in the west, the Siberian Craton in the east and smaller Karakum and Tarim Precambrian continents in the south (Figs. 1 and 2). The characteristic feature of the CAOB is voluminous multistage granitoid magmatism, which culminated in the Late Palaeozoic. Recent Sr–Nd isotope studies in several terranes show that the granites represent a significant addition of juvenile mantle component to the

continental crust, indicating that the CAOB was an important site of crustal growth during the Phanerozoic (Chen et al., 2000; Heinhorst et al., 2000; Jahn et al., 2000b, and references therein). However, timing and sources of diverse magmatism are still poorly constrained in many areas due to scarcity of geochemical and geochronological data.

The Tien Shan in SE Kyrgyzstan represents an example of granitoid, mafic and alkaline silica undersaturated intrusions emplaced during the Late Carboniferous–Early Permian. The regional, cross-terrane boundary nature and diverse character of this magmatism define its tectonic significance for the post-collisional evolution of the Tien Shan lithosphere. Metallogenic importance is outlined by the world-class gold deposits of the “Tien Shan gold belt” closely associated with the Late Paleozoic granitoids in time and space (Yakubchuk et al., 2002; Mao et al., 2004; Yakubchuk, 2004). In this paper we present ion probe U–Pb zircon ages, elemental geochemistry and Nd isotope data for post-collisional A-type granitoid

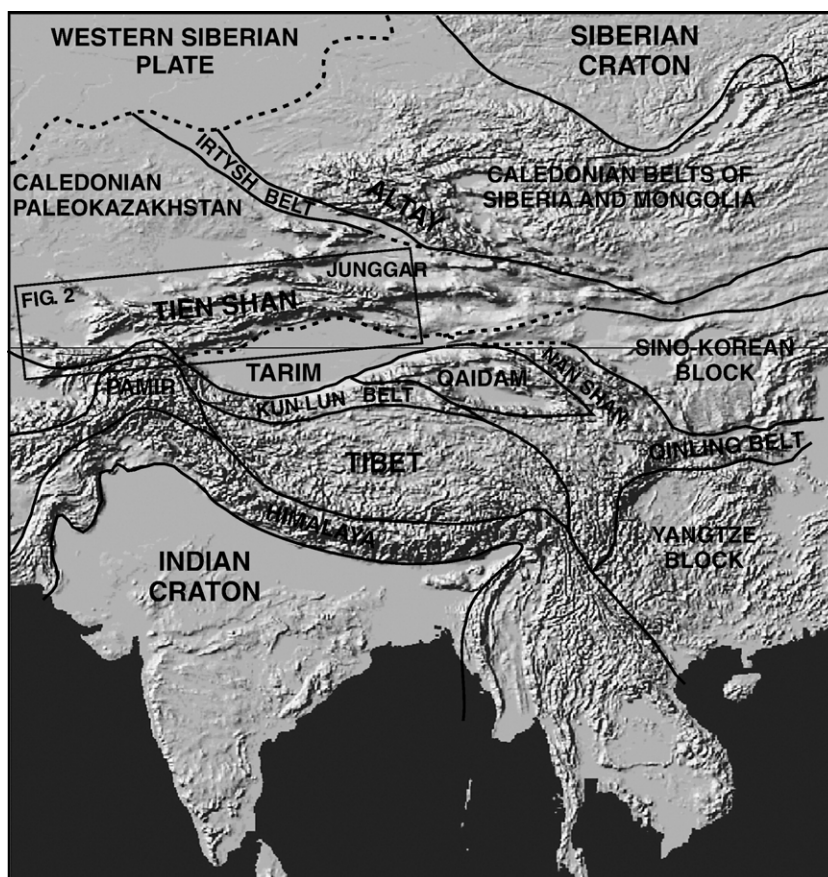


Fig. 1. Topography of Asia and major geo-tectonic units. The image compiled from USGS GTOPO30 digital topography data (800 m ground-resolution).

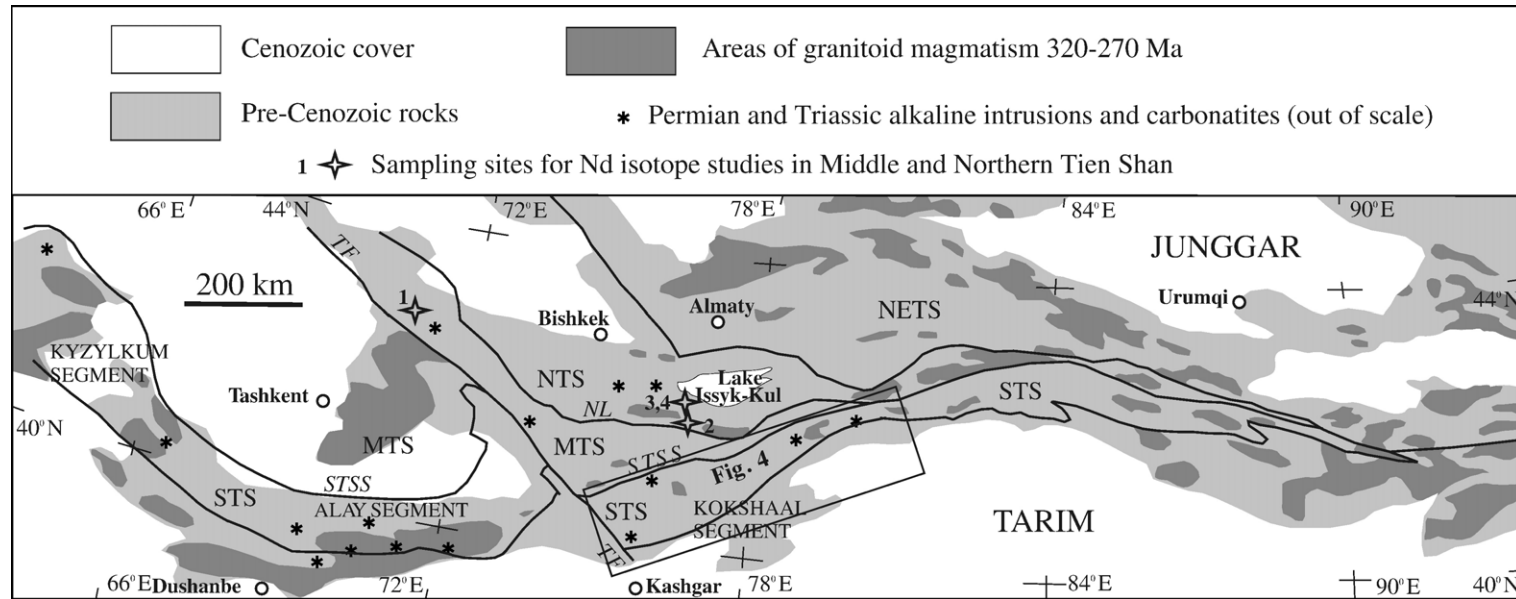


Fig. 2. Principal terranes and tectonic lineaments of the Tien Shan and distribution of Hercynian granites. Abbreviations: NTS — Northern Tien Shan, NETS — North-Eastern Tien Shan, MTS — Middle Tien Shan, STS Southern Tien Shan, NL — Nikolaev Line, STSS — Southern Tien Shan Suture, TF — Talas-Farghona strike-slip fault. Sampling sites outside the territory shown on Fig. 3: 1 — sample 301500, 2 — 301300, 3 — 301400, 4 — 301600. Alkaline intrusions on the Chinese territory are not shown.

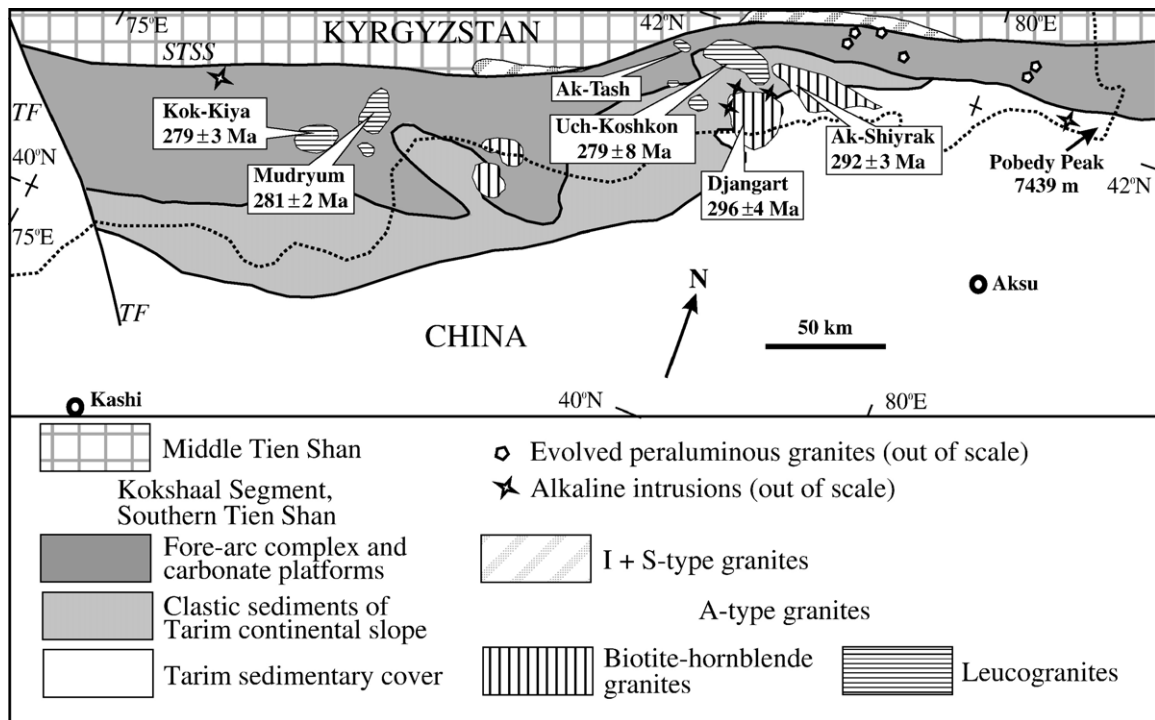


Fig. 3. Schematic geological map of the Kokshaal Segment of Southern Tien Shan with names and ages of granite intrusions under study. STSS — Southern Tien Shan Suture, TF — Talas-Farghona fault. Dashed line corresponds to international border.

intrusions in the 400 km long and 100 km wide Kokshaal range, SE Kyrgyzstan (Figs. 2 and 3). The geology and magmatism of the area are reviewed on a regional scale and regional tectonic implications of the obtained data are discussed.

2. Regional geological setting

2.1. The terranes

The Hercynian Tien Shan orogen formed during Late Palaeozoic collision between the Karakum–Tarim continent and the Paleo-Kazakhstan continent, a Caledonian component of the Altaid Collage. The western part of the Tien Shan in Kyrgyzstan and Uzbekistan is composed of three major structural units or terranes (Fig. 2): (1) the Northern Tien Shan, the deformed margin of the Palaeo-Kazakhstan continent; (2) the Middle Tien Shan, a Late Paleozoic volcano-plutonic arc; and (3) the Southern Tien Shan, an intensely deformed fold and thrust belt formed after the final closure of the Paleo-Turkestan ocean (Zonenshain et al., 1990). In Chinese territory, the Borohoro arc and Paleo-Kazakhstan terranes bordering the Northern Tien Shan, are also considered as a part of the Tien Shan orogen (e. g. Chen et al., 1999). These terranes are shown in Fig. 2 as the North-East Tien Shan.

The Northern Tien Shan in Kyrgyzstan is represented by the Early Palaeozoic continental arc and its Precambrian basement intruded by voluminous Ordovician granitoids. The main component of the Middle Tien Shan is the Carboniferous Beltau–Kurama volcano-plutonic belt developed on Precambrian basement. This belt is usually considered either as an active continental margin of the Palaeo-Kazakhstan or as a continental arc that was accreted to the Palaeo-Kazakhstan margin ca. 320 Ma ago (e.g. Yakubchuk et al., 2002). In Kyrgyzstan, the Northern and Middle Tien Shan are separated by the Nikolaev Line (Fig. 2), a Hercynian strike-slip fault generally following a Caledonian suture. The Southern Tien Shan (Figs. 2 and 3) includes intensely deformed fore-arc accretionary complexes together with passive margin sediments of the Karakum–Tarim continent. The Middle and Southern Tien Shan terranes are separated by the Southern Tien Shan Suture defined by ophiolites with ages ranging from the Early Silurian to Early Carboniferous (Jun et al., 1998; Chen et al., 1999). In Uzbekistan and Kyrgyzstan the Southern Tien Shan is traditionally divided into 3 segments from west to east: the Kyzylkum Segment, the Alay Segment and the Kokshaal Segment (Fig. 2). The Talas-Farghona dextral strike-slip fault separates the western terranes of the Tien Shan, the Kyzylkum and

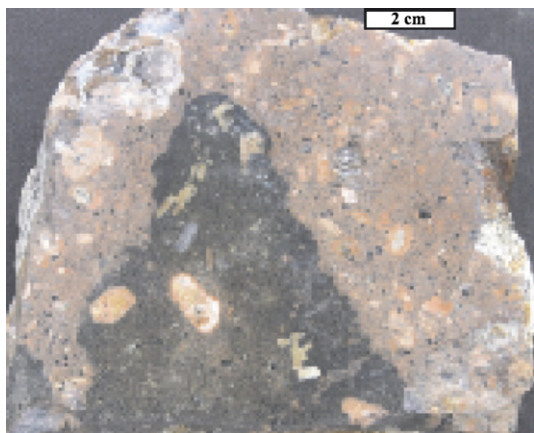


Fig. 4. Mafic enclaves in hybrid granitic matrix in the Mudryum intrusion.

Alay segments of the Southern Tien Shan and Chatkal–Kurama ranges of the Middle Tien Shan, from the eastern terranes (Fig. 2). Estimations of the age of the Tarim–Paleo-Kazakhstan collision vary from the Late

Devonian to Late Carboniferous–Early Permian (Windley et al., 1990; Allen et al., 1992; Biske, 1995; Biske and Shilov, 1998; Chen et al., 1999; Carroll et al., 2001; Zhou et al., 2001). Thick early Permian molasses indicate the final closure of the Paleo-Turkestan ocean and uplift. An eye-catching feature of the present day Tien Shan geology is a number of major east–west striking trans-crustal strike-slip faults dividing the Tien Shan into a series of tectonic blocks. These faults formed in the Early Permian (Laurent-Charvet et al., 2003) and controlled post-collisional magmatism and important mineralization (e.g., Mao et al., 2004; Konopelko et al., 2006).

2.2. Hercynian magmatism

Regional distribution of the 320–270 Ma granitoid intrusions in the Tien Shan is shown in Fig. 2. The published ages of magmatic rocks are mostly based on K–Ar and Rb–Sr isotopic systems that are sensitive to

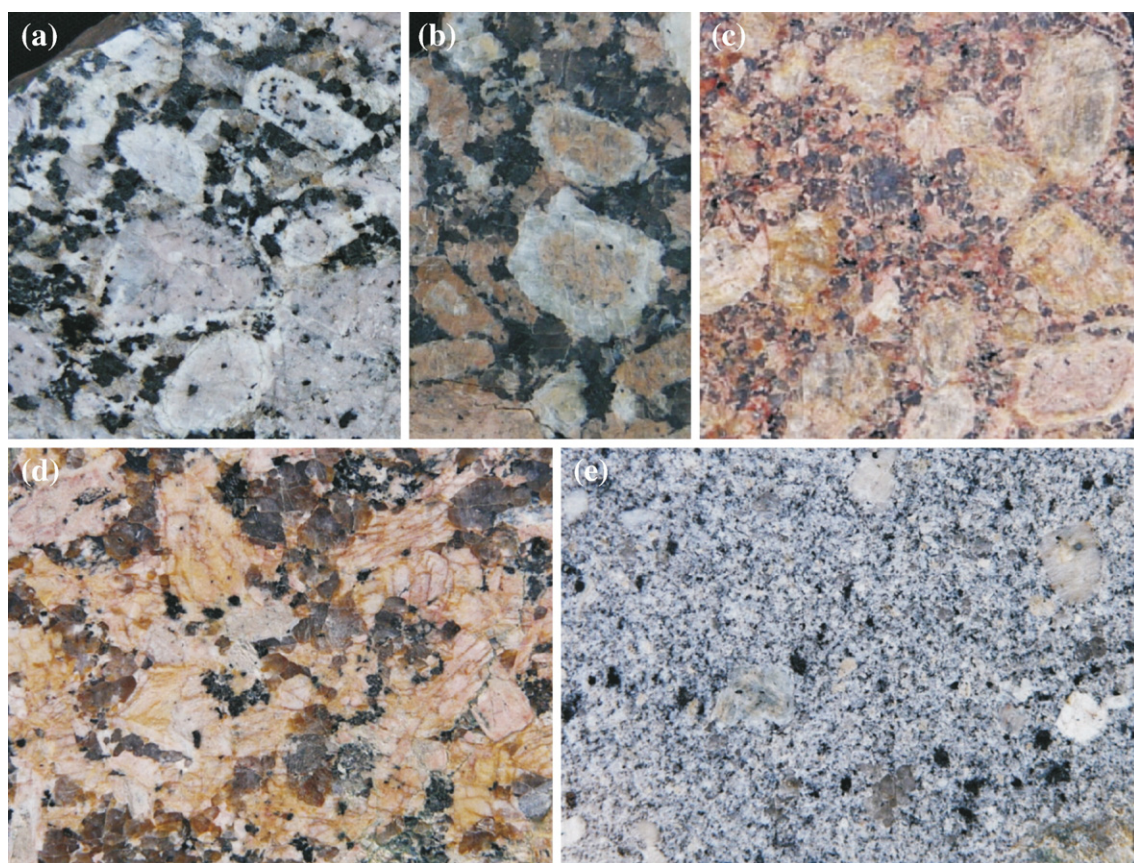


Fig. 5. Main rock-types of Kokshaal granites: (a) and (b) ovoidal rapakivi granites from Djangart intrusion, width of photographs 5.7 and 3.8 cm, respectively, (c) leucogranite from Kok-Kiya intrusion with unmantled ovoidal K-feldspar megacrysts, width 4 cm, (d) equigranular leucogranite from Uch-Koshkon intrusion, width 7 cm, (e) tourmaline-bearing miarolitic leucogranite from Mudryum intrusion, width 6.8 cm.

post-magmatic processes. However, two magmatic pulses are clearly distinguished in the literature (Biske, 1995; Jenchuraeva, 1997; Konopelko et al., 2006). The Middle Tien Shan comprises 320–300 Ma old thick volcanic units of the Beltau–Kurama arc and deformed calc–alkaline intrusions of the eastern Tien Shan in Kyrgyzstan. This calc–alkaline magmatism presumably indicates active subduction and predates the closure of the Paleo-Turkestan ocean. In contrast to the Carboniferous calc–alkaline intrusions, spatially associated with the east–west striking volcanic belts, the Early Permian post-collisional magmatism that culminated at 290–280 Ma affected the whole region across terrane boundaries. The diverse post-collisional granitoid intrusions are associated with mafic and silica undersaturated alkaline rocks (Konopelko and Biske, 1996). Undivided Permian and Triassic alkaline complexes and carbonatites of the Tien Shan are shown on Fig. 2.

3. The intrusions of the Kokshaal range

3.1. Geology

The Kokshaal Segment of the Southern Tien Shan consists of three major tectonic units (Fig. 3). The northernmost unit comprises turbidites, cherts and carbonate platforms of the fore-arc accretionary complex. The fore-arc complex is structurally underlain by deformed clastic sediments of the Tarim passive margin. The passive margin formations are bordered in the south by sedimentary cover of the Tarim microcontinent. The fore-arc and the Tarim continental slope sediments are intensely deformed and thrust to the south over the Precambrian basement of the Tarim.

Granitoid magmatism of the Kokshaal differs markedly from that of the westernmost Kyzylkum and Alay segments of the Southern Tien Shan (Fig. 2), where calc–alkaline suites prevail. In the Kokshaal, deformed syncollisional I and S granitoids occur only as large fragments within the Southern Tien Shan Suture zone or immediately south of it. To the south of the suture, in the Kyrgyz part of Kokshaal, some 25 granitoid intrusions of clearly postorogenic tectonic setting are situated (Fig. 3). About 20 intrusions in the western and central part of Kokshaal have affinity to the A-type granites while several small stocks in its eastern part are evolved, strongly peraluminous granites (Solomovich and Trifonov, 2002). Granites of both types host greisen-type Sn and Sn–W deposits (Seltmann et al., 2003). Previous publications on the Kokshaal granites (Biske et al., 1996; Solomovich and Trifonov, 2002 and references therein) provide detailed geological and petrographic descrip-

tions but lack precise geochemical and geochronological data. The present study is focused on the regionally developed A-type complex (Fig. 3). Two principal groups of intrusions were recognised in this complex in previous works (Biske et al., 1996; Konopelko and Biske, 1996; Solomovich and Trifonov, 2002; Konopelko et al., 2003):

- (1) Biotite–hornblende granites and quartz monzonites with rapakivi (wiborgite) texture form two large plutons, up to 200 km²: Djangart and Ak-Shiyarak. Ovoidal rapakivi granites represent the main facies at the present erosion surface. However, K-feldspar megacrystic granites with strong trachytoidal fabric comprise the second textural type in the Djangart pluton. Mafic rocks are represented by the small bodies of early biotite–hornblende monzonites and monzodiorites. Coeval alkaline silica undersaturated rocks are associated with the Djangart and Ak-Shiyarak granite plutons locally yielding a wide spectrum of hybrid rocks.
- (2) Biotite leucogranites form the Uch-Koshkon and Mudryum plutons and a number of smaller intrusions. A typical feature of all intrusions is the occurrence of equigranular, porphyritic, and tourmaline-bearing miarolitic facies. The only exception is the Kok-Kiya intrusion made up of biotite–hornblende leucogranite with unmantled ovoidal K-feldspar megacrysts (piterlite texture). The most evolved quartz porphyries and greisen-affected varieties are topaz-bearing. Gabbroic dykes and small bodies with local evidence of mingling cut leucogranites of the Mudryum and Kok-Kiya intrusions in the western part of Kokshaal. An illustration of co-mingled granitic and basaltic melts from the Mudryum intrusion is presented in Fig. 4. Detailed petrographic description of the rock-types was published by Solomovich and Trifonov (2002) and is not repeated in this paper. Photographs of main rock-types including ovoidal rapakivi granites, equigranular and tourmaline-bearing miarolitic leucogranites are given in Fig. 5.

3.2. Geochemistry

Representative analyses of the Kokshaal granites and related mafic rocks are given in Table 1. Major elements were analysed by XRF, trace elements by ICP-AES (Ecole des Mines de Saint Etienne, France), and in particular REE by ICP-MS (GFZ Potsdam, Germany)

Table 1

Chemical composition of Kokshaal granites and related mafic rocks

Intrusion	Ak-Tash	Djangart	Djangart	Djangart	Ak-Shiyarak	Ak-Shiyarak	Kok-Kiya	Kok-Kiya	Kok-Kiya	Kok-Kiya	Mudryum
Rock-type	Monzo-diorite	Rapakivi granite	Rapakivi granite	Trachitoidal granite	Rapakivi granite	Hybrid syenite	Ovoidal granite	Ovoidal granite	Ovoidal granite	Mafic enclave	Coarse-gr. granite
Sample	212305	209202	208905	100192	215701	215703	221801	280701	280500	280901	220702
SiO ₂	61.68	66.75	67.36	66.59	65.45	66.71	71.55	71.18	69.78	64.58	71.16
TiO ₂	0.98	0.53	0.51	0.71	0.78	0.20	0.32	0.38	0.40	0.70	0.33
Al ₂ O ₃	15.31	14.28	14.91	14.43	13.48	15.50	13.25	13.37	13.08	14.78	13.60
FeO ^{tot}	7.61	4.14	3.41	4.97	6.34	3.02	2.82	2.59	3.37	4.58	2.48
MnO	0.12	0.08	0.06	0.08	0.10	0.08	0.06	0.05	0.07	0.11	0.06
MgO	1.12	0.56	0.55	0.84	0.81	0.09	0.34	0.39	0.49	1.37	0.33
CaO	4.46	2.11	2.37	3.15	3.03	1.52	0.94	1.42	1.37	2.90	1.57
Na ₂ O	3.40	3.82	4.56	2.94	3.26	4.34	3.50	4.01	3.96	5.90	3.03
K ₂ O	3.87	5.28	4.57	4.54	4.29	6.15	4.84	4.93	4.76	3.21	4.82
P ₂ O ₅	0.35	0.15	0.14	0.21	0.24	0.04	0.07	0.08	0.08	0.17	0.10
LOI	0.68	0.59	0.88	0.42	0.63	0.51	0.38	1.70	0.59	0.61	0.59
F	0.02	0.31	#	0.03	0.13	#	0.06	0.18	0.04	0.07	0.15
Cr	7.8	7.8	11.3	5.7	4.5	2.8	4.7	5.8	4.9	24.3	4.7
Ni	5.5	4.0	6.9	3.7	3.1	1.6	2.6	2.9	3.1	12.2	2.6
V	40.7	22.1	27.3	42.9	24.0	2.5	12.4	15.7	15.6	73.3	12.5
Li	24	75	#	#	61	#	48	#	#	#	118
Rb	130	285	207	191	202	191	236	251	254	137	302
Ba	892	580	844	761	593	157	331	335	321	240	484
Sr	314	129	203	217	171	52	82	92	94	152	144
Ga	#	22.0	#	20.3	#	#	23.7	24.0	22.7	20.1	20.0
Zr	540	392	263	268	300	820	420	589	479	232	254
Hf	12.40	10.10	6.71	8.94	7.94	17.90	13.40	16.60	13.00	5.98	7.57
Y	45.9	61.0	38.1	35.2	70.8	39.1	62.2	69.7	77.2	49.8	36.9
Nb	45.0	42.0	35.3	31.4	64.7	78.4	37.4	42.4	48.8	24.0	36.3
Ta	2.67	2.64	2.30	1.92	4.30	3.67	2.29	3.65	3.03	1.42	3.04
U	2.08	8.95	2.90	1.29	4.16	5.08	5.12	4.85	4.25	3.79	6.04
Th	11.6	51.7	19.3	17.1	21.1	27.3	24.3	38.4	35.0	14.4	42.3
Pb	66.8	31.9	36.9	19.7	34.0	31.3	46.3	40.7	35.9	49.0	30.5
Sn	#	9.6	#	#	#	#	6.6	8.0	5.7	#	6.3
La	50.7	96.2	54.7	61.3	79.2	154.0	71.9	89.9	90.6	54.4	61.3
Ce	110	180	105	120	174	289	138	172	172	112	113
Pr	13.5	18.6	11.3	13.4	21.1	29.5	15.2	18.5	18.5	12.9	11.6
Nd	54.7	62.9	40.4	49.4	81.7	97.4	55.1	65.0	65.9	47.6	38.8
Sm	11.60	11.50	7.74	9.46	16.30	14.80	10.80	12.50	12.70	9.39	6.97
Eu	3.54	1.24	1.56	1.84	1.94	1.16	0.67	0.65	0.65	1.05	0.80
Gd	10.70	10.00	7.08	8.01	14.70	10.80	10.30	11.70	11.90	8.52	5.97
Tb	1.65	1.63	1.10	1.17	2.22	1.49	1.71	1.93	2.02	1.36	0.99
Dy	9.18	10.50	6.91	6.94	13.30	8.57	11.00	12.30	12.80	8.70	6.35
Ho	1.75	2.14	1.33	1.33	2.58	1.58	2.31	2.52	2.67	1.78	1.29
Er	4.82	6.39	4.03	3.63	7.31	4.39	6.94	7.56	8.28	5.37	4.07
Tm	0.65	0.92	0.56	0.48	1.02	0.61	0.99	1.10	1.22	0.79	0.61
Yb	4.17	5.99	3.59	3.25	6.60	4.02	6.72	7.57	8.27	5.22	4.44
Lu	0.59	0.84	0.48	0.47	0.93	0.61	0.97	1.07	1.19	0.76	0.67
ASI	0.85	0.90	0.89	0.93	0.87	0.93	1.04	0.92	0.92	0.80	1.04
Fe(Fe+Mg)	0.79	0.81	0.78	0.77	0.81	0.95	0.82	0.79	0.79	0.65	0.81
Ga/Al* 10000		2.91		2.66			3.38	3.39	3.28	2.57	2.78

SiO₂ — F wt.%; Cr — Lu ppm; # — element not determined. FeO^{tot} — total Fe as FeO; ASI = Al₂O₃/(CaO + Na₂O + K₂O) mol.; Fe(Fe + Mg) = FeO^{tot}/(MgO + FeO^{tot}) mol.

Intrusion	Mudryum	Mudryum	Mudryum	Mudryum	Uch-Koshkon	Uch-Koshkon	Uch-Koshkon	Uch-Koshkon	Uch-Koshkon	Ak-Tash
Rock-Type	Greizen granite	Coarse-gr. granite	Miarolitic granite	mafic dyke	Coarse-gr. granite	Coarse-gr. granite	Porphyritic granite	Miarolitic granite	Quartz porphyry	Quartz porphyry
Sample	280301	280001	220801	280401	205401	206801	207601	205201	206101	212301
SiO ₂	75.48	73.88	75.23	56.23	74.82	73.77	73.28	72.39	74.33	73.41
TiO ₂	0.10	0.10	0.08	1.80	0.14	0.22	0.26	0.11	0.06	0.21
Al ₂ O ₃	12.36	13.09	12.62	14.53	13.05	12.95	13.42	14.08	13.73	12.74
FeO	0.90	1.40	1.22	10.15	1.75	2.24	2.01	1.73	1.05	1.63
MnO	0.01	0.04	0.02	0.16	0.03	0.05	0.03	0.04	0.03	0.01
MgO	0.10	0.06	0.08	3.46	0.16	0.27	0.22	0.12	0.03	0.14
CaO	0.64	0.78	0.69	6.46	0.95	1.42	1.42	0.72	0.55	0.72
Na ₂ O	3.70	4.00	2.86	3.67	3.64	3.46	2.52	3.14	3.57	2.64
K ₂ O	4.88	4.96	4.94	2.34	4.68	4.78	5.33	5.26	4.97	5.60
P ₂ O ₅	0.03	0.03	0.03	0.39	0.04	0.07	0.06	0.04	0.03	0.06
LOI	0.77	0.62	0.87	0.46	0.91	0.85	0.95	1.17	0.73	1.43
F%	0.19	0.35	0.22	0.09	0.50	0.37	0.27	0.28	0.61	0.04
Cr	7.8	3.2	5.5	10.9	#	2.6	2.4	1.3	1.8	6.8
Ni	4.2	1.7	2.5	16.4	#	1.3	1.3	1.0	1.4	2.9
V	4.0	2.2	2.4	136.0	#	9.3	8.6	5.9	3.2	10.8
Li	#	#	67	#	202	#	111	#	#	#
Rb	405	473	423	179	496	373	420	567	824	254
Ba	56	42	47	546	212	250	284	235	43	286
Sr	20	15	20	356	47	74	61	48	12	56
Ga	20.8	23.0	20.8	21.0	24.0	22.0	20.5	24.5	28.0	22.5
Zr	143	157	152	227	167	206	264	167	122	213
Hf	5.98	6.74	6.40	5.55	6.80	6.88	8.04	6.47	6.30	6.62
Y	55.0	82.6	49.0	32.8	94.0	62.1	41.6	60.6	65.7	50.7
Nb	45.6	55.8	50.8	24.4	25.9	23.4	26.0	24.6	31.4	36.6
Ta	4.83	5.71	4.12	1.53	4.96	3.30	2.66	3.50	6.85	2.35
U	4.46	5.31	5.74	2.83	10.00	14.80	5.71	15.40	5.72	2.38
Th	48.5	59.9	51.6	11.1	58.9	56.4	50.5	38.3	50.5	23.8
Pb	34.2	43.5	46.9	13.1	34.0	37.0	42.6	43.4	44.5	35.6
Sn	6.1	#	#	20.2	22.0	9.0	9.7	67.4	19.0	8.7
La	48.5	54.3	42.8	36.6	44.5	55.6	81.9	35.0	24.4	73.1
Ce	96	112	88	73	96	115	159	70	62	152
Pr	10.6	12.6	9.6	8.4	10.8	12.7	16.3	8.5	6.9	16.7
Nd	35.6	43.9	33.1	32.8	41.1	44.2	55.0	31.0	27.7	61.1
Sm	7.18	9.85	6.73	6.67	9.81	9.31	9.53	7.58	7.85	12.30
Eu	0.20	0.18	0.15	1.73	0.41	0.58	0.60	0.39	0.05	1.20
Gd	6.82	9.43	6.39	6.54	10.30	8.54	7.56	8.05	8.02	10.60
Tb	1.23	1.72	1.12	1.01	2.09	1.47	1.16	1.47	1.77	1.58
Dy	8.32	11.70	7.63	6.08	13.80	9.72	7.15	9.85	11.30	9.34
Ho	1.81	2.48	1.61	1.22	2.90	2.05	1.41	2.03	2.31	1.73
Er	5.99	8.20	5.31	3.61	8.74	6.51	4.34	6.45	7.35	4.80
Tm	0.93	1.31	0.83	0.50	1.42	1.00	0.63	0.98	1.27	0.69
Yb	6.72	9.40	5.91	3.44	10.20	7.02	4.36	6.77	9.87	4.37
Lu	0.97	1.40	0.85	0.50	1.52	1.04	0.65	1.00	1.45	0.62
ASI	0.99	0.98	1.11	0.71	1.02	0.96	1.07	1.16	1.12	1.09
Fe(Fe+Mg)	0.83	0.93	0.90	0.62	0.86	0.82	0.84	0.89	0.95	0.87
Ga/Al* 10000	3.18	3.32	3.11	2.73	3.47	3.21	2.89	3.29	3.85	3.34

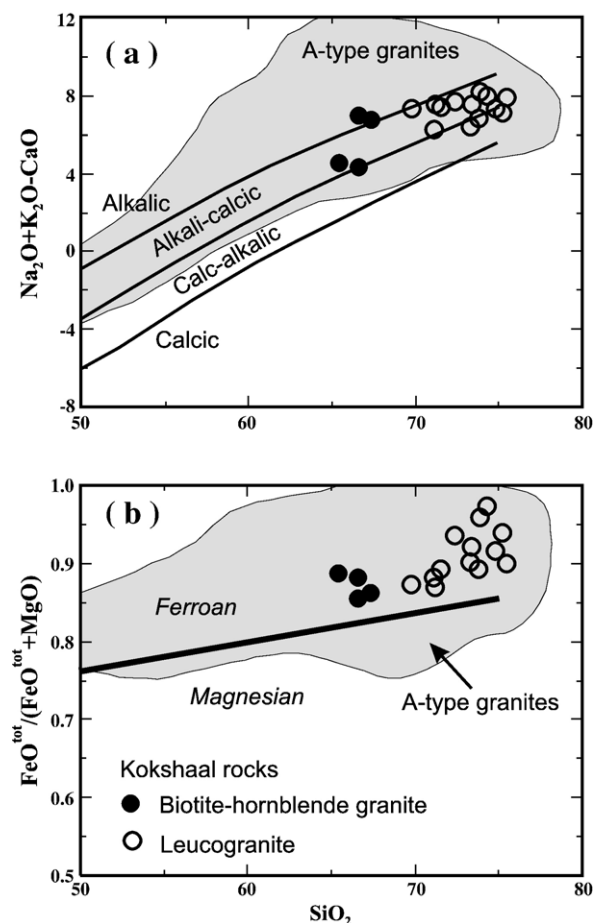


Fig. 6. Kokshaal granites on classification diagrams of Frost et al. (2001): $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ vs. SiO_2 , wt.% (a) and $\text{FeO}^{\text{tot}}/(\text{FeO}^{\text{tot}} + \text{MgO})$ vs. SiO_2 , wt.% (b) with a field for A-type granites of the world after Frost et al. (2001). See text for discussion.

methods. Fluorine and boron were analysed by wet chemistry method (Actlabs, Canada).

The biotite–hornblende granites and quartz monzonites of the Djangart and Ak-Shiyarak plutons, comprise a range of compositions with SiO_2 contents of 64–68 wt.%. According to the classification proposed by Frost et al. (2001) the rocks belong to a potassic alkali-calcic series with $\text{Na}_2\text{O} + \text{K}_2\text{O}$ from 7.5 to 10.5 wt.% and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ between 1.5 and 1.0 (Fig. 6a). The rocks are metaluminous with aluminium saturation indexes ($\text{ASI} = \text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ mol.) 0.87–0.93 and quite rich in iron relative to Mg with $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios ($\text{FeO}^{\text{tot}}/(\text{MgO} + \text{FeO}^{\text{tot}})$ mol.) from 0.77 to 0.95. The rocks are rich in HFSE (U, Th, Nb, Ta, Y, Zr, Hf, LREE) and F. Chondrite-normalized REE concentrations of the Djangart and Ak-Shiyarak granites are given in Fig. 7a. The rocks have slightly fractionated REE patterns with moderate negative Eu anomalies.

The leucogranites comprise a range of silica rich compositions with SiO_2 contents 69–75 wt.%. They are also potassic ($\text{Na}_2\text{O} + \text{K}_2\text{O}$ 7.8–9.0 wt.% and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 1.2–2.1) and generally follow the alkali-calcic trend (Fig. 6a). The rocks are metaluminous or slightly peraluminous with ASI 0.92–1.16. Leucogranites are poor in Ca and extremely rich in Fe relative to Mg with high and rather varying $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios from 0.8 to 0.95. Trace element composition of the leucogranites is characterized by low Ba and Sr, and high Rb and HFSE contents. Elevated concentrations of Li (from 50 to 200 ppm, 5 samples) and F (up to 0.61 wt.%) indicate the presence of Li-rich micas and in some cases topaz. Concentrations of boron, determined in 5 samples, vary from 20 to 40 ppm. Concentrations of Sn in the leucogranites range between 6 and 68 ppm indicating geochemical specialisation of the granites for tin. The REE patterns of the leucogranites are flat or very slightly fractionated with very strong negative Eu anomalies (Fig. 7b). Characteristic features are decreasing concentrations of LREE, growing concentrations of HREE and increasing Eu anomalies in the most evolved varieties of the leucogranites.

Mafic rocks associated with the Kokshaal granites occur as relatively small bodies or as mafic enclaves in the granites. The most primitive composition (sample 280401) is found in a 50 m wide and 1000 m long composite diabase dyke from the Mudryum leucogranite intrusion. The dyke compositionally corresponds to gabbro with tholeiitic affinity. It has a relatively low Al_2O_3 content (14.5%), high $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio (0.62 at 56% SiO_2) and elevated TiO_2 content (1.8%). Coarse-grained monzodiorite (sample 212305), representing mafic rocks associated with biotite–hornblende granites, has a similar composition. Both rocks plot in the tholeiitic field in the AFM diagram and in the field of within-plate basalts in the trace elements discrimination diagrams. The REE patterns of the mafic rocks are slightly fractionated without or with a moderate negative Eu anomaly (Fig. 7c). On the trace element abundance diagram (Fig. 7d) the mafic rocks demonstrate moderately increased concentrations of incompatible elements relative to N-type MORB and lack distinguishable negative Ta–Nb–Ti anomaly.

The Kokshaal granites of both types have a pronounced A-type affinity. They are mostly metaluminous with high Fe/Mg ratios. Because the Fe/Mg ratio is one of the most important signatures of an A-type granite, we present on Fig. 6b compositions of the Kokshaal granites plotted on the $\text{FeO}^{\text{tot}}/(\text{FeO}^{\text{tot}} + \text{MgO})$ vs. wt.% SiO_2 diagram with a field for A-type granites of the world after Frost et al. (2001). As seen in the figure, all the Kokshaal granites plot in the A-type field.

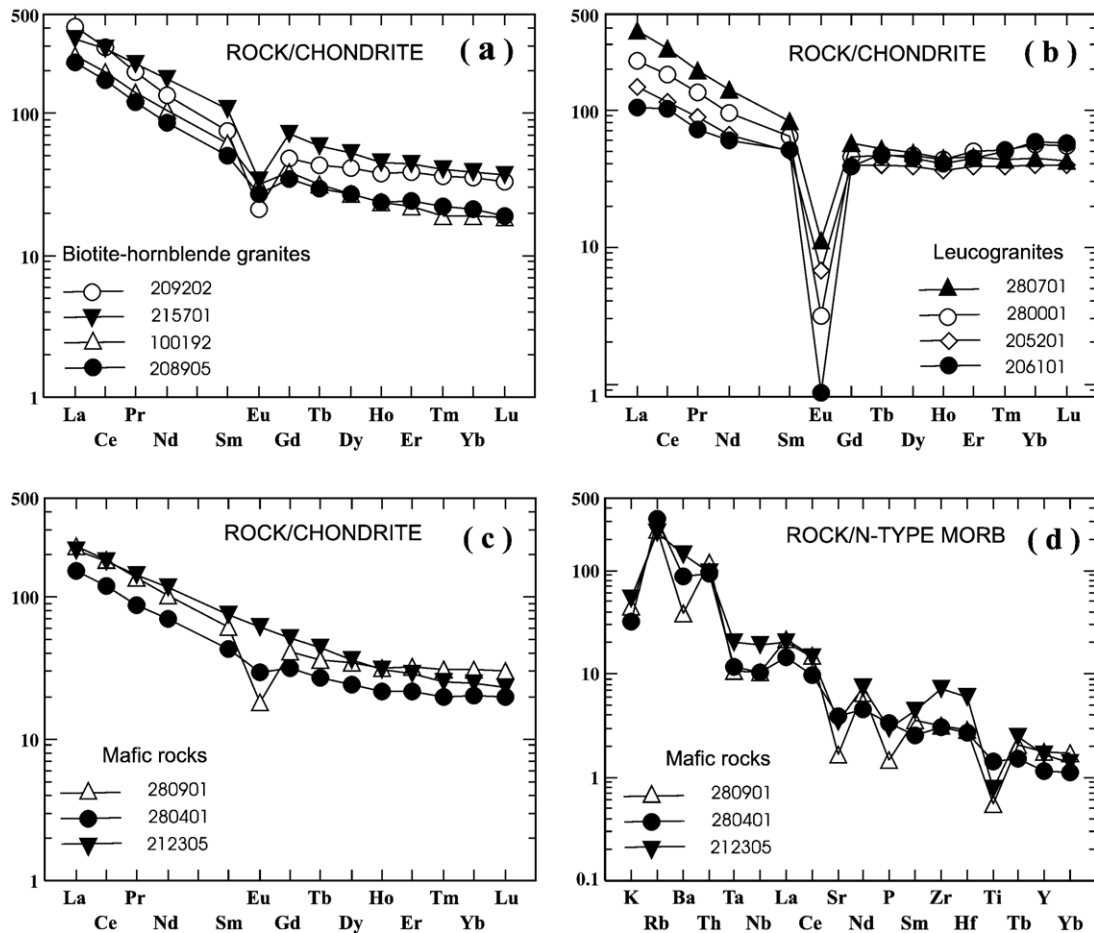


Fig. 7. Chondrite-normalized (Sun and McDonough, 1989) REE patterns of the Kokshaal rocks: (a) biotite–hornblende granites, (b) leucogranites, (c) mafic rocks; and N-type MORB-normalized (Sun and McDonough, 1989) trace element abundances of mafic rocks (d).

The trace element compositions of the Kokshaal rocks also correspond to that of the A-type granite. The granites, especially leucogranites, have very high concentrations of HFSE and they plot in the field of within-plate granites and A-type granites on the Pearce-type discrimination diagrams. The granites have elevated $10000 \cdot \text{Ga}/\text{Al}$ ratios characteristic for A-type granites (Fig. 8, Table 1).

4. Ion microprobe U–Pb zircon geochronology

Four intrusions were chosen for U–Pb zircon geochronology. Biotite–hornblende granite with plagioclase-mantled ovoidal K-feldspar megacrysts from the Djangart intrusion (sample 209202) represents large plutons of rapakivi granite. Biotite leucogranite from the Uch-Koshkon intrusion (206801) represents evolved tin-bearing granites of the eastern part of the study area.

Biotite leucogranite from the Mudryum intrusion (280001) and biotite–hornblende leucogranite from the Kok-Kiya intrusion (280701) characterize the leucogranite plutons of the western part of the study area. Chemical compositions of selected samples are given in Table 1.

4.1. Analytical procedures

Selected zircon grains were hand-picked from the heavy mineral separates, mounted in epoxy resin disk together with zircons used as a standard and polished to reveal zircon interiors. The zircons were studied at the Department of Geosciences, Stockholm University and at the NORDSIM laboratory of the Swedish Museum of Natural History, Stockholm. Prior to analysis, the zircons were investigated in transmitted and reflected light and under a Philips scanning

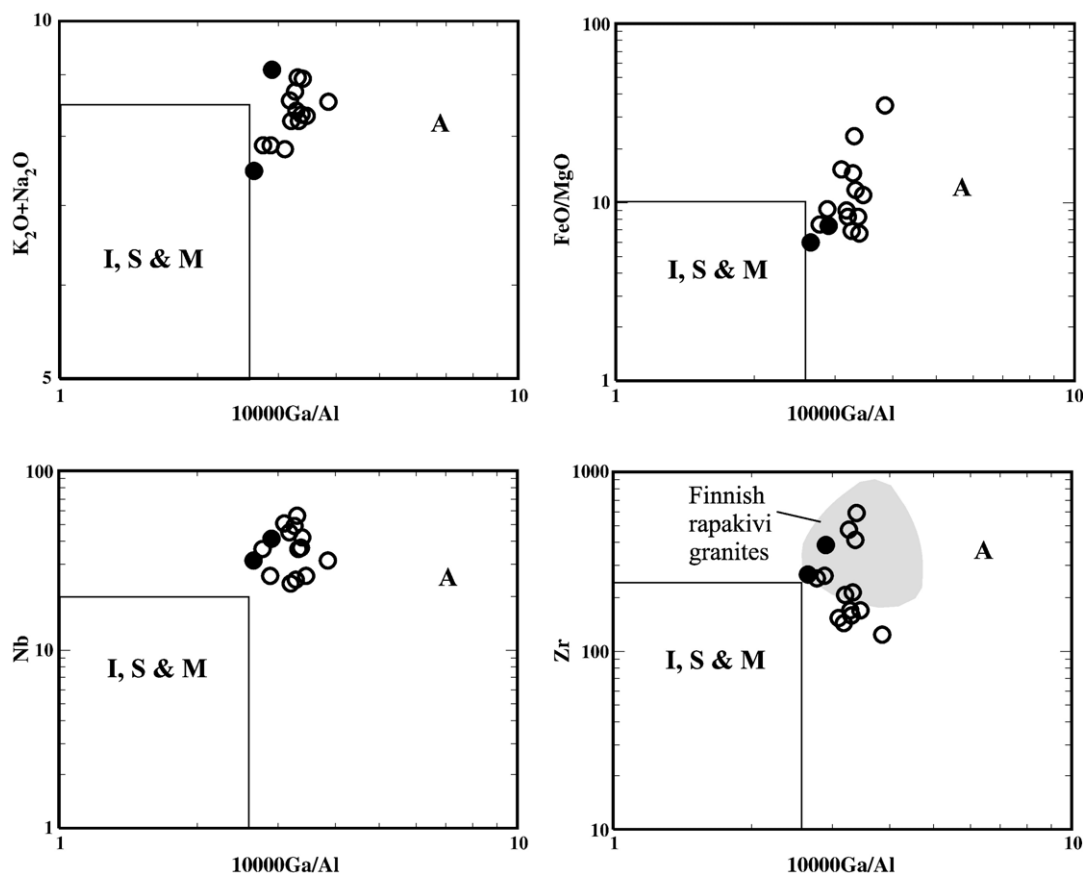


Fig. 8. $\text{K}_2\text{O}+\text{Na}_2\text{O}$, FeO/MgO , Nb and Zr vs. $10000\text{Ga}/\text{Al}$ discrimination diagrams of Whalen et al. (1987), showing the A-type nature of the Kokshaal granites. Field for the Finnish rapakivi granites after Haapala et al. (2005) shown on Zr vs. $10000\text{Ga}/\text{Al}$ plot for comparison. See Fig. 6 for legend.

electron microscope equipped with cathodoluminescence (CL) and back-scattered electron (BSE) units. U–Th–Pb isotope analyses were performed on a high-mass resolution, high-sensitivity Cameca IMS 1270 ion microprobe at the NORDSIM laboratory. The analysed spots were ca. $30\text{ }\mu\text{m}$ wide. Details of the analytical procedure and data reduction are similar to those described by Whitehouse et al. (1997, 1999) and Zeck and Whitehouse (1999). The calibration of the raw data was based on the analyses of the Geostandards zircon 91500 with an accepted age of 1065 Ma (Wiedenbeck et al., 1995).

4.2. Results

Zircons recovered from the four samples are rather similar and represent prismatic elongate grains with distinct facets. They vary significantly in size from $20\text{ }\mu\text{m}$ to 1 mm with length/width ratios from 2 to 5. In this study $200\text{--}400\text{ }\mu\text{m}$ long crystals were chosen for

analyses. The zircons are transparent or yellowish-brown in transmitted light without inherited cores. On BSE and CL images the zircon grains are homogeneous with weak magmatic zoning. Four to eight grains were analysed in each sample resulting in 5–12 analyses per sample. Analytical data are presented in Table 2 and plotted as 2σ error ellipses in concordia diagrams on Fig. 9 (Tera and Wasserburg, 1973, 1974). Age calculations were made using the Isoplot/Ex v. 2.05 program (Ludwig, 1999). All age errors quoted in the text are 2σ errors.

All analyses of zircons from the four intrusions plot on or near concordia. Analyses of zircons from the Djangart pluton yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $295\pm 4\text{ Ma}$ ($n=11$, $\text{MSWD}=0.32$). If 3 slightly discordant analyses are excluded from calculation, 8 analyses yield a concordia age of $296\pm 4\text{ Ma}$ ($\text{MSWD}=0.69$). Five analyses of zircon grains from the Uch-Koshkon intrusion give a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $283\pm 9\text{ Ma}$ ($\text{MSWD}=0.46$). If two

discordant analyses are excluded, three analyses give a concordia age of 279 ± 8 Ma (MSWD=4.9). All 12 analyses from the Mudryum intrusion are concordant and yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 280 ± 6 Ma (MSWD=0.49). However, if one slightly younger analysis is excluded the remaining data cluster yields a concordia age of 281 ± 2 Ma (MSWD=8.7). Seven analyses of zircons from the Kok-Kiya intrusion yield a concordant data cluster with weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 281 ± 7 Ma (MSWD=0.034) and concordia age of 281 ± 3 Ma (MSWD=0.084). The $^{208}\text{Pb}/^{232}\text{Th}$ ages of zircons are 10–20 Ma younger than corresponding U–Pb ages but coincide within error limits (Table 2).

The concordia ages of 296 ± 4 Ma, 279 ± 8 Ma, 281 ± 2 Ma and 281 ± 3 Ma are considered as crystallization ages for the Djangart, Uch-Koshkon, Mudryum and Kok-Kiya intrusions, respectively. The 296 ± 4 Ma age of the Djangart granite corresponds within error limits with the 292 ± 3 Ma zircon SHRIMP age recently obtained for the petrographically similar Ak-Shiyarak pluton (Konopelko et al., 2006). Thus, emplacement of the Kokshaal A-type granites took place 295–280 Ma ago. Plutons of rapakivi granites in the eastern part of Kokshaal apparently formed 10–15 Ma earlier than leucogranites in its western part, according to the data.

5. Nd isotopes

Eight samples of the Kokshaal granites and 2 samples of mafic rocks were analysed for their Nd isotopic composition. Because Nd data for adjacent terranes of the Tien Shan are very scarce, we also analysed 3 samples of the Ordovician granites representing the crust of the Middle and Northern Tien Shan and 1 sample of the Kochkorka gneiss from Northern Tien Shan with a U–Pb zircon age of 1050 ± 20 Ma (Kiselev, 1999). Sampling localities are shown on Figs. 2 and 3. Nd isotopic data are presented in Table 3 and initial Nd isotopic compositions of all analysed samples, as well as published Nd data for adjacent terranes, are shown in a ϵ_{Nd} vs. age diagram in Fig. 10.

5.1. Analytical procedure

Neodymium isotopic compositions were analysed at the IPGG RAS (St. Petersburg, Russia) utilising a Finnigan MAT 261 8-collector mass-spectrometer in static mode. Rock powders for Sm–Nd studies were dissolved in a mixture of HF, HNO₃ and HClO₄. Before decomposition all samples were totally spiked with

^{149}Sm – ^{146}Nd mixed solution. Neodymium and Sm were separated using conventional cation-exchange and extraction chromatography following the method of Richard et al. (1976). Total blanks in the laboratory were about 0.1 ng for Sm and 0.05 ng for Nd. Assigned errors (2σ) for $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ were $\pm 0.5\%$ and ± 0.000025 , as determined from multiple analyses of the standard (external reproducibility). Ratios of $^{143}\text{Nd}/^{144}\text{Nd}$ were normalized within-run to $^{148}\text{Nd}/^{144}\text{Nd}=0.241570$ and then adjusted to the $^{143}\text{Nd}/^{144}\text{Nd}$ value of 0.511860 for the La Jolla standard. The $\epsilon_{\text{Nd}}(T)$ values were calculated using the present-day values for a chondritic uniform reservoir (CHUR) $^{143}\text{Nd}/^{144}\text{Nd}=0.512638$ and $^{147}\text{Sm}/^{144}\text{Nd}=0.1966$ (DePaolo, 1981). The estimated error in the ϵ_{Nd} values is ± 0.5 ϵ -units. The depleted mantle model ages T_{DM} were calculated according to the model of DePaolo (1981).

5.2. Results

The Kokshaal rocks have relatively uniform $^{147}\text{Sm}/^{144}\text{Nd}$ (0.1089–0.1286) and $^{143}\text{Nd}/^{144}\text{Nd}$ (0.512127–0.512506) ratios with one exception of highly evolved quartz porphyry, sample 206101. The Middle and Northern Tien Shan rocks show a wider range of Sm and Nd concentrations and a range of $^{147}\text{Sm}/^{144}\text{Nd}$ (0.0778–0.12559) and $^{143}\text{Nd}/^{144}\text{Nd}$ (0.511808–0.512159) ratios. All analysed samples have negative initial ϵ_{Nd} values. The highest initial ϵ_{Nd} value of 0.0 (at 295 Ma) is characteristic for a mafic rock, namely quartz monzonite (sample 212305, Table 2), from the small composite Ak-Tash intrusion in the Kokshaal. The biotite–hornblende granites from the Djangart and Akshiyarak plutons have ϵ_{Nd} (at 295 Ma) values between -4.8 and -6.9 (3 samples). The leucogranites of the Uchkoshkon, Kok-Kiya, Mudryum and Ak-Tash intrusions have more variable ϵ_{Nd} (at 280 Ma) values between -1.6 and -5.9 (5 samples). Three granite samples from the Ordovician Almalinsky and Ottuk intrusions in the Middle and Northern Tien Shan have initial ϵ_{Nd} values between -4.9 and -5.6 and the Precambrian Kochkorka gneiss has an initial ϵ_{Nd} value -5.6 (at 1050 Ma).

Thus, low initial ϵ_{Nd} values of the Kokshaal granites (from -1.6 to -6.9 at 280 Ma) suggest a significant input of Precambrian crustal component (ϵ_{Nd} from -7 to -17 for the Early–Middle Proterozoic crust at 300 Ma, Fig. 10). This is supported by the Mesoproterozoic Nd model ages of the Kokshaal granites (1.05–1.43 Ga), calculated according to the model of DePaolo (1981). This conclusion also applies to the Ordovician granites of the Middle and Northern Tien Shan representing the Paleo-Kazakhstan crust.

Table 2

U–Pb analytical data and calculated ages

Grain(spot) # ^a	Calculated ages in million years						Disc.% ^b	Isotope ratios ^a			
	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁸ Pb/ ²³² Th	±1σ		²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ
<i>Djangart, sample 209202</i>											
1	272	19	302	4	291	8	11.5	0.0517	0.9	0.3420	1.5
1(b)	319	23	304	4	287	8	−5.0	0.0528	1.0	0.3509	1.6
2(a)	316	19	305	3	296	9	−3.5	0.0527	0.8	0.3524	1.4
2(b)	236	35	295	4	278	10	25.3	0.0509	1.5	0.3283	2.1
3(b)	127	66	288	4	253	11	129.4	0.0486	2.9	0.3062	3.2
4	288	27	292	3	278	8	1.2	0.0521	1.2	0.3322	1.7
5(a)	212	32	294	4	265	8	(3.6)	0.0504	1.4	0.3236	1.9
8	216	43	297	4	283	9	38.2	0.0505	1.9	0.3279	2.3
8(b)	163	77	290	3	274	11	79.5	0.0493	3.4	0.3126	3.6
9	222	24	290	3	280	8	(5.9)	0.0506	1.1	0.3215	1.6
10	314	30	290	3	273	9	−7.9	0.0527	1.3	0.3338	1.8
<i>Uch-Koshkon, sample 206801</i>											
2	245	33	286	3	272	9	17.0	0.0511	1.4	0.3196	1.9
3	216	17	292	4	276	8	(17.1)	0.0505	0.8	0.3223	1.5
5	209	48	278	3	241	9	33.5	0.0503	2.1	0.3054	2.4
7	151	24	285	4	269	8	(44.8)	0.0491	1.0	0.3054	1.7
11	140	78	274	4	238	11	97.5	0.0488	3.4	0.2929	3.7
<i>Mudryum, sample 280001</i>											
1	227	61	280	4	267	14	23.9	0.0507	2.7	0.3100	3.0
1(a)	221	57	284	3	267	14	29.0	0.0506	2.5	0.3142	2.8
1(b)	246	38	283	4	258	13	15.6	0.0511	1.7	0.3165	2.1
2	223	71	283	4	267	15	27.4	0.0506	3.2	0.3130	3.4
2(a)	209	68	289	3	259	14	39.1	0.0503	3.0	0.3178	3.2
2(b)	166	53	277	3	277	14	68.5	0.0494	2.3	0.2990	2.7
3	250	37	287	3	289	15	15.2	0.0512	1.6	0.3213	2.0
5	191	60	279	3	274	15	47.0	0.0499	2.6	0.3043	2.9
7	267	65	261	4	290	16	−2.4	0.0516	2.9	0.2938	3.3
12	166	64	279	4	264	14	69.6	0.0494	2.8	0.3012	3.1
12(b)	303	45	274	3	267	15	−9.8	0.0524	2.0	0.3142	2.4
12(c)	293	50	282	4	271	15	−4.1	0.0522	2.2	0.3211	2.6
<i>Kok-Kiya, sample 280701</i>											
1	260	49	277	4	269	14	6.9	0.0514	2.2	0.3113	2.5
1(b)	314	34	282	4	269	15	−10.3	0.0527	1.5	0.3250	2.0
3	181	64	278	4	269	15	54.7	0.0497	2.8	0.3021	3.1
3(b)	272	58	278	4	288	16	2.4	0.0517	2.6	0.3143	2.9
4	245	60	278	3	260	15	13.6	0.0511	2.7	0.3099	3.0
5	262	62	279	3	241	13	6.7	0.0515	2.8	0.3134	3.1
5(b)	287	44	280	3	266	14	−2.3	0.0520	1.9	0.3189	2.3

^a Corrected for common lead using averaged present day Pb isotope composition according to a model of Stacey and Kramers (1975).^b Age discordance in conventional concordia space. Positive values are reverse discordant. Values in parentheses indicate that the analysis is discordant in terms of 2 s error ellipse.^c Error correlation ²⁰⁷Pb/²³⁵U–²⁰⁶Pb/²³⁸U.^d Measured values.^e Th/U ratio directly from measured Th and U concentrations.

6.1. Petrogenesis of granites

The Kokshaal intrusions include rocks of several intrusive phases and host greisen deposits indicating individual differentiation histories of particular plutons. Geochemical data presented in this study may reveal

only a major trend of the geochemical evolution of the whole complex. This general evolutionary trend observed in the biotite–hornblende rapakivi granites and leucogranites of the Kokshaal is typical for A-type series. The trend is characterized by the evolution from hornblende±biotite granite to biotite granite and finally

$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	r^c	$^{208}\text{Pb}/^{232}\text{Th}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{204}\text{Pb}^d$	$f_{206}\%$	Concentrations			
							[U] ppm	[Th] ppm	[Pb] ppm	Th/U ^c
0.0480	1.3	0.83	0.0145	2.8	11380	0.16	1335	906	81	0.679
0.0482	1.2	0.77	0.0143	2.8	3557	0.53	1283	921	78	0.718
0.0485	1.2	0.81	0.0147	3.0	31545	0.06	923	488	54	0.529
0.0468	1.5	0.70	0.0139	3.5	24223	0.08	548	234	30	0.428
0.0457	1.3	0.42	0.0126	4.5	2711	0.69	356	116	19	0.325
0.0463	1.2	0.71	0.0138	3.0	12655	0.15	606	228	33	0.377
0.0466	1.3	0.68	0.0132	3.0	2085	0.90	1211	812	70	0.670
0.0471	1.3	0.56	0.0141	3.1	16273	0.11	351	133	19	0.379
0.0460	1.2	0.33	0.0136	3.9	2912	0.64	144	72	8	0.503
0.0461	1.2	0.75	0.0140	3.0	13722	0.14	579	207	31	0.358
0.0460	1.2	0.68	0.0136	3.1	7514	0.25	487	186	26	0.382
0.0454	1.2	0.65	0.0136	3.2	6995	0.27	442	164	23	0.370
0.0463	1.3	0.86	0.0137	2.9	12815	0.15	1105	606	62	0.549
0.0440	1.2	0.50	0.0120	3.6	718	2.60	992	401	51	0.404
0.0452	1.3	0.78	0.0134	3.0	6839	0.27	891	454	48	0.510
0.0435	1.4	0.38	0.0118	4.5	2843	0.66	244	102	12	0.417
0.0444	1.4	0.47	0.0133	5.4	4896	0.38	185	94	10	0.509
0.0451	1.3	0.45	0.0133	5.1	6109	0.31	269	181	15	0.671
0.0449	1.3	0.63	0.0128	5.1	8992	0.21	323	227	18	0.704
0.0449	1.3	0.39	0.0133	5.8	3812	0.49	135	62	7	0.457
0.0458	1.2	0.38	0.0129	5.5	4973	0.38	226	107	12	0.472
0.0439	1.3	0.48	0.0138	5.2	3851	0.49	216	129	12	0.599
0.0455	1.2	0.60	0.0144	5.1	7546	0.25	273	119	15	0.435
0.0442	1.2	0.42	0.0137	5.5	2767	0.68	218	89	11	0.409
0.0413	1.6	0.48	0.0145	5.6	5629	0.33	157	71	8	0.455
0.0442	1.3	0.43	0.0131	5.4	3346	0.56	199	107	11	0.537
0.0435	1.3	0.54	0.0133	5.6	5337	0.35	209	117	11	0.558
0.0446	1.4	0.52	0.0135	5.5	4998	0.37	188	101	10	0.535
0.0439	1.3	0.53	0.0134	5.3	7451	0.25	197	100	10	0.508
0.0448	1.3	0.65	0.0134	5.7	17607	0.11	351	246	20	0.700
0.0441	1.3	0.42	0.0134	5.5	3774	0.50	166	77	9	0.464
0.0441	1.3	0.45	0.0143	5.5	3636	0.51	172	85	9	0.495
0.0440	1.3	0.43	0.0129	5.7	3165	0.59	229	110	12	0.479
0.0442	1.3	0.42	0.0120	5.6	3896	0.48	229	113	12	0.495
0.0445	1.3	0.55	0.0133	5.1	12391	0.15	295	209	17	0.708

to topaz-bearing leucogranite. Geochemically, this trend is characterized by an increase in Si, Rb, Nb, F, Ga, Sn, HREE, Fe/(Fe + Mg), ASI, Eu/Eu* and a decrease in Ti, Al, Fe, Mg, Mn, Ca, Ba, Sr, Zr and LREE. This evolutionary trend is explained by K-feldspar + subaluminous mafic silicate (usually hornblende)

fractionation with trace amounts of apatite, zircon and allanite (Rämö and Haapala, 1995).

The major role of the K-feldspar + hornblende-dominated fractionation in producing the compositional range of the Kokshaal granites is illustrated by wt.% Al₂O₃ vs. wt.% SiO₂, ppm Eu vs. wt.% SiO₂ and ASI vs. wt.% SiO₂

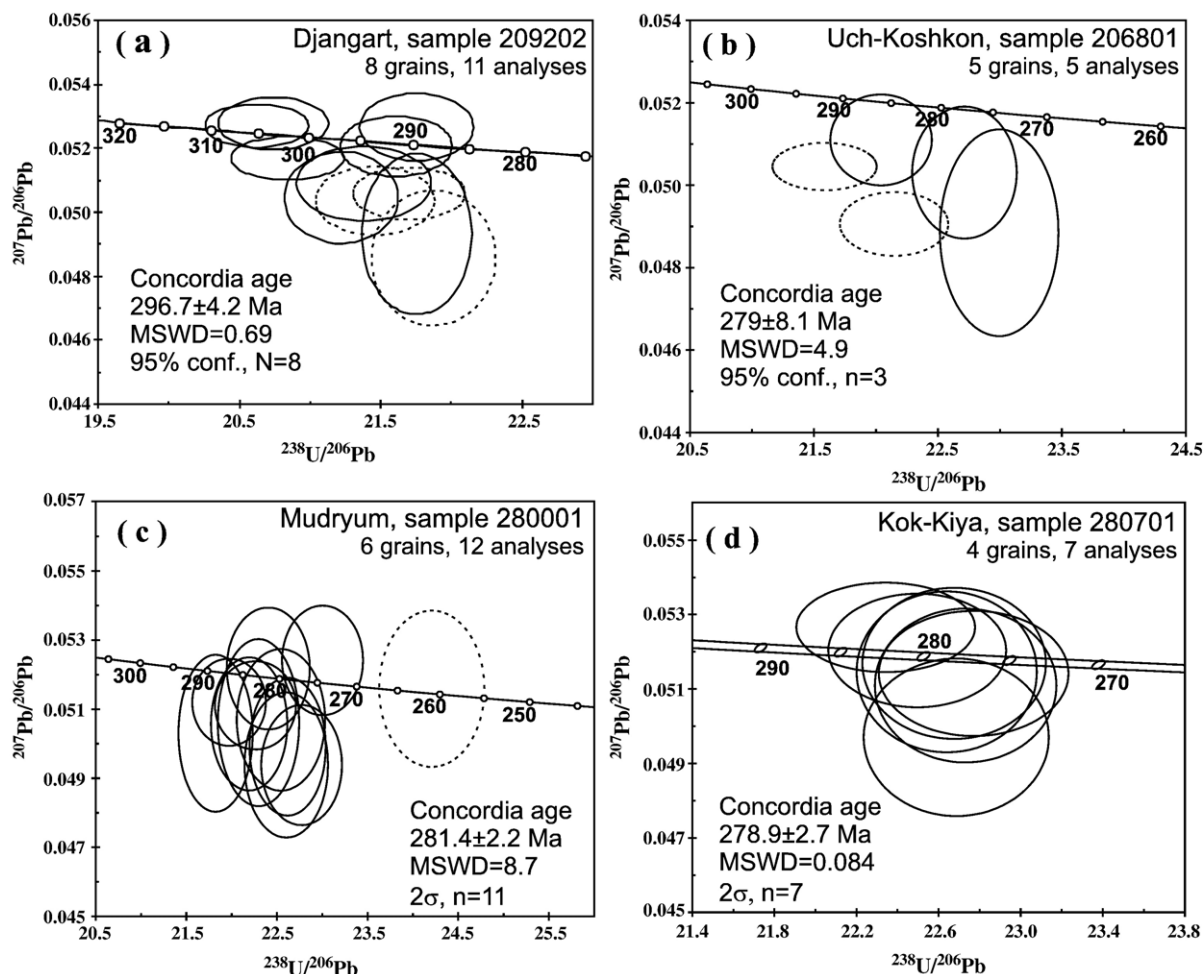


Fig. 9. U–Pb concordia diagrams for SIMS zircon data from (a) Djangart, (b) Uch-Koshkon, (c) Mudryum and (d) Kok-kiya granite intrusions. Error ellipses denote 2σ level of uncertainty. Dashed ellipses are excluded from concordia age calculations.

diagrams shown in Fig. 11a–c. A decreasing Al_2O_3 content with increasing silica indicates fractionation of rock-forming silicate minerals. A decreasing Eu content with increasing silica shows that K-feldspar played a major role in the fractionation assemblage. An increasing ASI with increasing silica content indicates that the second major mineral in the fractionation assemblage was a subaluminous mafic silicate, namely hornblende. Thus, the ovoidal biotite–hornblende rapakivi granites of the Djangart and Ak-Shiyarak plutons are cumulus-rich rocks.

A number of mechanisms have been suggested to explain the origin of A-type granite magmas of which fractionation of mantle-derived magma, reaction of mantle-derived magma with crustal rocks, and melting of deep continental crust are considered as the most important (Rämö and Haapala, 1995; Bonin, 1996). The

tectonic position of A-type granites is also not uniform as they can be formed in both postorogenic and anorogenic settings. Eby (1990) subdivided A-type granites into two groups: A1 and A2. The A1 group is mantle-derived and emplaced in anorogenic setting. The A2 group is derived from melting of continental crust and forms in various tectonic environments. On the Rb/Nb–Y/Nb and Y–Nb–Ce discrimination diagrams of Eby (1990) the Kokshaal A-type granites generally plot into the A2 field (Fig. 12a, b) which is compatible with postorogenic tectonic setting and crustal origin. Neodymium isotopic data for the Kokshaal A-type granites also suggest mixing of asthenospheric mantle and crustal components. The granites have negative initial ϵ_{Nd} values marginally overlapping with a field of evolution of the Middle–Late Proterozoic crust (Fig. 10), indicating a significant

Table 3
Nd isotope data for Tien Shan rocks

Sample Nr	Intrusion	Rock type ^a	Age (Ma)	Sm ppm	Nd ppm	¹⁴⁷ Sm/ ¹⁴⁴ Nd ^b	¹⁴³ Nd/ ¹⁴⁴ Nd ^c	$\epsilon_{\text{Nd}}(t)$ ^d	$T_{\text{DM1}}(\text{Ga})$ ^e
Southern Tien Shan, Kokshaal range									
Granites									
221801	Kok-Kiya	lgr	280	10.8	55.1	0.11886	0,512312±14	−3.6	1.18
220702	Mudryum	lgr	280	6.97	38.8	0.10894	0,512177±18	−5.9	1.26
206101	Uch-Koshkon	lgr	280	7.85	27.7	0.17185	0,512389±14	−4.0	1.26
206801	Uch-Koshkon	lgr	280	9.31	44.2	0.12773	0,512326±18	−3.6	1.27
212301	Ak-Tash	lgr	280	12.3	61.1	0.12211	0,512417±17	−1.6	1.05
215701	Ak-Shiyarak	gr	295	16.3	81.7	0.12098	0,512247±22	−4.8	1.31
209202	Djangart	gr	295	11.5	62.9	0.11087	0,512201±21	−5.3	1.25
100192	Djangart	gr	295	9.46	49.4	0.11612	0,512127±15	−6.9	1.43
Mafic rocks									
280401	Mudryum	dia	280	6.58	34.3	0.1206	0,512416±16	−1.6	1.03
212305	Ak-Tash	mz	295	11.6	54.7	0.12861	0,512506±17	0.0	0.97
Middle and Northern Tien Shan									
301500	Almalinsky	gr	420	7.81	60.9	0.07781	0,512026±18	−5.6	1.14
301400	Ottuk	gr	420	1.92	9.27	0.12559	0,512159±24	−5.5	1.53
301300	Ottuk	gr	420	4.40	31.6	0.08446	0,512078±14	−4.9	1.14
301600	Kochkorka	gn	1050	4.74	24.4	0.11772	0,511808±13	−5.6	1.96

Model age of the highly evolved granite sample 206101 is calculated according to 2-stage model.

^a Abbreviations: dia — diabase, gr — granite, gn — gneiss, lgr — leucogranite, mz — monzonite.

^b Estimated error is better than 0.5%.

^c Normalized to $^{148}\text{Nd}/^{144}\text{Nd}=0.241578$, within-run precision expressed as $2\sigma_m$ in the last digits.

^d Initial ϵ_{Nd} values calculated using chondritic ratios of $^{143}\text{Nd}/^{144}\text{Nd}=0.512638$ and $^{147}\text{Sm}/^{144}\text{Nd}=0.1966$, maximum error is ± 0.5 ϵ -units.

^e Depleted mantle model age calculated according to the model of DePaolo (1981).

involvement of Precambrian crustal component. A Precambrian crustal source for the Kokshaal granites was also proposed by Chiaradia et al. (2006), based on Pb isotope compositions of K-feldspar and whole rock samples.

The Kokshaal A-type granites are associated with coevally emplaced tholeiitic mafic rocks and alkaline silica undersaturated syenites. An association with tholeiitic mafic rocks is a typical feature of A-type series granites (e.g. Rämö and Haapala, 1995; Frost and Frost, 1997). However, association with alkaline rocks is mostly characteristic for Phanerozoic A-type granites in contrast to their Precambrian equivalents (Haapala et al., 2005). Mafic rocks associated with the A-type granites in the study area are represented by relatively small bodies. However, in Chinese territory, on the southern slope of the Kokshaal range and in the Northern Tarim, thick strata of bimodal Early Permian volcanics: rhyolites and tholeiitic to alkaline basalts with K–Ar ages around 280 Ma are known (Carroll et al., 2001; Jiang et al., 2004). These tholeiitic and alkaline basalts may represent juvenile asthenospheric material underplating the Tarim margin at the post-collisional stage and providing heat for generation of A-type granites from the Precambrian crust of Tarim. The ϵ_{Nd} values of the Kokshaal mafic rocks (this study) and of the Tarim basalts (Jiang et al., 2004) vary from chondritic

values to -3.7 (at 280–300 Ma). These values are higher or overlapping with ϵ_{Nd} values of the Kokshaal granites (Fig. 10) and may indicate mixing of asthenospheric mantle and crustal components.

The Kokshaal intrusions are post-tectonic and undeformed. The general east–west elongation of the Kokshaal magmatic arc and uniform ages of relatively distant intrusions may indicate a tectonic trigger for their formation and link to one of the shear zones parallel to the Southern Tien Shan Suture. Subsequent to collisional events, the Tien Shan was affected by trans-crustal strike–slip motions. Sense of these early strike–slip displacements was estimated as dextral in the eastern Chinese part of the Tien Shan (Laurent-Charvet et al., 2003) and as sinistral in the Kokshaal Segment (Biske, 1995; Biske and Shilov, 1998). The consequences of plate-scale strike–slip displacements were recently addressed in a number of studies (Leloup and Kienast, 1993; Maxson and Tikoff, 1996; Teyssier and Tikoff, 1998). It was shown that strike–slip partitioning in the upper crust is a result of shearing in the upper mantle. The transfer of displacement from the mantle to the upper crust is accommodated in the middle-lower crust by flat-lying detachment zones (Teyssier and Tikoff, 1998). This transpressional system may provide suitable conduits for ascending asthenospheric material and result in the influx of heat in the crust. This model well explains

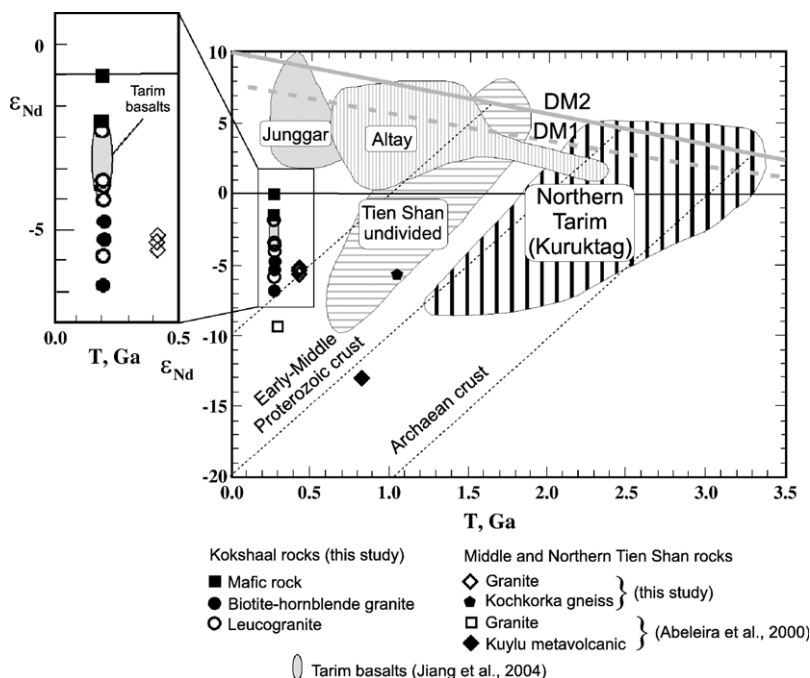


Fig. 10. ϵ_{Nd} vs. age diagram showing initial Nd isotopic composition of the Kokshaal rocks (this study) and rocks of adjacent terranes (this study; Abeleira et al., 2000; Jiang et al., 2004). Fields for basement rocks (amphibolites and gneisses) of the Junggar, Altay, Tien Shan and Tarim are from Hu et al. (2000). Fields of evolution of the Early-Middle Proterozoic and Archaean crust are after Jahn et al. (2000b). Nd isotope evolution of the depleted mantle is shown according to DePaolo (1981) (DM1) and as linear evolution $\epsilon_{\text{Nd}}=0$ at 4.56 Ga to +10 at present after Jahn et al. (2000b) (DM2).

the post-collisional evolution of the Kokshaal Segment and is illustrated by a sketch in Fig. 13. According to the model, ascending hot, mantle-derived melts triggered crustal melting and emplacement of granites exposed on the present erosion surface in the Kokshaal. The crustal protoliths that underwent melting comprised Precambrian metamorphic rocks of the Tarim basement underthrust to the north beneath the sedimentary piles of the Kokshaal. In this scenario coeval alkaline magmas originated from the lithospheric keel of the Tarim microcontinent affected by juvenile asthenospheric mantle.

Shear-related origin of the Kokshaal magmatic arc might result in syn-intrusive deformations of plutons. Such features are observed elsewhere in other post-collisional intrusions of the Tien Shan. There, intrusions with magmatic gneissosity and even alkaline ring complexes emplaced as lenses along major shear zones were described and dated at 280–290 Ma indicating that these shear zones were active at post-collisional stage (Konopelko et al., 2006). However, all the Kokshaal intrusions itself are undeformed. We suggest that formation of those granites was triggered by a ductile shear zones at depth and that the elongated shape of the magmatic arc is the only expression of the shear seen in the upper crust at the present level of erosion.

6.2. Nature of the Tien Shan crust

The depleted mantle Nd model ages of the Kokshaal granites are relatively uniform (1.05–1.43 Ga) and point to a homogeneous Middle-Neoproterozoic crustal source. These data are compatible with Nd data and U–Pb ages previously published and obtained in this study for the Tien Shan basement shown in Fig. 10. As seen in the figure, the Neoproterozoic metamorphic rocks of the Northern and Middle Kyrgyz Tien Shan fit well the evolution field of undivided Tien Shan basement rocks presented by Hu et al. (2000). This field includes the rocks of the northern Tarim basement, exposed in the Chinese territory west of the Kuruktag terrane and described by Hu et al. (2000) as Southern Tien Shan gneisses. Three Ordovician granites of the Middle and Northern Kyrgyz Tien Shan also have Middle–Early Proterozoic model ages (1.14–1.53 Ga, this study) indicating the similarity in age of the Tarim basement in the Kokshaal region and the basement of the southern margin of Paleo-Kazakhstan exposed in the Middle and Northern Tien Shan.

Recent Sr and Nd isotope studies carried out in the southern Altaids (Chen et al., 2000; Heinhorst et al., 2000; Jahn et al., 2000a,b) showed a significant juvenile component in terranes comprising the Altay, Junggar and

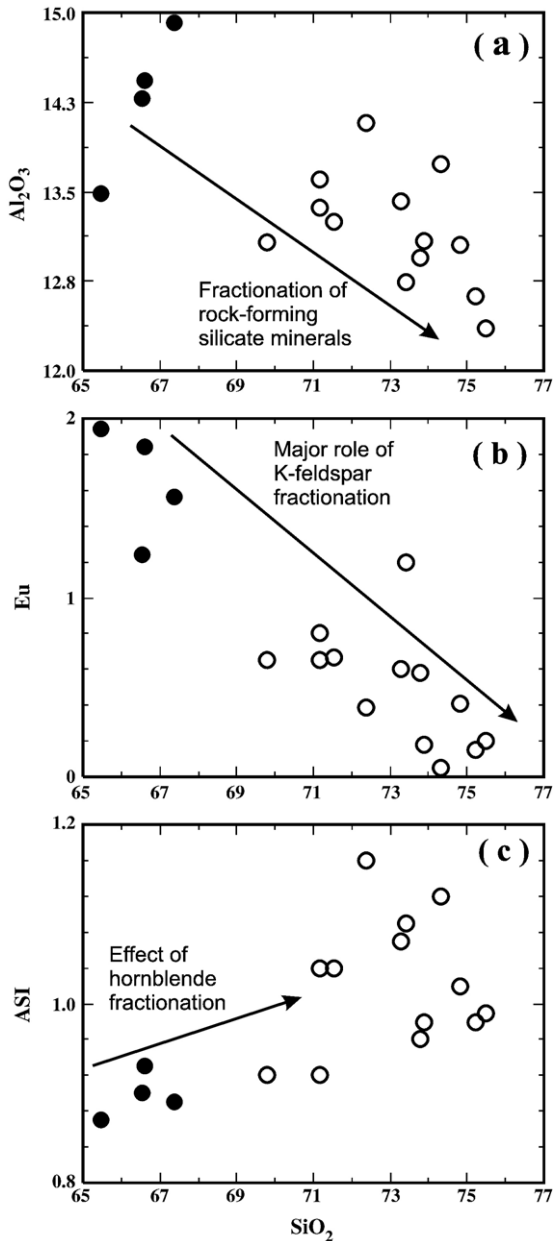


Fig. 11. Harker-type diagrams for Kokshaal granites: wt.% Al_2O_3 vs. wt.% SiO_2 (a), Eu (ppm) vs. wt.% SiO_2 (b), ASI ($=\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ mol.) vs. wt.% SiO_2 (c). Decreasing Al_2O_3 content with increasing silica indicates fractionation of rock-forming silicates. Decreasing Eu content with increasing silica show that K-feldspar played major role in the fractionation assemblage. Increasing ASI with increasing silica content indicates that the second major mineral in the fractionation assemblage was a subaluminous mafic silicate, namely hornblende. See Fig. 6 for legend.

Central Kazakhstan (see in Fig. 10 the fields for the Junggar and Altay basement rocks, after Hu et al., 2000). In the Tien Shan, however, available Nd data, in contrast,

indicate that most felsic rocks originated from Precambrian crustal source. The compositional diversity and volume of post-collisional magmatic rocks in various terranes of the Tien Shan differ markedly reflecting different compositions of the crust. The relatively uniform composition of the post-collisional A-type granites of the Kokshaal Segment is apparently a result of formation from a uniform protolith: the Precambrian basement of Tarim.

7. Conclusions

Post-collisional granites of the Kokshaal Segment of the Southern Tien Shan include about 20 post-tectonic intrusions varying in composition from biotite–hornblende rapakivi granite to biotite and topaz-bearing leucogranite emplaced in an extensional tectonic regime. The granites are associated with coevally intruded tholeiitic mafic rocks and with alkaline undersaturated syenites. The granites have a pronounced A-type affinity: they are metaluminous with high concentrations of $\text{Na}_2\text{O} + \text{K}_2\text{O}$, Rb, HFSE and

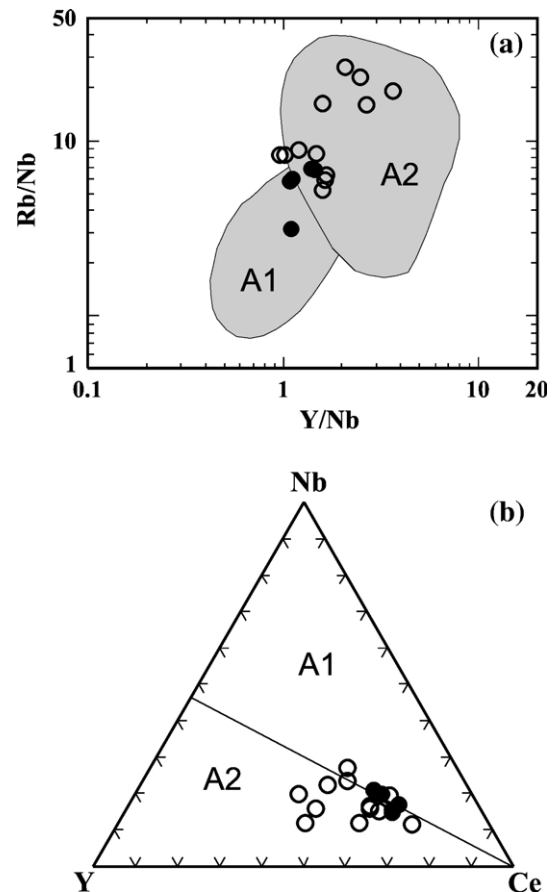


Fig. 12. Kokshaal granites on Rb/Nb vs. Y/Nb (a) and Y–Nb–Ce (b) diagrams. Fields for mantle-derived (A1) and crustal melting-derived (A2) A-type granites after Eby (1990). See Fig. 6 for legend.

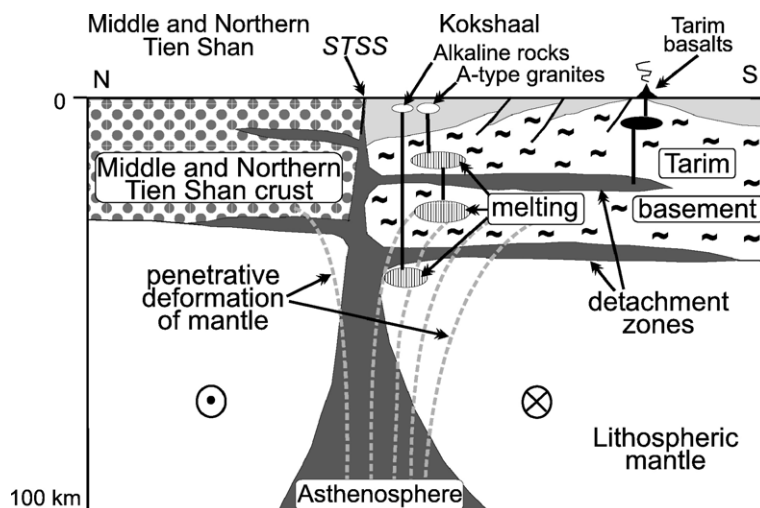


Fig. 13. Sketch illustrating post-collisional evolution of the Tien Shan. Sense of post-collisional plate-scale displacement is shown as sinistral after Biske (1995). The transfer of displacement from the mantle to the upper crust is accommodated in the lower-middle crust by the flat-lying detachment zones. This transpressional system provides suitable conduits for ascending asthenospheric material and influx of heat into the crust. Mantle-derived melts triggered melting of the Tarim basement and emplacement of the Kokshaal granites. Coeval alkaline magmas originated from the lithospheric keel of the Tarim. This sketch is based on the model of Teyssier and Tikoff (1998). STSS — Southern Tien Shan Suture. Structure of the Northern and Middle Tien Shan crust, as well as assumed subduction to the north that preceded collision, is not shown on this sketch.

high K_2O/Na_2O and $Fe/(Fe+Mg)$ ratios. On a regional scale the granites comprise a single geochemical trend explained by fractionation of K-feldspar and hornblende.

The U–Pb zircon SIMS ages of the granites vary from 295 Ma to 280 Ma. The ages of 290–295 Ma were obtained for the granites in the eastern part of the Kokshaal Segment while the leucogranites from its western part were dated at 280 Ma. This time span fits the known ages of post-collisional granitoids and important gold deposits elsewhere in the Tien Shan.

The granites have negative initial ϵ_{Nd} values (–1.6 to –6.9 at 280 Ma) and Mesoproterozoic depleted mantle model ages (1.05–1.43 Ga) indicating mixing of asthenospheric mantle and crustal sources. It is suggested that Mesoproterozoic crust comprised the basement of Tarim microcontinent underthrust to the north beneath the sedimentary piles of the Kokshaal. Mafic rocks associated with the granites may represent juvenile asthenospheric material underplating the Tarim margin at a post-collisional stage and providing heat for generation of A-type granites from its Precambrian crust. Coeval alkaline magmas could be produced from the lithospheric keel of Tarim as a result of interaction with ascending asthenospheric material. The east–west strike–slip motions affected the Tien Shan subsequent to collisional events and resulted in formation of plate-scale strike–slip shear zones. These shear zones provided suitable conduits for ascending asthenospheric material and heat influx in the crust.

On a regional scale, available Nd data for the Tien Shan show that all analysed Paleozoic felsic rocks originated from Precambrian crustal sources. The Northern Tarim rocks, exposed in the Kokshaal Range, and rocks of the Middle-Northern Tien Shan have similar Proterozoic depleted mantle model ages.

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