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SHRIMP zircon U-Pb dating of the Gangou granitoids, Central Tianshan Mountains, Northwest China and tectonic significances

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Two types of granitoids, highly deformed augen granitoids and undeformed fine-grained granitoids, are widely distributed in Gangou area, Central Tianshan Mountains, Northwest China. The augen granitoids are high-K calc-alkaline characterized by high K_2O, Rb, Y and Th, and low Sr and Sr/Y. They also have high contents of large ion lithophile elements (LILE), such as Ba, Rb, K and Th, and relatively low contents of high field strength elements (HFSE), such as Zr, Y and Nb. The fine-grained granitoids are calc-alkaline characterized by high Sr, low Y and HREE, similar to adakitic rocks, and with $Na_2O/K_2O<2$ (1.76−1.91), high I_{Sr} (0.70689−0.70981), and negative $\varepsilon_{Nd}(t)$ (−2.4−−5.3). High-precision SHRIMP U-Pb zircon dating results indicate that the Gangou augen granitiods were formed at 428±10 Ma, and the fine-grained granitoids were emplaced at 361−368 Ma. These geochemical and U-Pb zircon data have significant implications for the timing of closure of the Mishigou-Gangou Ocean and the evolution of the Central Tianshan orogenic belt.

SHRIMP dating, granitoids, Gangou, Xinjiang

The Tianshan (or Tien shan) Mountains are one of the most impressive intracontinental mountain belts, and played a key role in the construction of Paleozoic Eurasia[1]. The North Tianshan Fault has commonly been considered as the northern suture between Yili Block and Tuha Block in the Central Tianshan Mountains, although the timing of collision has long been debated[1−15]. Windley et al.[1], Allen et al.[5], Xiao et al.[11] and Wang et al.[15] proposed that the final collision of North Tianshan Ocean took place during the period between Late-Carboniferous and Early-Permian. By contrast, other workers proposed that the Tianshan Mountains entered the post-orogenic stage in the Carboniferous[2,3,9,10]. Identifications of Ordovician ophiolite and Silurian sediments in Mishigou area, Tokxun County, Xinjiang[16], the Ordovician ophiolitic melange and the Silurian foreland basin in Gangou area of Tokxun County[17,18], as well as the sedimentary-volcanic sequence of the Lower Carboniferous Ma'anqiao Formation[9,10,19] are all important to reinterpret the evolution of the Tianshan Ocean in Early Paleozoic. In addition to ophiolitic mélange and sedimentary-volcanic rocks, granitoids are widely distributed in Gangou area. These granitoids were commonly considered as products formed in island-arc environments[5,11] during the late Paleozoic Variscan period[20], but their emplacement ages were not well constrained[21,22]. In this paper, we conduct a geochemical study and SHRIMP zircon U-Pb dating on these granitoids, and use the new data to discuss the timing of closure of the Mishigou-Gangou Ocean and the evolution of the Central Tianshan orogenic belt.

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1 Regional geological setting and sample descriptions

A Paleozoic ophiolitic mélange was recently identified in the Gangou area of Tokxun County, Xinjiang[17,18] along the northern suture of the Central Tianshan Mountains (Figure 1). To the west, the mélange may be linked with the Paleozoic Mishigou ophiolite[16,17]. Silurian foreland basin occurs in the south of the Gangou area[17,18]. The Gangou augen granitoids are also exposed along the northern suture of the Central Tianshan Mountains, and intrude into the Silurian foreland basin sedimentary strata[20]. Apart from the augen granitoids, the fine-grained granitic intrusions are widely distributed on the southern side of the mélange. The youngest stratum intruded by the fine-grained granites is the Late Devonian Hazierbulake Formation, and the Lower Carboniferous Ma'anqiao Formation overlies the granites. All these granitoids have previously been considered to be formed during the Variscan period[20].

In this paper, 5 granitic samples have been chosen for geochemical and SHRIMP zircon U-Pb geochronological studies. The detailed geological information about the samples is summarized in Table 1.

2 Geochemistry

Major and trace elements were analyzed by XRF and ICP-MS, respectively, at the Key Laboratory of Continental Dynamics, Northwest University in Xi'an. Detailed analytical procedures and precisions can be found in ref. [23], and the results of the analyses are listed in Table 2.

Sr-Nd isotopic analyses were conducted at the Isotopic Laboratory, Chinese Academy of Geological Sciences, following the procedures described in ref. [24], and the results are listed in Table 3.

The Gangou augen granitoids are highly deformed high-K calc-alkaline granites (Figure 2). Sample XGG1 is characterized by high K_2O, Rb, Y and Th, and low Sr and Sr/Y. It also has high contents of large ion lithophile elements (LILE) such as Ba, Rb, K and Th, and relatively low contents of high field strength elements (HFSE) such as Zr, Y and Nb. The fine-grained granitoids are undeformed, calc-alkaline granites. Samples XGG2, XGG3 and XGG5 are characterized by high

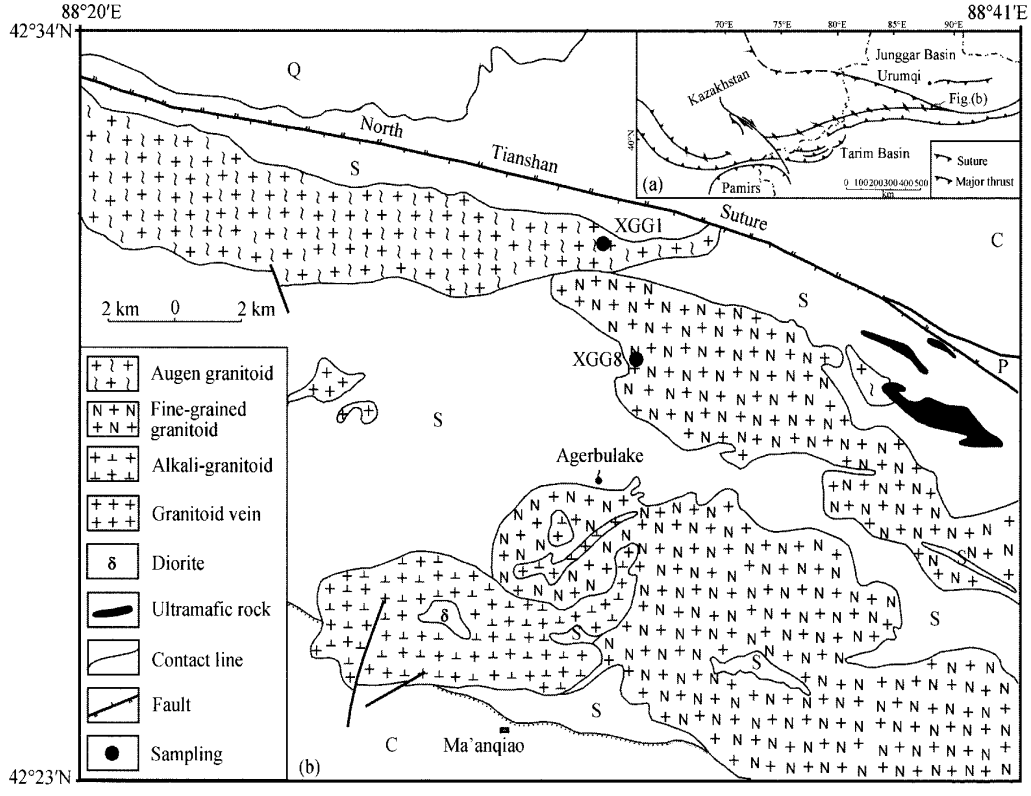

Figure 1 Geological sketch map of Gangou area, Xinjiang. (a) Modified from ref. [1]; (b) modified from ref. [20]).

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Table 1 Geological information of studied granitoids from Gangou area, Xinjiang

Sample	Locality	Lithology	Mineral assemblage [a)]	Accessory mineral	Age (Ma)	Chemical type
XGG1	42°31′20.5″N, 88°31′34.2″E	augen granite	Pl(40)+Kf(25)+ Q(20)+Bi(15) ± Hb	zircon+apatite+ titanite	428 ± 10	high-K calc-alkaline
XGG2	following the trip	medium- to fine-grained granite	Pl(60)+Q(30)+ Bi(10)	zircon+apatite	368 ± 10	calc-alkaline
XGG3	following the trip	fine-grained porphyritic granite	Pl(60)+Q(30)+ Mc(<10)	zircon+apatite	361 ± 11	calc-alkaline
XGG5	following the trip	fine-grained granite	Pl(55)+Q(25)+ Bi(15)+Mc(5)	zircon+apatite	-	calc-alkaline
XGG8	42°29′21.4″N 88°31′42.6″E	fine-grained granite	Pl(65)+Q(20)+ Bi(15)	zircon+apatite	368 ±9	-

a) Q, quartz; Pl, plagioclase; Kf, K-feldspar; Bi, biotite; Hb, hornblende; Mc, microcline.

Table 2 Chemical compositions of granitoids from Gangou area, Xinjiang

Sample	XGG1	XGG2	XGG3	XGG5
Lithology	Augen granite	Medium- to fine-grained granite	Fine-grained porphyritic granite	Fine-grained granite
Major elements (%)				
SiO_2	64.86	63.05	71.59	60.74
TiO_2	0.83	0.53	0.27	0.66
Al_2O_3	14.69	16.78	14.81	16.43
TFe_2O_3	6.67	4.84	2.75	5.40
FeO	2.88	3.15	1.52	2.78
MnO	0.09	0.06	0.04	0.07
MgO	1.67	2.23	0.57	2.58
CaO	3.19	3.88	2.41	5.32
Na_2O	3.32	3.75	4.06	3.93
K_2O	3.15	2.09	2.31	2.06
P_2O_5	0.29	0.17	0.11	0.17
LOI	1.06	2.74	1.03	2.48
Total	99.82	100.12	99.95	99.84
Na_2O/K_2O	1.05	1.79	1.76	1.91
Trace elements (ppm)				
Cs	7.58	1.86	1.27	0.90
Rb	107.9	89.5	66.9	63.1
Sr	234	605	361	608
Ba	976	596	940	526
Nb	23.0	7.2	11.7	6.7
Ta	1.43	0.38	0.67	0.57
Th	14.06	2.66	8.49	8.55
U	2.20	0.57	0.89	1.77
Zr	348	139	168	106
Hf	8.70	3.31	4.54	3.15
Y	49.5	9.3	13.6	16.5
Sc	17.4	6.4	4.4	12.5
V	69	82	15	107
Cr	33	27	5	21
Co	12.0	11.3	2.9	16.4
Ni	20.1	14.3	2.5	15.3
Cu	22.6	22.9	8.0	19.6
Zn	90.2	65.2	60.2	61.0
Ga	21.5	19.8	19.7	19.1
Ge	1.73	1.06	1.04	1.45
Sr/Y	4.7	65.1	26.5	36.8
La	50.20	10.80	33.70	25.30
Ce	97.70	21.00	66.50	53.10
Pr	11.70	2.48	7.36	5.79
Nd	49.00	10.32	28.64	23.30
Sm	10.10	2.18	5.35	4.28
Eu	2.46	0.96	1.24	1.14
Gd	9.94	2.04	4.72	3.97
Tb	1.52	0.28	0.61	0.52
Dy	8.60	1.49	2.84	2.69
Ho	1.72	0.29	0.45	0.51
Er	4.51	0.78	1.04	1.35
Tm	0.65	0.11	0.12	0.19
Yb	4.39	0.75	0.85	1.30
Lu	0.68	0.12	0.11	0.20
ΣREE	253.14	53.65	153.54	123.60
$(La/Yb)_N$	7.7	9.7	26.6	13.1

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Table 3 Sr/Nd isotopic data of granitoids from Gangou area, Xinjiang

Sample	Age (Ma)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ	I_{Sr}	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	T_{DM} (Ma)	$\varepsilon_{Nd}(t)$
XGG1	428	89.90	198.7	1.310	0.715184	11	0.70722	10.012	48.53	0.1248	0.512357	11	1358	−1.6
XGG2	368	70.45	499.6	0.4081	0.710200	14	0.70807	2.045	9.901	0.1249	0.512277	11	1496	−3.7
XGG3	361	58.50	322.3	0.5254	0.712502	12	0.70981	5.233	30.15	0.1050	0.512152	10	1397	−5.3
XGG5	≈360	38.52	482.5	0.2310	0.708075	14	0.70689	4.179	23.39	0.1081	0.512309	8	1213	−2.4

SiO_2 ($SiO_2 \geqslant 56\%$), Al_2O_3 (14.81%−16.78%) and Na_2O (>3%), and low MgO (<3%). They have high contents of Sr (361−608 ppm), but low Y (9.3−16.5 ppm) and HREE, similar to adakitic rocks[25] (Figures 3−5), and with low Na_2O/K_2O ratios (1.76 − 1.91), high I_{Sr} (0.70689−0.70981), negative $\varepsilon_{Nd}(t)$ values (−2.4−−5.3) and old T_{DM} ages of 1213−1496 Ma (Tables 2 and 3). The geochemistry of the fine-grained granitoids in the area is similar to that of adakitic rocks formed by partial melting of thickened mafic lower continental crust[29,30].

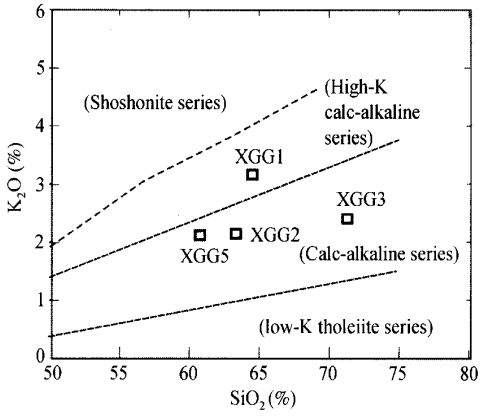

Figure 2 SiO_2-K_2O diagram for Gangou granitoids.

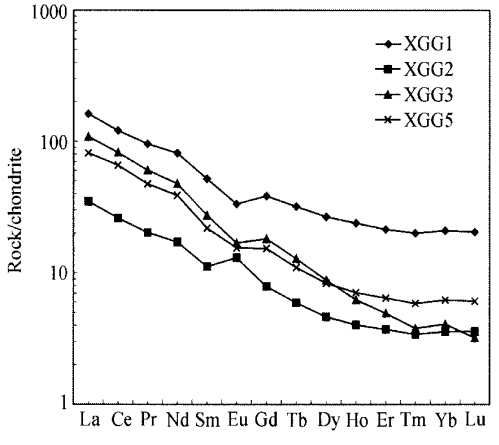

Figure 3 Chondrite (CHON) normalized REE patterns for Gangou granitoids. The CHON values are from ref. [26].

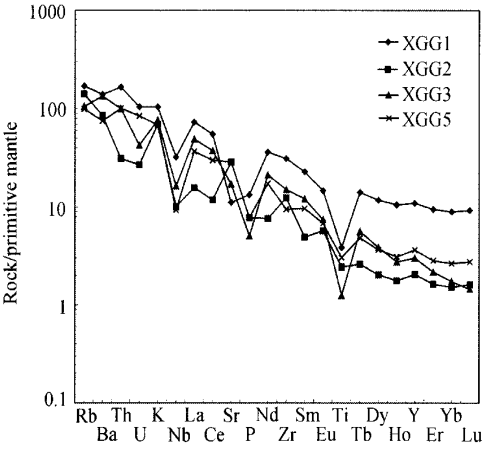

Figure 4 Primitive-mantle (PM) normalized spidergrams for Gangou granitoids. The PM values are from ref. [27].

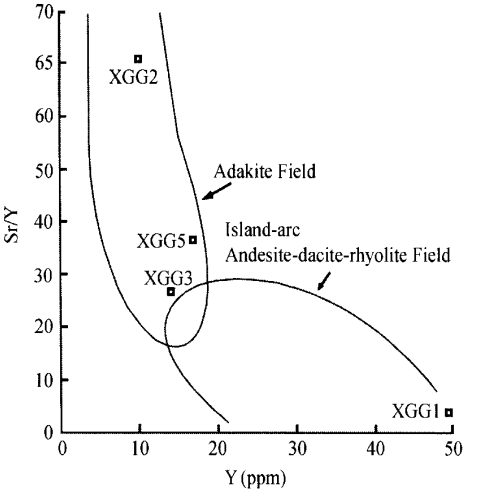

Figure 5 Sr/Y-Y diagram for Gangou granitoids modified from ref. [28].

3 Zircon SHRIMP U-Pb dating

3.1 Analytical technique

Zircons were extracted from ~5 kg fresh rocks. The samples were crushed, and mineral separations were undertaken after elutriation and magnetic vibration. Approximately 100 grains of zircon were handpicked from each sample under a binocular microscope. Together

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with standard zircons (TEMORA), they were mounted into epoxy resin discs and polished. After preparation of the mount, zircons were photographed and imaged for cathodoluminescence (CL) and backscatter electronic (BSE) using an electron microprobe. At last, the zircons in the mount were gold-coated and analyzed on SHRIMP II.

Zircon U-Th-Pb analyses were performed on SHRIMP II at Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences. Detailed analytical procedures were given in refs. [31−34]. Mass resolution during the analytical sessions was ~5000 (1% definition). Spot sizes were 25−30 μm and the intensity of the primary O_2^- ion beam was 4−6 nA. Each spot was rastered for 120−180 s prior to analysis. Data were determined by taking 5 scans on $^{90}Zr_2{}^{16}O^+$, $^{204}Pb^+$, background, $^{206}Pb^+$, $^{207}Pb^+$, $^{208}Pb^+$, $^{238}U^+$, $^{232}Th^{16}O^+$, $^{238}U^{16}O^+$. Standard SL13 (572 Ma, U content = 238 ppm) was referred to calibrating contents of U, Th and Pb of the standard TEMORA (417 Ma) and the analyzed zircons. The TEMORA was used to calibrate inter-elemental fractionation; Pb/U calibration follows the equation $^{206}Pb^+/^{238}U^+=A\ (UO^+/U^+)^2$[35]. Data were processed using the PRAWN program[36]. Common Pb correction uses measured ^{204}Pb; errors in data tables are 1σ, whereas weighted mean ages of individual samples are quoted at 2σ. All the analytical results are listed in Table 4.

3.2 Analytical results

(1) Augen granite (XGG1). Zircons from this sample are mostly transparent, light brown, euhedral, stubby to elongate prisms. CL images indicate that the zircons mostly have clear oscillatory zonations, indicative of a magmatic origin. Twelve spots of 14 analyses on 13 zircons (excluding discordant analyses 5.1 and 11.1) form a coherent group and cluster tightly on or around the concordia (Table 4; Figure 6(a)), and yield a weighted mean $^{206}Pb/^{238}U$ age of 428±10 Ma, with a chi-square (χ^2) of 0.1732. This age is interpreted as the emplacement age of the augen granite.

(2) Medium- to fine-grained granite (XGG2). Most zircons from this sample are transparent, pale yellow, stubby, euhedral prismatic crystals. CL images indicate that the zircons mostly have clear oscillatory zonations, and a few contain inherited cores. Twelve analyses on 12 zircons or fragments were performed. Excluding 2 analyses (spots 1.1 and 5.1), which gave old ages of 404 ± 17 Ma and 1821 ± 18 Ma ($^{207}Pb/^{206}Pb$ age), respectively, the remaining 10 analyses form a coherent group clustering tightly on the concordia (Table 4; Figure 6(b)), and yield a weighted mean $^{206}Pb/^{238}U$ age of 368 ± 10 Ma, with a chi-square of 0.5055. This age is considered as the emplacement age of the granite. The two old ages are interpreted as ages of the inherited or xenocrystal zircons.

(3) Fine-grained porphyritic granite (XGG3). Zircons from the sample (XGG3) are mostly transparent, light brown, elongate, euhedral prisms. CL images indicate that the zircons mostly have clear oscillatory zoning texture. Nine spots of 10 analyses on 10 zircons (excluding the statistic outlier of spot 1.1) form a coherent group and cluster tightly on or around the concordia (Table 4; Figure 6(c)), and yield a weighted mean $^{206}Pb/^{238}U$ age of 361 ± 11 Ma, with a chi-square of 0.3221. We interpret this age as the emplacement age of the porphyritic granite.

(4) Fine-grained granite (XGG8). Zircons from the sample XGG8 are mostly transparent, pale yellow in color, stubby, euhedral prismatic crystals, with clear magmatic oscillatory zonations. 14 analyses on 14 zircons form a coherent group clustering tightly on the concordia (Table 4; Figure 6(d)), and yield a weighted mean $^{206}Pb/^{238}U$ age of 368 ± 9 Ma, with a chi-square of 0.3807. This age is interpreted as the intrusive age of the granite.

4 Discussion

The closure of Paleozoic Tianshan Ocean has significant implications for understanding the tectonic evolution of the Tianshan orogenic belt. In recent years, the Early Paleozoic evolution of the belt has attracted increasing attentions of many researchers[8−10,17,18,37,38]. Ordovician Gangou ophiolite is an arc-type ophiolite, probably the eastern extension of the Mishigou ophiolite[17,18]. In Mishigou area Early Silurian graptolites have been identified[4,39]. The Mishigou – Gangou ophiolitic mélange could be extended to the south of Axiabulake in the east[4,40], and might be connected with the Tangbale ophiolite in western margin of Jungar basin in the west[4,18]. The $^{207}Pb/^{206}Pb$ age of sphenes and plagioclases from the Tangbale leucogabbro is 508±20 Ma[2,41,42], indicating that the ophiolite has a Cambrian age.

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Table 4 SHRIMP zircon U-Pb analytical results of Gangou granitoids[a)]

Spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	$^{206}Pb_c$ (%)	$^{204}Pb/^{238}U$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{207}Pb/^{206}Pb$	±1σ	$^{206}Pb/^{238}U$ age (Ma)	±1σ	$^{207}Pb/^{235}U$ age (Ma)	±1σ	$^{207}Pb/^{206}Pb$ age (Ma)	±1σ
XGG1																	
1.1	114	75	0.66	9	0.01	0.0688	0.0025	0.598	0.043	0.0630	0.0036	429	15	476	28	709	128
2.1	313	153	0.49	22	-	0.0663	0.0027	0.529	0.037	0.0579	0.0030	414	17	431	25	524	118
3.1	348	204	0.59	25	-	0.0685	0.0042	0.515	0.041	0.0546	0.0024	427	25	422	28	394	100
4.1	192	108	0.56	14	0.01	0.0688	0.0036	0.549	0.057	0.0579	0.0049	429	22	444	38	526	195
#5.1	138	103	0.75	10	-	0.0636	0.0041	0.585	0.054	0.0667	0.0039	398	25	468	35	828	126
6.1	95	52	0.54	7	0.02	0.0699	0.0031	0.480	0.096	0.0498	0.0094	435	19	398	68	188	389
6.2	289	151	0.52	21	-	0.0691	0.0032	0.511	0.032	0.0537	0.0020	430	20	419	22	359	85
7.1	228	153	0.67	17	0.01	0.0691	0.0040	0.501	0.042	0.0527	0.0029	430	24	413	29	314	128
8.1	354	154	0.43	24	-	0.0667	0.0047	0.505	0.041	0.0550	0.0017	416	29	415	28	411	71
9.1	310	104	0.33	21	-	0.0687	0.0034	0.559	0.035	0.0590	0.0018	428	21	451	23	567	69
10.1	240	91	0.38	17	-	0.0709	0.0029	0.536	0.038	0.0548	0.0029	441	17	435	25	404	121
#11.1	152	91	0.60	12	0.02	0.0744	0.0030	0.471	0.062	0.0459	0.0055	463	18	392	43	0	0
12.1	191	101	0.53	14	-	0.0674	0.0027	0.542	0.035	0.0583	0.0027	420	16	439	23	541	103
13.1	321	231	0.72	24	-	0.0683	0.0032	0.544	0.032	0.0578	0.0017	426	19	441	21	522	67
XGG2																	
#1.1	491	317	0.64	34	-	0.0647	0.0028	0.481	0.026	0.0539	0.0015	404	17	399	18	368	63
2.1	269	196	0.73	17	0.01	0.0564	0.0028	0.417	0.035	0.0536	0.0033	354	17	354	25	356	146
3.1	315	180	0.57	19	0.01	0.0581	0.0034	0.396	0.031	0.0495	0.0022	364	21	339	23	169	107
4.1	220	198	0.90	15	-	0.0587	0.0023	0.444	0.032	0.0548	0.0031	368	14	373	23	405	132
#5.1	304	107	0.35	65	-	0.2066	0.0096	3.170	0.154	0.1113	0.0011	1211	52	1450	38	1821	18
6.1	182	112	0.62	12	-	0.0609	0.0032	0.501	0.036	0.0596	0.0026	381	20	412	25	591	96
7.1	179	84	0.47	11	0.01	0.0611	0.0024	0.470	0.041	0.0557	0.0041	382	15	391	29	442	171
8.1	268	183	0.68	18	-	0.0603	0.0023	0.471	0.029	0.0566	0.0025	377	14	392	21	476	102
9.1	324	206	0.63	20	-	0.0577	0.0031	0.439	0.029	0.0552	0.0018	361	19	369	21	420	73
10.1	615	368	0.60	39	-	0.0588	0.0027	0.442	0.025	0.0546	0.0014	368	17	372	18	395	60
11.1	165	107	0.65	10	0.03	0.0554	0.0026	0.505	0.078	0.0661	0.0093	347	16	415	54	811	327
12.1	221	139	0.63	15	-	0.0618	0.0070	0.492	0.060	0.0577	0.0019	387	43	406	42	519	73
XGG3																	
#1.1	229	76	0.33	12	0.01	0.0532	0.0031	0.390	0.035	0.0532	0.0032	334	19	334	26	335	141
2.1	117	67	0.58	8	0.01	0.0608	0.0031	0.480	0.047	0.0573	0.0045	381	19	398	33	501	181
3.1	122	60	0.49	7	-	0.0580	0.0032	0.509	0.039	0.0637	0.0031	363	19	418	27	731	105
4.1	59	48	0.81	4	0.03	0.0591	0.0027	0.404	0.083	0.0496	0.0097	370	16	345	62	176	401
5.1	170	53	0.31	10	0.01	0.0567	0.0029	0.424	0.046	0.0542	0.0048	355	18	359	33	380	211
6.1	182	80	0.44	11	0.01	0.0592	0.0033	0.431	0.048	0.0527	0.0048	371	20	364	35	318	221
7.1	93	52	0.56	6	-	0.0561	0.0024	0.502	0.048	0.0650	0.0052	352	14	413	33	774	178
8.1	129	85	0.66	8	0.01	0.0568	0.0023	0.471	0.044	0.0602	0.0048	356	14	392	31	609	182
9.1	171	46	0.27	9	0.01	0.0563	0.0027	0.453	0.036	0.0584	0.0033	353	17	379	25	544	129
10.1	96	43	0.45	6	-	0.0580	0.0033	0.504	0.057	0.0631	0.0057	363	20	414	39	711	204
XGG8																	
1.1	99	78	0.79	6	0.02	0.0569	0.0026	0.442	0.085	0.0563	0.0102	357	16	372	62	464	457
2.1	121	98	0.81	8	0.02	0.0613	0.0028	0.459	0.092	0.0543	0.0103	384	17	383	66	382	382
3.1	181	111	0.61	11	0.01	0.0593	0.0025	0.400	0.035	0.0489	0.0035	371	15	342	26	144	159
4.1	202	130	0.64	13	0.01	0.0602	0.0025	0.435	0.041	0.0524	0.0042	377	15	367	29	303	192
5.1	146	120	0.82	10	0.01	0.0586	0.0028	0.492	0.047	0.0608	0.0047	367	17	406	32	633	174
6.1	138	96	0.69	8	0.01	0.056	0.0029	0.404	0.050	0.0523	0.0055	351	18	345	37	300	260
7.1	129	110	0.86	9	0.02	0.0584	0.0032	0.493	0.082	0.0613	0.0092	366	19	407	57	649	362
8.1	178	139	0.78	12	0.01	0.0592	0.0032	0.540	0.051	0.0662	0.0047	371	20	439	34	811	154
9.1	368	343	0.93	26	-	0.0604	0.0023	0.450	0.032	0.0540	0.0030	378	14	377	23	372	130
10.1	210	133	0.63	14	-	0.0599	0.0027	0.473	0.031	0.0572	0.0025	375	16	393	22	499	98
11.1	128	71	0.55	8	0.02	0.0585	0.0025	0.445	0.070	0.0552	0.0081	367	15	374	50	421	364
12.1	261	199	0.76	17	0.01	0.0587	0.0024	0.466	0.037	0.0576	0.0036	368	15	389	26	514	143
13.1	165	100	0.61	10	0.01	0.0558	0.0023	0.500	0.047	0.0645	0.0051	350	14	412	32	773	174
14.1	136	91	0.67	9	0.02	0.0596	0.0031	0.487	0.072	0.0593	0.0079	373	19	403	51	577	320

a) $^{206}Pb_c$ is the percentage of ^{206}Pb attributed to common Pb; Pb* indicates the radiogenic Pb; # indicates statistic outlier.

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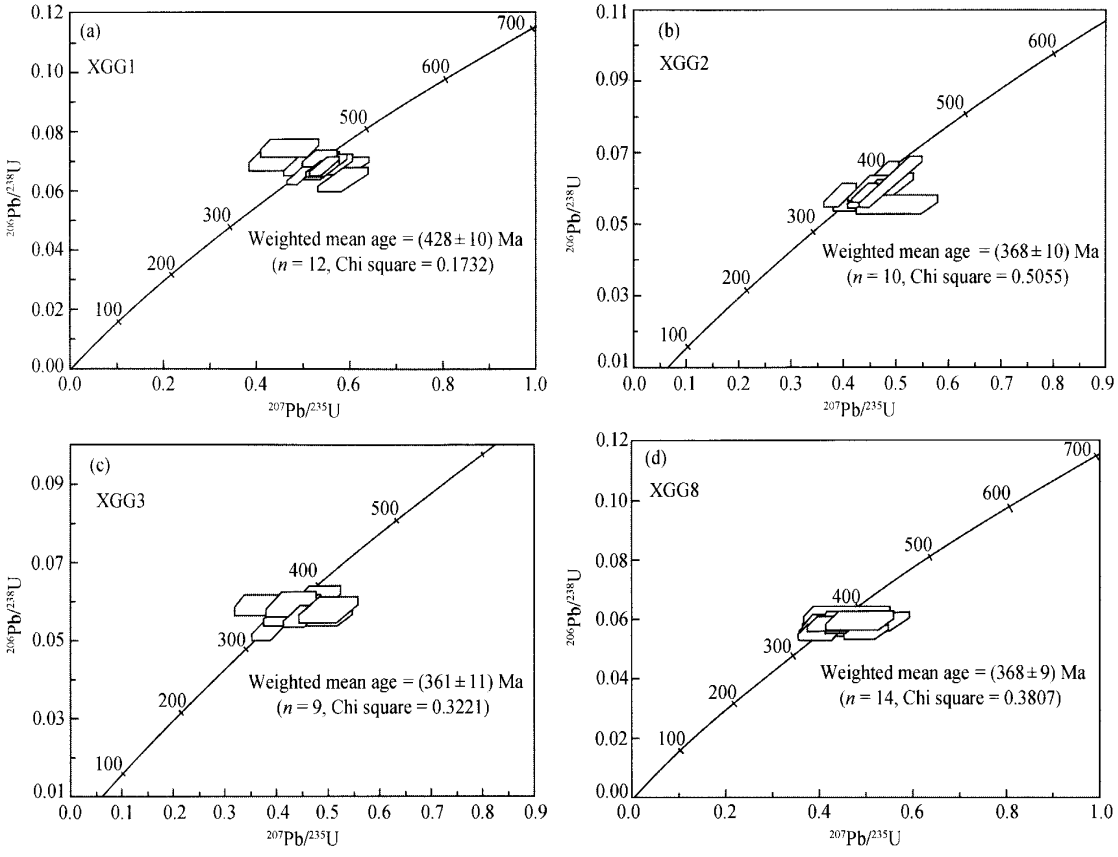

Figure 6 Concordia plots showing zircon SHRIMP U-Pb analytical data of granitoids from Gangou area, Xingjiang, Northwest China.

The Mishigou-Gangou Ocean was a part of Tianshan Ocean, which separated Yili Block from Tuha Block. Feng et al.[18] proposed that the closure of the Ocean took place before 400 Ma, earlier than northern Kalamaili Ocean. Zircon U-Pb dating results of clastic rocks (≥461 Ma) in the foreland basin of Gangou and granodiorites (386 Ma) intruding into the clastic rocks suggested that the subduction of the Early Paleozoic Mishigou-Gangou Ocean along the north margin of Central Tianshan Mountains took place in the Ordovician, and ended before 386 Ma[17].

The Gangou augen granite (XGG1) in this study was emplaced along the northern suture of Central Tianshan Mountains. The granite has low Sr and high Yb contents[43]. However, the high deformation nature, intrusive relations with Silurian foreland basin sedimentary strata[20], and the geochemical characteristics of the granite such as high-K calc-alkaline and high contents of LILE (e.g., Ba, Rb, K and Th) suggest that the granite was probably emplaced in a collisional setting. Shu et al.[44] proposed that early thrust shearing along the northern margin of the Central Tianshan Mountains occurred during Late Silurian time, probably corresponding to the coeval southward subduction of the ancient Tianshan ocean, and that the closure of the ocean as a result of collision between the Tuha continental block and the Central Tianshan arc occurred during the Late Silurian. SHRIMP U-Pb zircon age of 428 ± 10 Ma of the augen granite is indistinguishable within errors with a whole-rock Rb-Sr age of 452 ± 19 Ma[3] for the Mishigou gneissic granites. This U-Pb age represents the timing of the Silurian closure event of the Mishigou-Gangou Ocean.

The fine-grained granites (XGG2, XGG3, XGG8) from Gangou area yield zircon SHRIMP U-Pb zircon ages of 368 ± 10 Ma, 361 ± 11 Ma and 368 ± 9 Ma. Within analytical errors, these ages are identical, and are interpreted as the emplacement ages of the fine-grained granites. Thus, they were emplaced during the Late Devonian consistent with the field observations that the

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granites intruded into Upper Devonian Hazierbulake Formation and were overlain by Lower Carboniferous Ma'anqiao Formation. The sedimentary-volcanic sequence of the Lower Carboniferous Ma'anqiao Formation consists, from bottom to top, of pebblestone, gravelstone, sandstone, sandstone and siltstone interbedded with shale and intercalated with limestone, basic lavas and some rhyolite lavas, which is characterized by a progradational sequence showing a transition from continental to marine facies and indicates that the Central Tianshan orogenic belt entered an intraplate evolution stage during Early Carboniferous[9,10,19].

Preliminary geochemical data of this study show that these fine-grained granites geochemically resemble adakitic rocks (such as high Na_2O and Sr, low Y and HREE), except for relatively low Na_2O/K_2O ratios (1.76−1.91), high I_{Sr} values (0.70689−0.70981), negative $\varepsilon_{Nd}(t)$ values (−2.4− −5.3) and old T_{DM} ages of 1213−1496 Ma. Several origins have been proposed for adakites or Na-rich granitoids, such as melting of young subducted oceanic crust[25], melting of thickened mafic lower continental crust[29,30,45 − 48], melting of foundered lower crust[23,49], and so on. According to the features of the overlying Ma'anqiao Formation, the origin of the fine-grained granitoids in the Gangou area seems to be a result of melting of thickened lower continental crust during post-orogenic stage of Central Tianshan orogenic belt. It is noteworthy that only judging from the granites, other origins (e.g., underplating of basic magma[50,51]) cannot be excluded.

The conclusions of this paper are based on the previous detailed fieldwork in the area[9,10,17−19], and the precise SHRIMP zircon U-Pb dating, geochemical data, isotopic analyses of this study. Our interpretations are in agreement with the conclusions proposed by Xu et al.[52] that Bayingou rift-type Ocean occurred in Early Carboniferous. Furthermore, the Early Carboniferous "Red Sea-type" ocean basin was formed on the pre-existing continent. And Carboniferous adakite - high-Mg andesite - Nb-enriched arc basalt[15,53] occurring in the northern Tianshan Mountains were likely related to subduction of the Late Paleozoic Ocean.

5 Conclusions

(1) The Gangou augen granitoids belong to high-K calc-alkaline series, and are high in K_2O, Rb, Y and Th, and low in Sr and Sr/Y. They also have high contents of large ion lithophile elements (LILE), such as Ba, Rb, K and Th, and relatively low contents of high field strength elements (HFSE), such as Zr, Y and Nb, similar to those of collisional granitoids. SHRIMP U-Pb zircon age of 428 ± 10 Ma is interpreted as the emplacement age of the granite, corresponding to the closure of the Mishigou-Gangou Ocean during Silurian.

(2) The fine-grained granitoids are calc-alkaline characterized by high Sr, low Y and HREE, similar to the geochemical characteristics of adakitic rocks, with low Na_2O/K_2O, high I_{Sr}, and negative $\varepsilon_{Nd}(t)$. These granitoids were emplaced during Late Devonian between 368 ± 10 and 361 ± 11 Ma. Taking into consideration the characteristics of the overlying Ma'anqiao Formation, we suggest that the formation of the fine-grained granites was probably due to melting of a thickened lower continental crust during post-orogenic stage of Central Tianshan orogenic belt.

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SHRIMP zircon U-Pb dating of the Gangou granitoids, Central Tianshan Mountains, Northwest China and tectonic significances

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