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A new geological map of the western Junggar, north Xinjiang (NW China): Implications for Paleoenvironmental reconstruction

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Recently, new geochronological data and geological observations including the discovery of garnet amphibolite, Ordovician micro-fossils, unconformable contact between the ophiolitic mélange related flysch and the Devonian to Early Carboniferous terrestrial volcano-sedimentary strata provide critical evidences for Paleoenvironmental reconstruction in the western Junggar (Xinjiang, China). Two different geological layers could be clearly identified: the Early Paleozoic metamorphic terrane mainly consists of ophiolitic mélange and flysch, and the Late Paleozoic volcano-sedimentary units lying on the ophiolitic mélange and flysch. Both of these layers were intruded by granitic to dioritic magma during the Late Carboniferous to Early Permian period. Based on these data, a new geological map for the western Junggar has been compiled, which is essential not only for better understanding of the geological evolution but also for exploration of mineral resources.

Introduction

The Central Asian Paleozoic Ocean (CAPO) is represented by a complex collage of fragments of oceanic crust (ophiolites), oceanic islands, ancient micro-continent and arc terranes. It is interpreted as having formed by the accretion of island arcs and intervening oceans probably started from the Cambrian-Ordovician to Devonian (e.g., Zhu and Ogasawara, 2002; He et al., 2004; Windley et al., 2007; Xiao et al., 2008; Kröner et al., 2008; Han et al., 2011; Choulet et al., 2012; Wilhem et al., 2012; Zhao and He, 2012). Its multi-stage geological evolution makes this huge area a unique and complicated large-scale metal province (Heinhorst et al., 2000; Kurchavov et al., 2002; Yakubchuk, 2004). Locating on the central part of the CAPO, the western Junggar is characterized by linear zones of Paleozoic ophiolites, volcano-sedimentary rocks, and intermediate to granitic intrusions (see Fig. 1).

The Tangbale, Darbut-Sartohay, and Baijiantan-Baikouquan ophiolitic belts, as the major components of the western Junggar, have been studied for interpreting the Paleozoic subduction-accretion

processes. The Tangbale ophiolite mélange consists of radiolarian chert, pillow lava, metagabbro, serpentinite, harzburgite and lherzolite. Consistent with stratigraphical records, radiometric dating of metagabbro (489Ma, Zhang et al., 1993) and titanite in leucogabbro (502 Ma, Kwon et al., 1989) suggested that the Tangbale ophiolite mélange was formed at Late Cambrian. The time for other ophiolitic mélanges was not well constrained. For example, the wall-rocks of the Sartohay ophiolitic mélange contain Early to Middle Devonian fossils (Zhu et al., 1987; Wei et al., 1987), while the low-grade metamorphic gabbro samples were dated to be 395Ma (Sm-Nd isochrons, Zhang and Huang, 1992) and 391Ma (zircon U-Pb age, Gu et al., 2009). Previous studies demonstrated that different rock-units in the Darbut-Sartohay ophiolitic mélanges reflect their different origins. For example, basalts with geochemical characteristics similar to N-MORB, E-MORB and OIB randomly distribute in the Sartohay region (Yang et al., 2000; Lei et al., 2008; Yang et al., 2012). Both metabasites with prehnite-pumpellyite metamorphic phase (Zhang et al., 2001) and garnet amphibolite (Zhu et al., 2008) were found in the Sartohay ophiolitic mélange. The Darbut-Sartohay ophiolitic mélanges were studied since 1980s, while the newly identified Baijiantan-Baikouquan ophiolitic belt (Xu et al., 2006; He et al., 2007) needs more attention. The rock-units with different ages and metamorphic phases in these ophiolitic mélanges are not well-constrained. The newly uncovered geological data are conflicting with the previously proposed geological models. For example, the widespread Early Carboniferous volcano-sedimentary rocks in western Junggar, filling in the post-orogenic basin and occurring as molasse in most cases (Zhu et al., 2013), were mis-understood as island arc system in geological literatures. This is critical for tectonic reconstruction of the Kazakhstan-Junggar plate as well as the geological evolution of CAPO. To solve the above problems, more detailed field geological work and re-interpretation of present geological data are necessary. Recently, increase of geological data could illustrate a completely new version for geology evolution in the western Junggar. This paper displays a newly compiled geological map (see Figs. 1, 2) based on new data and the old geological map (BGMRXUA, 1993; He et al., 2004). Several key evidences are described in the following text.

Darbut-Sartohay region

The Darbut fault is a major sinistral north-eastern to eastern trending zone, which separates a sedimentary package from an

Figure 1. The newly compiled geological map of the western Junggar.

Figure 2. Geological map for the Hatu – Baobei – Sartohay region and a geological section across the Baobei-HLS and Darbut-Sartohay flysch-ophiolitic mélangé zones (insert, dashed line indicates the possible positions of the Early Carboniferous volcano-sedimentary strata and the eroded parts of the flysch-ophiolitic mélangé).

ophiolitic mélangé containing a chaotic assemblage of blocks of strongly deformed serpentinite, metagabbro, chert and basalts (Feng, 1986; Bai et al, 1995; Chen and Zhu, 2008). Flysch, mainly consisting of chert and siltstone-mudstone-tuff, lies on the ophiolitic mélangé. The layers in flysch, generally 5 to 9cm in thickness, might be turnover in many cases. In the case as shown in Figs. 3a-b, flysch with normal stratigraphic position lies on basalt and metagabbro. All these rocks are strongly deformed and showing close-spaced cleavage with direction nearly to EW. Magnesitite and fuchsite magnesitite with serpentinite relics, occurring at the lower part of the Sartohay ophiolitic mélangé (Fig. 3a), generally shows shearing deformation (Fig. 3c). Sulfide-bearing quartz veins in magnesitite are major target for gold exploration (Qiu and Zhu, 2012). Serpentinite with chromitite lenses occasionally occurs at the stratigraphic bottom of the Sartohay ophiolitic mélangé (Zhou et al., 2001; Tang and Zhu, 2010). The serpentinite is covered by the Devonian sandstone and conglomerate unconformably (Fig. 3d). The breccias in conglomerate are mainly chert-siltstone. This sandstone – conglomerate does not undergo deformation, while serpentinite was strongly deformed. Flysch, consisting mainly of

chert and siltstone with high-angle layers, contacts with flat-angle strata of the Early Carboniferous volcanoclastics unconformably (Figs. 3a, e, f).

The Baobei-HLS zone (see Fig. 2 for location), locating on the north of the Darbut-Sartohay zone, consists of chert, siltstone and tuff with basalt locally in the Baobei-Huilvshan region (Fig. 4). The stratigraphic layers of chert and siltstone-tuff are nearly perpendicular and extending NE-direction. Basaltic pillows were cemented by chert in some cases (Fig. 4b). The boundary between siltstone layer and tuff layer is uneven (Fig. 4c). The strata of chert - siltstone - tuff is stable in most cases and it is covered by the Devonian sandstone – conglomerate unconformably.

The ophiolitic mélangé near the Darbut bridge (Fig. 5a), consisting mainly of serpentinite, basalt, and small blocks of metagabbro, contacts with the Lower Carboniferous tuff, siltstone, and volcanoclastics via fault. The profile section shows a dome structure (Fig. 5b): ultramafic rocks were elevated in core part, where that basalt and metagabbro were mostly eroded. Metagabbro blocks in serpentinite matrix are mainly composed of hydrous garnet

Figure 3. (a) Geological section of the Sartohay ophiolitic mélangé (see Fig. 2 for location); (b) A trench exposing the stratigraphic sequence of the ophiolitic mélangé. The hills on north are flysch. All these units are strongly deformed; (c) Magnesitite and fuchsite magnesitite, containing Cr-spinel and locating under metagabbro, show shearing deformation; (d) Devonian conglomerate and sandstone lying on the ophiolitic mélangé; (e-f) Early Carboniferous volcanoclastics with basalt lie on the ophiolitic mélangé unconformably. Note: the chert-siltstone with perpendicular bands has been strongly deformed, while the strata of volcanoclastics do not undergo deformation.

Figure 4. (a) Photos showing chert and siltstone with tuff strata in the Baobei-HLS zone, locally see the basalt was cemented by chert (b); (c-d) Photos showing the perpendicular strata consisting mainly of siltstone and tuff in the Baobei-HLS zone.

(grossularite) and clinopyroxene (see Figs. 5c). The original texture was destroyed, while the assemblage of clinopyroxene and garnet with feldspar pseudomorph still preserves gabbro texture. Feldspar was broken down into albite + zoisite with grossularite locally. Chromite contains inclusion consisting of hornblende and grossularite occasionally (see Fig. 5d). Late-stage amphibole, chlorite, and epidote are widespread in these units.

Zircons were separated from metagabbro for SHRIMP dating. A zircon cathodoluminescence image is showing in Fig. 6a. This zircon has a complex texture with a core, a mantle showing sector-zoning

pattern, and a discontinuous rim. The rim was formed during metamorphism. The SHRIMP analyses are mainly performed on igneous zircons with Th/U ratio of 0.44 – 0.57. Apart from one relatively younger age (358Ma), other six U-Pb ages give a weighted mean age of 426.0 ± 5.8 Ma (MSWD = 0.87, Fig. 6b). This age represents the crystallization time of gabbro, and thus implies that the Paleo-ocean floor spreading occurred before the middle Silurian period. The younger age with extremely low Th/U ratio (358Ma, Th/U = 0.06), obviously differing from other data, might be a mixture between the igneous mantle and its metamorphic rim. Two detrital

Figure 5. (a-b) A simplified geological map for the outcrop and geological section (see Fig. 2 for location) near the Darbut bridge. Dashed line indicates possible position of the eroded part of the flysch-ophiolitic mélangé. Insert photo showing an outcrop of metagabbro blocks in serpentinite; (c-d) Microphotographs showing the mineral assemblages of metagabbro. Ab – albite, Amp – amphibole, Chl – chlorite, Cpx – clinopyroxene, Grs – garnet, Mt – magnetite, Zo – zoisite.

zircon cores give extremely old U-Pb ages of 2327Ma (Th/U of 0.62 for spot -3.1) and 1830Ma (Th/U of 0.03 for spot -9.1, see Table 1). Both of them might belong to relics of continental crust, which have been involved in ophiolitic melanges similar to the detrital zircons in Karamay OIB-type pillow basalt (Zhu et al., 2007) and in metagabbro from the Kujibai ophiolitic mélangé (Zhu and Xu, 2006).

Baijiantan-Baikouquan region

The Baijiantan-Baikouquan ophiolitic belts (Fig. 7a) were identified recently (Xu et al., 2006; He et al., 2007; Zhu et al., 2008).

The Baikouquan ophiolitic mélangé is mainly composed of serpentinite with lherzolite lenses, blocks of metagabbro and amphibolite. Marble is rare and basalt occurs as matrix. Although the ophiolitic mélangé was strongly weathered, some fresh rock samples still could be collected in the top of some small hills (see Figs. 7b, c). Basaltic rocks lie on serpentinite (see Fig. 7b). Both basalt and serpentinite have undergone strong deformation. The Devonian to Early Carboniferous volcanoclastics cover ophiolitic mélangé and flysch (see the section in Fig. 7d).

Differing from the blocks of lherzolite and metagabbro scattered in matrix randomly, blocks containing amphibolite and garnet

Figure 6. The cathodoluminescence image of a zircon from metagabbro (a) and zircon SHRIMP dating results (b). Scale bar is 10 mm in (a). Detrital zircon core with U-Pb apparent ages of 1830-2367Ma are much older than the igneous zircon mantle (M).

Figure 7. (a) Simplified geological map showing the Darbut-Sartohay and Beijiantan-Baikouquan ophiolitic mélanges; (b) Basalt lies on serpentinite with ilherzolite lenses; (c) Microphotograph showing the mineral assemblage in ilherzolite; (d) A geological section across the Baikouquan ophiolitic mélange showing blocks of metagabbro, garnet amphibolite, serpentinite in basaltic matrix. These units were overlaid by Devonian sandstone and Early Carboniferous volcanoclastics. Mt – magnetite, Ol- olivine, Sp – spinel, Srp – serpentine.

Table 1 SHRIMP dating results for zircons separated from different rocks in western Junggar (analytical method: zircons were hand picked under a binocular microscope, and cathodoluminescence images obtained using a CAMECA SX-50 microprobe. Zircons were dated using the SHRIMP II installed at the Beijing SHRIMP Center, data correction was based on Williams (1998))

	$^{206}\text{Pb}_c$	U ppm	Th ppm	$^{232}\text{Th}/^{238}\text{U}$	$^{206}\text{Pb}^*$ ppm	$^{206}\text{Pb}/^{238}\text{U}$ age, Ma	Disco- rdant, %	Total $^{238}\text{U}/^{206}\text{Pb}$	%	Total $^{207}\text{Pb}/^{206}\text{Pb}$	%	$^{207}\text{Pb}/^{206}\text{Pb}$	%	$^{207}\text{Pb}/^{235}\text{U}$	%	$^{206}\text{Pb}/^{238}\text{U}$	%	err corr
DB19																		
-2.1	1.59	92	39	0.44	5.58	431.3±8.5	-285	14.22	1.8	0.0612	2.6	0.0483	15	0.460	16	0.0692	2.0	0.131
-3.1	0.00	272	165	0.62	100	2327*±7.4	1	2.33	1.6	0.148	0.4	0.148	0.43	8.76	1.6	0.429	1.6	0.965
-5.1	0.94	163	70	0.44	9.71	427.3±7.1	-47	14.46	1.7	0.0597	2.1	0.0521	3.9	0.492	4.2	0.0685	1.7	0.406
-6.1	0.44	387	215	0.57	22.2	415.5±6.4	-6	14.95	1.6	0.0581	1.4	0.0545	1.9	0.501	2.4	0.0666	1.6	0.649
-7.1	0.21	856	444	0.54	50.2	425.0±6.4	-4	14.64	1.5	0.0567	1.0	0.0550	2.0	0.516	2.5	0.0681	1.5	0.613
-1.2	0.13	194	92	0.49	11.5	429.2±7.3	1	14.51	1.7	0.0565	2.1	0.0555	3.4	0.527	3.8	0.0688	1.8	0.458
-8.1	0.06	1162	64	0.06	57.1	358.1±5.7	-5	17.50	1.6	0.0538	0.9	0.0533	1.3	0.420	2.1	0.0571	1.6	0.782
-9.1	0.26	580	18	0.03	151	1830*±12	7	3.30	1.5	0.114	0.4	0.112	0.64	4.655	1.7	0.302	1.5	0.923
-5.2	0.45	147	71	0.50	8.83	433.9±7.8	0	14.30	1.8	0.0592	2.4	0.0556	4.2	0.534	4.6	0.0696	1.8	0.404
HT-QII																		
-5-1.1	4.66	172	156	0.94	8.35	338.9±7.4	-233	17.66	2.0	0.0858	4.0	0.0481	18	0.358	18	0.0540	2.2	0.125
-5-2.1	4.02	190	122	0.67	8.95	331.2±7.1	32	18.20	2.0	0.0892	4.7	0.0569	16	0.414	16	0.0527	2.2	0.139
-5-3.1	7.89	88	55	0.65	4.34	331.0±11	3	17.48	2.3	0.117	6.9	0.0530	43	0.390	43	0.0527	3.5	0.081
-5-4.1	2.89	297	307	1.07	14.1	336.7±6.4	-555	18.11	1.9	0.0697	2.1	0.0462	10	0.341	10	0.0536	2.0	0.187
-5-5.1	1.95	444	378	0.88	21.1	341.3±6.2	-26	18.03	1.8	0.0674	2.9	0.0517	7.0	0.388	7.2	0.0544	1.9	0.257
-5-6.1	6.91	148	74	0.52	7.18	330.3±7.7	173	17.71	2.1	0.0951	4.9	0.0380	29	0.279	30	0.0526	2.4	0.081
-5-7.1	2.20	289	158	0.57	13.5	333.0±7.9	24	18.45	2.3	0.0733	2.8	0.0557	12	0.407	12	0.0530	2.4	0.205
-5-8.1	3.24	217	160	0.76	10.1	330.9±6.9	21	18.37	2.0	0.0811	3.5	0.0551	11	0.400	12	0.0527	2.1	0.182
-5-9.1	3.48	276	135	0.51	13.1	335.4±6.8	529	18.07	1.9	0.0729	2.5	0.0446	16	0.328	16	0.0534	2.1	0.126
-5-10.1	5.50	150	84	0.58	7.35	339.2±9.0	-91	17.49	2.1	0.0941	2.9	0.0500	30	0.370	30	0.0540	2.7	0.091
BB10																		
-1.1	2.12	100	63	0.66	4.59	329.7±4.4	153	18.65	1.2	0.0629	5.2	0.0456	13	0.330	13	0.0525	1.4	0.105
-2.1	1.02	118	110	0.96	5.35	327.1±3.9	23	19.01	1.2	0.0636	4.1	0.0553	6.8	0.397	6.9	0.0521	1.2	0.175
-3.1	1.86	113	93	0.86	5.50	349.1±4.4	587	17.64	1.2	0.0599	2.7	0.0447	10	0.343	10	0.0556	1.3	0.122
-4.1	1.53	195	134	0.71	8.90	328.3±3.3	-781	18.85	0.96	0.0592	2.8	0.0468	7.4	0.337	7.5	0.0523	1.0	0.138
-5.1	0.68	200	132	0.68	9.10	329.9±3.1	4	18.91	0.95	0.0588	2.1	0.0533	3.6	0.386	3.8	0.0525	0.97	0.257
-6.1	1.66	95	39	0.43	4.36	329.2±4.3	-633	18.77	1.3	0.0604	5.0	0.0469	11	0.339	11	0.0524	1.4	0.125
-7.1	0.79	179	113	0.65	8.06	327.4±3.3	15	19.04	1.0	0.0607	4.5	0.0543	5.9	0.390	6.0	0.0521	1.0	0.170
-8.1	0.76	94	65	0.71	4.28	329.3±4.3	34	18.94	1.3	0.0634	3.0	0.0573	6.8	0.414	6.9	0.0524	1.3	0.195
-9.1	0.26	191	127	0.68	8.51	324.5±3.1	42	19.32	0.97	0.0608	4.3	0.0587	5.3	0.418	5.4	0.0516	0.99	0.184
-10.1	1.90	409	231	0.58	18.3	321.6±2.8	19	19.18	0.82	0.0698	1.5	0.0546	5.1	0.385	5.2	0.0512	0.88	0.171
-11.1	0.28	417	242	0.60	19.5	339.8±2.7	28	18.43	0.81	0.0587	1.5	0.0565	2.5	0.421	2.6	0.0541	0.82	0.310
-12.1	0.78	174	147	0.87	7.96	332.3±3.3	8	18.76	1.0	0.0600	5.3	0.0538	6.7	0.392	6.7	0.0529	1.0	0.152
-13.1	0.40	293	250	0.88	13.0	323.2±2.7	-7	19.37	0.84	0.0556	1.8	0.0524	3.1	0.372	3.2	0.0514	0.85	0.270
-14.1	0.85	373	414	1.15	17.2	334.5±2.7	-35	18.62	0.80	0.0580	1.6	0.0511	3.7	0.376	3.8	0.0533	0.83	0.217
-15.1	0.72	286	204	0.74	13.0	331.2±2.8	-8	18.83	0.85	0.0583	1.8	0.0525	3.7	0.382	3.8	0.0527	0.88	0.231
HT12																		
-1.1	1.09	109	74	0.70	4.19	278.6±7.0	340	22.40	2.2	0.0527	3.0	0.0440	24	0.267	24	0.0442	2.6	0.108
-2.1	0.16	290	151	0.54	16.8	420.2±8.4	17	14.82	2.1	0.0587	1.4	0.0575	2.4	0.534	3.1	0.0674	2.1	0.658
-3.1	0.15	452	217	0.50	28.4	454.2±9.0	9	13.68	2.0	0.0584	1.2	0.0572	2.1	0.576	3.0	0.0730	2.1	0.692
-4.1	0.16	218	137	0.65	9.98	333.5±7.0	14	18.81	2.1	0.0558	2.0	0.0544	4.7	0.399	5.1	0.0531	2.2	0.421
-5.1	1.39	257	137	0.55	10.3	289.2±6.2	-563	21.50	2.1	0.0581	2.1	0.0469	7.3	0.297	7.6	0.0459	2.2	0.287
-6.1	0.50	419	271	0.67	18.6	322.5±6.5	-46	19.39	2.0	0.0546	1.4	0.0506	3.0	0.358	3.6	0.0513	2.1	0.566
-7.1	0.87	131	73	0.58	4.90	273.1±5.9	-21	22.90	2.2	0.0577	4.1	0.0506	6.9	0.302	7.3	0.0433	2.2	0.305
-8.1	0.04	341	208	0.63	15.8	338.2±6.8	28	18.56	2.0	0.0568	1.4	0.0564	1.9	0.419	2.8	0.0539	2.1	0.726
-9.1	1.51	143	74	0.54	5.37	271.0±5.9	373	22.94	2.2	0.0564	6.0	0.0442	12	0.262	12	0.0429	2.2	0.185
-10.1	3.77	238	148	0.64	9.37	278.1±6.2	28	21.83	2.1	0.0845	3.1	0.0543	14	0.330	14	0.0441	2.3	0.163
-11.1	27.26	196	86	0.46	10.8	293.0±11	66	15.63	2.1	0.282	3.6	0.0670	43	0.430	43	0.0465	3.8	0.089
-12.1	1.83	176	89	0.52	6.59	270.7±6.3	176	22.89	2.2	0.0548	2.5	0.0399	18	0.236	19	0.0429	2.4	0.129
-13.1	0.65	129	78	0.62	5.03	283.9±6.2	-98	22.07	2.2	0.0541	2.8	0.0489	4.0	0.304	4.5	0.0450	2.2	0.489
-14.1	0.58	119	76	0.66	4.46	272.8±6.1	-34	23.00	2.2	0.0549	3.2	0.0502	7.7	0.299	8.0	0.0432	2.3	0.284
J34																		
-1.1	2.15	590	536	0.94	26.5	321.7±5.7	-120	19.13	1.8	0.0663	1.6	0.0490	6.4	0.345	6.6	0.0512	1.8	0.275
-2.1	3.71	226	116	0.53	9.96	311.0±6.3	8	19.48	2.0	0.0831	2.3	0.0532	11	0.363	12	0.0494	2.1	0.179
-3.1	5.07	118	63	0.55	5.40	318.7±7.9	1186	18.73	2.3	0.0866	7.3	0.0450	25	0.318	25	0.0507	2.5	0.101
-4.1	2.69	224	97	0.45	9.76	309.9±6.1	55	19.76	2.0	0.0836	3.0	0.0623	8.0	0.423	8.3	0.0493	2.0	0.246

Table 1. Contd...

	²⁰⁶ Pb _c	U	Th	²³² Th/ ²³⁸ U	²⁰⁶ Pb*	²⁰⁶ Pb/ ²³⁸ U age, Ma	Disco- rdant, %	Total ²³⁸ U/ ²⁰⁶ Pb	%	Total ²⁰⁷ Pb/ ²⁰⁶ Pb	%	²⁰⁷ Pb/ ²⁰⁶ Pb	%	²⁰⁷ Pb/ ²³⁵ U	%	²⁰⁶ Pb/ ²³⁸ U	%	err corr
-5.1	4.61	259	174	0.69	11.3	305.3±6.9	-797	19.66	2.2	0.0840	2.3	0.0467	15	0.312	15	0.0485	2.3	0.152
-6.1	2.97	370	189	0.53	16.5	316.5±6.0	-59	19.28	1.9	0.0740	2.0	0.0501	8.9	0.348	9.1	0.0503	1.9	0.211
-7.1	2.98	533	335	0.65	23.2	309.5±5.9	234	19.72	1.8	0.0662	1.7	0.0419	14	0.284	15	0.0492	2.0	0.134
-8.1	3.66	353	189	0.55	14.1	281.3±9.2	-723	21.60	3.2	0.0763	2.6	0.0467	16	0.287	16	0.0446	3.3	0.209
-9.1	10.19	60	22	0.39	2.96	325.0 ±12	57	17.38	2.7	0.145	3.5	0.0650	33	0.460	33	0.0517	3.8	0.113
-10.1	4.13	341	195	0.59	13.3	275.5±5.5	11	21.95	1.9	0.0856	3.7	0.0526	13	0.317	13	0.0437	2.0	0.154
-11.1	4.68	233	146	0.65	10.8	324.3±6.9	194	18.47	2.0	0.0783	2.4	0.0401	20	0.285	20	0.0516	2.2	0.111
-12.1	5.29	169	84	0.51	7.78	318.4±7.1	-116	18.71	2.0	0.0917	4.3	0.0490	19	0.342	19	0.0506	2.3	0.119
-13.1	3.63	374	196	0.54	16.7	314.3±6.0	-90	19.29	1.9	0.0787	1.9	0.0494	10	0.340	10	0.0500	1.9	0.190
-14.1	5.40	190	121	0.66	8.14	297.9±6.6	248	20.00	2.0	0.0863	3.3	0.0424	21	0.277	22	0.0473	2.3	0.106
-15.1	3.03	341	182	0.55	15.1	314.2±6.1	563	19.41	1.9	0.0694	3.5	0.0448	14	0.308	14	0.0500	2.0	0.142
-16.1	4.53	169	98	0.60	7.37	304.2±8.3	206	19.76	2.6	0.0779	3.9	0.0410	21	0.273	21	0.0483	2.8	0.131
-17.1	11.24	60	28	0.48	2.89	313.0±12	-114	17.82	2.5	0.140	7.4	0.0490	55	0.340	55	0.0498	3.9	0.071
-18.1	4.44	198	97	0.51	8.86	312.6±6.9	283	19.23	2.1	0.0791	4.3	0.0429	20	0.294	20	0.0497	2.3	0.115
-19.1	1.40	272	117	0.44	12.0	317.0±6.0	-456	19.56	1.9	0.0585	2.5	0.0472	6.3	0.328	6.6	0.0504	1.9	0.296
-20.1	4.11	270	178	0.68	11.9	308.9±6.2	791	19.53	1.9	0.0785	3.1	0.0452	14	0.306	14	0.0491	2.0	0.142
-21.1	4.67	268	140	0.54	12.0	312.2±6.3	246	19.21	1.9	0.0802	3.3	0.0422	17	0.289	17	0.0496	2.1	0.124
J35																		
-1.1	9.13	111	46	0.43	5.13	306.4±8.5	127	18.67	2.2	0.106	7.1	0.030	56	0.200	56	0.0487	2.8	0.051
-2.1	8.30	122	67	0.57	5.58	308.0±8.1	158	18.74	2.2	0.105	3.4	0.037	37	0.252	37	0.0489	2.7	0.073
-3.1	6.53	145	78	0.56	6.51	307.2±7.4	185	19.15	2.1	0.0931	4.3	0.040	29	0.268	29	0.0488	2.5	0.086
-4.1	7.56	128	69	0.56	5.78	306.6±7.7	164	18.97	2.1	0.0999	2.9	0.038	32	0.256	32	0.0487	2.6	0.081
-5.1	7.25	129	73	0.58	5.98	313.6±7.9	1339	18.60	2.1	0.104	4.6	0.046	29	0.313	29	0.0499	2.6	0.090
-6.1	8.15	128	66	0.53	5.89	309.4±7.9	152	18.68	2.1	0.103	3.6	0.036	36	0.247	36	0.0492	2.6	0.072
-7.1	8.51	120	65	0.56	5.53	307.9±8.3	137	18.70	2.3	0.103	4.0	0.033	41	0.225	42	0.0489	2.8	0.067
-8.1	5.12	147	79	0.56	6.85	323.4±7.3	53	18.44	2.1	0.103	5.9	0.062	17	0.443	17	0.0515	2.3	0.138
-9.1	7.73	122	63	0.53	5.64	311.5±8.2	127	18.64	2.2	0.0938	5.9	0.030	49	0.204	49	0.0495	2.7	0.055
-10.1	7.48	131	70	0.55	6.14	318.3±8.0	211	18.28	2.1	0.102	5.7	0.041	33	0.286	33	0.0506	2.6	0.078
-11.1	5.65	152	76	0.52	6.92	314.2±7.3	-293	18.89	2.1	0.0933	5.0	0.048	22	0.328	23	0.0499	2.4	0.106
-12.1	8.25	142	79	0.57	6.47	305.3±7.7	140	18.92	2.1	0.102	4.7	0.034	39	0.230	39	0.0485	2.6	0.065
-13.1	7.10	146	81	0.57	6.82	317.7±7.9	1089	18.39	2.1	0.103	4.4	0.045	28	0.316	28	0.0505	2.5	0.090
-14.1	7.74	135	76	0.58	6.30	314.9±8.3	265	18.43	2.1	0.106	3.2	0.043	33	0.294	34	0.0501	2.7	0.081
-15.1	8.19	137	74	0.56	6.12	300.7±7.8	152	19.23	2.1	0.104	4.4	0.037	38	0.242	38	0.0478	2.6	0.069
-16.1	8.00	140	80	0.59	6.43	309.3±7.8	153	18.72	2.1	0.102	3.2	0.037	35	0.248	35	0.0491	2.6	0.074
-17.1	6.74	155	84	0.55	7.04	309.3±7.3	262	18.97	2.1	0.0975	4.9	0.043	27	0.289	27	0.0492	2.4	0.089
-18.1	7.73	102	63	0.63	4.64	306.2±9.6	53	18.97	2.4	0.123	7.8	0.061	33	0.410	33	0.0486	3.2	0.097

* refers to the ²⁰⁷Pb/²⁰⁶Pb age.

amphibolite distribute along fault only (see Figs. 8a, b). The metamorphic degree for serpentinite, metagabbro, basaltic rocks, and chert (greenschist facies) are relatively lower than that for amphibolite and garnet amphibolite. Amphibolite consists of hornblende, plagioclase, titanite, ilmenite and epidote. Garnet amphibolite consists of hornblende, clinopyroxene (diopside-augite), garnet, zoisite, quartz, apatite, titanite, ilmenite and rutile. Hornblende was generally replaced by chlorite. Garnet amphibolite does not contain any plagioclase, which decomposed during prograde metamorphism. This implies that garnet amphibolite was formed at relatively high P-T condition (up to eclogite facies) comparing with amphibolite (amphibolite facies). Garnet contains abundant inclusions including quartz, ilmenite, rutile, apatite, and zircon (Figs. 8c-d). Pyrope contents in garnet vary from 10 mol.% to 26 mol.% (see Fig. 8e), which is similar to the garnet in eclogite coexisting with blueschist (Coleman et al., 1965). Blueschist, dated to be 458 ~ 470Ma by ⁴⁰Ar/³⁹Ar technique (for sodium amphibole, Zhang, 1997), occurs in the Tangbale ophiolitic mélange locating on the SW of the Baijiantan-Baikouquan ophiolitic belt (see Fig. 1 for location). We have suggested that the Baijiantan-Baikouquan

ophiolitic belt should be connected with the Tangbale ophiolitic mélange (Zhu et al., 2008).

Locating on the southwest of the Baikouquan region, the Baijiantan ophiolitic mélange consists of serpentinite, spinel lherzolite, olivine pyroxenite, metagabbro, and spinel dolomite marble (see Figs. 9a-b, 10a). Fresh lherzolite lenses consist of olivine, clinopyroxene, orthopyroxene and spinel. Pyroxene, showing exsolution texture with clinopyroxene lamellae in orthopyroxene, and orthopyroxene lamellae in clinopyroxene, generally underwent ductile-shearing deformation. The spinel dolomite marble, containing relics of spinel serpentinite (Fig. 9b), was transformed from serpentinite during metamorphism (Zhu et al., 2008).

As a result of intensive serpentinization, the mélange area is rather elastic and composes a negative landform (see Figs. 9a, 10a). Pillow basalt was cemented by lava and/or by red chert (Fig. 9c). All these units were covered by conglomerate-sandstone with chert breccia. Flysch with conodont-bearing chert has been intruded by the Permian pyroxene diorite dykes (Fig. 10b). He et al. (2007) found abundant conodonts in red chert (jasper, see Fig. 10c), and suggested that the

Figure 8. (a) An outcrop showing different units in the Baikouquan ophiolitic mélange; (b) Photo showing the locations of amphibolite and metagabbro blocks in serpentinite matrix; (c) Microphotograph showing garnet amphibolite. Garnet contains abundant mineral inclusions, crossed-polarized light; (d) BSE image showing mineral inclusions in garnet. Amp – amphibole, Ap – apatite, Grt – garnet, ilm – ilmenite, Ru- rutile, Zr – zircon; (e) Compositional space for garnet in the Baikouquan ophiolitic mélange.

Figure 9. Geological section and photos showing the Baijiantan ophiolitic mélangé. Dashed line indicates possible positions of the flysch, Devonian sedimentary strata and the eroded parts of the ophiolitic mélangé. (a) Devonian sandstone lying on ophiolitic mélangé, watching to NW-direction; (b) Serpentinite blocks (relics) in spinel dolomite marble; (c) Pillow basalt; (d) A fault boundary between serpentinite and Devonian sandstone.

Figure 10. (a) A hill of spinel dolomite marble in the Baijiantan ophiolitic mélangé, the dark-colored blocks are mainly serpentinite, some of them are metagabbro; (b) A Permian pyroxene diorite dyke intruded into deformed chert; (c) Conodont chert (Jasper) shows strong deformation.

Figure 11. (a) Geological section showing the relation among blocks of serpentinite with spinel dolomite marble, Devonian sandstone and volcanoclastics with andesite, which were covered by Cretaceous conglomerate unconformably in the Baijiantan region. (b) Photo showing Devonian sandstone; (c) Photo showing Cretaceous conglomerate and sandstone.

Paleo-Ocean occurred before the Late Ordovician. The Devonian sandstone, containing plant fossils (Wang, 2008; Ma et al., 2011), did not undergo deformation while serpentinite and chert had been strongly deformed.

Figure 11 displays a geological section showing the relationship among units in ophiolitic mélangé, the Devonian sandstone and the

Cretaceous conglomerate. The volcanoclastics and andesite continuously lie on the Devonian sandstone. These units contact with serpentinite via fault. Serpentinite and spinel dolomite marble occurring along fault only, which suggests a nappe structure. Cretaceous conglomerate and sandstone lie on the Devonian sandstone unconformably.

U-Pb ages for post-ophiolitic magmatic rocks

Ophiolitic mélanges and flysch in both the Darbut-Sartohay and Baijiantan- Baikouquan belts were covered by the Devonian conglomerate-sandstone and Early Carboniferous volcanosedimentary rocks (see Figs. 3d-e, 9a). Andesite and volcanoclastics lie on the Devonian sandstone continuously (see Fig. 11a). The Early Carboniferous volcanoclastics with basalt and andesite are widespread in western Junggar (An and Zhu, 2007, 2009) as well as in the west Tianshan (see Zhu et al., 2009). Zircons separated from andesite in the Hatu region with typical igneous cathodoluminescence patterns have been measured by SHRIMP (see Table 1 and Figs. 12a-b). Their Th/U ratios range between 0.51 and 1.07 with apparent U-Pb ages of 330 ~ 341Ma. All these SHRIMP data fall on U-Pb concordia and give an average age of 335.2 ± 2.9 Ma (MSWD = 1.3, $n = 10$). Zircons separated from tuff in the Baobei region show typical magmatic zonation with Th/U ratios of 0.43 - 1.15 and apparent U-Pb ages of 322 ~ 349Ma. These data fall on U-Pb concordia and give an average age of 328.1 ± 1.8 Ma (MSWD = 1.6, $n = 13$, Figs. 12c-d).

These U-Pb ages (335Ma, 328Ma), representing magma eruption in the Hatu and Baobei regions, are consistent with zircon U-Pb ages for volcanic rocks in the Baogutu region (328 - 343Ma, An and Zhu,

Figure 12. SHRIMP dating results for zircons separated from andesite in the Hatu (a-b), from tuff in the Baobei (c-d), and from diorite dyke intruded into Early Carboniferous volcanoclastics (e-f).

Figure 13. (a) Simplified geological map of the Baikouquan region. The large granite body (Hongshan pluton) has been dated to be 302Ma by Han et al. (2010), and a small diorite pluton has been dated to be 317Ma by Chen and Zhu (in press); (b) Photo showing an outcrop of diorite intruded into siltstone - chert - tuff, and has been cut by granite veins; (c) Photo showing an outcrop of granite porphyry intruded into siltstone-tuff; d-g) Zircon SHRIMP dating results for diorite (d-e) and for granite porphyry (f-g).

2009; Guo et al., 2010). Except for large granite bodies (~300Ma, Han et al., 2006), small granitic to diorite plutons and various dykes intruded into the Devonian to Early Carboniferous volcano-sedimentary units (Han et al., 2010; Liu et al., 2009; Wei et al., 2011). Zircons separated from a diorite dyke in the Hatu region have highly variable U-Pb ages (454 - 271Ma, see Fig. 12e) with Th/U ratios of 0.46 - 0.70. All these SHRIMP data fall on U-Pb concordia, and the apparently younger U-Pb age values give an average age of 277.0 ± 4.4 Ma (MSWD = 1.16, $n = 8$, see Figs. 12e-f). Two apparently older ages (454.2 Ma, 420.2Ma, see Table 1 for spot -2.1 and -3.1) are similar to the U-Pb age of metagabbro in ophiolitic mélangé (see Fig. 6).

Magmatic plutons generally intruded into the Early Carboniferous volcano-sedimentary strata, while some of them intruded into the flysch accompanying ophiolitic mélangé. Here we show two small intrusive bodies in the Baikouquan ophiolitic mélangé (Figs. 13a-c). A small diorite pluton, intruded into tuff-siltstone, was cut through by granite veins (see Fig. 13b). Zircons in this diorite show typical igneous zonation pattern in cathodoluminescence image. The apparent U-Pb ages vary from 300.7Ma to 323.4Ma with Th/U ratios of 0.43 - 0.63. All 18 analyses fall on U-Pb concordia and give an average age of 310.7 ± 3.7 Ma (MSWD = 0.52, see Figs. 13d-e). The zircons separated from a small granite porphyry (see Fig. 13c) have apparent U-Pb ages of 275.5 - 325Ma with Th/U ratios of 0.39 - 0.94. Except one analysis (spot -10.1), other 20 analyses fall on U-Pb concordia and give an average age of 312 ± 3 Ma (MSWD = 1.5, see Figs. 13f-g). The younger age (275.5 Ma) might relate with late-stage fluid alteration widespread in this region.

Discussion

New geological data suggest that the western Junggar mainly formed during the closing of the Cambrian-Ordovician Ocean. The relics of the Early Paleozoic oceanic crust (ophiolitic mélanges) were covered by Devonian sandstone and Early Carboniferous volcanoclastics with lavas. The latter are widespread in the western Junggar and were previously mis-understood as arc system in geological literature. Geological evidences for the closure of the CAPO at pre-Devonian (see Fig. 3 in the Sartohay region and Fig. 9a in the Baijiantan region) are consistent with the U-Pb age of metagabbro in the Darbut ophiolitic mélangé (426 Ma, see Fig. 6).

The new geological observations are critical for Paleo-environmental reconstruction of the western Junggar. As a major part of the Kazakhstan-Junggar plate, the western Junggar was formed during the Ordovician to Silurian period. Individual lithologic formations are well exposed in the western Junggar, where the Lower Devonian marine deposition is continuous with the Upper Silurian (Ma et al., 2011), and the Middle Devonian terrestrial deposition contains abundant plant fossils (Wang, 2008). However, the occurrence of Silurian strata is rare. In most cases, the Devonian to Early Carboniferous molasse covered on the strongly deformed ophiolitic mélanges and flysch. The post-orogenic intermediate to felsic magmatism intruded into molasse and controlled the copper-gold porphyry and lode gold deposits (Zhu et al., 2013).

The time scale for geological evolution could be simply illustrated with U-Pb age distribution pattern for magmatic rocks in the western Junggar (Fig. 14a). Most U-Pb age values vary between 300Ma and 360Ma with one peak at 318Ma and another peak at 345Ma. Some old age data (420 - 460Ma) belong to Silurian period. The SHRIMP

Figure 14. (a) Histogram of U-Pb age distribution for igneous rocks in the western Junggar (data from references: Xu et al., 2006; Han et al., 2006, 2010; An and Zhu, 2009; Gu et al., 2009; Guo et al., 2010; Chen et al., 2010; Wei et al., 2011; Chen and Zhu, in press); (b) Histogram of zircon SHRIMP ages for igneous rocks studied here (data are listed in Table 1); (c) The correlations for zircon U-Pb ages and their Th/U ratios.

data-set presented in Table 1 is shown in Fig. 14b, from which four age-peaks could be identified. The peak corresponding to the middle Silurian zircons separated from metagabbro in ophiolitic mélangé implies that the Paleo-Ocean floor spreading did not stop until the middle Silurian. One peak at Early Carboniferous is formed by zircons

separated from volcanoclastics lying on flysch, while the peak at Late Carboniferous corresponds to zircons in magmatic plutons intruded into flysch and volcano-sedimentary units. The Early Permian zircons are from dykes. All these zircons have high Th/U ratios (>0.4) except only one (<0.1 , see Fig. 14c), which might be a mixture between igneous zircon and its metamorphic rim. Although the U-Pb age value corresponding to such mixed zircon may not have definite geological significance (Zhu, 2011), the observation of such metamorphic rim after igneous zircon is consistent with the metamorphism developed in the studied metagabbro. This is also consistent with the ductile-shearing deformation recorded in magnesite (see Fig. 3c). The Devonian to Early Carboniferous sandstone and volcano-sedimentary units lying on the ophiolitic *mélange* did not undergo any metamorphism. This constrains the upper time limit for ductile-shearing deformation in the western Junggar, and implies that the emplacement of ophiolitic *mélanges* in the western Junggar happened pre-Devonian.

Conclusion

The newly-compiled geological map shows that the western Junggar mainly formed during the closing of the Cambrian-Ordovician Ocean. The relics of Early Paleozoic oceanic crust were mainly covered by Devonian sandstone to Early Carboniferous volcanoclastics with andesite and basalt. The latter are widespread and were previously misunderstood as arc system related to the closure of the CAPO. The evidences for the Devonian closing of the Paleoocean as represented by the Darbut-Sartohay and Baijiantan-Baikouquan ophiolitic *mélanges* are apparent in field observations and isotopic ages. The newly compiled geological map shows two different geological layers: the Early Paleozoic metamorphic terrane mainly consists of ophiolitic *mélanges* and flysch (the Baobei-HLS, Darbut-Sartohay, and Baijiantan-Baikouquan belts), which have undergone strong ductile-shearing deformation and metamorphism, and the Late Paleozoic sandstone and volcano-sedimentary units lying on the ophiolitic *mélanges* and flysch. Both of these geological layers have been intruded by granite to diorite during Late Carboniferous to Early Permian.

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