Paleozoic subduction of the southern Dunhuang Orogenic Belt, northwest China: metamorphism and geochronology of the Shuixiakou area

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ABSTRACT

Amphibolites in the Shuixiakou area of the southern Dunhuang Orogenic Belt, southernmost Central Asian Orogenic Belt (CAOB), occur as lenses within hornblende-biotite-plagioclase gneiss or pelitic schist, exhibiting block-in-matrix feature of tectonic mélangé. Three generations of metamorphic mineral assemblages (M1, M2, and M3) have been recognized in the garnet-bearing amphibolite lenses. The metamorphic prograde assemblage (M1) is documented with inclusion trails (hornblende + plagioclase + quartz) within garnet porphyroblasts, and are estimated to be formed under 610–690 °C and 6.5–10.2 kbar. The metamorphic peak assemblage (M2) consists of garnet + hornblende + clinopyroxene + plagioclase + quartz in the matrix and records metamorphic peak P-T conditions of 720–750 °C and 13.4–14.7 kbar. The retrograde assemblage (M3) is represented by the symplectic assemblage (hornblende + plagioclase + quartz ± biotite ± magnetite) rimming the garnet porphyroblast. The derived metamorphic P-T paths show similar tight clockwise loops including nearly isothermal decompression processes, typical of orogenic metamorphism. SIMS dating of metamorphic zircons from the amphibolites confirm that the high-pressure metamorphism (M2) occurred at ca. 438–398 Ma.

1. Introduction

The Central Asian Orogenic Belt (CAOB) is known as one of the largest accretionary orogenic systems in the world, formed via punctuated accretion and collision of multiple orogenic components, such as magmatic arc, seamount, (ophiolitic) mélangé, and (Precambrian) micro-continent, during the Neoproterozoic to the Late Paleozoic (Khain et al., 2002; Senger, Natalin, & Burtman, 1993; Tian et al., 2013, 2015; Wang, Kusky, et al., 2013; Windley, Alexeev, Xiao, Kroner, & Badarch, 2007; Xiao et al., 2008; Xiao, Huang, Han, Sun, & Li, 2010; Xiao, Kusky, Safonova, Sel tmann, & Sun, 2015; Xiao, Windley, et al., 2015).

The Dunhuang Orogenic Belt is situated in the southernmost CAOB (Figure 1(a)) and is bounded by the Beishan orogen to the north, the Qemo-Xingxingxia fault to the northwest, and the Altyn Tagh fault to the south (Figure 1(b)). The Dunhuang Orogenic Belt (Shi et al., 2017; Wang, Chen, et al., 2017; Wang, Wang, et al., 2017; Zhao et al., 2016) is made up of a series of medium- to high-grade metamorphic supracrustal rocks and subordinate granitoid gneisses (Lu et al., 2008; Mei et al., 1997; Wang et al., 2016; Zhao & Cawood, 2012; Zhao et al., 2016). It was dismembered by Tertiary strike-slip faults into several discrete blocks exposing along Dahongshan-Duobagou-Sanweishan areas in the north, Dongbatu-Mogutai areas in the middle, Qingshigou-Hongliuxia-Shuixiakou areas in the south (see Figure 1(a) in Wang et al., 2016). The Dunhuang Orogenic Belt has been long regarded as the Precambrian basement of the Tarim craton (Figure 1(b)) based on intensely deformed metamorphic rocks, and a limited set of isotopic data (Bureau of Geology & Mineral Resources of Gansu Province [BGMR], 1989; Li, 1994; Mei et al., 1998). Nevertheless, findings of Paleoproterozoic (~1.85 Ga; Zhang et al., 2012, 2013) and Silurian (ca. 440 Ma; Zong et al., 2012) high-pressure mafic granulites in the Shuixiakou (Figure 1) and Mogutai areas, respectively, led to debates on the nature and tectonic attribution of the Dunhuang Orogenic Belt. Some investigators proposed that it was the western extension of the North China craton (Yu et al., 2014; Zhang et al., 2012, 2013), but others consider it involved into the Early Paleozoic.
Figure 1. (a) General overview of the Central Asian Orogenic Belt (CAOB) and neighboring blocks (modified after Xiao et al., 2010); (b) Simplified tectonic map of the Dunhuang Orogenic Belt and adjacent tectonic units (modified after Zhang et al., 2017); and (c) Geological map of the Shuixiakou of the southern Dunhuang Orogenic Belt (modified after Mei et al., 1998).

Note: The geological traverse A-A’ is given depicted in Figure 3.
orogeny (Meng et al., 2011) and the southern extension (He et al., 2014; Zong et al., 2012) or the southernmost part of the CAOB (Peng et al., 2014; Wang, Chen, et al., 2017; Wang, Wang, et al., 2017; Wang, Han, et al., 2014, 2016; Zhao et al., 2016). Recently, based on new discoveries of Devonian eclogite in the Hongliuxia region and Silurian–Devonian high-pressure granulites found in the Dunhuang Orogenic Belt, Wang et al. (2016), Wang, Wang, et al. (2017) and Wang, Chen, et al. (2017) propose that the Dunhuang Orogenic Belt represents a Paleozoic subduction zone in the southernmost CAOB and the tectonic mélangé was formed during the uplift stage subsequent to subduction in the Paleozone (Wang, et al., 2017; Wang, Kusky, et al., 2013; Wang, Wang, et al., 2017; Wang, Xiao, et al., 2013; Wang, Han, et al., 2014; Wang et al., 2016; Zhao et al., 2013; Zhao, Diwu, et al., 2015, Zhao, Sun, et al., 2015, Zhao et al., 2016). However, the metamorphic-deformational evolution and exact tectonic setting of the Shuixiakou area, where the Neoarchean TTG gneisses (Mei et al., 1998) and Paleoarchean high-pressure granulite (Zhang et al., 2012) were discovered, still remain ambiguous (Mei et al., 1998; Zhang et al., 2012, 2013; Zhao et al., 2013; Zhao, Sun, et al., 2015), which in turn, limits our understanding of the tectono-metamorphic evolution of the Dunhuang Orogenic Belt and the CAOB as a whole.

Here we present an integrated study that combines meso- and microstructural analyses, metamorphic investigations and SIMS and LA-ICP-MS zircon U–Pb geochronology of the Shuixiakou area, eastern Hongliuxia block, southeastern Dunhuang Orogenic Belt (Figure 1). Our results indicate that the metamorphism and deformation of the Shuixiakou area is a result of the Paleoarchean orogenic event in the southeastern Dunhuang Orogenic Belt, southernmost CAOB.

2. Geological setting

The supracrustal rocks in the Dunhuang Orogenic Belt consist of (garnetiferous) paragneiss or schist, granulite, amphibolite, marble and calcisilicate (BGMG, 1989; Lu et al., 2008; Zhao & Cawood, 2012; Zong et al., 2012; Zhang et al., 2013). In the Shuixiakou area, metamorphic rocks are mainly composed of tonalitic gneiss, granitic gneiss, pelitic/felsic gneiss/schist, amphibolite and marble (BGMG, 1989; Mei et al., 1998; Zhang et al., 2013) and were intruded by later granites (Figure 1; Zhang et al., 2013; Zhao et al., 2013; this study). The TTG gneisses were dated to be Neoarchean to Early Paleoarchean to Early Paleoproterozoic (Mei et al., 1998; Zhang et al., 2013; Zhao et al., 2013). The amphibolites in the Shuixiakou area are lenses from decimeters to meters in length within pelitic or felsic gneiss / schist (Figures 1 and 2). These metamorphic rocks are characterized by block-in-matrix feature, typical of tectonic mélangé (e.g. Festa et al., 2012; Raymond & Bero, 2015; Silver & Beutner, 1980; Wakabayashi & Dilek, 2011; Wang, Kusky, et al., 2013).

Based on the geological map of the Shuixiakou area (modified after Mei et al., 1998) and our field investigation along the Shuixiakou transect (A–A’ in Figure 1(c)), three lithologic units have been recognized (Figure 3): (1) gneissic monzogranite, recording north- or southwest-dipping foliations (S2) in various parts; (2) mylonitic Kf-granite, recording south-dipping foliation (S2); and (3) metamorphic complex, mainly consists of biotite-hornblende-plagioclase-bearing gneiss and subordinate quartzo-feldspathic gneiss. These rocks contain some lenticular amphibolite lenses of different sizes (Figure 2(b), (d) and (f)). The matrix records south- or southwest-dipping whilst some lenses record northwest-dipping gneissosity (Figure 3). The Bt-Hbl-Pl-bearing gneiss is intruded by a granitic body along the main gneissosity (S2) (Figure 2(b) and (c)).

Three deformational episodes were recognized in the Shuixiakou amphibolite. The first deformation phase (D1) is testified by S1 foliation folded in tight to isoclinal F2 fold. The axial plane foliation related to F2 folds represents the main foliation documented in the area. During this phase top-to-the north thrusts also developed (Figures 2 and 3). The third deformational episode (D3) is represented by discontinuous open folds (F3) with wavelength of decimeters to meters (Figure 1(c)). We sampled representative samples including gneissic monzogranite (sample D138), mylonitic Kf-granite (sample D139), garnet-bearing amphibolite lenses (samples G67 and G69), and the granite (sample D140) emplaced post S2, along the Shuixiakou transect (Figures 2 and 3). The amphibolite lenses were chaotically welded into the Bt-Hbl-Pl gneiss (Figures 2(b), (d) and (f) and 3). The granite (sample D140) intruded into the Bt-Hbl-Pl gneiss along the foliation (S2) (Figures 2(b), (c) and 3). The garnet-bearing amphibolite (sample G56) was collected in eastern Shuixiakou, which occurs as tectonic lenses within pelitic schist. The aligned metamorphic peak minerals of the gneiss constitute the main gneissosity (S2), indicating that the metamorphic peak was coeval with the second deformational episode (D2).

3. Petrography

3.1. Garnet-bearing amphibolite

At least three generations of mineral assemblages have been recognized (samples G56, G67 and G69) and they are ascribed to the metamorphic prograde stage (M1), peak stage (M2) and retrograde stage (M3), respectively. The mineral abbreviations follow Whitney and Evans (2010) hereinafter.

The metamorphic prograde mineral assemblage (M1) consists of hornblende (Hbl,) + plagioclase (Pl,) + quartz (Qz), which occur as randomly distributed inclusions within the garnet porphyroblasts (Figure 4). The metamorphic peak assemblage (M2) is represented by the garnet porphyroblasts (Grt, 15–20 vol %) plus matrix
expense of the garnet and the adjacent matrix minerals, typifying the decompression process (e.g. Chen et al., 2015; Harley, 1989; Lu et al., 2013, 2014; Wang, Wang, et al., 2014; Xiao et al., 2011).

3.2. Deformed granitoids

The gneissic monzogranite (sample D138; Figure 5(a)) consists of ~5 vol % muscovite, ~10–15% biotite, ~35–40% minerals, ~10–15% Cpx, ~30–40% Hbl, ~20–25% Pl, and ~10–15% Qz (Figure 4). Titanite, zircon, rutile, and minor apatite exist as accessory minerals. The retrograde assemblages (M3) comprise fine-grained symplectic minerals rimming the garnet, forming the 'white-eye socket' texture (Ma & Wang, 1994) (Figure 4). The M3 assemblages consist of hornblende (Hbl) + plagioclase (Pl) + quartz (Qz) ± biotite (Bt) ± magnetite (Mag). The symplectites were possibly formed at the expense of the garnet and the adjacent matrix minerals, typifying the decompression process (e.g. Chen et al., 2015; Harley, 1989; Lu et al., 2013, 2014; Wang, Wang, et al., 2014; Xiao et al., 2011).

Figure 2. Outcrops of the Shuixiakou traverse. (a) Gneissic monzogranite and mylonitic Kf-granite exhibiting roughly E-W trending S2 foliations. A fault (red line) contact between them is inferred. (b) Garnet-bearing amphibolites occur as lenticular lenses within the Bt-Hbl-Pl gneiss, exhibiting block-in-matrix fabrics typical of mélangé. A granitic body is found intruding into the gneiss along the main gneissosity (S2). (c) The granitic body was emplaced by squeezing into the weak interface (S2). (d) Garnet-bearing amphibolite occurs as puddingstone within the Bt-Hbl-Pl gneiss. Their gneissosity are fairly discordant, intersecting at a high angle (see Figure 3). (e) The first deformation is preserved as tight and rootless F1 folds. (f) Amphibolite puddingstone preserved within the Bt-Hbl-Pl-bearing gneiss indicates a top-to-the N shear sense.
Figure 3. Geological traverse of central Shuixiakou area, southern Dunhuang Orogenic Belt. See Figure 1 for the location of this traverse. 

Note: The S2 foliation documented within some of gneiss enclaves is discordant to the external S2 foliation and the matrix rocks intersect.
Figure 4. Photomicrographs of the garnet-bearing amphibolite (a, b) sample G56, (c, d) sample G67 and (e, f) sample G69, the Shuixiakou area, southern Dunhuang Orogenic Belt. Notes: Three metamorphic mineral assemblages have been recognized: the prograde assemblage (M1) consists of Hbl$_1$ + Pl$_1$ + Qz$_1$, the peak assemblage (M2) consists of Grt$_2$ + Cpx$_2$ + Hbl$_2$ + Pl$_2$ + Qz$_2$, whereas the retrograde assemblage (M3) consists of the symplectic assemblage (Hbl$_3$ + Pl$_3$ + Qz$_3$ ± Bt$_3$) surrounding the garnet porphyroblast. The red lines with arrows indicate the analytical profiles of the garnet porphyroblasts depicted in Figure 7. Back scattered electronic photographs (b and f) show the retrograde symplectic texture in close-up.
Figure 5. Photomicrographs of the (a) gneissic monzogranite sample D138, (b) mylonitic sample D139, and (c) granitic intrusion sample D140 from the Shuixiakou area, southern Dunhuang Orogenic Belt. Note: Dotted lines show buckling of muscovite (a) or feldspar (c).
plagioclase, ~20–25% K-feldspar and ~25% quartz, and contains minor epidote and tourmaline. Slight buckling and undulatory extinction of muscovite (Figure 5(a)) reflect the deforma
tional imprint of the D2 or D3. The mylonitic Kf-granite (sample D139; Figure 5(b)) suffered strong deformation which resulted in elongation of quartz (~25%) and rotation of K-feldspars (~45%) and plagioclase (~10%) and strong dynamic recrystallization of quartz (~20%) (Figure 5(b)). The granitic body (sample D140; Figure 5(c)) intruding the Bt-Hbl-Pl gneiss, contains ~10% muscovite, ~40% plagioclase, ~25% K-feldspar and ~25% quartz and minor epidote. The buckling or kink structure and undulatory extinction of feldspar (Figure 5(c)) indicate a later deformational overprint (D3?) in this region.

Electronic microprobe analytical method and results as well as SIMS and ICP-LA-MS U-Pb dating of zircons and results are deposited in the Appendices.

4. Mineral chemistry of amphibolite

4.1. Garnet

X-ray compositional mapping (Figure 6) and transverse compositional profile analyses of the garnets from garnet-bearing amphibolites (red lines with arrow in Figure 4) show negligible zonation (Figure 7). Only at the outermost rims of the garnets, the X_Mn [=Mn/(Fe + Mg + Ca + Mn)] and/or Fe# [=Fe/(Fe + Mg)] values increase slightly, indicative of resorption and Fe–Mg re-exchange (diffusion) during the retrograde stage (Kohn & Spear, 2000; Spear & Florence, 1992). All the garnets consist mainly of almandine (X_Fe), grossular (X_Ca) and pyrope (X_Mn) with minor spessartine (X_Mn) (Figure 7; Table S2).

4.2. Plagioclase, clinopyroxene and hornblende

Plagioclases occur as inclusions (Pl1) within the garnet porphyroblasts, or as matrix minerals (Pl2), or as symplectites (Pl3) surrounding the garnet porphyroblast in the amphibolites. They are compositionally homogenous in each metamorphic stage. The inclusion-type plagioclases (Pl1) are labradorite to andesine (An24–An32), whereas the symplectite-type ones (Pl3) are all andesine (An57–An62). From the M1 to M2 then to M3, the anorthite components (X_An) of the plagioclases systematically increase and then decrease (Figure 8(a)), corresponding to the changes of metamorphic pressure (e.g. Holdaway, 2001).

Clinopyroxenes occur only as the matrix minerals in the garnet-bearing amphibolites and are chemically homogeneous. The clinopyroxenes contain very low amounts of jadeite (Na_2O = 0.49–0.65 wt.%) components and are all classified as diopside or wollastonite (Figure 8(b)) (Morimoto et al., 1988).

Three types of hornblends, i.e. the inclusion-type (Hbl1), matrix-type (Hbl2) and symplectite-type (Hbl3) have been identified in the garnet-bearing amphibolites. All the hornblends are classified as the calcic group of amphibole (Leake et al., 1997; Figure 8(c)). It is noted that the TiO_2 contents increase from the M1 (0.78–1.25 wt.%) to M2 (1.75–2.0 wt.%) then decrease to M3 (0.68–1.75 wt.%) assemblages, possibly responds to the variations of metamorphic temperatures.

5. Geothermobarometry and P-T paths

In order to retrieve the metamorphic P-T history of the metabasites in the Shuixiakou region, accurate geothermobarometers were applied to determine the P-T conditions of the prograde, peak and retrograde metamorphic stages.

The garnet-clinopyroxene (GC) Fe–Mg exchange geothermometer (Krogh, 1988; Ravna, 2000) and the garnet-clinopyroxene-plagioclase-quartz (GCPQ) geobarometer (Eckert et al., 1991) were applied for estimating the peak (M2) metamorphic P-T conditions. The inner rim compositions of garnets with lowest X_Mn and Fe# were used for P-T computation. The M1 assemblages formed prior to the garnet porphyroblasts, whilst the M3 assemblages formed from the decomposition of the garnet porphyroblasts and the adjacent matrix minerals. As a consequence, the prograde (M1) or retrograde (M3) assemblages could not be at equilibrium with garnet (Wu et al., 2014), therefore, garnet-absent geothermobarometers were applied for the M1 and M3 assemblages. Thus, the hornblende-plagioclase (PH) geothermometer (Holland & Blundy, 1994) coupled with the hornblende-plagioclase-quartz (HPQ) geobarometer (Bhadra & Bhattacharya, 2007) were applied to quantify the P-T conditions of these two assemblages. It is noted that the hornblende-plagioclase (PH) geothermometer (Holland & Blundy, 1994) was calibrated based on the net-transfer reaction and is almost pressure independent. Ferric iron contents of the ferromagnesian silicates were determined using the stoichiometric and charge-balance methods of Droop (1987).

The GCPQ geothermobarometers yield the M2 P-T conditions to be of 720–754 °C and 13.4–14.7 kbar (M2). The HPQ geobarometers yield the M1 and M3 P-T conditions as 612–688 °C (M1) and 6.5–10.2 kbar and 633–726 °C and 3.8–7.2 kbar (M3), respectively. The computed metamorphic P-T conditions are listed in Table 1.

The metamorphic P-T paths derived from the Shuixiakou area show similar clockwise loops including nearly isothermal decompression (ITD) processes (Figure 9). The metamorphic peak P-T-Conditions lie within the transition zone between the amphibolite and eclogite facies (Spear, 1993, p. 9) and approaches the lower
Figure 6. X-ray compositional maps of the Mn, Fe, Ca and Mg components of the garnet porphyroblasts in the garnet-bearing amphibolite (a) sample G56, (b) sample G67, and (c) sample G69. Note: Colors in the columns on the right side indicate relative element concentrations (wt.%).
Figure 7. Compositional profiles of garnet porphyroblasts of the garnet-bearing amphibolite (a) sample G56, (b) sample G67, and (c) sample G69 of the Shuixiakou area. Note: the garnets show negligible zonation.
Figure 8. Classifications of (a) plagioclase, (b) clinopyroxene, and (c) hornblende of the garnet-bearing amphibolites of the Shuixiakou area.
sector or black-bright zoning in CL images (Figure 10(a)–(c)), displaying characteristic morphology of high-grade metamorphic zircons (Hoskin & Black, 2000; Hoskin & Schaltegger, 2003).

Twenty grains were analyzed for amphibolite sample G56 (Figure 10(a)). The resulting data points yield a reliable lower and a rough upper intercept ages as limit of the high \( P/T \) facies series (Miyashiro, 1961), indicative of subduction zone metamorphism.

### 6. Geochronology

Zircons from the garnet-bearing amphibolites are stubby, ovoid or irregular in shape. Some grains show sector or black-bright zoning in CL images (Figure 10(a)–(c)), displaying characteristic morphology of high-grade metamorphic zircons (Hoskin & Black, 2000; Hoskin & Schaltegger, 2003).

Table 1. \( P/T \) conditions retrieved for the different metamorphic stages of the garnet-bearing amphibolites in the Shuixiakou area.

| Sample | Prograde assemblage (M1) | Peak assemblage (M2) | Retrograde assemblage (M3) |
|--------|--------------------------|----------------------|----------------------------|
|        | \( T (°C) \) | \( P (kbar) \) | Method | \( T (°C) \) | \( P (kbar) \) | Method | \( T (°C) \) | \( P (kbar) \) | Method |
| G56    | 612 | 6.5 | HPQ | 720–745 | 13.4–13.6 | Gc12PQ | 633 | 4.3 | HPQ |
| G67    | 688 | 10.2 | HPQ | 728–754 | 14.4–14.6 | Gc12PQ | 693 | 7.2 | HPQ |
| G69    | 685 | 7.7 | HPQ | 726–754 | 14.4–14.7 | Gc12PQ | 726 | 3.8 | HPQ |

Notes: Geothermobarometry symbols are list as follows:

HPQ is the abbreviation of the hornblende-plagioclase-quartz geobarometer (Bhadra & Bhattacharya, 2007) coupled with the hornblende-plagioclase geothermometer (Holland & Blundy, 1994).

Gc12PQ is the abbreviation of the garnet-clinopyroxene (Gc1) (Krogh, 1988) and garnet-clinopyroxene (Gc2) (Ravna, 2000) geothermometers paired with the garnet-clinopyroxene-plagioclase-quartz (GCPQ) geobarometer (Eckert et al., 1991).

Figure 9. Metamorphic \( P/T \) paths derived from the garnet-bearing amphibolites. (a) Sample G56, (b) sample G67, and (c) sample G69. (d) All the \( P/T \) paths show similar clockwise loops that contain nearly isothermal decompression (ITD) process, indicative of orogenic metamorphism.

Notes: Metamorphic facies and metamorphic facies series are from O’Brien and Rötzler (2003) and Spear (1993), respectively. The \( \text{Al}_2\text{Si}_3\text{O}_9 \) polymorph transition lines are from Holdaway and Mukhopadhyay (1993). Symbols for geothermobarometers are given in Table 1.
Figure 10. Representative cathodoluminescence (CL) images of zircons from the garnet-bearing amphibolite samples (a) G56, (b) G67, (c) G69, (d) gneissic monzogranite sample D138, (e) mylonitic K-feldspar granite sample (D139), and (f) granitic intrusion sample D140. The ellipses and circles on zircons show spot locations of SIMS analyses for the garnet-bearing amphibolites and LA-ICP-MS analyses for the granitoids, respectively. Bold digits adjacent to the zircons are, when <1.0 Ga, the $^{206}\text{Pb}/^{238}\text{U}$ or $^{207}\text{Pb}/^{206}\text{Pb}$ ages.
Twenty-four spot analyses were conducted on eighteen zircon grains separated from the amphibolite sample G67 (Figure 10(b)). A few zircons show dark-bright zoning. However, U-Pb analyses show higher U contents in dark domains but no apparent distinction in ages (Figure 10(b); Table S2). A few grains display obvious core-rim structure and some rims are brighter but quite thin (Figure 10(b)). In the concordia diagram (Figure 11(b)), 23 data points yield the lower and upper intercept ages of 398 ± 28 and 1828 ± 17 Ma, respectively. In the concordia diagram (Figure 11(a)), respectively. Eleven data points are concordant with 206Pb/238U ages ranging from 438 ± 6 to 400 ± 6 Ma, and have quite low Th/U ratios (0.007–0.188) (Figure 12), suggesting possible metamorphic origin (e.g. Hoskin & Schaltegger, 2003; Koralay, 2015). The remaining eight data points, with much higher Th/U ratios of 0.026–1.89, are discordant but form an isochron possibly owing to heavy Pb loss and the upper intercept age indicates the protolith age (~1555 Ma).

406 ± 10 Ma and 1555 ± 43 Ma (Figure 11(a)), respectively. Eleven data points are concordant with 206Pb/238U ages ranging from 438 ± 6 to 400 ± 6 Ma, and have quite low Th/U ratios (0.007–0.188) (Figure 12), suggesting possible metamorphic origin (e.g. Hoskin & Schaltegger, 2003; Koralay, 2015). The remaining eight data points, with much higher Th/U ratios of 0.026–1.89, are discordant but form an isochron possibly owing to heavy Pb loss and the upper intercept age indicates the protolith age (~1555 Ma).

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In this study, similar clockwise $P$-$T$ loops with ITD processes were derived from the garnet-bearing amphibolites in the Shuixiakou area. Such $P$-$T$ paths typify an orogenic metamorphism and are generally believed as a consequence of subduction and then exhumation process (Ernst, 1988). Furthermore, the metamorphic peak $P$-$T$ conditions (720–754 °C and 13.4–14.7 kbar) of these metabasites approach the high $P/T$ metamorphic series and give relatively 'cool' gradient of ~15–16 °C/km if a lithostatic pressure gradient (Spear, 1993, p. 8) is adopted, which are indicative of a subduction zone environment (Miyashiro, 1961; Spear, 1993, p. 9).

Regional metamorphism occurs commonly coupled with deformation, which results in several generations of folds and/or shearing at different stages of metamorphism (e.g. Li et al., 2005, 2010, 2011; Wernert et al., 2016). In the Shuixiakou area, three episodes of deformation (D1–D3) were distinguished in the metamorphic complex. The timing of the first deformational episode (D1) is hard to determine because the S1 was totally transformed by D2 which contributed the regional pervasive gneissosity (S2) (Figures 2 and 3). The D2 post-dates the emplacement of the monzogranite (sample D138; 411.5 ± 1.1 Ma) and Kf-granite (sample D139; 402 ± 1.1 Ma) since the two granites were deformed by the D2 and recorded the regional S2. The small granitic intrusion (sample D140; 313 ± 0.9 Ma) intruded the Bt-Hbl-Pl gneisses along S2 (Figure 2(b) and (c)), which suggests that the intrusion event postdates S2. On the other side, the main deformation (D2) is considered to be coeval with the metamorphic peak of the Bt-Hbl-Pl gneisses in the Shuixiakou area because the S2 is defined by the alignment of the metamorphic peak minerals (M2) of the gneisses. Therefore, the peak metamorphism occurred in the Paleozoic and was dated to be between 402 ± 1.1 Ma and 313 ± 0.9 Ma, respectively.

7. Discussion

Reconstruction of valid metamorphic $P$-$T$ paths of a metamorphic terrane is crucial for understanding its tectonic evolution (e.g. England & Thompson, 1984; Ernst, 1988; Harley, 1989; Spear, 1993; Thompson & England, 1984). In this study, similar clockwise $P$-$T$ loops with ITD processes were derived from the garnet-bearing amphibolites in the Shuixiakou area. Such $P$-$T$ paths typify an orogenic metamorphism and are generally believed as a consequence of subduction and then exhumation process (Ernst, 1988). Furthermore, the metamorphic peak $P$-$T$ conditions (720–754 °C and 13.4–14.7 kbar) of these metabasites approach the high $P/T$ metamorphic series and give relatively 'cool' gradient of ~15–16 °C/km if a lithostatic pressure gradient (Spear, 1993, p. 8) is adopted, which are indicative of a subduction zone environment (Miyashiro, 1961; Spear, 1993, p. 9).

Regional metamorphism occurs commonly coupled with deformation, which results in several generations of folds and/or shearing at different stages of metamorphism (e.g. Li et al., 2005, 2010, 2011; Wernert et al., 2016). In the Shuixiakou area, three episodes of deformation (D1–D3) were distinguished in the metamorphic complex. The timing of the first deformational episode (D1) is hard to determine because the S1 was totally transformed by D2 which contributed the regional pervasive gneissosity (S2) (Figures 2 and 3). The D2 post-dates the emplacement of the monzogranite (sample D138; 411.5 ± 1.1 Ma) and Kf-granite (sample D139; 402 ± 1.1 Ma) since the two granites were deformed by the D2 and recorded the regional S2. The small granitic intrusion (sample D140; 313 ± 0.9 Ma) intruded the Bt-Hbl-Pl gneisses along S2 (Figure 2(b) and (c)), which suggests that the intrusion event postdates S2. On the other side, the main deformation (D2) is considered to be coeval with the metamorphic peak of the Bt-Hbl-Pl gneisses in the Shuixiakou area because the S2 is defined by the alignment of the metamorphic peak minerals (M2) of the gneisses. Therefore, the peak metamorphism occurred in the Paleozoic and was dated to be between 402 ± 1.1 Ma and 313 ± 0.9 Ma, respectively.

Figure 12. Distinct Th/U ratios of the two pivotal age populations (ca. 0.4 Ga and ca. 1.82 Ga) of the garnet-bearing amphibolites, which suggest metamorphic or magmatic origins, respectively (see text). Notes: Th/U ratios of the zircons form the granitoids are all >0.1, indicating magmatic origin.

Tera-Wasserburg diagram (Figure 11(b)), 24 data points (one point was after common Pb corrected) yield the identical lower and upper intercept ages of 398 ± 26 and 1826 ± 16 Ma, respectively. Three data points cluster at the lower intercept point show fairly low Th/U ratios (0.001–0.1) (Figure 12). The lower intercept age is interpreted as the possibly metamorphic age of this sample. The remaining data points fix the upper intercept age and show much higher Th/U ratios (0.22–0.70), suggesting magmatic origin.

Twenty-three spot analyses were conducted on nineteen grains from the amphibolite sample G69 (Figure 10(c)). Most zircons display dark-bright zoning. Nevertheless, U-Pb analyses also show no apparent distinction in ages (Figure 10(c); Table S2). All the data points yield a reliable upper intercept age of 1836 ± 20 Ma (Figure 11(c)) and show high Th/U ratios (0.29–0.97) (Figure 12), suggesting magmatic origin. It is noted that several zircon grains have overgrowth rims (e.g. No. 2 and 12 in Figure 10(c)) but are too narrow to date.

Zircons from the gneissic granitoids exhibit characteristic euhedral shape and oscillatory zoning (Figure 11(d)–(f)), indicative of magmatic origin. Some inherited core (e.g. No. 1 in Figure 10(d)) and a few grains with metamorphic morphology (e.g. No. 10 in Figure 10(f)) are interpreted as xenocrysts. LA-ICP-MS U-Pb dating of the magmatic zircons with high Th/U ratios (0.12–2.26; Figure 12) indicate that the monzogranite (D138), Kf-granite (D139) and the granitic intrusion (D140) were emplaced at 411.5 ± 1.1 Ma, 402 ± 1.1 Ma and 313 ± 0.9 Ma, respectively. The other older ages are interpreted as xenocrystic ages.
Figure 13. Geochemistry of the granites within this study area. (a) Total alkalis vs. silica diagram (TAS, after Middlemost, 1994); (b) A/NK (molar Al$_2$O$_3$ / (Na$_2$O + K$_2$O)) vs. A/CNK (molar Al$_2$O$_3$/(CaO + Na$_2$O + K$_2$O)) (after Maniar and Piccoli (1989)); (c) primitive mantle-normalized trace elements spider diagram and (d) Chondrite-normalized REE pattern (normalizing values after Sun & McDonough, 1989).
Figure 14. (a) $\text{FeO}'/\text{MgO}$; (b) $(\text{K}_2\text{O} + \text{Na}_2\text{O})/\text{CaO}$ vs. $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ classification diagrams (Whalen et al., 2002); (c) $\text{Y} + \text{Nb}$ vs. $\text{Rb}$ and (d) $\text{Y}$ vs. $\text{Nb}$ diagrams (after Pearce, 1996).

Legend: FG, fractionated felsic granites; OGT, unfraccionated M-, I- and S-type granites; VA, volcanic arc granites; Syn-COLG, syn-collision granites; WPG, within plate granites; ORG, oceanic ridge granites; Post-COLG, post-collision granites.
ca. 412 and ca. 313 Ma. The granites (samples D138, D139 and D140; Figure 13(a)) in this study are weekly peraluminous with the value of A/CNK ranging from 1.03 to 1.06 (Figure 13(b)). They have high Na₂O content, low K₂O/Na₂O and Fe₂O₃/TiO₂ ratios (3.15–5.28, 0.20–1.15, and 2.04–5.24, respectively; Table S4), quite similar to the (high-K) calc-alkaline series granite. In addition, they do not contain mafic alkaline minerals, such as arfvedsonite, riebeckite. These granites display LREE-enriched pattern with relatively low contents of Zr, Nb, Y, La, Ce, Zn and Ga strongly (Figure 13(c) and (d)) showing I-type granite affinity (Figure 14(a), (b)). In the plot of Y + Nb vs. Rb and Y vs. Nb (Figure 14(c), (d)), these granites show volcanic-arc granite feature, implying that these granites were formed in the Paleozoic orogenic movement in the Shuixiakou area.

The garnet-bearing amphibolites in the Shuixiakou area usually occur as lenticular lenses enclosed by the Bt-Hbl-Pl gneiss or pelitic schist, exhibiting the characteristic block-in-matrix fabrics of tectonic mélangé (e.g. Festa et al., 2012; Raymond & Bero, 2015; Silver & Beutner, 1980; Wakabayashi & Dilek, 2011; Wang, Kusky, et al., 2013). The gneissosity of some lenses and the matrix rocks are discordant with a high angle intersection (Figure 3). SIMS zircon U-Pb dating indicates that the garnet-bearing amphibolites (lenses) were metamorphosed at ca. 438–398 Ma that is earlier than the metamorphic age of Bt-Hbl-Pl gneisses (matrix). It is noted that zircon in the amphibolite possibly records different stages of the prolonged metamorphism related to successive subduction and exhumation. Significant differences in orientations of gneissosity and metamorphic grade and age between the lenses and the matrix rocks highlight the mixing and juxtaposing of these rocks metamorphosed at different time and depth. In fact, lines of evidences (Wang, Chen, et al., 2017; Wang, Wang, et al., 2017; Wang et al., 2016), especially the discovery of the Paleozoic (ca. 411 Ma) eclogite in the Honglixia region (Wang, Chen, et al., 2017) to the west of the Shuixiakou area, support the subduction zone of the Dunhuang Orogenic Belt. Furthermore, metamorphic complex in the Honglixia and Qingshigou areas, southern Dunhuang Orogenic Belt, represents a tectonic mélangé consists of a chaotic mixture of rocks (Wang, Chen, et al., 2017; Wang, Han, et al., 2013, 2014; Wang, Wang, et al., 2017; Wang, Xiao, et al., 2013; Wang et al., 2016; Zhang et al., 2013) and they metamorphosed at different depth and different time in a subduction channel and then juxtaposed possibly during exhumation (Wang et al., 2016; Wang, Wang, et al., 2017; Wang, Chen, et al., 2017). These rocks were possibly subducted and equilibrated at various depths asynchronously, and in consequence, recorded heterogeneities in the timing of metamorphic equilibration and P-T paths. These data possibly point to independent tectonic evolutions of different slices inside the subduction channel (e.g. Federico et al., 2007; Li et al., 2016; Wang et al., 2016; Wang, Chen, et al., 2017) which shed new light on the genetic mechanism of tectonic mélangé in the orogens. U-Pb dating of the tonalitic gneiss from the Shuixiakou area (Zhao, Sun, et al., 2015) indicate that the metamorphism occurred between the Silurian to Devonian, and the Shuixiakou area is part of the tectonic mélangé that records the Paleozoic subduction of the southern Dunhuang Orogenic Belt.

8. Conclusions

(1) Three generations of metamorphic mineral assemblages have been recognized in the garnet-bearing amphibolite of the Shuixiakou area, southeastern Dunhuang Orogenic Belt. The derived metamorphic P-T paths of the garnet-bearing amphibolites are clockwise, passing from 610 to 690 °C/6.5–10.2 kbar, through 720–750 °C / 13.4–14.7 kbar, and finally to 630–730 °C and 3.8–7.2 kbar. The metamorphic peak lies within the transition zone between the amphibolite and eclogite facies, and approaches the lower limit of the high P/T metamorphic facies series, indicative of subduction metamorphism.

(2) High resolution SIMS U-Pb dating of metamorphic zircons separated from the garnet-bearing amphibolites indicates that the high pressure metamorphism occurred at ca. 438–398 Ma. LA-ICP-MS U-Pb dating of magmatic zircons of a non-deformed granitic body intruding along the S2 postdates the metamorphism at 313 ± 0.9 Ma in the Shuixiakou region.

(3) The metamorphic complex in the Shuixiakou area is part of the tectonic mélangé that records the Silurian-Devonian subduction-accretion process of the southern Dunhuang Orogenic Belt, southernmost Central Asian Orogenic Belt.

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