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2 **Identifying Late Carboniferous sanukitoids in Hala'ate**
3 **Mountain, NW China: New constraint on the closing time of**
4 **remnant ocean basin in West Junggar**

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Abstract: Volcanic rocks in Hala'alate and Aladeyikesai Formation, which are composed of basaltic andesite and pyroxene andesite, are widespread in Hala'alate Mountain, West Junggar, NW China. These rocks (plagioclase + clinopyroxene/olivine) formed in the Late Carboniferous and show a remarkable geochemical affinity with typical sanukitoids with oversaturated SiO₂ (52.9–56.9 wt.%) and high MgO (3.47–6.88 wt.%, Mg[#] > 48) contents. They also exhibit a narrow range of Sr-Nd-Pb isotopes within (⁸⁷Sr/⁸⁶Sr)_i = 0.7037–0.7041, εNd(*t*) = 4.4–6.2, ²⁰⁶Pb/²⁰⁴Pb = 18.22–18.41, ²⁰⁷Pb/²⁰⁴Pb = 15.48–15.52, ²⁰⁸Pb/²⁰⁴Pb = 37.99–38.30. Hala'alate Formation volcanic rocks are similar to sanukitoids of Karamay with the high Sr (633.5–970.1 ppm), Ba (268.7–796.3 ppm) and Sr/Y (61.34–84.28), formed by partial melting of the mantle metasomatised by slab-derived adakitic melts. In contrast, Aladeyikesai Formation volcanic rocks show some affinity with sanukitoids of the Hatu area and the Setouchi Volcanic Belt with the low Sr (442.2–508.7 ppm), Ba (199.2–485.1 ppm) and Sr/Y (25.03–30.28), generated by the partial melting of subducting sediments. Identification of Late Carboniferous sanukitoids in Hala'alate Mountain provides important constraints on the closing time of remnant ocean basin in West Junggar, and implies that multi-stage subduction-accretionary orogeny plays a crucial role in the evolution and growth of the continental crust in the Central Asian Orogenic Belt.

Keywords: sanukitoid, geochemistry, Late Carboniferous, island arc, West Junggar, Xinjiang

1. Introduction

The term sanukitoid was first used by [Koto \(1916\)](#) for all textural modifications of

volcanic rocks with the composition of Weinschenk's sanukite suite (Weinschenk, 1891). Tatsumi and Ishizaka (1981) used the term "sanukitoid" for a variety of relatively aphyric basalts and andesites with glass, orthopyroxene, magnetite and anorthose, also with a few phenocryst of olivine and clinopyroxene. In addition, sanukitoid was defined by Stern *et al* (1989) to refer to rocks containing between 55 and 60 wt.% SiO₂, with Mg[#] >0.6, Ni >100 ppm, Cr >200 ppm, K₂O >1 wt.%, Rb/Sr <0.1, Ba >500 ppm, Sr >500 ppm, enrichment in LREEs, and no or minor Eu anomalies. Shirey and Hanson (1984) first recognized a suite of Late Archaean felsic intrusive and volcanic rock in the Superior Province that had both mineralogical and chemical characteristics clearly different from Tonalite – Trondhjemite – Granodiorite (TTG). Owing to the major element geochemistry of these rocks resembled that of Miocene high-Mg andesite (Sanukite) from the Setouchi Volcanic Belt (SVB) of Japan (Tatsumi and Ishizaka 1982), Shirey and Hanson (1984) referred to them as "Archaean sanukitoids". Sanukitoid had been named both in volcanic and intrusive rocks which have the similar geochemical characteristics (Tatsumi and Ishizaka 1982). Although sanukitoid was originally used to define a variety of Archean rocks, now also includes younger rocks with similar geochemical characteristics (Shirey and Hanson 1984; Rogers *et al.* 1985; Stern *et al.* 1989; Kelemen *et al.* 2004).

Until now, there are three kinds of different views for the generation of sanukitoids:

- (a) partial melt of a metasomatised mantle source (Stern and Hanson 1991; Smithies and Champion 2000; Zhao and Zhou 2007), (b) interaction of mantle peridotite and slab-derived melts in a mantle wedge (Rapp *et al.* 1999, 2010), and (c) interaction

regime between mantle and melt from delaminated lower crust (Smithies *et al.* 2004, 2007). Tatsumi (2001) and Tatsumi *et al.* (2003) proposed that the genesis of sanukitoid magmas requires some unusual tectonic conditions. Identification of sanukitoids is crucial for understanding dynamic evolution of paleo-subduction system and provides important constraints on fate of subducted slabs (Tatsumi 1981, 1982; Tatsumi and Ishizaka 1981, 1982; Kamei *et al.* 2004; Martin *et al.* 2005). Therefore, the sanukitoid has attracted much attention of petrologists and geochemists (Tatsumi 1981, 1982; Tatsumi and Ishizaka 1981, 1982; Shirey and Hanson 1984; Tatsumi *et al.* 2003; Kamei *et al.* 2004; Zhang *et al.* 2004, 2005; Wang *et al.* 2006, 2007; Tang and Wang 2010; Yin *et al.* 2010, 2012, 2015a; Wang *et al.* 2011; Tang *et al.* 2012a; Ma *et al.* 2012; Sun *et al.* 2015).

Although few intrusive sanukitoid rocks have been documented in West Junggar, northwest China (Yin *et al.* 2010, 2012, 2015a; Tang *et al.* 2012a; Ma *et al.* 2012), no volcanic sanukitoid rocks are reported. More importantly, their temporal and genetic relationship with geodynamic evolution of West Junggar, the southwestern part of the Central Asian Orogenic Belt (CAOB), is not well constrained. Recently, based on 1 : 50000 regional geological survey in Hala'ulate Mountain, West Junggar, we are the first to identify Late Carboniferous volcanic sanukitoid rocks in this area. This study presents comprehensive whole-rock major-trace element and Sr-Nd-Pb isotope data of volcanic rocks. These data are used to document the petrogenesis of these rocks, constrain the associated geodynamic processes, and evaluate the implications for crustal growth.

2. Geological background and petrography

2.1. Geological background

West Junggar is located in the southwestern part of the CAOBS (Figure 1a). There are several Paleozoic ophiolitic mélanges and granites in this area. The Carboniferous strata are widely distributed in Baogutu-Hala'ulate Mountain area, the mid-eastern of West Junggar (Figure 1b). Early Carboniferous strata are composed of Baogutu and Xibeikulasi formations developed in a back-arc basin setting (Wang and Zhu 2007; An and Zhu 2009; Tong *et al.* 2009, 2014; Li *et al.* 2010; Guo *et al.* 2010; Geng *et al.* 2011; Sun *et al.* 2014a, b). Late Carboniferous strata include Chengjisihanshan, Hala'ulate and Aladeyikesai formations in Hala'ulate Mountain (Figure 1c). The Hala'ulate and Aladeyikesai formations are covered by Early Permian Jiamuhe Formation with angular unconformity in the Hala'ulate Mountain. Most geologists suggested that the Junggar ocean basin closed at Late Carboniferous, and then it went to intra-continental orogeny evolution (Jin and Zhang 1993; He *et al.* 2001; Han *et al.* 2006; Wang and Xu 2006; Su *et al.* 2006; Tang *et al.* 2010, 2012a, 2012b, 2012c; Xu *et al.* 2010; Gao *et al.* 2013).

The Hala'ulate Formation is dominated by neritic facies volcanic-sedimentary rocks with andesite, basalt, pyroxene andesite, volcanic breccias and amygdaloidal andesite, and few rhyolites. In addition, sandstone and conglomerate are sandwiched in volcanic rocks, showing a neritic facies calc-alkaline volcanic rocks combination. Zircon U-Pb dating on volcanic rocks has yielded weighted mean ages of 304.5–306.9 Ma (Li *et al.* 2015b), indicating a late Carboniferous age for the rocks, which are

consistent with the fossil constraints. By contrast, the Aladeyikesai Formation is dominated by terrigenous clastic, with a few volcanic rocks. These volcanics, which contain basalt, basaltic andesite, andesite and volcanic clastic rocks, are sandwiched in terrigenous clastic rocks. The fossils of Kasimov, such as corals *Bradyphyllum* sp., *Zaphrentes* sp., brachiopods *Balakhonia* cf. *silimica*, *Brachythyrida pingusiformis* and so on, were found in limestone of the Aladeyikesai Formation. Meanwhile, [Xiang et al. \(2015\)](#) obtained zircon U-Pb age of 303.8 ± 2.4 Ma from basalt, which indicates Aladeyikesai Formation is of the Late Carboniferous.

2.2. Petrography

Only fresh pyroxene andesite and basaltic andesite in the Hala'ulate and Aladeyikesai Formation, which commonly occur as thick-bedded and massive blocks (Figure 3a and c), were selected for this study (Figure 2). Pyroxene andesite possesses porphyritic texture consisting of plagioclase (8–10 vol.%) and clinopyroxene (5–10 vol.%). The plagioclase crystals occur as 0.5 to 1.7 mm subhedral phenocrysts with characteristic albite twins. Clinopyroxene occurs as granular crystals with 0.3–1.2 mm in length. The matrix exhibits hyalopilitic textures with microcrystalline plagioclases, glass and opaque mineral (e.g. magnetite) (Figure 3b). Basaltic andesite contains phenocrysts of subhedral plagioclase (10–15 vol.%) and euhedral – subhedral clinopyroxene (3–5 vol.%), subordinate magnetite and olivine. The pilotaxitic groundmass is composed of microcrystalline plagioclase (55–60 vol.%) and glass (10–12 vol.%) with accessory magnetite (5–10 vol.%) and titanite (up to 5 vol.%) (Figure 3d).

3. Analytical methods

3.1. Major and trace element analyses

Whole-rock samples were cleaned repeatedly using the diluted hydrochloric acid (3—5 wt.%) by ultrasonic to remove impurities on surface that after coarse crushed to 2—4 cm and then grinded to 200 mesh used for analytical testing. Major and trace element analyses were conducted at the Key Laboratory for the Study of Focused Magmatism and Giant Ore Deposits, Xi'an (China). Bulk-rock major element oxides were analyzed using X-ray fluorescence (XRF) with analytical uncertainties <3% for SiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, Na₂O, and K₂O, and <5% for TiO₂, MnO, and P₂O₅. Trace elements were analyzed using Thermo-X7 inductively coupled plasma mass spectrometer (ICP-MS). The uncertainty for most trace elements analysed is <2%. Reproducibility, based on replicate digestion of samples, is better than 10% for most analyses.

3.2. Sr-Nd-Pb isotope analyses

Sr–Nd–Pb isotopic ratios were determined using an IsoProbe-T Thermal Ionization Mass Spectrometer (TIMS) at Analytical Laboratory, Beijing Research Institute of Uranium Geology. Sample powders were dissolved in HF + HNO₃ + HClO₄ mixture. Digested samples were firstly dried and dissolved in 6 N HCl, and then dried again and redissolved in 0.5 N HCl (for Sr and Nd separation) or 0.5 N HBr (for Pb separation). Strontium and Nd fractions were separated following standard chromatographic techniques using AG50x8 and PTFE–HDEHP resins with HCl as eluent ([Sato *et al.* 1995](#)), while Pb fraction was separated using strong alkali anion

exchange resin with HBr and HCl as eluents (Babinski *et al.* 1999; Marques *et al.* 1999). $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotope ratios to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. A factor of 1‰ per mass unit for instrumental mass fractionation was applied to the Pb analyses, using NBS 981 as reference material. Measurement of the common-lead standard NBS 981 gave average values of $^{208}\text{Pb}/^{204}\text{Pb} = 36.531 \pm 0.008$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.440 \pm 0.003$; and $^{206}\text{Pb}/^{204}\text{Pb} = 16.900 \pm 0.003$, with uncertainties of less than 0.1% at the 95% confidence level.

4. Results

4.1. Major element concentrations

Major and trace element data are listed in Supplementary table 1. Most studied samples have low LOI values, indicating that these samples are essentially fresh. The studied volcanic rocks have basaltic andesite to andesite compositions with SiO_2 range from 52.9 wt.% to 56.9 wt.%, with an average of 55.5 wt.%. These volcanic rocks are characterized by high MgO (3.47–6.88 wt.%), $\text{Mg}^\#$ (48–64), Al_2O_3 (16.25–18.97 wt.%), and total alkalis (4.51–7.39 wt.%), and low TiO_2 (0.96–1.33 wt.%). On a total alkalis vs. silica (TAS) diagram, volcanic rocks plot in the basaltic andesite field and are sub-alkaline series (Figure 4a). Due to potential effect of alteration on whole-rock compositions, the classification based on immobile elements such as SiO_2 vs. $\text{Zr}/(\text{TiO}_2 \times 0.0001)$ diagram was employed to test the rock types. The results are consistent with the TAS diagram (Figure 4b). In addition, the samples show calc-alkaline characterized by enrichment of Na_2O relative to K_2O , with $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios varying from 1.6 to 4.99 (Figure 4c and d).

4.2. Trace element concentrations

As shown in the chondrite-normalized REE diagram (Figure 5a and c), the studied volcanic rocks display enrichment of light rare earth elements (LREEs) with $((\text{La}/\text{Sm})_N = 1.12\text{--}2.68$, and depletion of heavy rare earth elements (HREEs) with $(\text{Tb}/\text{Yb})_N = 1.21\text{--}2.38$). Weak negative Eu anomaly ($\delta\text{Eu} = 0.77\text{--}0.94$) has been observed in these samples, which indicates an fractionation of plagioclase. The rocks of the Hala'ate Formation show similar REE patterns to Karamay sanukitoids (Yin *et al.* 2010; Ma *et al.* 2012), while those of the Aladeyikesai Formation are comparable to Hatu sanukitoids (Yin *et al.* 2012, 2015a) (Figure 5a and c).

Their primitive mantle normalised trace element distribution patterns are characterized by significant depletion of high field strength elements (HFSEs, such as Nb, Ta) and enrichment in large-ion lithophile elements (LILEs) with positive Ba, K and Sr anomalies. These features of Hala'ate and Aladeyikesai formations are similar to sanukitoids in both Hatu area (Yin *et al.* 2012, 2015a) and northwestern Karamay (Yin *et al.* 2010; Ma *et al.* 2012) (Figure 5b and d).

4.3. Sr-Nd-Pb isotope compositions

The studied volcanic rocks have similar Sr-Nd-Pb isotopic compositions (Supplementary table 2). They have depleted-like Sr-Nd isotope composition with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios varying from 0.70366 to 0.70409 and $\epsilon\text{Nd}(t) = 4.4$ to 6.2. Such Sr-Nd isotopic compositions are similar to those of West Junggar sanukitoids rocks (Yin *et al.* 2010, 2012, 2015a; Ma *et al.* 2012) and plot within the field defined by Early Carboniferous island arc volcanic rocks from West Junggar (Geng *et al.* 2011) (Figure

6a). Lead isotope compositions of the studied volcanic rocks are also similar to Cenozoic sanukites in the SVB of SW Japan (Tatsumi *et al.* 2003; Figure 6b and c).

5. Discussion

5.1. Affinity to high-Mg andesite

The studied volcanic rocks have higher MgO contents than those of normal andesites but are similar to high-Mg andesite (HMA) at a given SiO₂ contents (Figure 7a). Although HMA is volumetrically rare in the modern Earth, which is defined as lava with SiO₂ = 54–65 wt% and Mg[#] > 45, they are important rock types, as the production of HMAs in the Earth's early history could have contributed greatly to continental crust formation (Kelemen 1995). The HMAs are commonly associated with young and/or hot slab subduction (Yogodzinski *et al.* 1995; Furukawa and Tatsumi 1999), meaning that the HMAs could be an important indicator of the thermal events like ridge subduction in arc systems (Kelemen *et al.* 2004; Wood and Turner 2009). HMA could, in principle, include boninite (Hickey and Frey 1982; Crawford *et al.* 1989), sanukitoid (Martin *et al.* 2005), bajaite (Rogers *et al.* 1985; Saunders *et al.* 1987) and high-Mg adakite (Defant and Drummond 1990; Shirey and Hanson 1984).

Late Carboniferous volcanic rocks from Hala'alate Mountain exhibit saturated to oversaturated Si with SiO₂ (52.9–56.9 wt.%), high MgO (3.47–6.88 wt.%, Mg[#] > 48) and Cr and Ni contents that similar to those of the typical sanukitoids. While the higher Sr (633.5–970.1 ppm), Ba (268.7–796.3 ppm) and Sr/Y (61.34–84.28) for Hala'alate Formation are similar to those of the Northwestern Karamay sanukitoids (Yin *et al.* 2010; Ma *et al.* 2012), the lower Sr (442.2–508.7 ppm), Ba (199.2–485.1

ppm) and Sr/Y (25.03—30.28) for Aladeyikesai Formation resemble those of the Hatu area sanukitoids (Yin *et al.* 2012, 2015a) (Figure 7b and c). Above characteristics are consistent with the features shown in REE patterns (Figure 5a and c). All Sr-Nd-Pb isotope compositions of the studied volcanic rocks, however, are similar to those of sanukitoids in Hatu and Karamay area (Figure 6; Supplementary table 3).

5.2. Fractional crystallization

The fact of large range of major and trace element compositions, but with nearly uniform Sr-Nd-Pb isotope data suggests that fractional crystallization may play a key role in producing the geochemical diversity of the studied volcanic rocks, but the crustal comminution is insignificant. The studied rocks have a wider range of MgO (3.47—6.88 wt.%) and Mg[#] (48—64) suggesting that their precursor magma probably underwent high degree of fractional crystallization. All samples showing high felsic indexes ($FL=30.74—62.63$) and mafic indexes ($MF=57.29—82.59$). Their relatively constant concentrations of TiO₂ suggest minor fractionation of Fe—Ti oxides (Figure 8a). The negative correlations between SiO₂ and MgO, MnO, TFeO and CaO/Al₂O₃ but the positive correlation between SiO₂ and K₂O and mafic indexes for sanukitoids suggest fractionation of olivine or/and pyroxene (Figure 4d and 8). Meanwhile, the weak negative Eu and positive Sr anomalies for volcanic rocks imply that plagioclase was an intermediate fractionating phase.

Overall, the geochemical data are consistent with olivine/pyroxene and plagioclase being the principal fractionation phases in the rocks. Therefore, the Hala'ate and Aladeyikesai formations with similar geochemical characteristics have

likely experienced analogical degree of fractional crystallization with parallel minerals.

5.3. Petrogenesis

The high $Mg^\#$ values indicate that the volcanic rocks were most likely derived from partial melting of mantle component (Rapp and Watson 1995). In subduction-related environment, reagent is mainly slab-derived fluid or melt, whereas in the case of an over-thickened crust, the reagent may come from delaminated lower crust. The zircon U-Pb ages (304.5–306.9 Ma for Hala’alate Formation and 303.8 Ma for Aladeyikesai Formation) display that the volcanic rocks formed prior to the Early Permian red molasse. The above lines of evidence strongly indicate a normal crustal thickness in the Late Carboniferous. Therefore, an over-thickened crust seems unlikely. According to our Sr–Nd isotopic data, the volcanic rocks of Hala’alate Mountain show strongly depleted signatures, with high $\epsilon Nd(t)$ (4.4 to 6.2) and low $(^{87}Sr/^{86}Sr)_i$ (0.7037 to 0.7041), consistent with the results of previous studies (Xu *et al.* 2006; Tang *et al.* 2010).

According to the description in Section 5.1, Hala’alate Formation sanukitoids not only have $(^{87}Sr/^{86}Sr)_i$ and $\epsilon Nd(t)$ values, and high $Mg^\#$ values and Cr and Ni contents, but also are characterized by high Sr, Ba, Sr/Y, and low Y (9.83–11.51 ppm), which are similar to those of adakite. These sanukitoids, which are akin to Karamay sanukitoids, were considered to be formed by partial melting of the mantle metasomatised by slab-derived adakitic melts during subduction of a hot, young oceanic slab (Figure 9, Ma *et al.* 2012; Tang *et al.* 2012a; Yin *et al.* 2013). However, the Aladeyikesai Formation sanukitoids that shown some affinity with sanukitoids of

the Hatu area, West Junggar and the Setouchi Volcanic Belt, SW Japan, have high Th/La and Th/Yb values suggesting that the reactant was dominated by sediment-derived melt (Figure 9). It is widely accepted that the sanukitoids from the Hatu area and the SVB generated by the partial melting of mantle peridotite enriched by subducted oceanic sediments (Tatsumi 2001; Tatsumi 2008; Yin *et al.* 2015a). Similarly, the Aladeyikesai Formation sanukitoids may be formed in a same mechanism. Consequently, subducted slab presumably melted under the adakitic melt, thereafter, the Hala'alate Formation sanukitoids were generated by the interaction of the adakitic melt with peridotite in the mantle wedge. In contrast, concerning the Aladeyikesai Formation sanukitoids, partial melting of subducting oceanic sediments and subsequent melt-mantle reaction might occur at a shallower depth. Therefore, the difference in geochemical features between the Hala'alate Formation and Aladeyikesai Formation sanukitoids can be explained by the difference in depth of origin composition and initial melting.

5.4. Tectonic implications

Identifying of Late Carboniferous sanukitoids volcanic rocks in West Junggar provide important constraints on the evolution of subduction system. However, there are two significantly different views on Late Paleozoic tectonic setting of West Junggar. The one is island arc tectonic setting (Xiao *et al.* 2006, 2008a and b, 2010; Tang *et al.* 2009), and the other is post-collisional setting (Su *et al.* 2006; Han *et al.* 2006). Recently, the Carboniferous adakite-high-Mg andesite-Nb-enriched arc basaltic rocks

had been reported in West Junggar. For instance, the basalts of Early Carboniferous Heishantou Formation had the similar geochemical characteristics with Nb-enriched arc basalts in Barnuke, West Junggar (Li *et al.* 2014). Moreover, adakites are mainly composed of acidic porphyry rocks in Baogutu area, central of West Junggar, and associated with copper and gold mineralization (Zhang *et al.* 2006; Tang *et al.* 2009). In addition, high-Mg andesites (sanukitoids) had been reported in eastern part of West Junggar, both in intrusive (Yin *et al.* 2010, 2012, 2015a; Ma *et al.* 2012) and volcanic (this study) rocks. In sum, the special rock association indicates that there might be an island arc tectonic setting in West Junggar during Carboniferous (Figure 10).

The subduction region, which reported by some researchers, was located in the western part of West Junggar. And the subduction-accretionary events almost occurred in the Early Carboniferous (Zhao *et al.* 2006; Shen *et al.* 2008; Tian *et al.* 2013; Li *et al.* 2014). Recently, the Late Carboniferous—Early Permian mafic dykes and plutons, which are located in both sides of Darbut Fault, were reported with typical features of sanukitoids (Yin *et al.* 2010, 2012, 2015a; Ma *et al.* 2012). Therefore, there is a close genetic connection between Baogutu-Hatu and Hala'ulate Mountain sanukitoids with the same locations and ages. The most likely explanation is that West Junggar had been formed twice subduction-accretionary from southeast to northwest at Early Carboniferous and Late Carboniferous—Early Permian. The first subduction-accretionary had finished at Early Carboniferous, and then it went to intra-continental post-collisional evolution. The second subduction-accretionary occurred in southern of West Junggar at Late Carboniferous and formed sanukitoid

arc volcanic rocks. Meanwhile, during forming granitic magma with post-collisional tectonic setting, the sanukitoid intrusive rocks, which have the same source with sanukitoid arc volcanic rocks, intruded upward along Darbut Fault in Early Carboniferous stratum. Some of them formed the independent pluton, but another formed magma mixing granites or mantle-derived inclusion and mafic dykes by magma mixing when they encountered the post-collisional granitic magma with the same period (Such as the Xiaerpu granite, also named as the Karamay granite, [Li et al. 2004, 2005, 2013, 2015a](#); [He and Chen 2009](#); [Kang et al. 2009](#); [Zhang et al. 2009, 2011](#); [He et al. 2011](#); [Zou et al. 2011](#)) (Figure 11). Therefore, our results display that the closing time of remnant ocean basin in West Junggar should be Late Carboniferous, rather than Early Carboniferous.

More importantly, the West Junggar is a part of the CAO, which is the largest accretionary orogen in the world with a long accretionary history from the late Proterozoic to the Mesozoic. However, mechanism of the continental-crust growth via successive or abrupt addition of mantle-derived remains an issue of dispute ([Sengör et al. 1993](#); [Windley et al. 2007](#); [Xiao et al. 2010, 2015](#); [Wilhem et al. 2012](#); [Kröner et al. 2014](#); [Xiao and Santosh 2014](#)). The most outstanding feature of the CAO is the vast expanse of granitoids and volcanic rocks characterized by positive $\epsilon\text{Nd}(t)$ values and young $T_{\text{DM}} - \text{Nd}$ model ages ([Geng et al. 2009](#); [Jahn et al. 2000](#); [Tang et al. 2012b](#)). As a key area, the West Junggar can provide crucial constraint on the mechanism of continental-crust growth in the CAO ([Kwon et al. 1989](#); [Yang et al. 2012a, 2012b, 2012c, 2013 and 2014](#); [Chen et al. 2014](#); [Yin et al. 2015b](#); [Zhu et al. 2015](#)). Therefore,

an arc setting not only has the capacity to create sanukitoids, but also generates massive volumes of juvenile continental crust. This study demonstrates that multi-stage subduction-accretionary orogeny plays a significant role in the evolution and growth of the continental crust in the CAOBS.

6. Conclusions

(1) The Hala'ate Formation and Aladeyikesai Formation volcanic rocks in the Hala'ate Mountain have similar $^{87}\text{Sr}/^{86}\text{Sr}$ and $\epsilon\text{Nd}(t)$ values and may be derived from similar mantle sources. Similarly, the Hala'ate and Aladeyikesai formations have likely experienced an analogous degree of fractional crystallization with olivine/pyroxene and plagioclase.

(2) Hala'ate Formation volcanic rocks are similar to sanukitoids of Karamay, formed by partial melting of the mantle metasomatised by slab-derived adakitic melts. In contrast, Aladeyikesai Formation volcanic rocks show some affinity with sanukitoids of the Hatu area, West Junggar and the SVB, Japan, generated by the partial melting of subducting sediments.

(3) The identifying of the Late Carboniferous sanukitoid volcanic rocks was the first in Hala'ate Mountain area, West Junggar. This achievement determined that there had been arc tectonic setting at the Late Carboniferous in this region, providing important geochemical information for study subduction-accretionary of CAOBS.

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Figures caption

Figure 1. (a) Simplified tectonic sketch of the CAOBS (Jahn *et al.* 2000). (b) Schematic tectonic map showing main tectonic units of the West Junggar (modified after Chen *et al.* 2010; Xu *et al.* 2012; Wang *et al.* 2013). (c) Geological map of Baogutu-Hala'ate Mountain area (modified after Sun *et al.* 2014b)

Figure 2. Geological map (a), simplified cross-section (b) and simplified stratigraphic column (c) of Hala'ate Mountain area, West Junggar

Figure 3. Typical field photographs (a, c) and micro-photos (b, d) of the volcanic rocks in Hala'ate Mountain area

Note: Cpx, clinopyroxene; Pl, plagioclase

Figure 4. Classification and series diagrams of Late Carboniferous volcanic rocks in Hala'ate Mountain area, Western Junggar. (a) Total alkalis vs. silica diagram (Le *et al.* 1986). (b) SiO_2 vs. $\text{Zr}/(\text{TiO}_2 \times 0.0001)$ diagram (Winchester and Floyd 1977). (c) AFM diagram (Irvine and Baragar 1971). (d) SiO_2 vs. K_2O diagram (Miller *et al.* 1999). Data of Hatu area are from Yin *et al.* (2012, 2015a). Data of northwestern Karamay area are from Yin *et al.* (2010), Ma *et al.* (2012).

Figure 5. Chondrite-normalized REE distribution patterns (a and c) and primitive mantle-normalized multi-element spider diagram (b and d). Chondrite data are from Boynton (1984). Primitive-mantle data are from Sun and McDonough (1989). Sanukitoid data of the Hatu area are from Yin *et al.* (2012, 2015a). The data of northwestern Karamay are from Yin *et al.* (2010) and Ma *et al.* (2012).

Figure 6. (a) $\epsilon\text{Nd}(t)$ vs. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagram. Early Carboniferous volcanic rocks data of Western

Junggar area are from Geng *et al.* (2011). (b) $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ diagram (after Zindler and Hart 1986). (c) $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ diagram (after Allegre *et al.* 1988). Sanukitoid data of Hatu area are from Yin *et al.* (2012, 2015a). Data of northwestern Karamay area are from Yin *et al.* (2010) and Ma *et al.* (2012). Data of SVB are from Tatsumi *et al.* (2003). Symbols in this and following figures are the same as those in Figure 4.

Note: MORB, mid-ocean ridge basalt; BSE: bulk silicate earth; NHRL: northern hemisphere reference line.

Figure 7. (a) SiO_2 vs. MgO classification diagram (modified after Mccarro and Smellie 1998). (b and c) Discrimination diagrams for HMA (Kamei *et al.* 2004). Data of Hatu area are from Yin *et al.* (2012, 2015a). Data of northwestern Karamay area are from Yin *et al.* (2010) and Ma *et al.* (2012). Data of SVB are from Tatsumi *et al.* (2003). Data of Banda and Kermadec normal arc andesite are from <http://georoc.mpch-mainz.gwdg.de/georoc/>. Note: HMA, high-Mg andesite.

Figure 8. Harker diagrams (after Bhatia 1983) showing major element variations for the Late Carboniferous Sanukitoids in Hala'alate Mountain area.

$$\text{mafic indices} = 100(\text{Fe}_2\text{O}_3 + \text{FeO}) / (\text{Fe}_2\text{O}_3 + \text{FeO} + \text{MgO}).$$

Figure 9. (a) Th/Yb - Ba/La diagram; (b) Th/La - Sr/Y diagram. Data of Hatu area are from Yin *et al.* (2012, 2015a). Data of northwestern Karamay area are from Yin *et al.* (2010) and Ma *et al.* (2012). Data of SVB are from Tatsumi *et al.* (2003).

Figure 10. Tectonic discrimination diagrams of Late Carboniferous Sanukitoids in Hala'alate Mountain area. (a) $\text{TiO}_2 \times 10 - \text{Al}_2\text{O}_3 - \text{K}_2\text{O} \times 10$ diagram (Zhao 1989). A—oceanic basalt; B—

735 continental rift basalt; C— island arc orogenic belt basalt, andesite. (b) Rb/10—Hf—Ta $\times$ 3 diagram
736 (Pearce 1982). A— collision zone; B— volcanic arc; C— within plate. (c) Hf/3—Th—Ta diagram
737 (Wood 1980). A— normal mid-ocean ridge basalt (N-MORB); B— enriched mid-ocean ridge basalt
738 (E-MORB); C— within plate alkaline volcanics; D— arc volcanics.

739 Figure 11. Non-scaled schematic cross-sections for the West Junggar orogenic belt, showing the
740 geodynamic evolution of the region from Early Carboniferous to Early Permian
741 Note: C₁G, Early Carboniferous Granite; XEP, Xiaerpu Granite

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Supplementary tables

Supplementary table 1. The concentration of major elements (wt.%), trace elements (ppm) and their parameters for volcanic rocks

Note: Data with * are from [Xiang et al. \(2015\)](#). $FL = 100 \times (Na_2O + K_2O) / (Na_2O + K_2O + CaO)$. $MF = 100 \times (Fe_2O_3 + FeO) / (Fe_2O_3 + FeO + MgO)$. $\delta Eu = Eu_N / (Sm_N \times Gd_N)^{1/2}$. $Mg^\# = 100 \times Mg^{2+} / (Mg^{2+} + Fe^{2+})$ molar ratio, $TFeO = TFe_2O_3 \times 0.8998 \times 0.85$. N = Chondrite, the values after [Boynton \(1984\)](#)

Supplementary table 2 Sr-Nd-Pb isotopic data of Late Carboniferous volcanic rocks in Hala'alate Mountain area

Note: Sample numbers corresponding with Supplementary table 1. The initial values of Hala'alate and Aladeyikesai formations set calculated by the age of 306 Ma ([Li et al. 2015b](#)) and 303.8 Ma ([Xiang et al. 2015](#)), respectively.

Supplementary table 3 Range value and average composition for sanukitoids in different regions from the literature

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Figure 11.