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Petrogenesis and tectonic implications of Early Cretaceous volcanic rocks from Lingshan Island in the Sulu Orogenic Belt

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ABSTRACT

The Dabie-Sulu orogenic belt in eastern China marks the boundary between the Yangtze Block and the North China Block. Here we investigate a suite of volcanic rocks from Lingshan Island in the Sulu belt comprising rhyolite, trachyte, trachyandesite and basaltic trachyandesite. We present petrological, geochemical and zircon U—Pb ages and Hf—O isotope data with a view to gain insights on the petrogenesis and tectonic implications. SHRIMP II analyses of zircon grains from the rhyolite yield $^{206}Pb/^{238}U$ age of 127.6 ± 1.3 Ma and LA-MC-ICP-MS dating show 126.3 ± 1.2 Ma and 127.3 ± 1.1 Ma, together constraining the eruption time as Early Cretaceous. LA-MC-ICP-MS analyses of zircon grains from the andesitic rocks yield $^{206}Pb/^{238}U$ ages of 129.0 ± 1.6 Ma, 129.8 ± 1.5 Ma and 130.9 ± 1.0 Ma. Geochemically, the rhyolite shows shoshonitic features with low MgO and Cr, but high $Na_2O + K_2O$. The zircon grains from these rocks yield negative $\varepsilon_{Hf}(t)$ values and low $\delta^{18}O$ values, and these together with the presence of Neoproterozoic inherited zircons suggest that the magma source involved melting of the Yangtze crust. The andesitic rocks, including basaltic trachyandesite, trachyandesite and trachyte, show a wide range of SiO_2, $Mg^{\#}$ values, and Cr, enriched in LILE and LREE, depleted in HFSE (Nb, Ta and Ti), and have significantly negative zircon $\varepsilon_{Hf}(t)$ values, suggesting derivation from subcontinental lithosphere mantle that was metasomatized by felsic melts. Our results, integrated with those from previous studies suggest heterogeneous magma involving the mixing of mantle and crustal sources within an extensional setting in the Early Cretaceous.

1. Introduction

Magmatism in convergent plate margins within oceanic and continental arcs contribute to crustal growth, and involve heterogeneous sources involving slab and sediment melts and fluids and their interaction with the overlying mantle wedge (e.g. Zheng et al., 2015; Meng et al., 2016; Santosh et al., 2017; Zhao et al., 2017; Hagen-Peter and Cottle, 2018). The exhumation of deeply subducted continental crust, and extension and collapse of the thickened orogenic belts can result in *syn*-exhumation and post-collision magmatism (Chung et al., 2005; Xu et al., 2016; Zhao et al., 2017). Compared with *syn*-exhumation magmatism, post-collisional magmatic activities are widespread in continental collisional orogenic belts (Zhang et al., 2010; Xu et al., 2016). The Dabie-Sulu orogenic belt is an ideal region to gain insights on the geodynamic processes of post-collisional magmatism and crust-mantle interaction (Xu et al., 2006, 2016; Zhang et al., 2012; Zhao et al., 2017). This belt was formed by the northward subduction of the Yangtze Block beneath the North China Block (NCB) during Triassic (Liou et al., 2000; Zheng et al., 2003; Yang et al., 2005a, b; Xu et al., 2006; Liu and Liou, 2011; Liu et al., 2017; Zhao et al., 2017). The belt has been in focus for investigations related to high pressure (HP) and ultra-high pressure (UHP) metamorphism rocks and continental deep subduction (e.g. Hacker et al., 1998; Yang et al., 2005a, b; Liu et al., 2017; Zhao et al., 2017). The magmatic suites in this belt are also important in gaining insights on crust-mantle interaction and post-collisional processes (e.g. Zhao et al., 2013, 2017). Previous studies suggest that the post-collisional magmatic rocks in this belt were formed in Late Triassic, Late Jurassic and Early Cretaceous (e.g. Zhao and Zheng, 2009; Zhao et al., 2017). The Late Triassic alkaline rocks and Late Jurassic magmatic suites are mainly exposed in the eastern segment of the Sulu orogenic belt (e.g. Yang et al., 2005a, b; Xu et al., 2016; Zhao et al., 2017), whereas the Early Cretaceous magmatic rocks, composed dominantly of granites, are widespread throughout the Sulu belt (Zhang et al., 2010, 2012; Xu et al., 2016; Zhao et al., 2016, 2017). Previous geochronological studies demonstrate that the post-collisional magmatism took place mainly during 110–130 Ma in the Sulu belt (e.g. Yang et al., 2005a, b; Zhao and Zheng, 2009; Zhang et al., 2010; Zhao et al., 2016, 2017). The peak of lithospheric destruction in the North China craton began

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at ca. 125 Ma (e.g. Zhu et al., 2012), and Early Cretaceous magmatic suites have been correlated to the craton destruction (e.g. Zhu et al., 2012; Wu et al., 2014). Previous studies on the Early Cretaceous magmatic rocks (Zhang et al., 2010; Zhao et al., 2017) mainly focused on granites and related assemblages (mafic dykes or stocks), and only few studies were carried out on the volcanic rocks. Compared with granites, the outcrops of volcanic rocks are relatively rare in the Sulu orogenic belt, and their timing of formation and petrogenesis are poorly constrained (Yang et al., 2004). Previous studies reveal that the Early Cretaceous granites have close affinities with the Yangtze crustal material as suggested by Sr-Nd-Hf isotopes and Neoproterozoic inherited zircons (Zhao and Zheng, 2009; Zhao et al., 2016, 2017), although some workers have invoked lower crustal components (Zhang et al., 2002a), or older crustal material (e.g. Kongling Group) (Bryant et al., 2004).

In order to understand the post-collisional geodynamic processes and recycling of deep-subducted crustal material in the Sulu orogenic belt, our present study focuses on the Early Cretaceous volcanic assemblages located on the isolated Lingshan Island (Wang et al., 2014, 2015). We present results from our field investigations, petrologic, whole-rock geochemical and zircon U—Pb and Lu-Hf-O isotope data on these rocks to gain insights on the magmatic pulses associated with post-collisional extension.

2. Geological background and sampling

2.1. Geological setting

The Triassic Dabie-Sulu orogenic belt is one of the largest UHP-HP terranes of the world from where coesite and microdiamond inclusions were reported in eclogites suggesting subduction of continental crust to depths of over 120 km (Xu et al., 1992; Liou et al., 2000; Ye et al., 2000; Zheng et al., 2003; Liu and Liou, 2011; Zhao et al., 2017). This region is also well-known for the widespread Mesozoic granitoid rocks related to *syn*-exhumation and post-collisional magmatism (Yang et al., 2005a, b; Zhao et al., 2012a, b, 2017; Xu et al., 2016; Dai, 2017). Previous studies suggested that the Mesozoic granitoid rocks preserve important evidence for deep-subduction crustal exhumation, as well as the recycling of continental lithosphere mantle (Zhang et al., 2010; Zhao and Zheng, 2009; Xu et al., 2016; Zhao et al., 2017). Consequently, the rock types, their emplacement ages, and geochemical and isotope characteristics of these rocks are important in understanding the post-collisional evolutionary history of the Dabie-Sulu orogenic belt.

Strike-slip along the Tan-Lu fault during Early Jurassic (e.g. Zhu et al., 2004), dissected the Dabie-Sulu orogenic belt into two segments, with the Dabie orogenic belt in the west and the Sulu orogenic belt in the east (Fig. 1a). The Sulu orogenic belt is bound by the Wulian-Qingdao-Yantai Fault (WQYF) to the north and by the Jiashan-Xiangshui Fault (JXF) to the south (Zhou et al., 2008; Wang et al., 2016; Liu et al., 2017) (Fig. 1b). The Sulu belt has been divided into HP and UHP metamorphic zones, marked by the Shuyang-Jinping Suture Zone (SJSZ) (Liu et al., 2017). The HP and UHP rocks were overprinted by amphibolite-facies retrograde metamorphism, and intruded by Mesozoic granitic rocks. Based on the timings of the magmatic activities (Yang et al., 2005a, b; Zhao and Zheng, 2009; Xu et al., 2016; Zhao et al., 2017), they are divided into three stages: (1) 225–205 Ma; (2) 160–150 Ma; (3) and 130–110 Ma. The Late Triassic granites and related complexes (225–205 Ma) outcrop in the Shidao region in the Shandong province. These plutons show high alkali contents ($Na_2O + K_2O$), belonging to K-rich and alkaline series (e.g. Xu et al., 2016). Geochemically, the Late Triassic alkaline complexes show enrichment of LREE with positive Pb anomalies, but with marked depletion of Nb, Ta and Ti. Recent studies correlate the Late Triassic magmatic activities to the *syn*-exhumation stage under a post-collisional setting (Yang et al., 2005a, b; Xu et al., 2016). Diverse models were suggested for the origin of the Late Triassic magmatic rocks including the partial melting of oceanic slab after its breakoff within buoyant continental lithosphere (Chen et al., 2003), partial melting of the subducted Yangtze lithosphere mantle (Yang et al., 2005a), partial melting of the NCB lithosphere mantle (Zhao et al., 2012a, b) and partial melting of the metasomatized sub-continental lithosphere mantle (enriched mantle) (Xu et al., 2016). The Late Jurassic granites, mainly located between Rushan and Wendeng district, intruded into the UHP-HP gneiss in the Sulu belt (Zhang et al., 2010, 2012). These rocks carry abundant inherited zircons that can be separated into three groups, Triassic, Neoproterozoic and Paleoproterozoic. Compared with the Late Triassic granitic complexes, the Late Jurassic granites show narrow compositional variations (Zhang et al., 2010, 2012; Zhao et al., 2017), and are characterized by sub-alkaline features. The Late Jurassic granites also are enriched in LREE and LILE, but depleted in HREE, showing arc-like affinities. They also display adakite-like features characterized by high Sr/Y and $(La/Yb)_N$ ratios (Zhang et al., 2010, 2012), and are considered to be products of partial melting of thickened continental crust in the Sulu belt (Zhao and Zheng, 2009). The Early Cretaceous granites are widespread in the Sulu orogenic belt and commonly contain old inherited zircons that show Neoproterozoic ages (700–800 Ma) (Yang et al., 2005a, b; Zhao et al., 2017). The Early Cretaceous granites display wide ranges of geochemical compositions, and have relatively high alkali contents. They show typical arc-like magma features marked by enrichment of LREE and LILE and depletion of HFSE. The Neoproterozoic inherited zircons, isotope characteristics and whole-rock geochemistry together suggest that the Early Cretaceous granites are products of partial melting of the Yangtze crustal material (e.g. Zhao and Zheng, 2009). The Jurassic and Early Cretaceous magmatic activities are considered to have occurred within post-collisional setting (Zhao and Zheng, 2009; Zhang et al., 2010; Zhao et al., 2017).

Lingshan Island, located in the central segment of the Sulu orogenic belt, covers 7.66 km^2 and has an elevation of 513.6 m, with the Early Cretaceous sedimentary and volcanic rocks as the dominant rock types (Fig. 1c) (Wang et al., 2014, 2015, 2016; Yang and van Loon, 2016). The Early Cretaceous sedimentary rocks are grouped under the Fajiaying Formation of the Laiyang Group, consisting of mud-stone and sand-stone, suggesting lacustrine setting. The volcanic rocks are grouped into the Bamudi Formation of the Qingshan Group, and are represented by intermediate volcanic rocks and volcanic breccia covering 60% volume of Lingshan Island. Younger rhyolite, with width in the range of 10–15 m, covers both the sedimentary units and intermediate volcanic rocks (Fig. 1c, Fig. 2a–c). The intermediate volcanic rocks include different rock types (Fig. 2b–c) and show gradational contacts, suggesting mixing of magmas (Fig. 2c). The presence of abundant volcanic breccia suggests that volcanic vents existed in this region. Only few investigations have been carried out so far on the volcanic rocks (Wang et al., 2015), with no detailed information on their precise ages and petrogenesis.

2.2. Sample description

In this study, we collected thirty-six representative samples, including both rhyolitic rocks and intermediate volcanic lavas. Six samples were used for zircon U—Pb dating, and twenty-four for whole-rock geochemical analyses. Details of the sampling localities including GPS information are summarized in Supplementary Table 1.

The rhyolites are gray in color, and display typical porphyritic textures with idiomorphic K-feldspar crystals (Fig. 2d) showing Carlsbad twins. The rhyolite matrices are composed of anhedral quartz grains, subhedral K-feldspar and plagioclase grains, with minor accessory minerals, such as chlorite and biotite (Fig. 2d).

Based on petrographic studies, the andesitic rocks can be divided into three groups: basaltic andesite, andesite and trachyandesite. The intermediate rocks show typical porphyritic textures composed of euhedral plagioclase (~35%) and hornblende (~10%). The matrix is composed of subhedral hornblende (~15%), plagioclase (~15%) and quartz (~10%), with minor amounts of pyroxene (~5%), biotite (~5%), and other accessory minerals (~5%) (Fig. 2e). Some of the plagioclase