Title:

Late Triassic alkaline complex in the Sulu UHP terrane: Implications for post-collisional magmatism and subsequent fractional crystallization

Authors: Haijin Xu ^{a, b*}, Junfeng Zhang ^{a, b}, Yongfeng Wang ^{a, b},
Wenlong Liu ^a

Address:

^a State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China

^b Center for Global Tectonics, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China

*** Correspondence should be addressed to Haijin Xu**

Haijin Xu:

Tel.: +86-15327190076;

Fax: +86-27-67883002;

E-mail: xuhaijin@cug.edu.cn (H. Xu).

Abstract

Continental subduction and its interaction with overlying mantle wedge are recognized as fundamental solid earth processes, yet the dynamics of this system remains ambiguous. In order to get an insight into crust-mantle interaction triggered by partial melting of subducted continental crust during its exhumation, we carried out a combined study of the Shidao alkaline complex from the Sulu ultrahigh pressure (UHP) terrane. The alkaline complex is composed of shoshonitic to ultrapotassic (K_2O : 3.4 – 9.3 wt.%) gabbro, pyroxene syenite, amphibole syenite, quartz syenite, and granite. Field studies suggest that the mafic rocks are earlier than the felsic ones in sequence. LA-ICPMS zircon U-Pb dating on them gives Late Triassic ages of 214 ± 2 to 200 ± 3 Ma from mafic to felsic rocks. These ages are slightly younger than the Late Triassic ages (225 – 210 Ma) of the felsic melts from partial melting of the Sulu UHP terrane during exhumation. The alkaline rocks have wide ranges of SiO_2 (49.7 – 76.7 wt.%), MgO (8.25 – 0.03 wt.%), Ni (126.0 – 0.07 ppm), and Cr (182.0 – 0.45 ppm) contents. The contents of MgO , total Fe_2O_3 , CaO , TiO_2 and P_2O_5 decrease with increasing SiO_2 contents. The contents of Na_2O , K_2O , and Al_2O_3 increase from gabbro to amphibole syenite, and decrease from amphibole syenite to granite, respectively. The alkaline rocks have characteristics of an arc-like pattern in trace element distribution, e.g., enrichment of LREE, LILE (Rb and Ba), Th and U, depletion of HFSE (Nb, Ta, P and Ti), and positive Pb anomalies. From the mafic rocks to the felsic rocks, the $(La/Yb)_N$ ratios and the contents of the total REE, Sr and Ba decrease but the Rb contents increase. The alkaline rocks with high SiO_2 contents

also display features of an A2-type granitoids, e.g., high contents of total alkalis, Zr and Nb and high ratios of $\text{Fe}_2\text{O}_3^{\text{T}}/\text{MgO}$, Ga/Al , Yb/Ta and Y/Nb , suggesting a post-collisional magmatism during exhumation of the Sulu UHP terrane. The alkaline rocks have homogeneous initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7058 – 0.7093) and negative $\varepsilon_{\text{Nd}}(\text{t})$ values (-18.6 to -15.0) for whole-rock. The Sr-Nd isotopic data remain almost unchanged with varying SiO_2 and MgO contents, suggesting a fractional crystallization (FC) process from the same parental magma. Our studies suggest a crust-mantle interaction in continental subduction interface as follows: (1) hydrous felsic melts from partial melting of subducted continental crust during its exhumation metasomatized the overlying mantle wedge to form a K-rich and amphibole-bearing mantle; (2) partial melting of the enriched lithospheric mantle generated the Late Triassic alkaline complex under a post-collisional setting; and (3) the alkaline magma experienced subsequent fractionational crystallization mainly dominated by olivine, clinopyroxene, plagioclase and alkali feldspar.

Key words: Crust-mantle interaction; Post-collisional magmatism; Alkaline complex; Fractional crystallization; Sulu UHP terrane

1. Introduction

Oceanic crusts undergo extensive metamorphic dehydration and partial melting during subduction and then significant amounts of fluid-mobile elements are transferred from subducting slab to overriding mantle wedge, leading to

syn-subduction arc magmatism (e.g., Tatsumi and Eggins, 1995; Schmidt, 1996; Schmidt and Poli, 1998). In contrast, large amounts of metamorphic fluids are almost absent during continental subduction (e.g., Liou et al., 1997; Zheng et al., 2003), although prograde metamorphic fluids have been reported occasionally (e.g., Liu et al., 2006; Wu et al., 2006; Xu et al., 2012a, 2013a). Therefore, the continental subduction zones are characterized by the absence of syn-subduction arc-type magmatism (e.g., Ernst et al., 1999; Zheng, 2012). However, partial melting is widespread during exhumation of deeply subducted continental crust (e.g., Wallis et al., 2005; Auzanneau et al., 2006; Hermann et al., 2006; Zheng et al., 2011; Zheng, 2012; Chen et al., 2013a, b; Xu et al., 2013a, b; Song et al., 2014a, b). Melts from subducted continental crusts can metasomatize the overlying mantle wedge, which might trigger arc-like magmatism, i.e., syn-exhumation and/or post-collisional magmatism (e.g., Guo et al., 2005; Yang et al., 2005; Zhang et al., 2010, 2012; Zhao et al., 2012). Thus, post-collisional magmatism in continental subduction zones is another dominant mechanism for the exchange of mass and energy between the mantle and the crust (e.g., Zhao et al., 2013).

The Sulu orogen is an ideal place to decipher crust-mantle interaction between melts from subducted continental crust and mantle wedge. The Sulu orogen was formed by the Early Triassic subduction of the South China Block beneath the North China Block (e.g., Cong, 1996). Partial melting of the Sulu UHP terrane during the Late Triassic (225 – 210 Ma) exhumation has been widely recognized as leucosomes (Chen et al., 2013a; Xu et al., 2013a, b), pegmatitic veins (Wallis et al., 2005; Liu et

al., 2010a, 2012; Zong et al., 2010; Chen et al., 2013b; Xu et al., 2013a, b; Song et al., 2014a, b) and granitic dikes (Liu et al., 2009). A Late Triassic (215 – 200 Ma) alkaline complex pluton has also been recognized in the Sulu UHP terrane (e.g., Chen et al., 2003; Guo et al., 2005; Yang et al., 2005; Chen and Jiang, 2011; Zhao et al., 2012). The alkaline magmatism followed right after the partial melting of the UHP terrane, indicating a genetic link between them.

The origin of alkaline rocks remains debatable, e.g., partial melting of a metasomatized mantle (e.g., Sutcliffe et al., 1990), residual melts formed by fractionation and hybridization of alkali basalt magma (e.g., Brown and Becker, 1986; Litvinovsky et al., 2002), or magma mixing of basic and silicic melts with a subsequent differentiation of the hybrid liquids (e.g., Sheppard, 1995; Zhao et al., 1995). It is generally assumed that these alkaline rocks are generated in a non-orogenic or within-plate environment (e.g., Eby, 1992). The alkaline complex in the Sulu UHP terrane has variable compositions (including gabbro, syenite and granite) with negative whole-rock $\epsilon_{\text{Nd}}(t)$ values (e.g., Gao et al., 2004; Yang et al., 2005; Chen and Jiang, 2011; Zhao et al., 2012), suggesting a mixed source involved in both the mantle and the crust. However, petrogenesis of the alkaline complex remains controversial. Chen et al. (2003) and Guo et al. (2005) suggested that they were syn-orogenic or syn-collisional magmatism, resulting from the oceanic slab break-off of the buoyant continental lithosphere during subduction. Yang et al. (2005) suggested that they were products of a post-orogenic magmatism derived from the subducted South China lithospheric mantle. Chen and Jiang (2011) and Zhao et al.

(2012) argued that they were derived from partial melting of the North China lithospheric mantle and the subducted continental crust in the stage of exhumation, i.e., Syn-exhumation magmatism. In addition, the complete rock association of the alkaline complex and the characteristics of magma evolution remain unclear. We report here detailed studies of fieldwork, petrology, chronology, and geochemistry on the alkaline complex in the Sulu UHP terrane. Our results suggest that the Late Triassic alkaline complex was a post-collisional pluton, derived from partial melting of an enriched mantle wedge source that was metasomatized by some subducted crustal components prior to magma generation, and has experienced a crystal fractionation.

2. Geological setting and petrology

2.1. Geological setting

The Dabie-Sulu orogenic belt was separated into two parts by the Tan-Lu fault with the Dabie orogen in the west and the Sulu orogen in the east (Fig. 1A). Findings of coesite and microdiamond inclusions in eclogites and gneisses from the orogenic belt demonstrate that the continental crust was subducted to mantle depths of at least 120 km (up to >200 km) to undergo ultrahigh pressure (UHP) metamorphism (e.g., Wang et al., 1989; Xu et al., 1992, 2003; Ye et al., 2000a,b; Liu et al., 2005, 2008a). The UHP terrane in the Sulu orogen is bounded by the Wulian-Qingdao and Mishan faults in the north, the Jiashan-Xiangshui fault in the south, and the Tan-Lu Fault in the west (Fig. 1B). The Sulu UHP terrane is mainly composed of granitic gneisses (e.g., Ye et al., 2000a; Liu et al., 2010a, 2012; Chen et al., 2013a,b; Xu et al., 2013a;

Song et al., 2014a, b) with subordinate other lithologies, e.g., eclogite, peridotite, marble, and paragneiss, which occur as scattered blocks or lenses within the regional granitic gneisses (e.g., Zheng, 2008).

Peak conditions of the UHP metamorphic rocks in the Sulu orogen were estimated at 2.8 – 4.5 GPa and 700 – 800 °C (e.g., Wang et al., 1993; Banno et al., 2000; Nakamura and Hirajima, 2000; Zhang et al., 2005, 2009). Various methods of geochronology suggested that the time of the Sulu UHP metamorphism in the coesite stability field ranges from ca 238 to 227 Ma (e.g., Yang et al., 2003; Liu et al., 2004, 2005, 2008a, 2010a; Zong et al., 2010). The UHP eclogites at the Weihai-Rongcheng region in the northeastern Sulu orogen have experienced a granulite-facies overprinting with a temperature ranging from 800 to 850 °C, (e.g., Wang et al., 1993; Banno et al., 2000; Nakamura and Hirajima, 2000), indicating a rise of temperature during early exhumation stage. The margins of most eclogite lenses at the Weihai-Rongcheng region have transformed to amphibolite (ca. 220 – 205 Ma) (e.g., Liu et al., 2004, 2006, 2008a, Zhang et al., 2009). The temperatures of the amphibolite-facies retrogression were 770 to 530 °C (e.g., Xu et al., 2012a), indicating a cooling process during late exhumation stage. Partial melting of UHP metamorphic rocks during exhumation has been recently identified in the Sulu UHP terrane (e.g., Wallis et al., 2005; Liu et al., 2010a, 2012; Zong et al., 2010; Xu et al., 2012a, 2013a, b; Chen et al., 2013a, b; Song et al., 2014b). The melts, such as felsic leucosomes and veins, give variable U-Pb ages from 210 to 227 Ma (e.g., Liu et al., 2010a, 2012; Zong et al., 2010; Xu et al., 2013a, b; Chen et al., 2013a, b), which are well consistent

with the exhumation time of the Sulu UHP terrane.

<Figure 1>

2.2. The Shidao alkaline complex

Beside the UHP metamorphic rocks, Mesozoic magmatic rocks are widely outcropped in the Sulu orogen. Most of them are high-K calc-alkaline granitic rocks formed in the Late Jurassic (160 – 150 Ma) and the Early Cretaceous (130 – 125 Ma) (e.g., Guo, et al., 2005; Yang et al., 2012 and references therein). Only one syenitic complex (the Shidao alkaline Complex) has been reported of a Late Triassic age (214 – 200 Ma) at the Rongcheng region in the northeastern Sulu orogen (e.g., Chen et al., 2003; Guo et al., 2005; Yang et al., 2005; Chen et al., 2011; Zhao et al., 2012).

We report here the Late Triassic Shidao alkaline complex that intruded into the UHP granitic gneisses (Fig. 1C). The Shidao complex covers an area of ~150 km². Based on field mapping, contact relation and petrographic data, the Shidao alkaline complex can be divided into five lithological units from early to late in view of their emplacement time (e.g., Guo et al., 2005; Yang et al., 2005; Chen et al., 2011; Zhao et al., 2012; this study): gabbro, pyroxene syenite with mafic microgranular enclave (MME), amphibole syenite and quartz syenite, and granite (Fig. 1C). The syenitic series were simply separated into pyroxene syenite and quartz syenite in previous studies (e.g., Guo et al., 2005; Yang et al., 2005; Chen et al., 2011; Zhao et al., 2012). In this study, they are further divided into pyroxene, amphibole, and quartz syenites according to detailed field mapping and petrology. The gabbros were intruded by the quartz syenite dykes (Figs. 2A-B). The pyroxene syenites contain xenoliths (Fig. 2C)

or MMEs (Fig. 2D) of gabbro-monzodiorite. The pyroxene syenites were intruded by the amphibole syenites, which were both cut across by the quartz syenites (Fig. 2E). The quartz syenites were intruded by the granites (Fig. 2G). In addition, xenoliths of the early intrusions commonly occur in the late ones. For example, the granites commonly contain xenoliths of the syenites.

<Figure 2>

The gabbro samples (12-XJ-02A, 12-XJ-02B, 12-XJ-02C, 12-XJ-02D, and 12-XJ-02E) are medium- to coarse-grained (Fig. 3A). They are composed of 30 – 45% plagioclase, 15 – 20% diopside, 20 – 30 % K-feldspar, ~10% biotite, and ~5% olivine with accessory minerals of amphibole, apatite, nepheline, magnetite, ilmenite, titanite and zircon. Some samples display a cumulate structure, e.g., olivine, diopside and metallic minerals clump together.

The mafic enclaves or xenoliths (samples 12-DS-01A, 12-DS-01B, and 12-DS-01C) are generally hosted in the pyroxene syenites. They display a gabbro texture with poikilitic olivine (Fig. 3B). Their mineral assemblage is gabbroic with 20 – 40% plagioclase, 20 – 35% K-feldspar, 15 – 20% diopside, ~15% biotite, and 5 – 10% olivine with accessory minerals of apatite, nepheline, magnetite, ilmenite, titanite and zircon. All of the mafic rocks including gabbros and mafic inclusions are fresh, and no alteration textures have been observed. For example, hydrous minerals (e.g., biotite and amphibole) typically exhibit euhedral or subhedral shapes and show equilibrium texture (Figs. 3A-B) with pyroxene and feldspar.

The syenites can be divided into three units: pyroxene syenite, amphibole syenite,

and biotite quartz syenite. The pyroxene syenites can further be divided into two types: pegmatitic and coarse-grained pyroxene syenites. The pegmatitic pyroxene syenites have a pegmatoidal texture (Fig. 3C). For example, the K-feldspar phenocrysts is up to ~7 cm long with a concentrically zoning (Fig. 2F). The pegmatitic pyroxene syenites (samples 12-JZS-01, 12-DS-04, and 12-DS-09) are composed of 35 – 50% subhedral to euhedral K-feldspar, 30 – 40% plagioclase, ~10% pyroxene, 5 – 10% biotite, and ~5% amphibole with minor apatite, titanite, magnetite, and zircon. The other pyroxene syenites (samples 12-JZS-03, 12-DS-02, 12-DS-05, 12-DS-06A, and 12-DS-06B) are mainly medium- to coarse-grained (Fig. 3D) with a porphyritic structure, consisting of 40 – 50% K-feldspar, 30 – 40 % plagioclase, 10 – 15% pyroxene, 5 – 10% biotite, ~5% amphibole with accessory minerals of apatite, nepheline, magnetite, titanite and zircon. These rocks contain mafic enclaves or xenoliths (Figs. 1C and 2C-D). The amphibole syenites (samples 12-DS-08, 12-DS-10, 12-CH-01, and 12-TBS-01) have a medium- to coarse-grained structure (Fig. 3E). Compared with the pyroxene syenites, they have relatively high contents of amphibole (~10 – 15%) but low contents of diopside (<5%), and the occurrence of quartz (<5%) (Fig. 3E). They have almost the highest contents of K-feldspar (50 – 65%). The quartz syenites (samples 12-TBS-03, 12-TBS-04, 12-XZ-02, 12-JZS-02, 12-SD-01, and 12-XJ-01) have a generally medium-grained structure (Fig. 3F), and consist of 45 – 50% K-feldspar, 30 – 40% plagioclase, and 10 – 20% quartz with accessory biotite (Fig. 3F), amphibole, apatite, titanite, magnetite and zircon. They are featured by high quartz content and the absence of diopside.

The granites can further be divided into two types: coarse- and fine-grained granites (Figs. 3G-H) with the later intruding into the former (Fig. 2H). They have similar mineral assemblages. The coarse-grained granites (samples 12-GS-01, 12-CS-02, 12-CS-03, and 12-XZ-01) consist of 35 – 45% K-feldspar, 15 – 25% plagioclase, 25 – 30% quartz, and 5 – 10% biotite with accessory magnetite and zircon. The fine-grained granites (samples 12-CS-01, 12-CS-04, and 12-CS-05) contain 30 – 40% K-feldspar, 15 – 25% plagioclase, ~35% quartz, and ~5% biotite with accessory magnetite and zircon. The fine-grained granites contain higher quartz contents than the coarse-grained granites.

<Figure 3>

3. Analytical methods

Fresh whole-rock samples were powdered to grain size <200-mesh using an agate mill for major- and trace-elemental and Sr-Nd isotopic analyses. Single grains of zircon were picked out from part of the selected samples for U-Pb dating and Lu-Hf isotopic analyses.

3.1. Zircon morphology

Rock samples were crushed in a steel crusher. Shaking bed and heavy liquid techniques were used to concentrate heavy minerals. Zircons were picked out from the concentrated heavy minerals under a binocular microscope and mounted in epoxy. The resin discs were then polished until most zircon grains expose grain centers. The internal structure of grains was imaged using a Gatan MonoCL4 cathodoluminescence (CL) spectrometer equipped in a FEI Quanta 450 FEG scanning

electron microscope at the State Key Laboratory of Geological Processes and Mineral Resources (SKLGPMR), China University of Geosciences (Wuhan). The work conditions of the CL imaging are set at 10 kV. The CL images were used for revealing zircon growth history and as a guide for appropriate spots for in situ isotope and trace element analyses. Typical CL images are presented in Fig. 4, together with the U-Pb ages for the corresponding spots.

3.2. Zircon U-Pb dating and trace element analyses

Zircon U-Pb age and trace element analyses were conducted synchronously using a LA-ICP-MS at the SKLGPMR, China University of Geosciences (Wuhan). Details of operating methods for the laser ablation system and the ICP-MS instrument and data processing can be found in Liu et al. (2008b). Laser sampling was performed using a GeoLas 2005. An Agilent 7500a ICP-MS instrument was used to acquire ion-signal intensity. Helium was applied as a carrier gas. Argon was used as the make-up gas and mixed with the carrier gas via a T-connector before entering the ICP. Nitrogen was added into the central gas flow (Ar+He) of the Ar plasma to decrease the detection limit and improve resolution (Hu et al., 2008). Each analysis incorporated a background acquisition of approximately 20-30 s (gas blank) and a sample acquisition of 50 s. The Agilent Chemstation was utilized for the acquisition of each individual analysis. Off-line selection and integration of background and analyte signals, and time-drift correction and quantitative calibration for trace element analysis and U-Pb dating were performed by *ICPMSDataCal* (Liu et al., 2008b).

Zircon 91500 was used as external standard for U-Pb dating, and was analyzed twice every 5 sample analyses. Time-dependent drifts of U-Th-Pb isotopic ratios were corrected using a linear interpolation (with time) for every five analyses according to the variations of 91500 (i.e., 2 zircon 91500 + 5 samples + 2 zircon 91500) (Liu et al., 2010b). Preferred U-Th-Pb isotopic ratios used for 91500 are from Wiedenbeck et al. (1995). Uncertainty of preferred values for the external standard 91500 was propagated to the ultimate results of the samples. Concordia diagrams and weighted mean calculations were made using Isoplot/Ex_ver3 (Ludwig, 2003). Trace element compositions of zircons were calibrated against multiple-reference materials (BCR-2G and BIR-1G) combined with internal standardization (Liu et al., 2010b). The preferred values of element concentrations for the USGS reference glasses are from the GeoReM database (<http://georem.mpch-mainz.gwdg.de/>). The results are listed in Table S1 with 1σ (95% confidence) errors of the mean for isotopic ratios and calculated ages and Table S2 for trace element compositions.

3.3. Whole-rock Major and trace element analyses

Major-element compositions of whole rocks (Table S3) were measured by X-ray fluorescence (XRF) using fused glass disks. XRF analysis was carried out on a Shimadzu XRF-1800 sequential X-ray fluorescence spectrometer using a Rh-anode X-ray tube with a voltage of 40 kV and current of 70 Ma at the SKLGPMR, China University of Geosciences (Wuhan). Analytical procedures were described by Ma et al. (2012). Calibration curves used for quantification were produced by bivariate regression of data from ~63 reference materials encompassing a wide range of silicate

compositions. Precision is better than 4% and accuracy is better than 3% for major elements. Trace element contents were analyzed by double focusing inductively coupled plasma mass spectrometer (ICP-MS) in the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS), Beijing, using Finnigan MAT Element. Analytical procedures were described in detail by Xu et al. (2007). Analytical errors are generally better than $\pm 5\%$ (2σ). The results of the selected samples are listed in Table S3.

3.4. Whole-rock Sm-Nd isotopic analyses

About 100-150 mg whole rock powder was completely decomposed in a mixture of HF-HClO₄ for Sr-Nd isotopic analysis. Sr and REE were separated on quartz columns with a 5 ml resin bed of AG 50W-X12, 200-400 mesh. Nd was separated from other REEs on quartz columns using 1.7 ml Teflon[®] powder as cation exchange medium. Procedural blanks were <200 pg for Sr and Rb and <50 pg for Nd and Sm. For the measurements of isotopic composition, Sr was loaded with a Ta-HF activator on a single W filament and Nd was loaded as phosphates and measured in a Re-double-filament configuration. ¹⁴³Nd/¹⁴⁴Nd ratios were normalised to ¹⁴⁶Nd/¹⁴⁴Nd=0.7219 and ⁸⁷Sr/⁸⁶Sr ratios to ⁸⁶Sr/⁸⁸Sr=0.1194. Isotopic ratios were measured on a Finnigan MAT-262 thermal ionization mass spectrometer (TIMS) at the Laboratory for Radiogenic Isotope Geochemistry, Institute of Geology and Geophysics, CAS, Beijing. Technique details on chemical separation and measurement are described in Chen et al. (2000). Raw data obtained were calculated using the Isoplot program (Ludwig, 2001), giving 2 σ error. The Sr-Nd isotopic data of

the selected samples are listed in Table S4.

4. Results

4.1. Zircon microstructure and U-Pb geochronology

Eight representative samples of the Shidao alkaline complex including gabbro (12-XJ-02D), pegmatitic pyroxene syenite (12-JZS-01), coarse-grained pyroxene syenite (12-DS-02) with mafic enclave (12-DS-01B), amphibole syenite (12-SD-10), biotite quartz syenite (12-TBS-03), coarse-grained granite (12-XZ-01) and fine-grained granite (12-CS-01) were selected for zircon U-Pb dating. LA-ICPMS zircon U-Pb analytical data are summarized in Table S1. Errors on individual analyses are cited as 1σ , and the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages are quoted at the 95% confidence level. CL images of the representative zircon grains with $^{206}\text{Pb}/^{238}\text{U}$ ages are shown in Fig. 4.

<Figure 4>

Zircons in the gabbro (12-XJ-02D) are subhedral to euhedral (Fig. 4A). They are prismatic, colorless and transparent. They are granular ranging from 100 to 300 μm in length. The CL images show that these zircons have a concentric oscillatory zoning with medium luminescence (Fig. 4A). Nine analyses on zircons yield concordant $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 212 ± 2 Ma to 218 ± 4 Ma (without spot 1) with a weighted mean of 214 ± 2 Ma (MSWD=0.51; n=9) (Fig. 5A). This age can be interpreted as the crystallization age of the gabbro, and is consistent with the zircon U-Pb ages of 210-213 Ma previously reported by Zhao et al. (2012).

Zircons in the mafic enclave (12-DS-01B) hosted in the pyroxene syenite are

euhedral, colorless and transparent. They are prismatic (100 to 300 μm in length) with length/width ratios of 2:1 to 3:1. They have magmatic euhedral rhythmic oscillatory zoning with variable CL brightness (Fig. 4B). Ten analyses yield concordant $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 206 ± 3 Ma to 219 ± 3 Ma with a weighted mean of 214 ± 4 Ma (MSWD=3.3; n=10) (Fig. 5B). This age can be interpreted as the crystallization age of the mafic enclave, and is similar to the zircon U-Pb age (214 ± 2 Ma, Fig. 5A) of the gabbro.

Zircons in the pegmatitic and coarse-grained pyroxene syenites (12-JZS-01 and 12-DS-02) are euhedral, prismatic, colorless and transparent. They range from 200 to 500 μm in length with length/width ratios of 1.5:1 to 3:1. The CL images show that these zircons have a wide concentric oscillatory zoning with medium to variable luminescence (Figs. 4C-D). Fifteen age-spots on zircons of the pegmatitic pyroxene syenite (12-JZS-01) yield concordant $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 206 ± 2 Ma to 217 ± 4 Ma with a weighted mean of 212 ± 2 Ma (MSWD=1.9; n=15) (Fig. 5C). Eighteen age-spots on zircons of the coarse-grained pyroxene syenite (12-DS-02) give concordant $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 200 ± 4 Ma to 219 ± 5 Ma with a weighted mean of 211 ± 3 Ma (MSWD=2.3; n=18) (Fig. 5D). These ages are consistent with the zircon U-Pb ages of 209-211 Ma previously reported by Guo et al. (2005) and Zhao et al. (2012).

Zircons in the amphibole syenite (12-SD-10) and biotite quartz syenite (12-TBS-03) are mostly granular, colorless and transparent. They range from 150 to 300 μm in length, with length/width ratios of 1:1 to 1.5:1. They have magmatic

ehedral rhythmic oscillatory zoning with variable CL brightness (Figs. 4E-F). A few zircon grains in the amphibole syenite display a core-rim structure (Fig. 4E). Twelve age-spots on the new grains and rims of zircons in the amphibole syenite yield concordant $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 204 ± 2 Ma to 216 ± 2 Ma with a weighted mean of 210 ± 3 Ma (MSWD=2.7; n=12) (Fig. 5E). Two inherited cores of zircons give the same concordant $^{206}\text{Pb}/^{238}\text{U}$ age of 220 ± 3 Ma (Fig. 5E). Seventeen age-spots on zircons of the biotite quartz syenite give concordant $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 202 ± 2 Ma to 214 ± 2 Ma with a weighted mean of 208 ± 2 Ma (MSWD=2.1; n=17) (Fig. 5F). These ages recorded in the amphibole and biotite quartz syenites are consistent with the ages of 209 ± 2 Ma and 212 ± 2 Ma previously reported by Chen and Jiang (2011) and Zhao et al. (2012), respectively.

Zircon grains in the coarse-grained granite (12-XZ-01) and fine-grained granite (12-CS-01) are euhedral with lengths of 150 to 300 μm and length/width ratios of 1.5:1 to 3:1. They are semitransparent with a pale-yellow to brown color. The CL images show a euhedral rhythmic oscillatory zoning with variable CL brightness for the zircon grains from the coarse-grained granite (Fig. 4G). The zircon grains from the fine-grained granite have a dark luminescence (Fig. 4H). The coarse-grained granite (12-XZ-01) has concordant $^{206}\text{Pb}/^{238}\text{U}$ ages between 197 ± 2 Ma to 218 ± 3 Ma with a weighted mean of 205 ± 3 Ma (MSWD=2.7; n=19) (Fig. 5G). A magmatic inherited core of zircon has been founded in the coarse-grained granite (Fig. 4G). The inherited core has a concordant $^{206}\text{Pb}/^{238}\text{U}$ age of 690 ± 10 Ma (Fig. 5G). The fine-grained granite (12-CS-01) has concordant $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 194 ± 2

Ma to 211 ± 4 Ma with a weighted mean of 200 ± 3 Ma (MSWD=2.4; n=17) (Fig. 5H). These ages recorded in the coarse-grained and fine-grained granites are consistent with the ages of 201 ± 2 Ma and 206 ± 1 Ma previously reported by Guo et al. (2005) and Zhao et al. (2012), respectively.

<Figure 5>

4.2. Zircon trace element composition

Zircons from the Shidao alkaline complex, i.e., gabbro, mafic enclave in the pyroxene syenite, pegmatitic pyroxene syenite, coarse-grained pyroxene syenite, amphibole syenite, biotite quartz syenite, coarse-grained granite and fine-grained granite share some common features in trace element compositions (Table S2). They have high heavy rare earth element (HREE) contents and low $(\text{Gd/Lu})_N$ ratios (< 0.22) leading to steep heavy-enriched REE patterns and display strong positive Ce anomalies and various negative Eu anomalies ($\text{Eu/Eu}^* = 0.19 - 0.71$) (Figure S1 in Appendix). Generally, they have high Th (96 - 9638 ppm) contents with high Th/U (0.12 - 4.61, most > 1.0) ratios. These are common features of magmatic zircons (Rubatto, 2002). It's important to note that the Th and U contents and the related Th/U ratios in zircons are obviously different from those of the mafic to felsic rocks (Fig. 6). Zircons from the gabbro, the mafic enclave and the pyroxene syenite have high Th but low U (< 1800 ppm) contents with high Th/U ratios. Zircons from the amphibole and quartz syenites have variable Th and U contents and variable Th/U ratios. However, zircons from the coarse- and fine-grained granites have relatively low Th and high U (most > 2000 ppm) contents with low Th/U ratios. Fig. 6 also shows that the Th/U

ratio decreases with the increase of U content from the gabbro to the granite.

<Figure 6>

4.3. Whole-rock geochemistry

The major and trace element compositions for the Shidao alkaline rocks are listed in Table S3. The alkaline rocks are composed of gabbro, mafic enclave in the syenite, pegmatitic pyroxene syenite, coarse-grained pyroxene syenite, amphibole syenite, biotite quartz syenite, coarse- and fine-grained granites (Fig. 3) (e.g., Chen et al., 2003; Gao et al., 2004; Yang et al., 2005; Chen and Jiang, 2011; Zhao et al., 2012). They have wide ranges in SiO₂ contents from 49.7 to 76.7 wt.%. All the samples are rich in K₂O and Na₂O with high K₂O/Na₂O ratios (1.3-2.9, except for one sample of 0.9), belonging to the shoshonitic and ultrapotassic series (Fig. 7A). They have high total alkalis (Na₂O + K₂O = 7.3 – 12.5 wt.%). Except for some granitic samples, other samples plot into the alkaline field on the total alkalis-silica (TAS) diagram (Fig. 7B). As shown in Fig. 8, the alkaline rocks exhibit correlations between SiO₂ and other oxides. The Na₂O, K₂O, and Al₂O₃ contents increase with the increasing SiO₂ contents from the gabbro or the mafic enclave to the amphibole syenite, whereas they decrease with the increasing SiO₂ contents from the amphibole syenite to the granite. The turnover values of the SiO₂ contents are ca. 60 – 65 wt.% when the Na₂O, K₂O, and Al₂O₃ contents reach their maxima (Figs. 8A-C). The contents of Na₂O + K₂O also have the same rule with the SiO₂ contents (Fig. 7B). However, the contents of CaO, P₂O₅, TiO₂, total Fe₂O₃ and MgO decrease with the increasing SiO₂ contents from the mafic to the felsic rocks (Figs. 8D-H).

<Figure 7>

<Figure 8>

Chondrite-normalized diagrams (Figs. 9A, C and E) show that the Shidao alkaline rocks generally have LREE enrichment patterns with the $(La/Yb)_N$ values decrease from the gabbros to the granites (Fig. 10A). The gabbros, mafic enclaves, pyroxene syenites and amphibole syenites have negligible Eu anomalies with $Eu/Eu^*=0.60 - 1.58$ (mostly ranging from 0.9 to 1.2), while the quartz syenites and granites display significantly negative Eu anomalies with Eu/Eu^* values ranging from 0.40 to 0.85 (Table S3). The Eu/Eu^* values decrease from the mafic to the felsic rocks in the Shidao alkaline complex (Fig. 10B). Some pyroxene and amphibole syenites have obviously high Eu/Eu^* values (> 1.0) with the SiO_2 contents ranging from 59.85 to 63.24 wt.% (Table S3). In addition, the total REE contents (ΣREE) decrease with the increase of the SiO_2 contents (Fig. 10C).

The primitive mantle-normalized trace element diagrams (Figs. 9B, D and F) show that the Shidao alkaline rocks are generally characterized by enrichment of large ion lithophile elements (LILEs, e.g., Rb, Ba, Th and U), positive Pb anomalies but negative high-field strength elements (HFSEs, e.g., Nb, Ta, P and Ti) anomalies. The gabbros, mafic enclaves, pyroxene syenites and some amphibole syenites have strongly positive Ba anomalies (Figs. 9B and D). However, the amphibole syenites, quartz syenites, and granites have positive Rb anomalies but negative Ba anomalies (Figs. 9 D and F). Correspondingly, with the increase of the SiO_2 contents, the Rb contents increase (Fig. 10D) but the Ba and Sr contents decrease (Figs. 10E-F). Meanwhile, the contents of Ni and Cr decrease from the mafic to the felsic rocks (Figs.

10G-H).

<Figure 9>

<Figure 10>

4.4. Whole-rock Sr-Nd isotopes

Sr-Nd isotopic data of the Shidao alkaline rocks are presented in Table S4. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and the $\epsilon_{\text{Nd}}(t)$ values are calculated at $t=210$ Ma. The alkaline rocks have very similar Nd and Sr isotopic ratios, although their geochemical compositions are obviously different. They have negative $\epsilon_{\text{Nd}}(t)$ values ranging from -18.6 to -15.0 and low radiogenic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.7058 and 0.7093 (Fig. 11), agreeing with previous studies (e.g., Gao et al., 2004; Yang et al., 2005; Chen and Jiang, 2011; Zhao et al., 2012). As illustrated in Fig. 11, these isotopic characteristics are similar to those of the granitic gneisses but are different from those of the eclogites in the Dabie-Sulu UHP terrane (calculated back to $t=210$ Ma) (e.g., Jahn, 1998; Li et al., 2000; Ma et al., 2000; Tang et al., 2008; Xu et al., 2008; Song et al., 2014a, b), suggesting that the alkaline rocks have a potential affinity with the felsic continental rocks.

<Figure 11>

5. Discussion

5.1. Tectonics: post-collisional setting

It is generally accepted that the Late Triassic alkaline magmatism in the Sulu UHP terrane was closely related to the continental collision. However, its tectonic setting was hotly debated. One view suggests that the Shidao alkaline rocks were

resulted from syn-collisional magmatism during subduction of continental crust (e.g., Chen et al., 2003; Gao et al., 2004; Guo et al., 2005). Another view argues that they were caused by post-collisional magmatism during exhumation of subducted continental crust, i.e., syn-exhumation magmatism (e.g., Yang et al., 2005; Chen and Jiang, 2011; Zhao et al., 2012). In this study, we agree with the latter that the Shidao alkaline rocks were generated under a post-collisional extensional setting.

The Shidao alkaline rocks, especially the more siliceous rocks (syenites and granites, $\text{SiO}_2 > 60$ wt.%), display characteristics of the A-type magmas as defined by Whalen et al. (1987) and Eby (1992). They have a characteristic mineralogy consisting of iron- and alkali-rich mafic silicates (Figs. 3A-D). They generally have an alkaline chemical affinity (Figs. 7A-B and 8A-B). Figure S2 in Appendix shows that the $\text{Fe}^\#$ values ($\text{Fe}^\# = \text{FeO}^{\text{T}} / (\text{FeO}^{\text{T}} + \text{MgO})$) increase with the SiO_2 contents, and the syenites and the granites have been plotted into area of the A-type granites. The high concentrations of Zr, Nb, Ce and Y distinguish the Shidao alkaline rocks from the I-, S- and M-type granites and classify them as an A-type granite on the $10000 \times \text{Ga}/\text{Al}$ versus $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (Fig. 12A), Zr (Fig. 12B), and Nb (Fig. 12C) discrimination diagrams (Whalen et al., 1987; Eby, 1992).

<Figure 12>

The A-type granitic magmas are emplaced in post-collisional or within plate settings, i.e., an extensional environment. (Whalen et al., 1987; Eby, 1992). Eby (1992) further divided the A-type granitoids into two types: the A1- and A2-type granitoids. The A1-type granites are associated with an anorogenic within-plate

setting, generally separated from periods of compressional tectonics by 50 to 100 Ma or more (e.g., Eby, 1992; Eby et al., 1995). In terms of trace elements, the A1-type granites have OIB-like signatures (e.g., Eby et al., 1995). However, the A2-type granites are often emplaced in a post-collisional or post-orogenic setting shortly (10-20 million years) after compressional tectonism (e.g., Eby, 1992; Eby et al., 1995; Bonin et al., 1998; Dahlquist et al., 2010). The A2-type granites have a variety of source signatures of both sub-continental lithosphere and crust (e.g., Dahlquist et al., 2010).

The Shidao alkaline rocks belong to the A2-type granites. First, the emplacement age of the Shidao alkaline complex ranges from 200 to 215 Ma (e.g., Guo et al., 2005; Chen and Jiang, 2011; Zhao et al., 2012; and this study). The UHP metamorphism and the amphibolite-facies retrogression occurred at 238 to 220 Ma and 218 to 205 Ma, respectively, in the Sulu UHP terrane (e.g., Liu et al., 2004, 2005, 2008a; Zheng, 2008; Zhang et al., 2009; Zong et al., 2010). This suggests that the Shidao alkaline rocks emplaced shortly ($\leq 10\text{-}20$ Ma) after the continental collision between the South China and the North China blocks. Second, the Yb/Ta versus Yb/Nb diagram (Figure S3 in Appendix) shows that the Shidao alkaline rocks plot into area of the A2-type granitoids. They display a trend extending from average continental crust to island-arc basalts (IAB) (Figure S3 in Appendix), suggesting that the sources of these alkaline rocks were related to an extensional setting after subduction or continent-continent collision. Third, they have characteristics of a sub-continental lithospheric mantle and crust in geochemistry (Tables S3-S4). Furthermore, the K-rich (shoshonitic to

ultrapotassic, Fig. 7A) magmas of the Shidao alkaline complex were derived from an enriched sub-continental lithospheric mantle or crustal source. They are distinguished from the anorogenic Na-rich granitoid suites derived from an OIB-type mantle source (e.g., Bonin et al., 1998).

5.2. Petrogenesis: crust-mantle interaction along continental subduction interface

Aqueous fluids are released from the subducting oceanic crust to metasomatize the overlying mantle wedge peridotite, resulting in syn-subduction arc magmatism (e.g., Tatsumi and Eggins, 1995; Schmidt, 1996; Schmidt and Poli, 1998). Zheng (2012) extended the geochemical recycling in oceanic subduction zones to all convergent plate margins. Melts from the exhumated continental crusts could also metasomatize the overlying mantle-wedge peridotite and produce arc-like magmatism. The Shidao alkaline complex is a typical pluton generated by crust-mantle interaction between melts from continental crust and mantle wedge in the continental subduction interface.

Melts from partial melting of the exhumated continental crust in the Sulu UHP terrane have been widely recognized as Pl-rich leucosomes (ca. 224 – 228 Ma; Chen et al., 2013a; Xu et al., 2013a, b), Kfs-rich pegmatitic veins (ca. 210 – 220 Ma; Wallis et al., 2005; Liu et al., 2010a, 2012; Chen et al., 2013b; Xu et al., 2013b; Song et al., 2014b), quartz pegmatitic veins (219 ± 2 Ma; Zong et al., 2010), and granitic dikes (219 ± 2 Ma; Liu et al., 2009). The formation ages of these melts are slightly earlier than or similar to the ages (ca. 215 – 200 Ma) of the Shidao alkaline complex (e.g.,

Guo et al., 2005; Chen and Jiang, 2011; Zhao et al., 2012; and this study). The timing suggests that it is possible that continental melts have metasomatized the overlying mantle-wedge peridotite and produced the alkaline rocks. Fig. 9 shows that the Shidao alkaline rocks have significant signatures of arc-like magmas such as enrichment in LILE and LREE and depletion in HFSE. Furthermore, their high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and negative $\epsilon_{\text{Nd}}(t)$ values (Fig. 11) suggest an enriched part of the lithosphere. Thus, we suppose that partial melting of the Sulu UHP slices during exhumation might have migrated significant amounts of K-rich felsic melts into the overlying mantle wedge and resulted in the Shidao alkaline complex.

With respect to the mechanism of crust-mantle interaction, the nature of involved crustal melts has been debated. Zhao et al. (2012) suggested that the melts were resulted from partial melting of both UHP eclogites and granitic gneisses. In this study, we propose that the melts were mostly resulted from partial melting of UHP granitic gneisses with negligible contribution of eclogites. Although evidence of partial melting such as multiphase solid inclusions in the minerals have been recognized in the Dabie-Sulu eclogites (e.g., Ferrando et al., 2005; Liu et al., 2013; Chen, 2014), several tiny felsic veins observed in the eclogites suggest a low degree partial melting (e.g., Wang et al., 2014). The eclogites are a small fraction in the UHP terrane occurring as lenses in the massive granitic gneisses (e.g., Liou et al., 2009; Zong et al., 2010; Xu et al., 2013a). Thus, low degree partial melting of the eclogites might not be able to produce enough melts to cause significant metasomatism. Furthermore, the Sr-Nd isotopic features of the eclogites in the Dabie-Sulu UHP

terrane do not match with that of the Shidao alkaline complex (Fig. 11). As for the granitic gneisses, they are the main part of the UHP terrane (e.g., Liou et al., 2009). A magmatic inherited core of zircon has been founded in the coarse-grained granite (Fig. 4G). The protolith zircon domain gives a Neoproterozoic U-Pb concordant age (Ca. 690 Ma) (Fig. 5G), which is consistent with previous studies on granitic gneisses in the Weihai-Rongcheng region (e.g., Wallis et al., 2005; Liu et al., 2010a; Zong et al., 2010; Xu et al., 2013a; Song et al., 2014a). This evidence indicates the origin of partial melting of granitic gneisses for the Shidao alkaline complex. They are migmatized due to strong anatexis, producing a mass of felsic melts as mentioned above (e.g., Wallis et al., 2005; Liu et al., 2010a, 2012; Zong et al., 2010; Chen et al., 2013a, b; Xu et al., 2013a, b; Song et al., 2014a, b). Magma mixing model shows that a large amount of crustal melts (~50-60 vol.%) are needed to produce the Shidao alkaline rocks (Fig. 11). Thus, partial melting of granitic gneisses can meet the demand better than the eclogites. In addition, the Sr-Nd isotopic features of the granitic gneisses and the felsic melts are consistent with those of the Shidao alkaline rocks (Fig. 11).

The involved mantle is the overlying sub-continental lithospheric mantle (SCLM) wedge of the North China Block (e.g., Zhao et al., 2012). However, the nature of the mantle is still unclear, especially for the explanation of the high-K (K_2O content up to 9.29 wt.%, Table S3) of the Shidao alkaline complex. As mentioned above, the hydrous melts from the exhumated continental crust are rich in K_2O and SiO_2 . The melts react with peridotite at the slab-mantle interface to form not only phlogopite but

also amphibole at the bottom of the mantle wedge. The melt-peridotite reaction at the slab-mantle interface in subduction channel is a feasible way to form phlogopite at the bottom of the mantle wedge (e.g., Zheng, 2012). Phlogopite is a common K-rich mineral in the mantle and its partial melting is capable of producing high-K melts (e.g., Sudo and Tatsumi, 1990). Notably, the gabbro and mafic enclaves in the Shidao alkaline complex have high Ba/Rb ratios (32.2 – 156.2) and low Rb/Sr ratios (0.03 – 0.09) (Table S3), suggesting an amphibole related melting in its mantle source because amphibole generally has higher $D_{Ba/Rb}$ value and lower $D_{Rb/Sr}$ value than those of phlogopite (e.g., Furman and Graham, 1999). So, the source of the Shidao alkaline complex is a K-rich and amphibole-bearing mantle. In addition, the tectonic affinity of the mantle source has also been debated. Yang et al. (2005) suggested that the mafic rocks (gabbros) of the Shidao alkaline complex were from partial melting of the South China lithospheric mantle and the felsic rocks (syenites and granites) of the Shidao alkaline complex were from partial melting of the lower crust of the South China Block. Zhao et al. (2012) suggested that the gabbros were generated by partial melting of the metasomatized SCLM of the North China Block and the felsic rocks were produced from partial melting of South China lower crust. In view of the similarity in trace element patterns (Fig. 9) and the homogeneity in Sr-Nd isotope compositions (Fig. 13) of the Shidao alkaline complex from the mafic to felsic rocks, we suggest that the Shidao alkaline rocks were from a common magma source which is the metasomatized SCLM of the North China Block.

Many lines of evidence indicate that partial melting of the subducted continental

crust during exhumation occurred at the HP eclogite-facies to granulite-facies conditions (e.g., Xu et al., 2013a, b) or even the initial exhumation stage at the UHP eclogite-facies conditions (e.g., Chen et al., 2013a, b, 2014). We suggest that the K-rich felsic melts metasomatized the overlying mantle wedge at the deep level of mantle wedge. In order to decipher the crust-mantle interaction, a two-component mixing model is selected to test the metasomatism. The granitic gneiss and the mantle wedge peridotite in the Dabie-Sulu UHP terrane are selected as hypothetical felsic and ultramafic end members, respectively, to simulate a possible metasomatism (Fig. 11). The mantle wedge peridotites in the Dabie-Sulu UHP terrane were widely reported (e.g., Yang and Jahn, 2000; Zhang et al., 2000; Xie et al., 2013 and references therein). Fig. 11 shows that most of the peridotites have been hybridized by crustal materials in some degrees and have negative $\epsilon_{\text{Nd}}(t)$ values (-4.9 to -8.2) and relatively high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7055 – 0.7089). Only few of them have positive $\epsilon_{\text{Nd}}(t)$ values (-1.8 to 2.9) and low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7036 – 0.7042), e.g., the Rizhao peridotites in the Sulu UHP terrane and the Bixiling lherzolites in the Dabie UHP terrane (Zhang et al., 2000). The Rizhao peridotites (type A peridotites) were derived from mantle wedge, however, the Bixiling peridotites (type B peridotites) are the ultramafic portions of crustal mafic-ultramafic complexes that were differentiated from mafic magma prior to continental subduction (e.g., Zhang and Liou, 1998; Zhang et al., 2000; Zhang et al., 2009). So, the Rizhao peridotites (initial $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.7037, $\epsilon_{\text{Nd}}(t)$ = 1.2) represent a “primitive” mantle wedge. As discussed above, the crustal melts were derived from partial melting of granitic gneisses. So, the granitic gneiss in the

Sulu UHP terrane is selected as the felsic end member. Sample 02SD41 (initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7143$, $\epsilon_{\text{Nd}}(t) = -21.0$) in the Weihai-Rongcheng region is a typical sample of granitic gneiss (Tang et al., 2008). Fig. 11 shows that the addition of ~50-60 % felsic melt to the mantle wedge might result in a K-rich and amphibole-bearing mantle. Partial melting of the metasomatized mantle could have generated the Shidao alkaline complex.

5.3. Magma evolution: fractional crystallization (FC)

Comagmatic mafic and felsic rocks are generally explained by magma mixing (e.g., Mingram et al., 2000; Xu et al., 2012b, 2014) or assimilation and fractional crystallization (AFC) (e.g., DePaolo, 1981; Marsh, 1989). Magma mixing and crustal AFC process should generate variable isotopic compositions and isotopic ratios (e.g., initial $^{87}\text{Sr}/^{86}\text{Sr}$ or $\epsilon_{\text{Nd}}(t)$) changing with certain elements (e.g., MgO or SiO_2). These features are not observed in the Shidao alkaline complex (Fig. 13). Thus, both magma mixing and crustal AFC can not explain the magma evolution of the Shidao alkaline complex. We suggest that FC process is a feasible mechanism for the explanation of the isotopic compositions and the geochemical characteristics of the Shidao alkaline complex, e.g., the homogeneous Sr-Nd isotopic compositions (Fig. 13), a progressive decrease in CaO, P_2O_5 , TiO_2 , $\text{Fe}_2\text{O}_3^{\text{T}}$, MgO, $(\text{La}/\text{Yb})_{\text{N}}$, Total REE, Sr, Ba, Ni and Cr and an increase in Rb with the SiO_2 contents (Figs. 8 and 10). The following evidence supports a FC process of parental magma in a closed system.

<Figure 13>

FC is the removal and segregation from a melt of mineral precipitates. Removal

of crystals changes the composition of the magma. Hence, the crystallization sequence is critical in understanding how melt compositions evolve. Field relationships clearly show that the gabbros and pyroxene syenites are in the central of the pluton, the hornblende syenites generally distribute symmetrically in the both sides of the pyroxene syenites, and then the quartz syenites and granites are subsequently intrusive (Figs. 1C and 2). Cumulatic textures also exist widely in the gabbro and pyroxene syenites (Figs. 2C and F). Furthermore, mineral compositions of rocks provide insights of the FC process as documented in the early 1900s by Bowen's reaction series, e.g., the dominated dark minerals are olivine, clinopyroxene, amphibole and biotite from the mafic to felsic rocks (Fig. 3). These strongly suggest a FC process in crystallization sequence.

With respect to the crystallization ages of the Shidao alkaline rocks, they gradually decrease from 214 ± 2 Ma to 200 ± 3 Ma with increasing SiO_2 contents (Fig. 14A). Although the weighted mean ages show a difference of more than 10 Ma between the gabbro and the fine-grained granite, there is a significant overlap between all of them when view all the age data as a whole (Fig. 14B). From the mafic to the felsic rocks, the mafic ones are slightly older than the felsic ones (Fig. 14B). Moreover, two inherited cores of zircons in the amphibole syenite are magmatic zircons (Fig. 4E). They give a concordant $^{206}\text{Pb}/^{238}\text{U}$ age of 220 ± 3 Ma (Fig. 5E) which is consistent with some spot ages recorded in the gabbro and pyroxene syenite, suggesting a successive growth around the pre-crystallized ones. These age data suggest not only a FC process but also duration of the cooling

crystallization of the Shidao alkaline complex. Meanwhile, the Th and U contents and the related Th/U ratios in zircons are obviously different from the mafic to the felsic rocks (Fig. 6). Zircons from the gabbro, mafic enclave and pyroxene syenite have high Th but low U (<1800 ppm) contents with high Th/U ratios. Zircons from the amphibole and quartz syenites have variable Th and U contents and variable Th/U ratios. However, zircons from the coarse- and fine-grained granites have relatively low Th and high U (> 2000 ppm) contents with low Th/U ratios. Fig. 6 also shows that the Th/U ratio decreases with the increase of the U content from the gabbro to the granite. This also suggests a FC process during magma evolution.

<Figure 14>

The major oxides (together with CIPW standard minerals) and trace elements are in agreement with a FC process of the Shidao alkaline complex. The contents of CaO, MgO, $\text{Fe}_2\text{O}_3^{\text{T}}$, Ni, and Cr decrease with increasing SiO_2 contents (Figs. 8D, G-H and 10G-H), suggesting a clinopyroxene- and olivine-dominated fractionation (Figs. 3A-D) in the early stage of magma evolution. This is supported by the diagrams of Cr versus Ni (Fig. 15A) and V (Fig. 15B). Their variations in the gabbros, mafic enclaves and pyroxene syenites are consistent with the fractionation of clinopyroxene and olivine. Figs. 15A and B also show that amphibole dominates the fractionation in the intermediate rocks, agreeing with the rock series of the Shidao alkaline complex that the amphibole syenites were crystallized after the pyroxene syenites (Figs. 2E and 5D-E). CIPW standard minerals show that the mafic rocks including gabbros and mafic enclaves have high normative clinopyroxene (up

to 49.2 %) and olive (up to 13.5 %) contents (Fig. 16A) (e.g., Gao et al., 2004; Yang et al., 2005; Chen and Jiang, 2011; Zhao et al., 2012; this study). With increasing SiO₂ contents, the contents of normative clinopyroxene and olive decrease (Fig. 16A). When normative olivine is absent, quartz occurs and its content increases from the syenite to the granite (Figs. 16A-B).

<Figure 15>

<Figure 16>

In contrast to the CaO contents that decrease with increasing SiO₂ contents (Fig. 8D), the contents of Na₂O, K₂O and Al₂O₃ increase from the gabbro to the quartz syenite but decrease roughly from the quartz syenite to the granite (Figs. 8A-C). It's because anorthite continuously crystallize and fractionate from the magma (Fig. 16D). Meanwhile, orthoclase and albite increase with increasing SiO₂ contents (up to ~65 wt.%) (Fig. 16C). When the residue magma is rich in SiO₂, the contents of orthoclase and albite also decrease (Fig. 16C). Feldspar fractionation corresponds to significant depletions in Sr, Ba and Eu of some syenites (e.g., the quartz syenites) and the granites (Figs. 9C-F). Negative Eu anomalies (Figs. 9C and E) combined with decreases in Ba and Sr (Figs. 9D and F) of the felsic rocks indicate that alkali feldspar and plagioclase have been removed during magma evolution (e.g., Yang et al., 2005). The diagrams of Rb/Sr and Ba versus Sr (Figs. 17 A-B) further indicate that the decrease in Ba and Sr and the increase in Rb/Sr ratios are resulted from fractionation of alkali feldspar and plagioclase with biotite. It suggests that plagioclase and alkali feldspar dominate fractionation in the late stage of magma

evolution.

<Figure 17>

6. Concluding remarks and model hypothesis

The Shidao complexes are composed of gabbros, pegmatitic and coarse-grained pyroxene syenites, amphibole syenites, biotite quartz syenites, coarse- and fine-grained granites. The crystallization ages successively decrease from the mafic to the felsic rocks, corresponding to their emplacement sequences. The Shidao complexes are alkaline rocks with a wide span of SiO₂ content (49.7 – 76.7 wt.%) and high K₂O contents (up to 9.3 wt.%). They are characterized by arc-like patterns of REE and trace element distribution. The alkaline rocks have similarly high initial ⁸⁷Sr/⁸⁶Sr ratios and negative ε_{Nd}(t) values. Meanwhile, the alkaline rocks with high SiO₂ contents display features of the A2-type granitoids. Thus, the Shidao alkaline complex is the product of post-collisional magmatism during the Late Triassic exhumation of the Sulu UHP terrane and the initial magma subsequently experienced a FC process during magma evolution to produce the variable alkaline rocks.

The evolutionary scenario of the Sulu orogen can be briefly illustrated by a model shown in Fig. 18. Subduction of the South China Block beneath the North China Block resulted in continent-continent collision and HP/UHP metamorphism (Fig. 18A). Unlike the oceanic subduction zone, the continental subduction was absent of arc-type magmatism. Due to the break-off of eclogitized oceanic lithosphere at the transition between the continental and oceanic lithospheres, the subducted

continental lithosphere ceased to descend further and was rising with buoyancy. The exhumation of the deeply subducted continental crust resulted in decompressional dehydration and partial melting of the UHP metamorphic slices to generate aqueous felsic melts. The felsic melts reacted with the overlying mantle wedge to cause a metasomatized mantle (Fig. 18B). Partial melting of the metasomatic mantle wedge could generate post-collisional or syn-exhumation arc-like magmatism (i.e., the Shidao alkaline complex) (Fig. 18C). The alkaline magmatism experienced a successive FC process dominated by olivine, clinopyroxene, plagioclase and alkali feldspar during its rising and emplacement.

<Figure 18>

Acknowledgements

This research was supported by State Key Development Program for Basic Research of China (Grant No. 2015CB856101), the National Science Foundation of China (No. 41372076 and 41072046) and the Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan) (No. CUG140501). Constructive comments from Dr. Yixiang Chen and another anonymous reviewer improved the manuscript significantly. We thank Prof. Zeming Zhang for editorial handling. We thank Prof. Zhaochu Hu in China University of Geosciences (Wuhan) for his help with the LA-ICPMS zircon U-Pb dating. Dr. Zhuyin Chu in the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS) is also thanked for the help with the Sr-Nd isotopic analyses.

References

- Auzanneau, E., Vielzeuf, D., Schmidt, M.W., 2006. Experimental evidence of decompression melting during exhumation of subducted continental crust. *Contributions to Mineralogy and Petrology* 152, 125-148.
- Banno, S., Enami, M., Hirajima, T., Ishiwatari, A., Wang, Q.C., 2000. Decompression P-T path of coesite eclogite to granulite from Weihai, eastern China. *Lithos* 52, 97-108.
- Bonin, B., Azzouni-Sekkal, A., Bussy, F., Ferrag, S., 1998. Alkali-calcic and alkaline post-orogenic (PO) granite magmatism: petrologic constraints and geodynamic settings. *Lithos* 45, 45-70.
- Brown, P.E., Becker, S.M., 1986. Fractionation, hybridisation and magma-mixing in the Kialineq centre East Greenland. *Contributions to Mineralogy and Petrology* 92, 57-70.
- Chen, F., Hegner, E., Todt, W., 2000. Zircon ages, Nd isotopic and chemical compositions of orthogneisses from the Black Forest, Germany - evidence for a Cambrian magmatic arc. *International Journal of Earth Sciences* 88, 791-802.
- Chen, J.F., Xie, Z., Li, H.M., Zhang, X.D., Zhou, T.X., Park, Y.S., Ahn, K.S., Chen, D.G., Zhang, X., 2003. U-Pb zircon ages for a collision-related K-rich complex at Shidao in the Sulu ultrahigh pressure terrane, China. *Geochemical Journal* 37, 35-46.
- Chen, J.Z., Jiang, N., 2011. Petrogenesis of the Late-Triassic alkaline magmatism in the Jiaodong area: evidence from U-Pb age, Hf-O isotopes of zircons. *Acta*

Petrologica Sinica 27(12), 3557-3574 (Chinese with English abstract).

Chen, Y.X., Zheng, Y.F., and Hu, Z.C., 2013a. Synexhumation anatexis of ultrahigh-pressure metamorphic rocks: Petrological evidence from granitic gneiss in the Sulu orogen: *Lithos* 156-159, 69-96.

Chen, Y.X., Zheng, Y.F., Hu, Z.C., 2013b. Petrological and zircon evidence for anatexis of UHP quartzite during continental collision in the Sulu orogen: *Journal of Metamorphic Geology* 31, 389-413.

Chen, Y.X., Zheng, Y.F., Gao, X.Y., Hu, Z.C., 2014. Multiphase solid inclusions in zoisite-bearing eclogite: evidence for partial melting of ultrahigh-pressure metamorphic rocks during continental collision. *Lithos* 200-201, 1-21.

Cong, B.L., 1996. Ultrahigh-Pressure Metamorphic Rocks in the Dabieshan-Sulu Region of China. Science Press, Beijing, p. 224.

Dahlquist, J.A., Alasino, P.H., Eby, G.N., Galindo, C., Casquet, C., 2010. Fault controlled Carboniferous A-type magmatism in the proto-Andean foreland (Sierras Pampeanas, Argentina): Geochemical constraints and petrogenesis. *Lithos* 115(1-4), 65-81.

DePaolo, D.J., 1981. Trace element and isotopic effects of combined wallrock assimilation and fractionation crystallization. *Earth and Planetary Science Letters* 53, 189-202.

Eby, G.N., 1992. Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. *Geology* 20, 641-644.

Eby, G.N., Roden-Tice, M., Krueger, H.L., Ewing, W., Faxon, E.H., Woolley, A.R.,

1995. Geochronology and cooling history of the northern part of the Chilwa Alkaline Province, Malawi. *Journal of African Earth Sciences* 20 (3-4), 275-288.
- Ernst, W.G., 1999. H₂O and ultrahigh-pressure subsolidous phase relations for mafic and ultramafic systems. *International Geology Review* 41, 886-894.
- Ferrando, S., Frezzotti, M.L., Dallai, L., Compagnoni, R., 2005. Multiphase solid inclusions in UHP rocks (Su-Lu, China): Remnants of supercritical silicate-rich aqueous fluids released during continental subduction. *Chemical Geology* 223, 68-81.
- Furman, T., Graham, D., 1999. Erosion of lithospheric mantle beneath the East African Rift system: geochemical evidence from the Kivu volcanic province. *Lithos* 48, 237-262.
- Gao, T.S., Chen, J.F., Xie, Z., Qian, H., 2004. Geochemistry of Triassic igneous complex in the Sulu UHP metamorphic belt. *Acta Petrologica Sinica* 20(5), 1025-1038 (Chinese with English abstract).
- Guo, J.H., Chen, F.K., Zhang, X.M., Siebel, W., Zhai, M.G., 2005. Evolution of syn- to post-collisional magmatism from north Sulu UHP belt, eastern China: zircon U-Pb geochronology. *Acta Petrologica Sinica* 21(4), 1281-1301 (Chinese with English abstract).
- Hermann, J., Spandler, C., Hack, A., Korsakov, A.V., 2006. Aqueous fluids and hydrous melts in high-pressure and ultra-high pressure rocks: Implications for element transfer in subduction zones. *Lithos* 92, 399-417.

- Hu, Z.C., Gao, S., Liu, Y.S., Hu, S.H., Chen, H.H., Yuan, H.L., 2008. Signal enhancement in laser ablation ICP-MS by addition of nitrogen in the central channel gas. *Journal of Analytical Atomic Spectrometry* 23, 1093-1101.
- Jahn, B.M., 1998. Geochemical and isotopic characteristics of UHP eclogites and ultramafic rocks of the Dabie orogen: implications for continental subduction and collisional tectonics. In: Hacker, B.R., Liou, J.G. (Eds.), *When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-pressure Rocks*. Kluwer Academic Publishers, Dordrecht, p. 203-239.
- Le Maitre R.W., Bateman, P., Dudek, A., Keller, J., Lameyre Le Bas, M.J., Sabine, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Woolley, A.R., Zanettin, B., 1989. *A classification of igneous rocks and glossary of terms*. Blackwell, Oxford.
- Li, S.G., Jagoutz, E., Chen, Y.Z., Li, Q.L., 2000. Sm-Nd and Rb-Sr isotopic chronology and cooling history of ultrahigh pressure metamorphic rocks and their country rocks at Shuanghe in the Dabie Mountains, Central China. *Geochimica et Cosmochimica Acta* 64 (6), 1077-1093.
- Liou, J.G., Ernst, W.G., Zhang, R.Y., Tsujimori, T., Jahn, B.M., 2009. Ultrahigh-pressure minerals and metamorphic terranes — the view from China. *Journal of Asian Earth Sciences* 35 (3-4), 199-231.
- Liou, J.G., Zhang, R.Y., Ernst, W.G., 1997. Lack of fluid during ultrahigh-P metamorphism in the Dabie-Sulu region, Eastern China: Proceedings of the International Geological Congress 17, 141-155.

- Liu, F.L., Gerdes, A., Liou, J.G., Xue, H.M., Liang, F.H., 2006. SHRIMP U-Pb zircon dating from Sulu-Dabie dolomitic marble, South China: constraints on prograde, ultrahigh-pressure and retrograde metamorphic ages. *Journal of Metamorphic Geology* 24, 569-589.
- Liu, F.L., Gerdes, A., Zeng, L.S., Xue, H.M., 2008a. SHRIMP U-Pb dating, trace elements and the Lu-Hf isotope system of coesite-bearing zircon from amphibolite in the SW Sulu UHP terrane, eastern China. *Geochimica et Cosmochimica Acta* 72, 2973-3000.
- Liu, F.L., Liou, J.G., Xu, Z.Q., 2005. U-Pb SHRIMP ages recorded in the coesite-bearing zircon domains of paragneisses in the southwestern Sulu terrane, eastern China: New interpretation. *American Mineralogist* 90, 790-800.
- Liu, F.L., Robinson, P.T., Gerdes, A., Xue, H.M., Liu, P.H., Liou, J.G., 2010a. Zircon U-Pb ages, REE concentrations and Hf isotope compositions of granitic leucosome and pegmatite from the north Sulu UHP terrane in China: Constraints on the timing and nature of partial melting. *Lithos* 117, 247-268.
- Liu, F.L., Robinson, P.T., Liu, P.H., 2012. Multiple partial melting events in the Sulu UHP terrane: zircon U-Pb dating of granitic leucosomes within amphibolite and gneiss. *Journal of Metamorphic Geology* 30, 887-906.
- Liu, F.L., Xu, Z.Q., Liou J.G., Song, B., 2004. SHRIMP U-Pb ages of ultrahigh-pressure and retrograde metamorphism of gneisses, south-western Sulu terrane, eastern China. *Journal of Metamorphic Geology* 22, 315-326.
- Liu, F.L., Xue, H.M., Liu, P.H., 2009. Partial melting time of ultrahigh-pressure

- metamorphic rocks in the Sulu UHP terrane: constrained by zircon U-Pb ages, trace elements and Lu-Hf isotope compositions of biotite-bearing granite. *Acta Petrologica Sinica* 25 (5), 1039-1055 (in Chinese with English abstract).
- Liu, Q., Hermann, J., Zhang, J.F., 2013. Polyphase inclusions in the Shuanghe UHP eclogites formed by subsolidus transformation and incipient melting during exhumation of deeply subducted crust. *Lithos* 177, 91-109.
- Liu, Y.S., Gao, S., Hu, Z.C., Gao, C.G., Zong, K.Q., Wang, D.B., 2010b. Continental and oceanic crust recycling-induced melt-peridotite interactions in the Trans-North China Orogen: U-Pb dating, Hf isotopes and trace elements in zircons of mantle xenoliths. *Journal of Petrology* 51, 537-571.
- Liu, Y.S., Hu, Z.C., Gao, S., Günther, D., Xu, J., Gao, C.G., Chen, H.H., 2008b. In situ analysis of major and trace elements of anhydrous minerals by LA-ICP-MS without applying an internal standard. *Chemical Geology* 257, 34-43.
- Litvinovsky, B.A., Jahn, B.M., Zandievich, A.N., Shadaev, M.G., 2002. Crystal fractionation in the petrogenesis of an alkali monzodiorite-syenite series: the Oshurkovo plutonic sheeted complex, Transbaikalia, Russia. *Lithos* 64, 97-130.
- Lubala, R.T., Frick, C., Roders, J.H., Walraven, F., 1994. Petrogenesis of syenites and granites of the Schiel Alkaline complex, Northern Transvaal. *South African Journal of Geology* 102, 307-309.
- Ludwig, K.R., 2001. Isoplot/Ex, rev. 2.49: A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronological Center, Special Publication No. 1a, 58.
- Ludwig, K.R., 2003. ISOPLOT 3.00: A Geochronological Toolkit for Microsoft

Excel. Berkeley: Berkeley Geochronology Center, California.

Ma, C.Q., Ehlers, C., Xu, C.H., Li, Z.C., Yang, K.G., 2000. The roots of the Dabieshan ultrahigh-pressure metamorphic terrane: constraints from geochemistry and NdSr isotope systematics. *Precambrian Research* 102, 279-301.

Ma, Q., Zheng, J.P., Griffin, W.L., Zhang, M., Tang, H.Y., Su, Y.P., Ping, X.Q., 2012. Triassic “adakitic” rocks in an extensional setting (North China): Melts from the cratonic lower crust. *Lithos* 149, 159-173.

Marsh, J.S., 1989. Geochemical constraints on coupled assimilation and fractional crystallization involving upper crustal compositions and continental tholeiitic magma. *Earth and Planetary Science Letters* 92, 78-80.

Middlemost, E.A.K., 1972. A simple classification of volcanic rocks. *Bulletin of Volcanology* 36, 382-397.

Middlemost, E.A.K., 1994. Naming materials in the magma/igneous rock system. *Earth-Science Reviews* 74, 193-227.

Mingram, B., Trumbull, R.B., Littman, S., Gertenberger, H., 2000. A petrogenetic study of anorogenic felsic magmatism in the Cretaceous Paresis ring complex, Namibia: evidence for mixing of crust and mantle-derived components. *Lithos* 54, 1-22.

Nakamura, D., Hirajima, T., 2000. Granulite-facies overprinting of ultrahigh-pressure metamorphic rocks, northeastern Sulu region, Eastern China. *Journal of Petrology* 4, 563-582.

- Rubatto, D., 2002. Zircon trace element geochemistry: partitioning with garnet and the link between U-Pb ages and metamorphism. *Chemical Geology* 184, 123-138.
- Schmidt, M.W., 1996. Experimental constraints on recycling of potassium from subducted oceanic crust. *Science* 272, 1927-1930.
- Schmidt, M.W., Poli, S., 1998. Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation. *Earth and Planetary Science Letters* 163, 361-379.
- Schmidt, M.W., Poli, S., 1998. Experimentally based water budgets for dehydration slabs and consequences for arc magma generation. *Earth and Planetary Science Letters*, 163: 361-379.
- Sheppard, S., 1995. Hybridization of shoshonitic lamprophyre and calc-alkaline granite magma in the Early Proterozoic Mt. Bundey igneous suite, Northern Territory. *Australian Journal of Earth Sciences* 42, 173-185.
- Song, Y.R., Xu, H.J., Zhang, J.F., Wang, D.Y., Liu, E.D., 2014a. Syn-exhumation partial melting and melt segregation in the Sulu UHP terrane: Evidences from leucosome and pegmatitic vein of migmatite. *Lithos* 202-203, 55-75.
- Song, Y.R., Xu, H.J., Zhang, J.F., Wang, D.Y., Liu, E.D., 2014b. Effects of melt fractional crystallization on Sr-Nd and Lu-Hf isotope systems: a case study of Triassic migmatite in the Sulu UHP terrane. *International Geology Review* 56(7), 783-800.
- Sudo, A., Tatsumi, Y., 1990. Phlogopite and K-amphibole in the upper mantle:

Implication for magma genesis in subduction zones. *Geophysical Research Letters* 17(1), 29-32.

Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), *Implications for Mantle Composition and Processes, Magmatism in the Ocean Basins*. Geological Society, London 42, 313-345.

Sutcliffe, R.H., Smith, A.R., Doherty, W., Barnett, R.L., 1990. Mantle derivation of Archean amphibole-bearing granitoids and associated mafic rocks: evidence from the southern Superior Province, Canada. *Contributions to Mineralogy and Petrology* 105, 255-274.

Tang, J., Zheng, Y.F., Wu, Y.B., Gong, B., Zha, X.P., Liu, X.M., 2008. Zircon U-Pb age and geochemical constraints on the tectonic affinity of the Jiaodong terrane in the Sulu orogen, China. *Precambrian Research* 161, 389-418.

Tatsumi, Y., Eggins, S., 1995. *Subduction Zone Magmatism*. Blackwell Science, Oxford, p. 211.

Wallis, S., Tsuboi, M., Suzuki, K., Fanning, M., Jiang, L.L., Tanaka, T., 2005. Role of partial melting in the evolution of the Sulu (eastern China) ultrahigh-pressure terrane. *Geology* 33(2), 129-132.

Wang, L., Kusky, T.M., Polat, A., Wang, S.J., Jiang, X.F., Zong, K.Q., Wang, J.P., Deng, H., Fu, J.M., 2014. Partial melting of deeply subducted eclogite from the Sulu orogen in China. *Nature Communications*, DOI: 10.1038/ncomms6604.

Wang, Q., Ishiwatari, A., Zhao, Z.Y., Hirajima, T., Hiramatsu, N., Enami, M., Zhai,

- M., Li, J., Cong, B., 1993. Coesite-bearing granulite retrograded from eclogite in Weihai, eastern China. *European Journal of Mineralogy* 5, 141-151.
- Wang, X.M., Liou, J.G., Mao, H.K., 1989. Coesite-bearing eclogites from the Dabie Mountains in central China. *Geology* 17, 1085-1088.
- Whalen, J.B., Currie, K.L., Chapell, B.W., 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* 95, 407-419.
- Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Quadt, A.V., Roddick, J.C., Spiegel, W., 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostandards and Geoanalytical Research* 19, 1-23.
- Wu, Y.B., Zheng, Y.F., Zhao, Z.F., Gong, B., Liu, X.M., Wu, F.Y., 2006. U-Pb, Hf and O isotope evidence for two episodes of fluid-assisted zircon growth in marble-hosted eclogites from the Dabie orogen. *Geochimica et Cosmochimica Acta* 70, 3743-3761.
- Xie, Z.P., Hattori, K., Wang, J., 2013. Origins of ultramafic rocks in the Sulu Ultrahigh-pressure Terrane, Eastern China. *Lithos* 178, 158-170.
- Xu, H.J., Ma, C.Q., Ye, K., 2007. Early Cretaceous granitoids and their implications for Collapse of the Dabie orogen, eastern China: SHRIMP zircon U-Pb dating and geochemistry. *Chemical Geology* 240, 238-259.
- Xu, H.J., Ma, C.Q., Zhang, J.F., 2012b. Generation of Early Cretaceous high-Mg adakitic host and enclaves by magma mixing, Dabie orogen, Eastern China.

Lithos 142-143, 182-200.

Xu, H.J., Ma, C.Q., Zhao, J.H., Zhang, J.F., 2014. Magma mixing generated Triassic I-type granites in South China. *Journal of Geology* 122, 329-351.

Xu, H.J., Song, Y.R., Ye, K., 2013b. Partial melting time of the Sulu UHP terrane: constraints from zircon U-Pb age, trace element and Lu-Hf isotope composition of leucosome in Rongcheng granitic gneiss. *Acta Petrologica Sinica* 29(5), 1594-1606 (in Chinese with English abstract).

Xu, H.J., Ye, K., Ma, C.Q., 2008. Early Cretaceous granitoids in the North Dabie and their tectonic implications: Sr-Nd and zircon Hf isotopic evidences. *Acta Petrologica Sinica* 24 (1), 87-103 (In Chinese with English abstract).

Xu, H.J., Ye, K., Song, Y.R., Chen, Y., Zhang, J.F., Liu, Q., Guo, S., 2013a. Prograde metamorphism, decompressional partial melting and subsequent melt crystallization and segregation in the Weihai migmatitic gneisses, Sulu UHP terrane, Eastern China. *Chemical Geology* 341, 16-37.

Xu, H.J., Ye, K., Zhang, J.F., 2012a. Temperature of prograde metamorphism, decompressional partial melting and subsequent melt fractional crystallization in the Weihai migmatitic gneisses, Sulu UHP terrane: constraints from Ti-in-zircon thermometer. *Journal of Earth Science* 23(6), 813-827.

Xu, S.T., Liu, Y.C., Chen, G.B., Roberto, C., Franco, R., He, M.C., Liu, H.F., 2003. New finding of microdiamonds in eclogites from Dabie-Sulu region in central-eastern China. *Chinese Science Bulletin* 48, 988-994.

Xu, S.T., Okay, A.I., Ji, S.Y., Sengor, A.M.C., Su, W., Liu, Y.C., Jiang, L.L., 1992.

Diamond from the Dabie Shan metamorphic rocks and its implication for tectonic setting. *Science* 256, 80-82.

Yang, J.H., Chung, S.L., Wilde, S.A., Wu, F.Y., Chu, M.F., Lo, C.H., Fan, H.R., 2005.

Petrogenesis of post-orogenic syenites in the Sulu Orogenic Belt, East China: geochronological, geochemical and Nd-Sr isotopic evidence. *Chemical Geology* 214, 99-125.

Yang, J.J., Jahn, B.M., 2000. Deep subduction of mantle-derived garnet peridotites from the Su-Lu UHP metamorphic terrane in China. *Journal of metamorphic Geology* 18, 167-180.

Yang, J.S., Wooden, J.L., Wu, C.L., 2003. SHRIMP U-Pb dating of coesite-bearing zircon from the ultrahigh-pressure metamorphic rocks, Sulu terrane, east China. *Journal of Metamorphic Geology* 21, 551-560

Yang, K.F., Fan, H.R., Santosh, M., Hu, F.F., Wilde, S.A., Lan, T.G., Lu, L.N., Liu, Y.S., 2012. Reactivation of the Archean lower crust: Implications for zircon geochronology, elemental and Sr-Nd-Hf isotopic geochemistry of late Mesozoic granitoids from northwestern Jiaodong Terrane, the North China Craton. *Lithos* 146-147, 112-127.

Ye, K., Cong, B.L., Ye, D.N., 2000b. The possible subduction of continental material to depths greater than 200 km. *Nature* 407, 734-736.

Ye, K., Yao, Y.P., Katayama, I., Cong, B.L., Wang, Q.C., Maruyama, S., 2000a. Large areal extent of ultrahigh-pressure metamorphism in the Sulu ultrahigh-pressure terrane of East China: new implications from coesite and omphacite inclusions

- in zircon of granitic gneiss. *Lithos* 52, 157-164.
- Zhang, J., Zhao, Z.F., Zheng, Y.F., Dai, M.N., 2010. Postcollisional magmatism: Geochemical constraints on the petrogenesis of Mesozoic granitoids in the Sulu orogen, China. *Lithos* 119, 512-536.
- Zhang, J., Zhao, Z.F., Zheng, Y.F., Liu, X.M., Xie, L.W., 2012. Zircon Hf-O isotope and whole-rock geochemical constraints on origin of postcollisional mafic to felsic dykes in the Sulu orogen. *Lithos* 136-139, 225-245.
- Zhang, R.Y., Liou, J.G., 1998. Dual origin of garnet peridotites of Dabie-Sulu UHP terrane, eastern-central China. *Episodes* 21, 229-234.
- Zhang, R.Y., Liou, J.G., Yang, J.S., Yui, T.F., 2000. Petrochemical constraints for dual origin of garnet peridotites from the Dabie-Sulu UHP terrane, eastern-central China. *Journal of metamorphic Geology* 18, 149-166.
- Zhang, R.Y., Liou, J.G., Ernst, W.G., 2009. The Dabie-Sulu continental collision zone: A comprehensive review. *Gondwana Research* 16, 1-29.
- Zhang, Z.M., Shen, K., Wang, J.L., Dong, H.L., 2009. Petrological and geochronological constraints on the formation, subduction and exhumation of the continental crust in the southern Sulu orogen, eastern-central China. *Tectonophysics* 475(2), 291-307.
- Zhang, Z.M., Xiao, Y.L., Liu, F.L., Liou, J.G., Hoefs, J., 2005. Petrogenesis of UHP metamorphic rocks from Qinglongshan, southern Sulu, east-central China. *Lithos* 81, 189-207.
- Zhao, J.X., Shiraishi, K., Ellis, D.J., Sheraton, J.W., 1995. Geochemical and isotopic

studies of syenites from the Yamoto Mountains, East Antarctica: implication for the origin of syenitic magmas. *Geochimica et Cosmochimica Acta* 59, 1363-1385.

Zhao, Z.F., Zheng, Y.F., Zhang, J., Dai, L.Q., Liu, X.M. 2012. Syn-exhumation magmatism during continental collision: Evidence from alkaline intrusives of Triassic age in the Sulu orogen. *Chemical Geology* 328, 70-88.

Zhao, Z.F., Dai, L.Q., Zheng, Y.F., 2013. Postcollisional mafic igneous rocks record crust-mantle interaction during continental deep subduction. *Scientific Reports* 3, 3413; doi:10.1038/srep03413.

Zheng, Y.F., Fu, B., Gong, B., Li L., 2003. Stable isotope geochemistry of ultrahigh pressure metamorphic rocks from the Dabie-Sulu orogen in China: Implications for geodynamics and fluid regime. *Earth-Science Reviews* 62, 105-161.

Zheng, Y.F., 2008. A perspective view on ultrahigh-pressure metamorphism and continental collision in the Dabie-Sulu orogenic belt. *Chinese Science Bulletin* 53(20), 3081-3104.

Zheng, Y.F., 2012. Metamorphic chemical geodynamics in continental subduction zones. *Chemical Geology* 328, 5-48.

Zheng, Y.F., Xia, Q.X., Chen, R.X., Gao, X.Y., 2011. Partial melting, fluid supercriticality and element mobility in ultrahigh-pressure metamorphic rocks during continental collision. *Earth-Science Reviews* 107, 342-374.

Zong, K.Q., Liu, Y.S., Hu, Z.C., Kusky, T., Wang, D.B., Gao, C.G., Gao, S., Wang, J.Q., 2010. Melting-induced fluid flow during exhumation of gneisses of the

Figure captions

Fig. 1. (A) Sketch map of the Dabie-Sulu orogen. (B) Geological map of the Sulu orogen in the eastern China (modified after Ye et al., 2000a). WQF = Wulian-Qingdao Fault; QYF = Qingdao-Yantai Fault; MF = Mishan Fault. (C) Geological map of the Shidao alkaline complex in the Sulu ultra-high pressure (UHP) terrane (modified after Chen et al., 2005). The green dashed line marks an approximate boundary between the coarse- and the fine-grained granites.

Fig. 2. Field photos show magmatic sequences of the Shidao alkaline complex from early to late: gabbro, pyroxene syenite, amphibole syenite, quartz syenite, coarse- and fine-grained granites. (A-B) The gabbro is intruded by the quartz syenite; (C) “Layered” mafic microgranular enclave (MME) or xenolith in the pyroxene syenite; (D) A fusiform MME exhibiting a semi-plastic state in the pyroxene syenite; (E) The pyroxene syenite is intruded by the amphibole syenite, and both of them are subsequently intruded by the quartz syenite; (F) The pegmatitic pyroxene syenite is the local enlargement of (E); (G) The quartz syenite is intruded by the granite; and (H) The coarse-grained granite is intruded by the fine-grained granite.

Fig. 3. Photomicrographs (perpendicular polarized light) show textures and mineral assemblages of the Shidao alkaline rocks. (A) Gabbro (sample 12-XH-02E); (B)

Mafic enclave containing poikilitic olivine (sample 12-DS-01B); (C) Pyroxene syenite with pegmatitic feldspar (sample 12-DS-09); (D) Pyroxene syenite with a coarse-grained texture (12-JZS-03); (E) Amphibole syenite (sample 12-DS-10); (F) Quartz syenite (sample 12-JZS-02); (G) Coarse-grained Granite (sample 12-CS-03); and (H) Fine-grained granite (sample 12-CS-02). Abbreviation: Ol = olivine, Di = diopside, Am = amphibole, Bt = biotite, Pl = plagioclase, Kfs = K-feldspar, Qtz = quartz, Ap = apatite, Ne = nepheline, Mm = metallic mineral.

Fig. 4. Representative zircon CL images for the Shidao alkaline complex. Circles denote the analytical spots with LA-ICPMS zircon U-Pb ages. (A) Gabbro; (B) Mafic enclave; (C) Pegmatitic pyroxene syenite; (D) Coarse-grained pyroxene syenite; (E) Amphibole syenite; (F) Biotite quartz syenite; (G) Coarse-grained granite; and (H) Fine-grained granite.

Fig. 5. Concordia diagrams of LA-ICPMS zircon U-Pb ages for the Shidao alkaline complex. (A) Gabbro; (B) Mafic enclave; (C) Pegmatitic pyroxene syenite; (D) Coarse-grained pyroxene syenite; (E) Amphibole syenite; (F) Biotite quartz syenite; (G) Coarse-grained granite; and (H) Fine-grained granite.

Fig. 6. Diagram of zircon Th/U versus U showing magmatic evolution array for the Shidao alkaline complex.

Fig. 7. (A) K_2O versus Na_2O diagram (after Middlemost, 1972) showing the Shidao alkaline complex is shoshonitic and ultrapotassic. (B) Total alkalis-silica (TAS) diagram (after Le Maitre et al., 1989). The dashed thick line shows approximate the alkaline-subalkaline boundary after Middlemost (1994). The published data of the Shidao alkaline complex are from Gao et al. (2004), Yang et al. (2005), Chen and Jiang (2011), and Zhao et al. (2012).

Fig. 8. Plots of SiO_2 versus various major oxides (A-H) for the Shidao alkaline complex. The referenced data are from the same data sources as in Fig. 7.

Fig. 9. Diagrams of chondrite normalized REE patterns (A, C, and E) and primitive mantle normalized trace elements patterns (B, D, and F) of the Shidao alkaline complex. Values of the chondrite and the primitive mantle are from Sun and McDonough (1989). The cited data are from the same data sources as in Fig. 7.

Fig. 10. Plots of SiO_2 versus various selected trace elements Rb (A), Sr (B), Ba (C), Eu (D), Ni (E), and Cr (F) for the Shidao alkaline complex. The referenced data are from the same data sources as in Fig. 7.

Fig. 11. Sr and Nd isotopic compositions of the Shidao alkaline complex. Initial Sr and Nd isotopic ratios were calculated at 210 Ma. Data sources: the referenced Shidao alkaline rocks are from Gao et al. (2004), Yang et al. (2005), Chen and Jiang (2011)

and Zhao et al. (2012); eclogites and granitic gneisses in the Dabie-Sulu UHP terrane are from Jahn (1998), Li et al. (2000), Ma et al. (2000), Tang et al. (2008), Xu et al. (2008) and Song et al. (2014a); and mantle wedge peridotites in Dabie-Sulu HUP terrane are from Yang and Jahn (2000), Zhang et al. (2000) and references therein.

Fig. 12. (A) $\text{Na}_2\text{O}+\text{K}_2\text{O}$, (B) Zr, and (C) Nb versus $10000\text{Ga}/\text{Al}$ discrimination diagrams showing that the Shidao alkaline rocks are A-type granites after Whalen et al. (1987) and Eby (1992), I=I-type, S=S-type and M=M-type granitoids.

Fig. 13. (A-B) SiO_2 versus initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $\epsilon_{\text{Nd}}(t)$, and (C-D) MgO versus initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $\epsilon_{\text{Nd}}(t)$ diagrams of the Shidao alkaline complex in the Sulu UHP terrane. FC: fractional crystallization, and AFC: assimilation and fractional crystallization. The Shidao alkaline rocks are from Gao et al. (2004), Yang et al. (2005), Chen and Jiang (2011), Zhao et al. (2012), and this study.

Fig. 14. (A) Age versus SiO_2 diagram showing a magmatic evolution with time; (B) Zircon crystallization ages of the Shidao alkaline complex.

Fig. 15. (A) Ni and (B) V versus Cr diagrams showing clinopyroxene- and hornblende- dominated fractionation in the evolution of parental magmas to the Shidao alkaline complex (after Yang et al., 2005).

Fig. 16. CIPW standard minerals versus SiO_2 (wt.%) diagrams showing a FC process

during evolution of the Shidao parental magmas. (A) olivine and clinopyroxene, (B) quartz, (C) orthoclase + albite, and (D) anorthite.

Fig. 17. Rb/Sr (A) and Ba (B) versus Sr diagrams showing plagioclase-, K-feldspar-, and biotite-dominated fractionation in the evolution of the Shidao alkaline complex (after Yang et al., 2005).

Fig. 18. Schematic diagrams showing evolution of the Sulu continental collision orogen (modified after Zheng et al., 2012). (A) Subduction of the South China Block beneath the North China Block, resulting in continent-continent collision and HP/UHP metamorphism. (B) Exhumation of the deeply subducted continental crust due to slab break-off at the transition between the continental and oceanic lithospheres, resulting in decompressional partial melting of the UHP metamorphic slices for the metasomatism of the overlying mantle wedge. (C) Partial melting of the metasomatic mantle wedge, generating the Shidao arc-like alkaline complex.

(A) Continent-continent collision and HP/UHP metamorphism

(B) Exhumation and partial melting of UHP metamorphic slice

(C) Post-collisional or syn-exhumation magmatism

(A) Exhumation and partial melting of UHP metamorphic slice

(B) Post-collisional or syn-exhumation magmatism