2.2 Ga magnesian andesites, Nb-enriched basalt-andesites, and adakitic rocks in the Lüliang Complex: Evidence for early Paleoproterozoic subduction in the North China Craton

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A B S T R A C T

The Lüliang Complex is located at the western margin of the middle segment of the Trans-North China Orogen, along which the Western and Eastern Blocks amalgamated to form the basement of the North China Craton. The complex consists of the Paleoproterozoic granite plutons and meta-supracrustal rocks, of which the latter are subdivided into the Jiehekou, Lüliang, Yejishan, and Heichashan/Lanhe Groups. A meta-volcanic rock from the Yejishan Group gives a magmatic zircon U–Pb age of 2188 ± 48 Ma and εNd(t) values of +0.06 to +5.42. Based on the geochemical characteristics, four different ~2.2 Ga igneous rock suites have been identified in the Lüliang Complex. The calc-alkaline basalts and andesites show the geochemical features of typical ‘normal’ arc volcanics with pronounced LREE enrichments relative to HREE, negative Nb, Ta, P and Ti anomalies and εNd(t) values of −2.69 to +2.14. The adakitic rocks are characterized by high Na2O/K2O ratios, weak to positive Eu anomalies, positive Sr and Ba but negative Nb and Ti anomalies, and relatively clustered and near to zero εNd(t) values. The Nb-enriched basalts and andesites have higher Nb, Zr and TiO2 contents, higher Nb/Ta (14.4–19.3) and Nb/U (20.6–23.2) ratios than the majority of arc basalts and andesites and relatively variable εNd(t) values (−1.54 to +3.02). The magnesian andesites are characterized by anomalously high MgO, Cr and Ni contents and have εNd(t) values of −3.90 to +1.17. The occurrence of adakitic rocks, Nb-enriched basalts and andesites and magnesian andesites has been described from many modern arcs featuring subduction of oceanic slab. Therefore, we suggest that similar mechanism may have played an important role in the production of the ~2.2 Ga igneous rocks in the Lüliang Complex and thus the final collision between the Eastern and Western Blocks along the TNCO must have happened at some time after ~2.2 Ga.

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1. Introduction

The Trans-North China Orogen (TNCO) in the North China Craton (NCC), one of the oldest cratonic blocks in the world, has been studied on the lithology, structural style, metamorphic evolution, geochemistry and geochronology in the last decades (e.g. Faure et al., 2007; Kröner et al., 2005a, 2005b; Kusky and Li, 2003; Polat et al., 2005; Wang et al., 2010b; Wilde et al., 2002; Zhai et al., 2005; Zhao et al., 2012). Different models for the tectonic subdivision and amalgamation of the NCC have been proposed to explain the important tectonothermal events, especially the ~2.5 Ga and ~1.85 Ga events (Faure et al., 2007; Kusky, 2011; Kusky and Li, 2003; Santosh, 2010; Trap et al., 2007, 2012; Wang et al., 2010a; Zhai and Santosh, 2011; Zhai et al., 2005; Zhao et al., 2005). In the last decades, an increasing lines of evidence for the 2.2–2.1 Ga tectonothermal events in the TNCO have been reported in the Hengshan Complex (Kröner et al., 2005b; Wang et al., 2010b; Zhao et al., 2011), Wutai Complex (Du et al., 2010, 2013; Peng et al., 2005; Wilde, 2002; Wilde and Zhao, 2005), Fuping Complex (Guan et al., 2002; Zhao et al., 2002), Lüliang Complex (Geng et al., 2000; Liu et al., 2012a, 2014a; Zhao et al., 2008), Zanhuan Complex (Liu et al., 2012b; Xie et al., 2012; Yang et al., 2011) and Zhongtiao Complex (Sun et al., 1990) in the TNCO. However, the petrogenesis and tectonic setting of the 2.2–2.1 Ga igneous rocks remain controversial, partly resulting in the different models for the tectonic evolution of the craton. Zhai (2004, 2011), Zhai and Peng (2007) and Du et al. (2013) suggested that these igneous rocks were related with the 2.30–1.95 Ga rift events after ~2.5 Ga cratonization of the NCC. On the contrary, Zhao et al. (2005), Liu et al. (2012a, 2014a) and Wang et al. (2010b) considered these magmatic rocks to be subduction-related at an Andean-style convergent margin or in a marginal arc-back-arc basin system. Therefore, the nature and tectonic significance of the tectonothermal events at 2.2–2.1 Ga and their relevance to the tectonic evolution of the TNCO is of particular importance.

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A rock association of adakites, magnesian andesites (MA) and Nb-enriched basalts and andesites (NEBA) with ‘normal’ arc basalts and andesites has been reported from Cenozoic arcs featuring subduction of hot, young (~20 Ma) oceanic lithosphere (Drummond et al., 1996; Kelemen, 1995; Martin, 1999). Such an association is also known from Neoarchean greenstone terranes of the Dharwar craton (Manikyamba et al., 2009), Superior (Polat and Kerrich, 2001), Baltic block (Shchipansky et al., 2004) and the NCC (Guo et al., 2013; Peng et al., 2012a, 2012b; Wang et al., 2004). In this paper, we report new zircon (Shchipansky et al., 2004) and the NCC (Guo et al., 2013; Peng et al., 2014) data, we suggest that the ~2.2 Ga meta-igneous rocks in the Lüliang Complex include an association of adakitic rock, MA and NEBA. Based on the results, we evaluate the petrogenesis of these rocks and compare these to counterparts in Cenozoic arc with a view to further understand the tectonic evolution of the TNCO in the early Paleoproterozoic.

2. Geological setting

The NCC is composed of Archean to Paleoproterozoic metamorphic basement overlain by Mesoproterozoic to Cenozoic unmetamorphosed cover (Zhao et al., 2012). As mentioned above, a number of models have been proposed for the tectonic subdivision and amalgamation of the NCC (Faure et al., 2007; Kusky, 2011; Kusky and Li, 2003; Santosh, 2010; Trap et al., 2007, 2012; Wang et al., 2010b; Zhai and Santosh, 2011; Zhao et al., 2005), most of which agree the division of the NCC into the Eastern and Western Blocks and emphasize the importance of continent–continent collisional belts to the tectonic evolution of the NCC. The two blocks collided along the NS-trending TNCO (Fig. 1; Zhao et al., 2005), which is also called the Central Orogenic Belt (Kusky and Li, 2003) or the Jinyu Belt (Zhai and Santosh, 2011). The Eastern Block is subdivided into the Longang Block (also called the Yanliao Block; Santosh, 2010) and the Langrim Block, which are separated by the Liao-ji Belt (Zhai and Santosh, 2011) or the Jiao-Liao-Ji Belt (Li et al., 2004, 2005, 2006, 2010, 2012b; Liu et al., 2013c, d, e, 2014b; Lu et al., 2008; Luo et al., 2004, 2008; Tam et al., 2011, 2012a, b, c; Wang et al., 2014a; Zhang et al., 2014a; Zhou et al., 2008), whereas the EW-trending Khondalite Belt (also called the Fengzhen Belt or Inner Mongolian Suture Zone; Zhai and Peng, 2007; Santosh, 2010; Zhai and Santosh, 2011) subdivides the Western Block into the Yinshan and Ordos Blocks (Zhao et al., 2005; Xia et al., 2006a, b, 2008; Yin et al., 2009, 2011, 2014; Zhao, 2009; Li et al., 2011a, 2011b; Wang et al., 2011; Liu et al., 2014c; Zhang et al., 2014b).

The TNCO, a nearly NS-trending ~1200 km long and 100–300 km wide belt across the central part of the NCC (Fig. 1), is composed of Neoarchean to Paleoproterozoic TTG gneisses, meta-supracrustal rocks (metamorphosed sedimentary and volcanic rocks), syn- to post-tectonic granites and mafic dykes. Geochemical and isotopic studies suggest that the dominant Neoarchean to Paleoproterozoic rocks represent arc-related juvenile crust with minor reworked basement (Liu et al., 2002, 2004, 2005, 2012a; Sun et al., 1992; Wang et al., 2004, 2014b, 2014c). Ancient oceanic fragments and mélangé have been identified in the Jingangku Formation of the Wutai Complex (Polat et al., 2005; Wang et al., 1996, 1997). Most recently, syn-tectonic foreland basin deposits represented by the younger sequence-set of the low-grade supracrustal successions have been found in the Wutai, Lüliang, Zanhuang and Zhongtiao Complexes (Faure et al., 2007; Liu et al., 2013a; Trap et al., 2007). The TNCO also possesses numerous structural and metamorphic features as classical indicators of collision tectonics, such as linear structural belts characterized by strike-slip ductile shear zones, large-scale thrusting and folding, transcurent tectonics, sheath folds and mineral lineations (Li et al., 2010; Trap et al., 2007; Zhang et al., 2007, 2009, 2012), high-pressure granulites and retrograde eclogites in the Hengshan, Huai’an, Xuanhua and Chengde Complexes (Guo et al., 2002, 2005; Zhai et al., 1992, 1995; Zhao et al., 2001) and clockwise metamorphic P–T paths involving near-isothermal decompression (Zhao et al., 2001; Xiao et al., 2011; Qian et al., 2013). These lithotectonic features contrast with those in the Eastern and Western Blocks and led Zhao et al. (2000) to propose that the TNCO is a continent–continent collisional belt, along which the Eastern and Western Blocks amalgamated to form the coherent basement of the NCC. Available metamorphic ages obtained from metamorphic zircons and monazites in different complexes of the TNCO are consistent at

![Fig. 1. Tectonic subdivision of the North China Craton. Modified after Zhao et al. (2005).](Image)
- 1.85 Ga, which is interpreted as the timing of the collisional event leading to the final cratonization of the NCC (Guan et al., 2002; Guo et al., 2005; Kröner et al., 2005a, 2005b, 2006; Liu et al., 2006; Wang et al., 2010a; Zhao et al., 2002, 2008).

The Lüliang Complex is situated at the western margin of the central segment of the TNCO (Fig. 1) and consists of Paleoproterozoic granitic plutons and meta-supracrustal rocks (Fig. 2; Geng et al., 2000, 2006; Zhao et al., 2008; Liu et al., 2012a). The granitoid rocks have been subdivided into pre-tectonic TTG (tonalitic–trondhjemitic–granidioritic) gneisses, syn-tectonic gneissic granites and post-tectonic massive granites (Zhao et al., 2008). The pre-tectonic TTG gneisses include the 2499 Ma Yunzhongshan TTG gneiss (Zhao et al., 2008), 2375 Ma Gaijiazhuang porphyritic gneiss (Zhao et al., 2008) and 2182–2151 Ma Chijianling–Guandishan TTG gneiss (Du et al., 2012; Geng et al., 2000; Liu et al., 2009a; Zhao et al., 2008), and geochemical data indicate that these rocks are mostly calc-alkaline and formed in a continental arc setting (Liu et al., 2009a). It is worthy to note that the Yunzhongshan TTG gneiss has been considered equivalent to the 2520–2475 Ma Hengshan and Fuping TTG gneisses to the northeast of the Lüliang Complex (Zhao et al., 2008). The syn-tectonic gneissic granites are mainly distributed in the southern Lüliang Complex and represented by the 1832 Ma Huijiazhuang gneissic granite, which intrudes the Chijianling-Guandishan TTG gneiss and contain its xenoliths (Zhao et al., 2008). The post-tectonic massive granites include the ~1800 Ma Luyashan charnockite (Geng et al., 2000, 2006; Zhao et al., 2008), 1807 Ma Lucaogou porphyritic granite (Zhao et al., 2008) and ~1800 Ma Tangershang–Guandishan massive granite (Geng et al., 2006; Zhao et al., 2008), all of which intrude the Chijianling–Guandishan TTG gneiss or the Yunzhongshan TTG gneiss. On the other way, the meta-supracrustal rocks in the Lüliang Complex have been subdivided into the Jiehekou, Lüliang, Yejishan and Heichashan/Lanxian Groups (Fig. 2; Yu et al., 1997a; Geng et al., 2000).

The Jiehekou Group is located in the western part of the complex (Fig. 2) and consists mainly of graphite-bearing pelitic gneisses/schists, quartzites, fine-grained felsic paragneisses, graphite marbles, calc-silicate rocks and minor amphibolites (Wan et al., 2000). U–Pb detrital zircon dating results in the upper sequence of the group have an age range between 2.3 and 2.0 Ga and the metamorphic zircons gave ages around 1.85 Ga, which suggests that the Jiehekou group has been deposited in the period of 2.0–1.85 Ga (Liu et al., 2013b; Wan et al., 2006; Xia et al., 2009). Based on the similarities in the rock assemblage and geochemical features of the Jiehekou Group and the “khondalite series” in the Western Block, which crop out along the northern and eastern margins of the Ordos Block respectively, they are proposed to represent

Fig. 2. (A) A simplified geological map of the Lüliang Complex (modified after Zhao et al., 2008); (B) a cross section through the middle part of the Lüliang Complex.
stable continental margin deposits surrounding the block (Liu et al., 2013b; Wan et al., 2006; Zhao et al., 2005). On the contrary, the discovery of igneous plutons and metamorphic volcanics in the group led Liu et al. (2012a) to interpret it as the active continental margin products.

The Lüliang Group is distributed only in the central part of the complex (Fig. 2) and consists predominantly of amphibolite- to greenschist-facies metamorphosed sedimentary rocks in the lower sequence and volcanic rocks in the upper sequence (Yu et al., 1997a). The protoliths of these meta-sedimentary rocks are considered to have sourced mainly from the Lüliang and Taihua complexes in the TNCO, and they were deposited during the period between 2.2 and 2.1 Ga, based on the ages of the youngest detrital zircons and the Daorengou adamellite intruding the group (Liu et al., 2014a). For the upper sequence, Geng et al. (2000) reported a Sm–Nd whole-rock isochron age of 2351 ± 56 Ma from amphibolites and a single zircon U–Pb age of 2360 ± 95 Ma from a meta-rhyolite, both interpreted as their rock-forming ages. However, Yu et al. (1997a) reported single zircon U–Pb ages of 2051 ± 68 and 2099 ± 41 Ma for a meta-basalt and a meta-rhyolite respectively, also interpreted as the timing of the volcanic eruption. Most recently, Liu et al. (2012a) reported a LA-ICP-MS magmatic zircon U–Pb age of 2213 ± 47 Ma and a metamorphosed zircon age of 1832 ± 56 Ma for a metabasalt from the group. Similar zircon crystallization ages have also been obtained for the metabasites (2209–2178 Ma; Liu et al., 2014a) and feldspar porphyritic rocks (2189–2186 Ma; Du et al., 2012) from the upper sequence. Based on the geochemistry of metavolcanics in the group, Yu et al. (1997b) and Geng et al. (2003) suggested that the Lüliang Group developed in a continental marginal rift environment. However, Faure et al. (2007), Liu et al. (2012a) and Liu et al. (2014a) interpreted the group as having formed in a magmatic arc and/or a back-arc basin environment.

The Yejishan Group is distributed along a narrow, NE–SW-trending belt in the northwestern part of the complex (Fig. 2). The group has been subdivided into the Qingyangshuwan, Bailongshan, and Chengdaogou Formations (Geng et al., 2003), all of which were metamorphosed in subgreenschist- to amphibolite-facies. The lowest Qingyangshuwan Formation is composed of ~635 m thick basal conglomerates, quartzites and phyllites interbedded with minor metavolcanics. These terrigenous deposits show vertical facies changing from coarse clastic sediments into finer-grained siliciclastic rocks, suggesting that they were deposited in a graben-related environment (SBGMR, 1989). The basal conglomerates consist of pebble-sized clasts of quartzite, granite, pegmatite, gneiss and marble (in decreasing order of abundance; SBGMR, 1989). Conformably overlying the Qingyangshuwan Formation is the Bailongshan Formation which consists of more than 1500 m-thick bed of metabasites interlayered with phyllites and quartzites in the lower part. Widespread pillow lavas preserved in the formation suggest a submarine eruption (Geng et al., 2003). The Chengdaogou Formation is more than 900 m thick and has a conformable contact with the underlying amphibole schists of the Bailongshan Formation. The main lithologic sequence of the formation is thick layer conglomerates and coarse-grained sandstones with large-scale tabular oblique bedding and mud crack structures (Liu et al., 2009b). Geng et al. (2000) reported a zircon U–Pb age of 2124 ± 38 Ma for a meta-volcanic rock from the Bailongshan Formation, which is consistent with the youngest age peak of 2086 ± 10 Ma from a meta-sandstone in the same formation (Liu et al., 2011). More recently, Liu et al. (2012a) reported an older zircon U–Pb age of 2210 ± 13 Ma for a meta-subvolcanic rock from the Bailongshan Formation. For the Qingyangshuwan Formation, the youngest detrital zircon age of 1835 ± 24 Ma from the metamorphosed clastic rocks places constraints on the maximum depositional age (Liu et al., 2011). Like controversy on the tectonic setting of the Lüliang Group, debates on the tectonic setting of the Yejishan Group also remain, ranging from the continent marginal rift (Geng et al., 2003) to the active continental margin (Liu et al., 2009b, 2012a).

The Heichashan/Lanhe Groups are mainly distributed in the western part of the complex and unconformably overlie the Jiehekou, Lüliang and Yejishan Groups (Fig. 2). The main lithologic changes are from the meta-conglomerates, quartzites, phyllites and dolomites of the Lanhe Group to the meta-conglomerates and quartzites of the Heichashan Group. The similarities of the upper coarse-grained sediment sequence of the Yejishan Group with the Heichashan/Lanxian Group in metamorphic grade and rock assemblage led Liu et al. (2009b) to propose that they formed in a late Paleoproterozoic foreland basin.

3. Samples and analytical techniques

Twenty-one meta-volcanic samples from the Yejishan Group were selected for major and trace element analysis. Samples for geochemical analyses were collected from the least weathered outcrops. After petrographic screening, least altered samples were selected for detailed geochemical studies. Major elements were measured by X-ray fluorescence spectrometry (XRF, Rigaku-2100) with relative standard deviations less than 3%. Rare earth elements and other trace elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, TJA-PQ-Excel) at the National Research Center for Geoanalysis, Beijing. Precision and accuracy are better than 5% for the majority of trace elements. Geochemical data of meta-volcanic rocks from the Lüliang Group (Du et al., 2012; Liu et al., 2014a; Yu et al., 1997b) and meta-intrusive rocks from the Guandishan TTG gneisses (Du et al., 2012; Liu et al., 2009a) are also used in this study. Whole-rock geochemical data were processed with the “GeoPlot” Excel™ plug-in by Zhou and Li (2006).

Nd isotopic analyses of six meta-volcanic rocks from the Yejishan Group were carried out at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Whole-rock powders for Nd isotopic analyses were dissolved in Savillex Teflon screw-top capsule prior to HF + HNO3 + HCIO4 dissolution. Nd was separated using the classical two-step ion exchange chromatographic method and measured using a Triton Plus multi-collector thermal ionization mass spectrometer. The Nd isotopic ratios were calculated for mass fractionation by normalizing to 146Nd/144Nd = 0.7219. Five runs of the JNdi-1 international standard averaged 142Nd/144Nd = 0.511203 ± 0.000008. 147Sm/144Nd ratios were calculated from Sm and Nd contents determined by the ICP-MS method. The Nd isotopic analysis followed procedures described by Li et al. (2011a, 2012a), Sm–Nd isotopic data of meta-volcanic rocks from the Lüliang Group (Liu et al., 2014a; Yu et al., 1998) and meta-intrusive rocks from the Guandishan TTG gneisses (Liu et al., 2009a) are also used in this study. εNd values were calculated from the present-day Chondrite Uniform Reservoir (CHUR), assuming 147Sm/144Nd ratio of 0.1967 and 143Nd/144Nd ratio of 0.512638 (DePaolo and Wasserburg, 1976).

One amphibolite (12L118–1) from the Bialongshan Formation of the Yejishan Group was selected for zircon U–Pb and Lu–Hf isotopic analyses. The fresh portions of whole-rock were powdered in an agate mill to about 40–80 mesh and zircons were separated using heavy liquid and magnetic separation methods. The zircons were hand-picked under a binocular microscope and then mounted into epoxy resin disks, which were polished to reveal cross sections of the grains and photographed in both reflected and transmitted light. Cathodoluminescence (CL) images of the zircons were obtained before zircon U–Pb analysis, using a JSM6510 SEM attached with a Gatan CL detector. Zircon U–Pb isotope analyses were conducted using a Newwave UP 213 laser ablation system coupled to a Thermo Finnigan Neptune MC–ICP-MS at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing. The ablation protocol employed a spot diameter of 32 μm at 10 Hz repetition rate. Zircon GJ1 was used as the external standard and analyzed twice every 10 analyses. Detailed descriptions for the analytical procedures have been given by Hou et al. (2009). Off-line raw data selection, integration of background and analytical signals, and time-drift correction and quantitative calibration for U–Pb dating were calculated using
the ICPMSDataCal 8.4 (Liu et al., 2010). Concordia diagrams and weighted mean ages were made using Isoplot/Ex_ver 3.23 (Ludwig, 2003).

After zircon U–Pb analyses, Hf analyses were also finished at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing, using the method of Hou et al. (2007). Analyses were carried out in situ with a Newwave UP213 laser-ablation system, attached to a Neptune MC–ICP–MS. All analyses used a beam diameter of 44 μm and energy density of 15–20 J/cm². Zircon GJ1 was used as the reference standard during our routine analyses, with a weighted mean 176Hf/177Hf ratio of 0.282009 ± 0.000013 (2σ, n = 15), indistinguishable from the weighted mean 176Hf/177Hf ratio of 0.282000 ± 0.000005 (2σ) using a solution analysis method by Morel et al. (2008). For the calculation of εHf(t) values, we have adopted the present day chondritic 176Hf/177Hf ratio of 0.282772 (Blichert-Toft and Albarede, 1997). Depleted mantle model ages (TDM) were calculated based on the measured 176Lu/177Hf ratios, referred to the depleted mantle with present-day 176Hf/177Hf = 0.28325 and 176Lu/177Hf = 0.0384 (Griffin et al., 2004).

4. Results

4.1. Zircon U–Pb geochronology

We present U–Pb zircon ages for an amphibolite (12LL18–1) from the Bailongshan Formation of the Yejishan Group. The CL images of representative zircons are shown in Fig. 3 and the U–Pb analytical data are presented in Supplementary Table 1 and plotted in Fig. 4.

Sample 12LL18–1 is an amphibolite from the Bailongshan Formation and is composed of plagioclase (~50%) + amphibole (~45%) and minor apatite, zircon and ilmenite. This sample is originally basaltic, and geochemically belongs to calc-alkaline basalts to andesites (Supplementary Table 3). A total of seventeen U–Pb isotopic analyses were obtained on 17 grains from this sample. These zircons have prismatic or rounded shapes and range in size from 124 to 32 μm with length/width ratios of 2:1 to 1:1. The CL images reveal that most of zircons have oscillatory or sector zonings with high luminescence rims (Fig. 3), suggesting their magmatic origins (Corfu et al., 2003) and subsequent growth. Seven analyses gave a relative wide range of Th/U ratios of 1.64–0.25 and the measured 207Pb/206Pb ages vary from 3170 Ma to 2146 Ma. As shown in Fig. 4, eight analyses of them form a regression line with the upper intercept age of 2188 ± 48 Ma (MSWD = 8), which is similar to the 2210 ± 13 Ma for meta-subvolcanic rocks from the same Formation (Liu et al., 2012a). We therefore consider that the age of 2188 ± 48 Ma might represent the time of crystallization of the igneous protolith. The remaining nine older ages with 3170 Ma to 2298 Ma are most likely xenocrysts that were captured during the ascent of the magma. It is worthy to note that the crystallization ages of the meta-volcanics from the Yejishan Group (2210–2188 Ma) is nearly the same with those of the Chijianling–Guandishan TTG gneiss

4.2. Zircon Lu–Hf isotopic results

In situ Lu–Hf isotopic analyses of zircons from Sample 12LL18–1 are listed in Supplementary Table 2 and shown in Fig. 5. Two groups of zircons have been recognized from amphibolite sample 12LL18–1, magmatic zircons with old ages (xenocrysts) and magmatic zircons recording the crystallization age of the igneous protolith. The xenocryst zircons (2702–2488 Ma) have variable Hf isotopic compositions, with 176Hf/177Hf ratios of 0.281161–0.281254, εHf(t) values of −2.9 to +1.7 and TDM values of 3.0–2.8 Ga (Supplementary Table 2 and Fig. 5). Results of Hf analyses on magmatic zircons display higher εHf(t) values relative to the xenolithic zircons. All of their εHf(t) values are located between the CHUR and DM evolution lines and gave εHf(t) values of +0.1 to +5.4 and TDM model ages of 2.6 to 2.3 Ga (Supplementary Table 2 and Fig. 5).

4.3. Geochemical characteristics

In the Lüliang Complex, four different ~2.2 Ga igneous rock suites are recognized based on their geochemical characteristics (Supplementary Table 3). A total of nineteen analyses were obtained on 19 grains from this sample. These zircons have prismatic or rounded shapes and range in size from 124 to 32 μm with length/width ratios of 2:1 to 1:1. The CL images reveal that most of zircons have oscillatory or sector zonings with high luminescence rims (Fig. 3), suggesting their magmatic origins (Corfu et al., 2003) and subsequent growth. Seven analyses gave a relative wide range of Th/U ratios of 1.64–0.25 and the measured 207Pb/206Pb ages vary from 3170 Ma to 2146 Ma. As shown in Fig. 4, eight analyses of them form a regression line with the upper intercept age of 2188 ± 48 Ma (MSWD = 8), which is similar to the 2210 ± 13 Ma for meta-subvolcanic rocks from the same Formation (Liu et al., 2012a). We therefore consider that the age of 2188 ± 48 Ma might represent the time of crystallization of the igneous protolith. The remaining nine older ages with 3170 Ma to 2298 Ma are most likely xenocrysts that were captured during the ascent of the magma. It is worthy to note that the crystallization ages of the meta-volcanics from the Yejishan Group (2210–2188 Ma) is nearly the same with those of the Chijianling–Guandishan TTG gneiss

Fig. 3. Representative selection of cathodoluminescence (CL) zircon images. Circles (44 and 32 μm) show positions of Hf and U–Pb analytical sites, respectively. 207Pb/206Pb and 64Ag(1) values are also plotted. The scale bar is 100 μm long.

Fig. 4. Concordia plot of Sample 12LL18–1 from the Yejishan Group, insets showing the weighted average 207Pb/206Pb age. (2182–2151 Ma; Geng et al., 2000; Zhao et al., 2008; Liu et al., 2009a; Du et al., 2012) and meta-igneous rocks from the Lüliang Group (2213–2178 Ma; Du et al., 2012; Liu et al., 2012a; Liu et al., 2014a) dated by zircon U–Pb method.

Fig. 5. Results of Hf analyses on magmatic zircons display higher εHf(t) values relative to the xenolithic zircons. All of their εHf(t) values are located between the CHUR and DM evolution lines and gave εHf(t) values of +0.1 to +5.4 and TDM model ages of 2.6 to 2.3 Ga (Supplementary Table 2 and Fig. 5).
Table 3). These igneous suites, in decreasing relative abundance, are (1) calc-alkaline basalts and andesites, (2) adakitic rocks, (3) Nb-enriched basalts and andesites and (4) magnesian andesites.

### 4.3.1. Calc-alkaline basalts and andesites

Calc-alkaline basalts and andesites in the Lüliang Complex are mainly represented by chlorite–albite schists, metabasites, amphibolites and amphibole schists, and exposed in the Jinzhoyubing Formation of the Lüliang Group (nine samples) and the Qingshengan Formation of the Jiyuan Group (twenty-one samples). These samples plot mostly in the tholeiitic basalt field on the FeO*/MgO vs. SiO2 diagram of Miyashiro (1974; not shown), yet fractionated REE patterns (Fig. 6a), high Zr/Y ratios (3.4–10.6) and K2O contents (Supplementary Table 3) are more indicative of calc-alkaline suits. Therefore, they are collectively referred to here as the calc-alkaline suite for convenience. These rocks appear to form continuous trends on diagrams of major elements vs. MgO, over the range of 47–57 wt.% SiO2 and Mgs of 32–77 (Supplementary Table 3). The most obvious characteristic of the calc-alkaline suite is its similarity to common arc basalts and andesites. On the REE diagrams, they have light rare earth elements (LREEs) at ~50–70 times chondrite, fractionated LREEs with La/YbCN ratios of 3.0–5.0, and fractionated HREEs with Gd/YbCN ratios of 1.5–2.2 (Fig. 6a). On primitive mantle-normalized spider diagrams, the calc-alkaline rocks have coherent patterns with: (1) uniformly enriched Th and U over La (Fig. 7a); (2) variable Nb troughs relative to Th and La (Nb/Thpm = 0.12–0.38 and Nb/Lapm = 0.25–0.40); and (3) generally negative anomalies at P (P/Ndpm = 0.16–0.73) and Ti (Ti/Smpm = 0.23–1.03).

Whole rock Nd isotopic data for the ~2.2 Ga magmatic rocks in the Lüliang Complex are presented in Supplementary Table 4 and Figs. 9 and 10a. Initial Nd isotopic ratios and εNd(t) values are calculated at t = 2.2 Ga. The calc-alkaline basalts to andesites display εNd(t) values of −2.69 to +2.14 and TDM of 2.93 to 2.46 Ga (Supplementary Table 4 and Fig. 9).

### 4.3.2. Adakitic rocks

Adakitic rocks in the Lüliang Complex occur within the Guandishan gneiss (six samples) and consist of gneissic tonalities and granodiorites (Liu et al., 2009a). Like typical adakites in the world (Defant and Drummond, 1990; Martin et al., 2005), they are characterized by high Al2O3 contents (13–19 wt.%), Na2O/K2O ratios (1.26–2.34), high La (14–70 ppm) but low Yb (0.9–1.6 ppm) contents resulting in extremely fractionated REE patterns (La/YbCN = 19–51), generally negligible to positive Eu anomalies (Fig. 6b), and positive Sr and Ba but negative Nb and Ti anomalies in the spider diagrams (Fig. 7b). They all plot in or very near to the field of adakites on the Sr/Y vs. Y and La/YbCN vs. YbCN diagrams (Fig. 8a and b). As a group, the adakitic rocks are characterized by relatively clustered and near to zero εNd(t) values (−0.59 to +0.90; Fig. 9).

### 4.3.3. Nb-enriched basalts and andesites (NEBA)

The NEBAs have been identified in the Jinzhoyubing (three samples), Yuanjiaucun (two samples) and Dujiaocun (one sample) Formations of the Lüliang Group. Collectively, they are characterized by higher absolute Nb contents (7–17 ppm) and Nb/Thpm and Nb/Lapm ratios than most Phanerzoic oceanic island arc basalts and andesites (Nb < 2 ppm), plotting above the diagonal line on Fig. 8c (Polat and Kerrich, 2001). Compositionally, they vary in the SiO2 contents of 49–54 wt.% and Mg# of 31–60 and, as a group, possess moderately fractionated REE patterns (La/YbCN = 3.0–10.2) and weakly negative Eu anomalies (Eu/Eu* = 0.7–0.9; Fig. 6c). They are distinguished from the calc-alkaline suite by their higher Zr (119–317 ppm) and TiO2 (1.05–2.29 wt.%) contents, and higher Nb/Ta (14.4–19.3) and Nb/U (20.6–23.2) ratios. On the primitive mantle-normalized spider diagrams, the NEBAs display primitive minor negative or positive anomalies in Ba, Nb, Zr and Ti (Fig. 7c), which are almost identical to those of the Cenozoic NEBAs (Aguillon-Robles et al., 2001; Sajona et al., 1996; Wang et al., 2013). The NEBAs display the highest εNd(t) values (+2.50 and +3.02) in the four rock types (Fig. 9).

### 4.3.4. Magnesian andesites (MA)

The Lüliang MAs were found in the Jinzhoyubing Formation of the Lüliang Group (three samples) where they coexist with NEBAs. An orthogneiss sample from the Guandishan gneiss reported by Du et al. (2012) is also compositionally similar to the above MAs, which will be discussed together. The four samples are characterized by anomalously high MgO (5.2–12.2 wt.%), Cr (74–1078 ppm) and Ni (35–341 ppm) contents for an andesitic–dacitic range of SiO2. They plot above the line between the normal arc andesites and magnesian andesites (McCarron and Smellie, 1998; Fig. 8d), and thus they are designated as magnesian andesites. Compared to the calc-alkaline suite, the MAs have less TiO2 at a given value of MgO and more fractionated REE patterns (La/YbCN = 5–19; Fig. 6d). Similar to the other igneous suites, the MAs are featured by negative anomalies of Nb, Ta and Ti relative to neighboring REE on the spider diagrams, whereas the anomalies
increase from the NEBAs through MAs to adakitic rocks (Fig. 7). The MAs gave the lowest $\varepsilon$Nd(t) values of $-3.90$ to $-1.17$ and TDM of 2.79 to 2.58 Ga (Supplementary Table 4 and Fig. 9). Collectively, the whole-rock Nd isotopic date from the four igneous suites plot collinearly with an ‘age’ of 2144 ± 430 Ma, and an initial $^{143}$Nd/$^{144}$Nd ratio of 0.50981 ± 35 (Fig. 10a).

5. Discussion

5.1. Petrogenesis

5.1.1. Assessing post-magmatic alteration and crustal contamination
Given that all samples analyzed for this study have witnessed multi-phase deformation and subgreenschist- to amphibolite-facies regional metamorphism (Liu et al., 2012a; Trap et al., 2009; Zhao et al., 2000), it is essential to assess the effects of post-magmatic
alteration on geochemical compositions of these meta-igneous rocks before using them to evaluate their petrogenesis and tectonic setting (Polat et al., 2002). It is generally believed that in fine-grained igneous rocks the Al, REEs (except Ce and Eu), HFSEs, Y, and Sc are least susceptible to post-magmatic alteration and greenschist- to amphibolite-facies metamorphism (Kerrich and Fryer, 1979; Manikyamba et al., 2009).

Following the criteria proposed by Polat and Hofmann (2003), samples having significant carbonate and silica replacement (>2%), high loss on ignitions (LOI > 6 wt.%), or large Ce anomalies (Ce/Ce* > 1.1 and <0.9) are considered strongly altered. All of the samples reported in this study have LOI between 0.17 and 4.65 wt.% and Ce/Ce* ratios of 0.9–1.1 (except one NEBA sample and one calc-alkaline sample; Supplementary Table 1). Furthermore, good correlations between the Zr (an element immobile under most metamorphic conditions) and La, Nb in each of the four igneous suits (Fig. 5e and f), along with coherent chondrite-normalized REE and primitive mantle-normalized HFSE patterns in each of the four igneous suites, endorse limited mobility of these elements. In addition, the 2144 Ma isochron age, similar to the 2.21–2.18 Ga migmatic zircon crystallization ages, suggests that the Sm–Nd system has not been significantly disturbed during post-magmatic alteration.

Significant contamination of the calc-alkaline suite volcanics in the Lüliang Complex by continental crust during the magma ascent can be ruled out based on the following observations: (1) the pillowed structures of the meta-basalts in the Yejishan Group and their close spatial association with the flysch-type sediments are consistent with an oceanic rather than a continental setting (Liu et al., 2009b); (2) the presence of positive εNd(t) value (+2.14); (3) the lack of correlations between εNd(t) values and contents of contamination-sensitive elements or ratios, such as Si, Ni, Th, Zr, La/Sm, Th/Sm, Nb-La, and Nb-Th (not shown; Polat et al., 2011); and (4) no correlation between 147Sm/144Nd and εNd(t), which argues strongly against crustal contamination (not shown; Vervoort and Blichert-Toft, 1999). Many of the above arguments also apply to the adakitic rocks, NEBAs and MAs. In conclusion, the geochemical and Nd isotopic compositions of the ~2.2 Ga igneous rocks in the Lüliang Complex, which are consistent with insignificant interaction with older continent crust during the ascent and have not been significantly

Fig. 8. (a) Y vs. Sr/Y diagram (Defant and Drummond, 1993). (b) YbCN vs. La/YbCN diagram (Martin, 1999), the field for subducted oceanic crust-derived adakites is after Wang et al. (2006). (c) Nb/LaPM vs. Nb/ThPM diagram, the dashed line is after Polat and Kerrich (2001). (d) MgO vs. SiO2 diagram, the dashed line is after McCarron and Smellie (1998). (e) Zr vs. La diagram. (f) Zr vs. Nb diagram.
disturbed during post-magmatic alteration and metamorphism, are interpreted to reflect their near-primary source compositions.

5.1.2. Calc-alkaline basalts and andesites

The calc-alkaline basalts and andesites have fractionated LREEs, enrichment in LREEs relative to HREEs, fractionated HREEs (La/Sm$_\text{CN}$ = 1.6–3.6, La/Yb$_\text{CN}$ = 3.0–15.7 and Gd/Yb$_\text{CN}$ = 1.2–2.2; Fig. 6a), and negative anomalies at Nb, Ta, P and Ti (Fig. 7a), characteristic of convergence margin and volcanic arc magmas (Perfit et al., 1980; Hawkesworth et al., 1993; Pearce and Peate, 1995). Furthermore, the calc-alkaline basalts and andesites plot in the mantle source Hf/Sm diagram (Fig. 10b; LaFlèche et al., 1998). These geochemical features most likely resulted from the slab dehydration-wedge melting, when HFSEs are retained in the slab whereas LILEs, Th, U and LREEs are removed from slab-derived fluids to the mantle wedge (McCulloch and Gamble, 1991; Pearce and Parkinson, 1993). Furthermore, nearly all the calc-alkaline samples plot on the spinel-garnet lherzolite (50:50) line with ~5% degree of partial melting (Fig. 10c). On the other way, the calc-alkaline samples have Nb contents of 2.13 ppm and Zr/Nb ratios of 15–23, higher than those of N-MORB (2.3 ppm and 11–39; Sun and McDonough, 1989), and $\varepsilon$Nd(t) values of −2.69 and +2.14, suggesting that their mantle source was heterogeneous and generally enriched relative to N-MORB.

5.1.3. Adakitic rocks and magnesian andesites

Adakitic rocks are believed to be generated by crustal assimilation and fractional crystallization (AFC) processes from “normal” arc mafic magmas (Castillo et al., 1999), partial melting of the mafic lower crust under eclogites-facies conditions (Atherton and Petford, 1993; Chung et al., 2003; Condie, 2005) or young and hot slab melting under eclogites facies or garnet bearing amphibolite conditions (Kay et al., 1993; Stern and Kilian, 1996).

In the case of the ~2.2 Ga Lüliang adakitic rocks, an oceanic setting has been supported by several lines of evidence as we discussed earlier in this study and “E-MORB signatures” of some metabasites from the Lüliang Group (Liu et al., 2014a). Such geochemical features provide additional evidence that the AFC process has not been significant. For example, the adakitic rocks display coherent REE and HFSE patterns over a range of absolute abundances, which are clearly different from those of the calc-alkaline suit (Figs. 6b and 7b). Moreover, most of them have relatively low Th/Ce ratios (Supplementary Table 3), suggesting that they are more comparable with slab melting rather than partial melting of a thickened crust (Wang et al., 2008). Isotopic evidence also argues against lower crust origin for these adakitic rocks, as they have Nd isotopic compositions distinct from those of lower crust pyroxenite xenoliths in the NCC (Ying et al., 2010; Fig. 9). In particular, the 2.18–2.17 Ga age of the adakitic rocks is consistent with the 2112–211 Ma subduction-related magmatism in the TNCO (Kröner et al., 2005b; Wang et al., 2010b; Wilde, 2002; Wilde and Zhao, 2005; Zhao et al., 2008). Collectively, these lines of evidence suggest that the adakitic rocks in the Lüliang Complex were produced by the partial melting of a subducted oceanic crust.

The continuous trends between the Lüliang adakitic rocks and MAs on many of the variation diagrams (Fig. 8b and d) provide a strong support for the affinity of the adakitic rocks to those related to the slab melting. The generation of MAs is most likely accounted for by progressive interaction of adakitic melts with a peridotite mantle wedge (Kelemen, 1995; Rapp et al., 1999), which is also against a lower crustal melting model for the adakitic rocks. Moreover, this model for the MAs can account for their ‘normal’ arc geochemical features, such as fractionated REEs and pronounced negative Nb and Ti anomalies (Fig. 7d).

5.1.4. Nb-enriched basalts and andesites (NEBA)

Two models have been proposed to explain the origin and distinctive geochemical features of the NEBAs: (1) mixing of an OIB or enriched mantle with a depleted mantle wedge (Castillo et al., 2002); and (2) a mantle wedge metamasitized by adakitic melts (Defant and Kepezhinskas, 2001; Defant et al., 1992). In the case of the Lüliang NEBAs, we suggest that the latter mechanism is more possible based on the following evidences: (1) as discussed above, the continuous trends between the Lüliang adakitic rocks and MAs provide support for the interaction of adakitic melts with mantle peridotite; (2) the poor correlation between Rb and Nb in the Lüliang NEBAs (Fig. 10d) indicates that the enrichment of Nb was not produced by varying degrees of partial melting or source depletion (Wang et al., 2008); (3) the positive correlations between Th, La and Nb (Fig. 10e and f) indicate a mantle source metasomatized by melts carrying HFSEs more easily than hydrous fluids (Keppler, 1996); and (4) the approximately linear positive correlation between $^{143}$Sm/$^{144}$Nd and $^{143}$Nd/$^{144}$Nd for the Lüliang NEBAs, MAs and adakitic rocks (Fig. 10a) suggests their close relationship in petrogenesis (Polat and Kerrich, 2002).

On the other way, the Lüliang NEBAs do not display correlations between Th/Nb, La/Nb and Yb (Fig. 10g and h), which indicates that their Nb...
enrichments did not result from enrichment mantle “blobs” as suggested by Castillo et al. (2002).

5.2. Tectonic implication

5.2.1. Redefinition of the Yejishan Group

Our new and recently published geochronological and geochemical results have led to a better understanding of the stratigraphic sequences of the Yejishan Group. These results suggest similarities between the Qingyangshuwan and Bailongshan Formations of the Yejishan Group and the Lüliang Group based on the following aspects:

1) They are composed chiefly of meta-clastic rocks and variable amounts of meta-volcanics, of which the latter show typical subduction-related geochemical features.

2) The eruption ages of the metabasites from the two groups are nearly contemporaneous, at 2.21–2.18 Ga (Liu et al., 2012a, 2014a; Du et al., 2012; this study), which are almost coeval or slightly older than the subduction-related 2.18–2.15 Ga Chijianling–Guandishan TTG

Fig. 10. (a) 143Nd/144Nd vs. 147Sm/144Nd diagram. (b) (Ta/La)$_N$ vs. (Hf/Sm)$_N$ diagram (after LaFlèche et al., 1998). (c) Sm vs. Sm/Yb diagram (after Peng et al., 2010). (d) Nb vs. Rb diagram. (e) Nb vs. Th diagram. (f) Nb vs. La diagram. (g) Yb vs. Th/Nb diagram. (h) Yb vs. La/Nb diagram.
The depositional environment change is supported by the angular unconformity between the Bailongshan and Chengdaogou Formations (Liu et al., 2009b).

1) The depositional environmental change is supported by the angular unconformity between the Bailongshan and Chengdaogou Formations (Liu et al., 2009b).

2) The Chengdaogou Formation consists mainly of shallow-marine to fluvial facies conglomerates and coarse-grained sandstones, which are different from the underlying deep-marine sediments.

3) The maximum depositional age of the Chengdaogou Formations is constrained at ~1.84 Ga by the youngest detrital zircon age peak (Liu et al., 2011), which overlaps with the timing of the major collisional event in the TNCO (Guan et al., 2002; Kröner et al., 2005a, 2005b, 2006; Liu et al., 2006; Wang et al., 2010b; Zhang et al., 2009; Zhao et al., 2002, 2008) and much younger than the 2.21 Ga and 2.06 Ga maximum depositional ages of the Lüliang Group and the Qingyangshuan Formation of the Yejishan Group, respectively (Liu et al., 2011, 2014a).

On the basis of these data, we agree with the redefinition of the Yejishan Group proposed by Liu et al. (2009b, 2011), which suggested that the Qingyangshuan and Bailongshan Formations should be removed from the Yejishan Group and assigned to the Lüliang Group and the redefined Yejishan Group could be comparable with the Heichashan/Lanhe Groups.

5.2.2. Constraints on the tectonic evolution of the Trans-North China Orogen

As mentioned above, the 2.2–2.1 Ga geological events are widespread across the TNCO and have important implications on the tectonic evolution of the NCC in the Paleoproterozoic (Du et al., 2010, 2012, 2013; Kröner et al., 2005b; Liu et al., 2012a, 2014a; Sun et al., 1990; Wang et al., 2010b; Wilde, 2002; Wilde and Zhao, 2005; Xie et al., 2012; Yang et al., 2011; Zhao et al., 2011). However, controversy still remains over the petrogenesis and tectonic setting of the 2.2–2.1 Ga igneous rocks. One school of researchers suggested a continental rift basin setting based on the “A-type” signatures of the Xuting granite in the Zanhuang Complex and the Duijagou feldspar porphyritic rocks in the Lüliang Complex (Du et al., 2012; Yang et al., 2011). However, based on the whole-rock and mineral geochemistry, Liu et al. (2012a, 2014a) and Wang et al. (2010b) proposed that the metabasites of the Lüliang and Yejishan Groups in the Lüliang Complex and the Yunnengmian mafic-ultramafic intrusion in the Hengshan Complex were subduction-related.

In this study, the geochronological and geochemical evidence indicates that the subduction of oceanic slab may have been responsible for the generation of adakitic rocks, MAs and NEBAs in the early Paleoproterozoic Lüliang Complex, similar to such modern rock assemblages in the Philippines (Sajona et al., 1996), southern Andes (Stern et al., 1995), and the Paleoproterozoic Lüliang Complex, similar to such modern rock assemblages in the Philippines (Sajona et al., 1996), southern Andes (Stern et al., 1995), and the Paleoproterozoic Lüliang Complex.

The adakitic magmas along with the liberated hydrous fluids. The adakitic rocks and MAs is similar to those in many modern subduction-related environments. The NEBAs originated from mantle wedge metasomatized by adakitic melts and the associated MAs were products of interaction of adakitic magmas and mantle wedge peridotite.

3) The close spatial and temporal association of the NEBAs with adakitic rocks and MAs is similar to those in many modern subduction-related environments, suggesting that the final collision between the Eastern and Western Blocks along the TNCO must have happened at some time after ~2.2 Ga.

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