Geochemistry, geochronology and zircon Hf isotopic study of peralkaline-alkaline intrusions along the northern margin of the North China Craton and its tectonic implication for the southeastern Central Asian Orogenic Belt

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Abstract:

A giant Permian alkaline magmatic belt has recently been identified in southern Inner Mongolia, along the northern margin of the North China Craton (NCC). This belt is mainly composed of syenite, quartz syenite, alkaline granite and mafic microgranular enclaves (MME)-bearing granodiorite. In order to study the petrogenesis and tectonic implications of these rocks, we undertook zircon U-Pb dating and geochemical analysis of two Permian alkaline plutons. The first Guangxingyuan Pluton occurs in the Hexigten area and is composed of MME-bearing tonalite, K-feldspar granite and syenite. The second Durenwuliji Pluton, located in the Xianghuangqi area, comprises syenite, quartz syenite and K-feldspar granite. Zircon U-Pb dating on tonalite, K-feldspar granite, syenite and quartz syenite from the two plutons yielded a tight range of ages from 259 to 267 Ma. The peralkaline-alkaline rocks show high abundance of total alkalis ($K_2O+Na_2O=7.9-12.9\%$) and K_2O contents (3.9-8.0%), enrichment in large ion lithophile elements (LILE) and light rare earth element (LREE), and depletion of high field strength elements (HFSE). The associated tonalite and MMEs display I-type granitic geochemical affinity, with less total abundance of trace elements than the peralkaline-alkaline rocks. Zircon Hf isotopic analysis of the Guangxingyuan pluton yielded a large range of $\epsilon_{Hf}(t)$ values from -15.5 to +6.7 and model ages (T_{DM}^C) from 781 to 2012 Ma. By contrast, the Hf isotopic data of the Durenwuliji pluton shows a small range of $\epsilon_{Hf}(t)$ from +6.2 to +8.9 and T_{DM}^C from 667 to 816 Ma. The geochemical and Hf isotopic characteristics indicate that the parental magma was derived from a mixing of metasomatic

mantle-derived mafic magma with different amount of crust-derived felsic magma, and followed by fractional crystallization. Considering previous tectonic studies in Inner Mongolia, a Permian post-orogenic extension was proposed to account for these peralkaline-alkaline intrusions following the amalgamation of NCC and its northern blocks in the southeastern part of Central Asian Orogenic Belt.

Key words: peralkaline-alkaline intrusion, Middle Permian, southern Inner Mongolia, Central Asian Orogenic Belt, post-orogenic extension

1. Introduction

Peralkaline-alkaline rocks (e.g., alkaline granites and syenites), occur mainly in post-orogenic, rift and intraplate tectonic settings and form an important constituent of the upper continental crust (e.g., Bonin, 1990; Bonin et al., 1998; Nedelec et al., 1995; Eby et al., 1998; Frost et al., 1999; Yang et al., 2008). These rocks are formed at temperatures higher than that of common granites, thus the role of mantle-derived magma in an extensional environment is implied (Clemens et al., 1986; Bonin et al., 1998; King et al., 1997; 2001; Yang et al., 2008).

Alkaline magmatic rocks often form huge belts, extending hundreds to thousands of kilometers. For example, they occur in North America (Anderson, 1983; Windley, 1993), North Europe (Marks et al., 2003; Andersen et al., 2010), Africa (Eby et al., 1998) and Central Asia (Litvinovsky et al., 2002; 2011; Jahn et al., 2009; Reichow et al., 2010;). The Central Asian Orogenic Belt (CAOB), also known as the Altaid orogenic collage, covers a vast area of Central Asia bounded by the Tarim Craton and North China Craton in the south, the Siberian Craton in the north, and the European Craton in the west (Sengör et al., 1993; Fig. 1a). The successive accretion of micro-continental blocks and magmatic arcs to cratons from the Neoproterozoic to Late Paleozoic generated several Paleozoic fold belts and produced significant juvenile crustal mass in Central Asia (Fig. 1b; Sengör et al., 1993; Jahn et al., 2000; 2009; Windley et al., 2007; Kruk et al., 2011). After the amalgamation, voluminous peralkaline-alkaline intrusions emplaced in Central Asia during the Late Paleozoic and Early Mesozoic, and together with coeval bimodal volcanic rocks, several Late

Paleozoic and Mesozoic peralkaline-alkaline rock belts were formed, such as the Mongolian–Transbaikalian Belt and Gobi–Tien Shan Belt (Fig. 1b; Litvinovsky et al., 2002; 2011; Jahn et al., 2009).

The region of Inner Mongolia is located in the northern margin of the North China Craton (NCC); much of it constitutes the southeastern part of CAO (Fig. 1b). Microcontinents, such as the Songliao-Hunshandake and Xing'an-Airgin Sum Blocks, and magmatic arcs were accreted to the north margin of NCC during the Paleozoic (Xiao et al., 2003; Xu et al., 2013; 2015). After the accretion, several episodes of alkaline magmatism have been recorded in this region. Early-Middle Devonian alkaline intrusions were identified in the north margin of NCC (Jiang, 2005; Zhang et al., 2010; Zeng et al., 2012), indicating the termination of the Early Paleozoic orogenic cycle (Zhang et al., 2010). A Late Carboniferous-Early Permian alkaline magmatic belt has been recognized in the regions along China-Mongolia border for decades (Fig. 2a; Hong et al., 1994; 1996; Jahn et al., 2009; Zhang et al., 2014b; Tong et al., 2015), suggesting an intra-plate extension within the Erguna-Xing'an Block. This belt extends westward through South Mongolia to eastern Tien Shan (Fig. 1b; Yarmolyuk et al., 2008; Jahn et al., 2009).

In recent years, several Middle Permian alkaline magmatic intrusions were identified along the northern margin of NCC (Fig. 2a; Table 1). They are mainly composed of peralkaline-alkaline rocks with coeval calc-alkaline rocks, and closely related to the mineralization of Au, Mo, Ag, Pb and Zn (Zeng et al., 2012; Lu et al., 2012). So far, these coexisting peralkaline-alkaline and calc-alkaline intrusions have

not attracted enough attention, and their petrogenesis and tectonic implications are poorly studied. In this paper, we report new geochemical, zircon U-Pb age and Hf isotopic data to decipher the petrogenesis of these Permian magmatic rocks. The data will then be used to discuss the tectonic evolution of the southeastern CAOB.

2. Geological setting

The study area is located in the southern margin of the Songliao-Hunshandake Block (referred to as the Songliao Block hereafter; Fig. 2a). This block was separated from the NCC by the Late Silurian Southern Suture zone, and from the Xing'an-Airgin Sum Block (referred to as the Xing'an Block hereafter) by the Late Devonian Northern Suture zone (Fig. 2a; Xu et al., 2013; 2014).

The Songliao Block is mainly composed of Proterozoic basement rocks, overlain by metamorphosed and deformed Early Paleozoic successions, and Late Paleozoic sedimentary rocks (Tang, 1990; Xu et al., 2013; 2015). Paleoproterozoic (1.8-1.9 Ga) and Neoproterozoic (750-850 Ma) granitoids and gneisses occur in southern and eastern Songliao Block (Pei et al., 2006; Wang et al., 2006; Wang et al., 2013). The Early Paleozoic Ondor Sum Group overlies the Precambrian basement rocks, and is composed of schists, marble, metavolcanic rocks, and quartzite. The protoliths of the Ondor Sum rocks have been dated at 490-470 Ma (Li et al., 2012; Xu et al., 2013). The Precambrian basement and Ondor Sum rocks underwent ductile deformation and metamorphism at ca. 450 Ma due to the subduction of the Paleo-Asian Ocean (Tang and Yan, 1993; De Jong et al., 2006; Liao et al., 2015). Two Early Paleozoic arc

magmatic belts occur in juxtaposition with the Southern and Northern Suture zones (Jian et al., 2008; Zhang et al., 2009; Zhang et al., 2013). The magmatic belts comprise intrusive and extrusive rocks with the age of 500-420 Ma, which also show strongly ductile deformation. The Late Silurian and Late Devonian sedimentary rocks, overlying unconformably the Southern and Northern Suture zones, are mainly composed of conglomerate and coarse-grained sandstone (Xu et al., 2013). They were considered as post-orogenic molasse deposit (Tang, 1990; Xu et al., 2013). The Late Carboniferous to Early Permian strata are thick sequences of shallow marine clastic and carbonate rocks (Zhao et al., 2015). The Early-Middle Permian strata were dominated by a volcanic-sedimentary sequence, while the Late Permian sedimentary rocks are consisted of fluvial conglomerate-sandstone and lacustrine black shales (Mueller et al., 1991; Shao et al., 1991; 2014). It is notable that all these post-Silurian strata display no ductile deformation with just folding and tilting.

During the Late Carboniferous-Early Permian, voluminous magmatic rocks were emplaced in the Xing'an Block, Songliao Block and in the northern margin of NCC. The magmatic rocks occur on both sides of the suture zones, and comprise calc-alkaline granitoids, A-type granites, gabbro, basalts, and rhyolites (Shi et al., 2004; Bao et al., 2007; Zhang et al., 2008; 2012; Zhang et al., 2009; Chen et al., 2012). The later Middle Permian magmatism was relatively weak, and was manifested by peralkaline-alkaline intrusions and granitoids occurring along the northern margin of NCC (Fig. 2a; Table 1).

3. Petrographic characteristics

Granitic samples from two plutons were subject to zircon dating, zircon Hf isotopic and whole-rock geochemical analyses. The petrographic characteristics of the two plutons are summarized in Table 2 and briefly described below.

3.1 Guangxingyuan Pluton

The Guangxingyuan Pluton from the Hexigten area occurs to the south of the Xar Moron River (Fig. 2a). In the new tectonic division, it is situated within the Songliao Block and to the north of the Southern Suture zone (Fig. 2a; Xu et al., 2014; 2015). The pluton intruded into the Lower Permian Qingfengshan Formation volcanic rocks and was overlain by the Upper Permian Tieyingzi Formation conglomerate (Fig. 2b). It consists of tonalite, K-feldspar granite and syenite. All these rocks display no metamorphism or deformation.

Tonalite contains mafic microgranular enclaves (MMEs) of 5-60 cm (Fig. 3a). The tonalite is composed of plagioclase (45%), quartz (30%), amphibole (15%) and biotite (5%), with accessory zircon and Fe-oxide (Fig. 3b). All minerals are euhedral to subhedral (Fig. 3b). Fine-grained plagioclase, amphibole, quartz, biotite constitute the matrix (Fig. 3b). The MMEs consist mainly of plagioclase (50%), amphibole (40%), biotite (5%) and minor amount of pyroxene, and accessory Fe-oxide (Fig. 3c). The mineral grains in most MMEs are subhedral to anhedral and relatively small (Fig. 3c).

K-feldspar granite is composed of K-feldspar (50%), plagioclase (20%), quartz (20%), and amphibole (5%), with accessory apatite and Fe-oxide (Fig. 3d). All

minerals are euhedral to subhedral (Fig. 3d).

Syenite is flesh pink in the field (Fig. 3e). It consists of K-feldspar (80%), plagioclase (15%), with minor amount of quartz, and accessory apatite, allanite and Fe-oxide (Fig. 3f).

3.2 Durenwuliji Pluton

The Durenwuliji Pluton in the Xianghuangqi area is located to the south of the Southern Suture zone (Fig. 2a; Xiao et al., 2003; Liu et al., 2003; Xu et al., 2015). It intruded into the Late Carboniferous and Early Permian strata and was overlain by the Jurassic strata (Fig. 2c). It is composed mainly of quartz syenite and syenite.

Quartz syenite (Fig. 3g) is composed of K-feldspar (70%), quartz (15%) and plagioclase (10%), with accessory allanite and Fe-oxide (Fig. 3h).

Syenite comprises K-feldspar (80%), plagioclase (10%) and quartz (5%), with accessory allanite and Fe-oxide. All minerals are euhedral to subhedral (Fig. 3g).

4. Analytical Methods

4.1 Zircon U-Pb dating and Hf isotopic analysis

Zircons were separated using conventional heavy liquid and magnetic techniques and followed by handpicking under a binocular microscope at the Langfang Regional Geological Survey, Hebei Province, China. Handpicked zircons were photographed under transmitted and reflected light under optical microscope and subsequently cathodoluminescence (CL) imaged using a Quanta 200 FEG Scanning Electron Microscope at Peking University. The CL images revealed the internal textures and potential target sites for U-Pb analyses.

Zircon U-Pb dating was carried out using an Agilent 7500c ICP-MS instrument coupled with a 193-nm ArF Excimer laser with an automatic positioning system at the Key Laboratory of Orogeny and Crust Evolution, Peking University. Calibrations for elemental concentration analysis in zircon were performed using NIST 610 glass as an external standard and ^{29}Si as internal standard. U-Pb isotope fractionation effects were corrected using zircon Plesovice (337 Ma) as external standard. Zircon standard 91500 was used as a secondary standard to supervise the deviation of age measurement/calculation. Isotopic ratios and element concentrations of zircons were calculated using software GLITTER (ver. 4.4.2, Macquarie University). Concordia diagrams were constructed using Isoplot/Ex (3.0) (Ludwig, 2003). Common lead was corrected using LA-ICP-MS Common Lead Correction (ver. 3.15), following the method of Andersen (2002). The analytical data are illustrated on U-Pb Concordia diagrams. The weighted mean ages are quoted at at 95% confidence level (Ludwig, 2003).

In situ Hf isotopic analysis was conducted using a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Germany) in combination with a Geolas 2005 excimer ArF laser ablation system (Lambda Physik, Göttingen, Germany) at the state Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan. The detailed operating conditions for the laser ablation system and the MC-ICP-MS instrument and analytical method are the same as described by Hu et al. (2012). The $^{179}\text{Hf}/^{177}\text{Hf}$ and $^{173}\text{Yb}/^{171}\text{Yb}$ ratios were used to calculate the mass bias of Hf (β_{Hf}) and Yb (β_{Yb}), which were normalized to $^{179}\text{Hf}/^{177}\text{Hf}=0.7325$ and

$^{173}\text{Yb}/^{171}\text{Yb}=1.132685$ (Fisher et al., 2014) using an exponential correction for mass bias. Interference of ^{176}Yb on ^{176}Hf was corrected by measuring the interference-free ^{173}Yb isotope and using $^{176}\text{Yb}/^{173}\text{Yb} = 0.79639$ (Fisher et al., 2014) to calculate $^{176}\text{Yb}/^{177}\text{Hf}$. Similarly, the minor interference of ^{176}Lu on ^{176}Hf was corrected by measuring the intensity of the interference-free ^{175}Lu isotope and using the recommended $^{176}\text{Lu}/^{175}\text{Lu} = 0.02656$ (Blichert-Toft et al., 1997) to calculate $^{176}\text{Lu}/^{177}\text{Hf}$. We used the mass bias of Yb (β_{Yb}) to calculate the mass fractionation of Lu because of their similar physicochemical properties. Off-line selection and integration of analytical signals, and mass bias calibrations were performed using ICPMSDataCal (Liu et al., 2010).

4.2 Whole-rock geochemical analysis

Whole-rock chemical compositions were analyzed at Acme Analytical Laboratories in Vancouver, Canada. Major elements were determined using ICP-emission spectrometry with detection limit 0.01%. Loss on ignition (LOI) was measured by placing 1 g of sample in furnace at 1000 °C for several hours before being cooled in desiccators and reweighing. Trace and rare earth elements were analyzed by ICP-MS. Rock standards DS10, GS311-1, GS910-4, SO-18, SY-4 and OREAS45EA were used to calibrate elemental concentrations of the measured samples.

5. Results

All analytical results are presented in Supplementary Tables S1, S2 and S3.

5.1 Zircon U-Pb ages and Hf isotopic compositions

5.1.1 Tonalite of the Guangxingyuan Pluton

Zircon grains of sample 110718-13 are euhedral, about 100 to 200 μm long and 50-80 μm wide, with a length/width ratio of 2 to 5. Some grains show fine-scale oscillatory growth zoning in CL images (Fig. 4a). Th/U ratios range from 0.52 to 1.22. All these characteristics indicate a magmatic origin. All 25 analyses are concordant (we use discordance $< 10\%$ as concordant analysis), and give ages between 274 ± 4 Ma to 261 ± 4 Ma (Supplementary Table S1). The data points form a tight cluster with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 267 ± 2 Ma (MSWD = 1.1; Figs. 4a and 4b). This age is interpreted as the emplacement time of the tonalite of the Guangxingyuan Pluton.

Zircon Hf isotopic analysis yielded $\varepsilon_{\text{Hf}}(t)$ values of -12.4 to +4.7. The calculated crustal model ages are 903-1840 Ma (mostly 903-1266 Ma) (Fig. 5; Supplementary Table S2).

5.1.2 K-feldspar granite of the Guangxingyuan Pluton

Zircon grains from sample 130619-10 are euhedral, with sizes of 120-250 μm long and 60-80 μm wide, and a length/width ratio of 3 to 4 (Fig. 4c). Most zircon grains are homogeneous in CL images without clear oscillatory growth zoning (Fig. 4c). Th/U ratios range from 0.43 to 1.51. All these features indicate a magmatic origin. Twenty-four of the 25 analyses are concordant (Supplementary Table S1). The ages for 24 concordant grains seem to fall into two groups. The first group (19 grains) is in the range of 280 ± 3 Ma and 264 ± 3 Ma, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 270

± 3 Ma (MSWD = 2.4). The ages for other 5 grains range from 259 ± 3 Ma to 255 ± 3 Ma and give a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 257 ± 3 Ma (MSWD = 0.24; Figs. 4c and 4d). The two age groups may be caused by long-time cooling of this complex massif. Therefore, the younger age is interpreted as the final emplacement time for the K-feldspar granite of the Guangxingyuan Pluton.

Zircon Hf isotope analysis yielded $\varepsilon_{\text{Hf}}(t)$ values of +1.1 to +5.1 with crustal model ages of 882-1089 Ma (Fig. 5; Supplementary Table S2).

5.1.3 Syenite of the Guangxingyuan Pluton

Zircon grains from sample 110718-07 are euhedral, ranging from 100 to 200 μm in length and 60-80 μm in width, with a length/width ratio of 2 to 3, and display wide oscillatory growth zoning in CL images (Fig. 4e). Th/U ratios range from 0.61 to 1.04. All these characteristics indicate a magmatic origin. Twenty-four of the total 25 analyses are concordant, and give an age population from 270 ± 4 Ma to 261 ± 4 Ma (Supplementary Table S1), which yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 265 ± 2 Ma (MSWD = 0.60; Figs. 4e and 4f). This age is interpreted as the emplacement time for the syenite of the Guangxingyuan Pluton.

Zircon Hf isotope analysis yielded $\varepsilon_{\text{Hf}}(t)$ values of -15.5 to +6.7. The calculated crustal model ages of 781-2012 Ma (mostly 781-1087 Ma) (Fig. 5; Supplementary Table S2).

5.1.4 Quartz syenite of the Durenwuliji Pluton

Zircon grains of sample 130610-01 are euhedral, with sizes of 120-200 μm long and 60-80 μm wide, and a length/width ratio of 2 to 3. Most zircon grains display wide

oscillatory growth zoning in CL images (Fig. 4g). Th/U ratios range from 0.49 to 0.93. All these features indicate a magmatic origin. All 25 analyses are concordant (Supplementary Table S1). Except two grains (291 ± 5 Ma and 225 ± 5 Ma), the remaining 23 analyses fall in a cluster between 275 ± 5 Ma to 245 ± 7 Ma (Supplementary Table S1). A weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 261 ± 4 Ma (MSWD = 3.5; Figs. 4g and 4h) is calculated with 20 concentrated analyses. This age is interpreted as the emplacement time for the quartz syenite of the Durenwuliji Pluton.

Zircon Hf isotope analysis yielded $\varepsilon_{\text{Hf}}(t)$ values of +6.2 to +8.9, with crustal model ages of 667-816 Ma (Fig. 5; Supplementary Table S2).

5.2 Whole-rock chemical compositions

The whole-rock chemical data for 23 samples are listed in Table S3. These samples can be divided into two groups according to their distinct mineralogical (alkali-feldspar content) and geochemical (K_2O content, A/NK ratios and REE pattern) features: (1) peralkaline-alkaline rocks (including syenite and K-feldspar granite of the Guangxingyuan Pluton, quartz syenite and syenite of the Durenwuliji Pluton) and (2) calc-alkaline rocks (tonalite of the Guangxingyuan Pluton and MMEs therein).

The LOI (loss on ignition) of most samples are less than 2, except syenite samples and one MME sample from the Guangxingyuan Pluton (Supplementary Table S3), indicating that most samples didn't suffer severe alteration/weathering and their geochemical data are reliable. However, we can still see some secondary minerals in the thin section (Fig. 3). For further identifying the impact of alteration to our samples,

we use A-CN-K diagram ($A=Al_2O_3$, $C=CaO$, $N=Na_2O$, $K=K_2O$; Nesbitt and Young, 1984; 1989) to identify the mineral alteration, CIW diagrams [$CIW=(Al_2O_3/(Al_2O_3+CaO+Na_2O))*100$, molecular ratio; Harnois, 1988] to determine the effects of alteration on major element compositions, and bivariate plots of Zr against selected trace elements to evaluate the mobilities of such elements during alteration (e.g., Polat et al., 2002; Wang et al., 2010). In the A-CN-K diagram (Supplementary Fig. 1), all samples are plotted close to the feldspar join and near the plagioclase point, indicating least alteration effect. The calculated CIW values for studied samples range from 46 to 65 (Supplementary Table S3), indicating insignificant influence of alteration for these samples (Harnois, 1988). Meanwhile, Al_2O_3 , TFe_2O_3 , Na_2O , K_2O , MgO , and P_2O_5 show no correlation with CIW, also implying essential immobility (Supplementary Fig. 2). However, SiO_2 shows slightly positive correlation with CIW, implying that the alteration caused some enrichment in SiO_2 , whereas CaO shows slightly negative correlation with CIW at $CIW>55$, indicating the alteration might result in CaO depletion. The bivariate plots show that REE (e.g., Nd, Yb and Lu), HFSEs (e.g., Nb and Ta) are correlated with Zr, indicating that these elements are immobile during alteration, whereas the LILEs (e.g., Rb, Cs, Sr and Ba) are scattered, implying varying degrees of mobility (Supplementary Fig. 3; Wang et al., 2010).

5.2.1 Peralkaline-alkaline rocks

The syenitic and alkali-granitic rocks exhibit a wide variation of SiO_2 content (57-72%) and high total alkalis ($Na_2O+K_2O = 7.9-12.9\%$; Table S3). All

peralkaline-alkaline samples belong to the alkaline series in the total alkali vs. SiO_2 diagram (figures not shown). Based on the Q' vs. ANOR classification (Streckeisen and Le Maitre, 1979), peralkaline-alkaline samples fall into 5 rock-types: alkali feldspar granite, quartz alkali feldspar granite, alkali feldspar syenite, quartz syenite and quartz monzonite (Fig. 6a). In the K_2O vs. SiO_2 classification diagram (Fig. 6b), all peralkaline-alkaline samples fall into the shoshonite field (Le Maitre, 1989). They display different characteristics in the A/NK vs. A/CNK diagram (Fig. 6c). K-feldspar granites of the Guangxingyuan Pluton are mainly metaluminous ($\text{A/CNK}=0.89\text{-}0.93$, $\text{A/NK}=1.29\text{-}1.51$), and syenites of the Guangxingyuan Pluton are weakly metaluminous to peralkaline ($\text{A/CNK}=0.64\text{-}0.99$, $\text{A/NK}=0.92\text{-}1.09$), while quartz syenite and syenite of the Durenwuliji Pluton are weakly peraluminous ($\text{A/CNK}=1.04\text{-}1.07$, $\text{A/NK}=1.09\text{-}1.13$) (Fig. 6c).

The four kinds of peralkaline-alkaline rocks display very similar chondrite-normalized REE patterns and PM-normalized spidergrams (Fig. 7). All of them are characterized by “typical” granitic patterns with enrichment of light REE and relatively low and near-flat heavy REE, and $(\text{La/Yb})_N$ ratios of about 10 (Fig. 7). The K-feldspar granites and syenites of the Guangxingyuan Pluton present small negative Eu anomalies [$(\text{Eu/Eu}^*)_N = 0.67\text{-}0.88$] (Figs. 7a and 7b). However, the quartz syenite and syenite of the Durenwuliji Pluton show greater negative Eu anomalies [$(\text{Eu/Eu}^*)_N = 0.38\text{-}0.58$] (Figs. 7c and 7d). In the spidergrams, they show depletion in Ba, Nb, Ta, Sr, P and Ti (Fig. 7f-h), which is characteristic of A-type granites (Fig. 7e). In the $\text{K}_2\text{O}+\text{Na}_2\text{O}$ vs. $10000*\text{Ga}/\text{Al}$ and $\text{Zr}+\text{Nb}+\text{Ce}+\text{Y}$ vs. $10000*\text{Ga}/\text{Al}$ diagrams,

peralkaline-alkaline samples fall in the A-type granites field (Figs.9a and 9b; Whalen et al., 1987). In the Y+Nb vs. Rb plot (Pearce et al., 1984), they all fall in the post-orogenic granite field (Fig. 9c).

5.2.2 Calc-alkaline rocks

The tonalite samples show SiO₂ (63-64 %) and Na₂O+K₂O (5.5 -5.9 %) lower than the peralkaline-alkaline rocks. They belong to the subalkaline series (Fig. 6a), and fall into the Medium-K series in the K₂O vs. SiO₂ discrimination diagram (Fig. 6b). The tonalites are metaluminous with high A/NK value ($A/CNK = 0.92-1.00$, $A/NK = 2.13-2.37$) (Fig. 5c).

The MMEs display low SiO₂ (49-56%) and relatively high Na₂O+K₂O (4.8-6.3%), straddling the boundary of alkaline-subalkaline series in the total alkali vs. SiO₂ plot (Figure not shown). In the K₂O vs. SiO₂ plot, they fall into the Medium- and High-K series (Fig. 6b). Like the host tonalite, the MME's are metaluminous with high A/NK value ($A/CNK = 0.82-0.94$, $A/NK = 1.73-2.92$) (Fig. 6c).

The tonalite and MMEs present very similar REE patterns and spidergrams (Figs. 8a and 8b). They show moderate enrichment in light REE, $((La/Yb)_N = 3.4-9.6)$ and absence of significant Eu anomalies $[(Eu/Eu^*)_N = 0.81-1.00]$. One MME sample (KQ-02) shows slightly positive Eu anomaly $[(Eu/Eu^*)_N = 1.09]$ (Figs. 8a and 8b). In the spidergrams, depletion of Th, Nb, Ta and P are noticeable (Fig. 8c and 8d). The overall patterns are similar to that of peralkaline-alkaline intrusions, except for the absence of negative Ba and Sr anomalies (Figs. 7 and 8). In the K₂O+Na₂O vs. $10000 \cdot Ga/Al$ and Zr+Nb+Ce+Y vs. $10000 \cdot Ga/Al$ diagrams, tonalite samples fall in

the I- and S-type granite field (Figs.9a and 9b; Whalen et al., 1987). In the Y+Nb vs. Rb diagram (Pearce et al., 1984), they all fall in the volcanic arc granite field (Fig. 9c).

6. Discussion

6.1 The Middle Permian alkaline rocks along the northern margin of NCC

In the past few years, a number of Middle Permian peralkaline-alkaline intrusions have been reported from the Siziwangqi-Xianghuangqi and Hexigten-Chifeng areas. These intrusions form an alkaline magmatic belt in parallel with the northern margin of NCC (Fig. 2a). As shown in Fig. 2a, this belt is sub-parallel with the Late Carboniferous-Early Permian alkaline rock belt, about 200 km to the north, and nearly along the China-Mongolia border. The Middle Permian intrusions have geochemical features akin to A-type granite and are probably related to post-collisional extension (Liu et al., 2011; Zhang et al., 2009; Jiang et al., 2013). Furthermore, calc-alkaline intrusions also occurred contemporaneously and in association with peralkaline-alkaline intrusions. They are composed mainly of granite and tonalite, and show typical I-type granitic geochemical characteristics. The calc-alkaline intrusions are considered as syn-collisional granites (Fan et al., 2009; Zhang et al., 2009; Liu et al., 2010b; Meng et al., 2013).

The contemporaneity and close association of peralkaline-alkaline and calc-alkaline intrusions have led to controversial explanations about the tectonic setting of the northern margin of NCC during the Middle Permian. The controversy

has also confused the reader about the Late Paleozoic evolution of the southeastern CAO. Here we try to solve the controversy and propose a petrogenetic model and a suitable tectonic setting.

6.2 Petrogenesis

Several petrogenetic models have been proposed for the generation of peralkaline-alkaline intrusions: (1) fractional crystallization of mantle-derived basaltic magmas (e.g., Eby et al., 1998; Frost et al., 1999; Litvinovsky et al., 2002, 2015; Wang et al., 2005; Bonin et al., 2007; Jahn et al., 2009); (2) mixing of mantle-derived basaltic magma with continental crust (e.g., Mingram et al., 2000; Wu et al., 2002; Vernikovsky et al., 2003; Kemp et al., 2005); and (3) partial melting of crustal rocks (e.g., King et al., 1997; Tchameni et al., 2001; Martin, 2006).

The lack of inherited zircon crystals (Fig. 4) and dominance of positive $\epsilon_{\text{Hf}}(t)$ (Fig. 5a) suggest that the peralkaline-alkaline granitoids from the Guangxingyuan and Durenwuliji plutons could not be generated only by partial melting of crustal rocks (Clemens et al., 1986; Eby, 1990). The large span of $\epsilon_{\text{Hf}}(t)$ values from -15 to +7 of the Guangxingyuan Pluton also precluded the direct derivation by fractional crystallization of mantle-derived basaltic magmas. Moreover, the syenitic intrusions have Th/Ce ratios (0.14-0.26), that fall between the values of the Global Subducting sediments (0.12) and Archean shale (0.22) (Hawkesworth et al., 1997), but significantly higher than that of MORB (0.016) and OIB (0.052; Sun and McDonough, 1989). This also argues against a direct generation of the alkaline-peralkaline magmas from fractional crystallization of mantle-derived basaltic magmas. Some intermediate

processes must have occurred. For the Guangxingyuan Pluton in Hexigten, the large ranges of zircon Hf model ages (T_{DM}^C)(781-2012 Ma; mostly 781-1266 Ma), and $\epsilon_{Hf}(t)$ values (-15.5 to +6.7; mostly 0 to +5), suggest the input of crustal component during the magma differentiation (e.g., Griffin et al., 2002; Jahn et al., 2014). This kind of Hf isotopic heterogeneity can be produced by mixing of mantle-derived mafic magma with crust-derived felsic magma or contamination of crustal material (e.g., Griffin et al., 2002; Yang et al., 2007; 2012). For the crustal contamination, inherited zircon grains can be commonly identified (Griffin et al., 2002; Yang et al., 2012). However, in our study, no inherited zircon grain was found from any pluton (Fig. 4). Therefore, mixing of mantle-derived mafic magma with crust-derived felsic magma seems a better mechanism for the Hf isotopic heterogeneity of the Guangxingyuan Pluton. By contrast, the Durenwuliji Pluton in Xianghuangqi shows rather restricted ranges of Hf model age (667-816 Ma) and $\epsilon_{Hf}(t)$ values(+6.2 to +8.9). Although the $\epsilon_{Hf}(t)$ values are positive, they are significantly lower than that of the depleted mantle (Fig. 5), thus involvement of older crustal rocks in the generation of syenite is also implied (e.g., Jahn et al., 2014). Therefore, the peralkaline rocks of Durenwuliji pluton were derived mainly from mantle-derived mafic magma mixed with less amount of crust-derived magma. The Hf isotopic differences between the Guangxingyuan and Durenwuliji Plutons can be ascribed to the presence of Proterozoic basement in the Hexigten area in which the Guangxingyuan Pluton occurs (IMBGM, 1991; Li et al., 2008).

The spidergrams of peralkaline-alkaline rocks show negative anomaly in Ba, Nb-Ta, Sr, P and Ti (Fig. 7). The anomaly is generally attributed to the fractionation of

accessory minerals, such as titanite and ilmenite (for Ti), magnetite, ilmenite and amphibole (for Nb-Ta), apatite (for P), and some major phases, such as feldspars (for Sr). The large Sr negative anomalies in the spidergrams (Fig. 7), and the large negative Eu anomalies in the REE patterns of the peralkaline-alkaline intrusions probably indicate fractionation of feldspars in the petrogenesis. This is supported by the Rb/Sr and Ba versus Sr diagrams (Fig. 10a and 10b; Rollinson, 1993; Yang et al., 2008), in which they plot along the plagioclase fractionation trends.

In addition, published geochemical studies have well demonstrated that the mantle component beneath Inner Mongolia has gone through strong metasomatism due to the subduction of Paleo-Asian Ocean (Liu et al., 2012; Pan et al., 2013; Zou et al., 2014). The geochemistry and isotopic features of Triassic high-Mg andesites from Linxi (Inner Mongolia) suggest that it could be derived from a subducted Paleo-Asian oceanic slab with sediments shed from the NCC (Liu et al., 2012). Meanwhile, the geochemical studies of Cenozoic Xilinhote alkali basalt from central Inner Mongolia demonstrated a moderately refractory lithospheric mantle beneath the Xing'an and Songliao Blocks, which was significantly influenced by the melt/fluid-peridotite interactions caused by the Paleo-Asian Ocean subduction (Pan et al., 2013; Zou et al., 2014). The metasomatized mantle might serve as the primitive magma source for the Permian magmatic rocks.

The experimental study of Clemens et al. (1986) suggested that the generation of peralkaline-alkaline rocks requires a high melting temperature ($> 900\text{ }^{\circ}\text{C}$). This high temperature regime could be realized by the emplacement of mantle-derived mafic

magma or upwelling of asthenosphere at the base of continental crust (Yang et al., 2008). The mantle contribution is supported by mafic microgranular enclaves within both peralkaline-alkaline intrusions (Zeng et al., 2012) and calc-alkaline intrusions (e.g., the tonalite of the Guangxingyuan Pluton (this study; Zhang et al., 2009).

Tonalite is commonly generated in island arc setting through partial melting of mafic lower crust that experienced alteration due to subducting slab (e.g., Selbekk et al., 2002; Molina et al., 2012; Castro, 2013). However, in this study, tonalite is situated within the peralkaline-alkaline magmatic belt and constitutes a composite pluton with contemporaneous peralkaline-alkaline rocks. Hence, the generation of tonalite might be not directly related to subduction. A petrogenesis in non-subduction setting should be considered to explain the existence of tonalite within the peralkaline-alkaline magmatic belt. Note that both the peralkaline-alkaline intrusions and tonalite were located in the Early Paleozoic Bainaimiao Arc, which was formed through southward subduction of the Paleo-Asian Ocean beneath the northern margin of the North China Craton (Jian et al., 2008; Zhang et al., 2013). The Early Paleozoic arc magmatic rocks display a wide range of $\epsilon_{\text{Nd}}(t)$ from -10 to +6 and $\epsilon_{\text{Hf}}(t)$ values from -10 to +11 (Jian et al., 2008; Zhang et al., 2014a). Based on the isotopic characteristics, Zhang et al. (2014a) proposed that a Precambrian basement existed beneath the Bainaimiao Arc. As aforementioned, the mantle component beneath the Bainaimiao Arc has been metasomatized during the subduction of the Paleo-Asian Ocean. The lower crust beneath the Bainaimiao Arc might have experienced the same metasomatism (Fig. 11a). A New study on the Permian quartz diorite and

syenogranite in the Xianghuangxi area led Yang et al. (2015) to propose that modification took place on both the mantle and lower crust beneath the Bainaimiao Arc due to the subduction of the Paleo-Asian Ocean. In the Early Permian, due to the asthenosphere upwelling, partial melting of the metasomatized mantle produced peralkaline-alkaline intrusions, whereas partial melting of the subduction modified lower crust island arc mafic rocks generated tonalite (Fig. 11b). Early Paleozoic mafic rocks in the Bainaimiao Arc, such as basalt and gabbro (Jian et al., 2008; Zhang et al., 2013), might provide the source rocks for the generation of tonalite. The wide range of zircon Hf model ages and $\epsilon_{\text{Hf}}(t)$ values of tonalite (Fig. 5) suggest crustal assimilation during the magma differentiation. Meanwhile, remelting of these enriched arc magmatic rocks may have also contributed to the enriched isotopic characteristics of Permian tonalite and peralkaline-alkaline rocks. Partial melting of both metasomatized mantle and subduction modified lower crust can explain the coexistence of contemporaneous peralkaline-alkaline and calc-alkaline intrusions along the northern margin of the North China Craton (e.g., Yang et al., 2015).

Zeng et al. (2012) carried out a Sr-Nd-Pb isotopic study on the Middle Permian syenogranite porphyry from northwestern Chifeng area (Fig. 2a). The syenogranitic rocks have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7057-0.7068, $\epsilon_{\text{Nd}}(t)$ values of -10 to -12, and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of 17.23 to 17.48, indicating that the parental magma was derived from partial melting of a Precambrian basement triggered by upwelling of mantle-derived mafic magma (Zeng et al., 2012).

6.3 Tectonic implication

The peralkaline-alkaline rocks usually occurred in post-collisional, post-orogenic, and anorogenic rift settings (Sylvester, 1989; Bonin, 1990). The present features of peralkaline-alkaline rocks in southern Inner Mongolia are typical of post-orogenic alkaline granitoids (Bonin et al., 1998). In the K_2O+Na_2O vs. $Ga/Al \times 10,000$ and $Zr+Nb+Ce+Y$ vs. $Ga/Al \times 10,000$ plots (Whalen et al., 1987), the peralkaline-alkaline samples fall in the field of A-type granite, whereas the tonalites in the field of I- and S-type granites (Figs. 9a and 9b). In the Rb vs. Y+Nb diagram (Pearce et al., 1984; Pearce, 1996), the peralkaline-alkaline samples plot in the post-orogenic granite field, while the tonalites fall in the field of volcanic arc granites (Fig. 9c). The same characteristics have been revealed by previous studies of the Middle Permian granitoids along the north margin of NCC (Fan et al., 2009; Zeng et al., 2012; Jiang et al., 2013; Meng et al., 2013).

The coexistence of peralkaline-alkaline A-type granite and MMEs-bearing calc-alkaline I-type granitoids can be found in other orogens, such as the post-Variscan orogenic magmatism in the Alps (Bonin, 2004) and non-subduction magmatism in East Junggar (Liu et al., 2013a). In the Late Paleozoic Variscan belt along the Alpine-Apenninides, post-collisional and post-orogenic intrusions yielded association of medium- to high-K calc-alkaline to alkaline and peralkaline signatures, with mafic microgranular enclaves (Poli and Tommasini, 1991; 1999; Bonin et al., 1998; Bonin, 2004). In East Junggar, underplating caused the melting of an older subducted oceanic crust, together with significant magma mixing of continental crust, producing the coexisting A-type granites and MMEs-bearing I-type granitoids in

non-subduction environment (Liu et al., 2013a).

The timing of the Paleo-Asian Ocean closure in southeastern CAOBS has been debated for decades and no consensus has been reached. Broadly, there are two schools of thought: (1) the first considered that the final closure occurred in the Late Devonian based mainly on unconformable contact between Late Devonian molassic deposits and ophiolitic mélangé, and their different deformation styles (Tang, 1990; Xu et al., 2013; 2015). The molassic deposition was followed by extension-related Late Carboniferous-Early Permian A-type granite (Shi et al., 2004; Luo et al., 2009; Zhang et al., 2014b), A-type rhyolite (Chen et al., 2014), bimodal volcanic rocks (Zhang et al., 2008; 2011; Tang et al., 2011) and mafic intrusions (Zhao et al., 2011; Chen et al., 2012); (2) The second proposed that the ocean closure took place in a Late Permian-Early Triassic time on the basis of geochemistry and geochronological studies of Late Paleozoic mafic-ultramafic rocks and granitoids, which display OIB/MORB and arc-like geochemical affinities, respectively (Chen et al., 2000; Miao et al., 2007; 2008; Zhang et al., 2009; Liu et al., 2013b).

The Late Carboniferous-Early Permian intrusive and extrusive rocks are widely distributed in the whole central Inner Mongolia (IMBGMR, 1991), which is distinguishable from the linearly distributed arc magmatic rocks. The generation of the Early Permian A-type granites can be precluded from subduction environment (Shi et al., 2004; Luo et al., 2009; Zhang et al., 2014b). The alkaline magmatic belt along the north margin of NCC also indicates an extensional setting during the Middle Permian. Hence, these features of Carboniferous-Permian magmatism are in favor of

the Late Devonian closure of the Paleo-Asian Ocean, followed by post-orogenic extension. The hypothesis of the Late Devonian ocean closure may be supported by recent studies of the Late Carboniferous-Early Permian sedimentation in central Inner Mongolia (Zhao et al., 2015). The Late Carboniferous-Early Permian strata in central Inner Mongolia display a consistent unconformable contact with underlying rocks, and upward deepening sequence from coarse-grained clastic rocks to stable carbonate deposition, indicating an extensive transgression on a welded continent and being considered as the first stable sedimentary cover after the Late Devonian amalgamation (Zhao et al., 2015).

In addition, paleomagnetic studies performed on the Devonian-Permian strata from the Songliao Block show that this block was located at the northern margin of NCC ever since the Late Devonian (Zhao et al., 2013). Meanwhile, paleomagnetic data obtained for the Late Carboniferous strata from the northern margin of NCC and southern margin of Xing'an Block present a consistent paleolatitude, indicating that Xing'an Block was situated close to NCC during the Late Carboniferous (Li et al., 2012). In recent paleontological studies, the mixture of Cathaysia flora with Angara flora was identified from both the Upper Carboniferous-Lower Permian and Lower-Middle Permian strata in East-Ujimqin (near China-Mongolia border; Zhou et al., 2010; Xin et al., 2011). All the data shown above favor the Late Devonian closure of the Paleo-Asian Ocean.

6.4 Late Paleozoic peralkaline-alkaline rock belts in eastern CAOB

Three huge Late Paleozoic peralkaline-alkaline rock belts have been documented

from the eastern segment of the CAOB (Fig. 1b). From north to south, they are North Mongolian–Transbaikalian Belt (No. 1 in Fig. 1b), South Mongolia-Xing’an Belt (No. 2 and 8 in Fig. 1b), and Northern margin of North China Craton Belt (No. 9 in Fig. 1b). The main characteristics of the three belts are summarized in Table 3.

These belts are composed mainly of peralkaline-alkaline granitic and syenitic rocks, and bimodal volcanic rocks with associated calc-alkaline granotoids and a few mafic intrusions (Table 3). The magmatic rocks are emplaced from the Late Carboniferous to Middle Permian, with an age peak in the Early Permian (Table 3). This contemporaneous emplacement indicates an important peralkaline-alkaline magmatic event in the eastern segment of CAOB. Whole-rock Sr-Nd and zircon Hf isotopic results suggest the important contribution of mantle for the generation of these magmatic rocks (Table 3; Jahn et al., 2009). In addition, pre-Permian evolution of the Paleo-Asian Ocean has resulted in strong metasomatism on the mantle component beneath the eastern segment of CAOB (e.g., Tong et al., 2015). Therefore, the metasomatized mantle is considered as the primitive magma for the Permian magmatic rocks (Table 3; Zeng et al., 2012; Tong et al., 2015). In most cases, mixing of mantle-derived magmas and crustal components was considered to be the most suitable model for the generation of peralkaline-alkaline magmatic rocks (e.g., Jahn et al., 2000; 2009). The emplacement of these magmatic rocks was commonly considered in an extensional setting (intracontinental rift or post-orogenic extension), which is beneficial of extensive mantle upwelling and underplating (Hong et al., 1994; 1996; Jahn et al., 2000; Yarmolyuk et al., 2008; Tong et al., 2015). Consequently,

large-scale continental extension might occur in eastern segment of CAOBB during the Late Carboniferous-Permian. The extension resulted in voluminous intraplate magmatism, which was probably a significant process of continental growth in Central Asia during the Phanerozoic (Jahn et al., 2000; 2009).

7. Conclusions

Based on the newly obtained zircon U-Pb ages, geochemical and Hf isotopic data, we draw the following conclusions:

(1) LA-ICP-MS zircon U-Pb dating revealed that the emplacement of Guangxingyuan Pluton and Durenwuliji Pluton syenitic intrusions and MMEs-bearing tonalite took place in the Middle Permian (261-267 Ma).

(2) The geochemical and Hf isotopic features of the peralkaline-alkaline intrusions indicate that the parental magma was formed by mixing of metasomatized mantle-derived with various amounts of crust-derived magma, and followed by fractional crystallization.

(3) A Permian post-orogenic extension was proposed to account for the peralkaline-alkaline intrusions following the amalgamation of NCC and its northern blocks in the southeastern part of Central Asian Orogenic Belt (CAOB).

(4) The closure of the Paleo-Asian Ocean outboard the northern NCC most likely occurred in the Late Devonian.

Acknowledgements:

We thank Zhang Chenhao, Wang Yanyang, Liao Wen and Luo Zhiwen for their

support in the field and in the lab. We appreciate very much the constructive and detailed comments and suggestions by Dr. M.L. Kuybida and other two anonymous reviewers that significantly improved this manuscript. This work has been funded by the National Key Basic Research Program of China (2013CB429806), the National Science Foundation of China (40872145 and 41121062). Bor-ming Jahn acknowledges the support of the Ministry of Science and Technology (MOST) of Taiwan through research grants MOST 103-2116-M-002-013 and MOST104-2923-M-002-005.

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Figure and Table caption:

Table 1. Geochronological data for the Middle Permian peralkaline-alkaline intrusions

along northern margin of North China Craton.

Table 2. Lithology and mineralogy of studied intrusions.

Table 3. Comparison of main characteristics of Late Paleozoic peralkaline-alkaline rock belts in eastern CAOB.

Figure 1. (a) Tectonic sketch map of Central Asian Orogenic Belt (after Sengor et al., 1993 and Windley et al., 2007) (b) Distribution of the Late Paleozoic and Mesozoic granitoid belts in the Central Asian Orogenic Belt (after Jahn et al., 2009). The map area corresponds to the rectangle of the inset map. Granite belts: 1 = Mongolian–Transbaikalian, 2 = Great Xing'an, 3 = Zhangguangcai, 4 = Jiamusi, 5 = Gobi–Altai, 6 = Main Mongolian Lineament, 7 = Eastern Kazakhstan, 8 = Gobi–Tien Shan, 9 = Northern margin of North China Craton.

Figure 2. (a) Sketch geological map of central Inner Mongolia showing the location of two Silurian-Devonian suture zones (Southern Suture zone and Northern Suture zone) (compiled from Xu et al., 2013); XAB: Xing'an-Airgin Sum Block; SHB: Songliao-Hunshandake Block; NCC: North China Craton. The Permian strata, alkaline rocks and granitic rocks were highlighted in this map (compiled from IMBGM, 1991). Age data of Permian alkaline rocks can be found in Table 1. (b) Geological map of the Guangxingyuan Pluton in southern of Hexigten. (c) Geological

map of the Durenwuliji Pluton in northern of Xianghuangqi.

Figure 3. Field photographs and photomicrographs of Guangxingyuan Pluton (a-f) and Durenwuliji Pluton (g-h). (a) Field photograph of MME-bearing tonalite, the diameter of MMEs ranging from 2-50 cm; (b) photomicrograph of tonalite; (c) photomicrograph of MME; (d) photomicrograph of K-feldspar granite; (e) and (f) field photograph and photomicrograph of syenite; (g) and (h) field photograph and photomicrograph of quartz syenite. Hb: hornblende; Pl: plagioclase; Kfs: K-feldspar; Q: quartz.

Figure 4. U-Pb concordia diagrams and weighted mean age plots of tonalite (a and b), K-feldspar granite (c and d), syenite (e and f) and quartz syenite (g and h). The inset CL images showing the internal texture of dated zircons. The yellow circles show the dated points, the diameter of which is 32 μm .

Figure 5. (a) Histograms of $\varepsilon\text{Hf}(t)$ and (b) Hf model ages for zircon grains from Guangxingyuan and Durenwuliji Plutons.

Figure 6. Geochemical classification diagrams for Guangxingyuan Pluton and Durenwuliji Pluton. (a) Q' vs. ANOR diagram (after Strackeisen and Le Maitre, 1979); (b) SiO_2 - K_2O diagram (after Le Maitre, 1989); (c) A/NK vs. A/CNK diagram (after Maniar and Piccoli, 1989).

Figure 7. Chondrite-normalized REE patterns and Primitive mantle-normalized spider diagrams of K-feldspar granite (a and e) and syenite (b and f) of Guangxingyuan Pluton, and quartz syenite (c and g) and syenite (d and h) of Durenwuliji Pluton. Chondrite and N-MORB normalizing values from Sun and McDonough (1989), respectively.

Figure 8. Chondrite-normalized REE patterns and Primitive mantle-normalized spider diagrams of tonalite (a and c) and MMEs (b and d) of Guangxingyuan Pluton.

Figure 9. (a) Diagram of $10,000 \cdot \text{Ga}/\text{Al}$ vs. $\text{K}_2\text{O} + \text{Na}_2\text{O}$ (after Whalen et al., 1997). (b) Diagram of $10,000 \cdot \text{Ga}/\text{Al}$ vs. $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ (after Whalen et al., 1997). (c) Y+Nb vs. Rb discrimination diagram (after Pearce, 1996). VAG: volcanic arc granites; ORG: ocean ridge granites; WPG: within-plate granites; syn-COLG and post-COLG: syn- and post-collision granites.

Figure 10. Rb/Sr (a) and Ba vs. Sr (b) diagrams show plagioclase-dominated fractionation in the evolution of the syenitic magma. Fractionation trends for different minerals are from Yang et al., 2008.

Figure 11. Schematic cartoons show the tectonic setting and the petrogenetic model of

the Permian contemporaneous peralkaline-alkaline and calc-alkaline intrusions along the northern margin of North China Craton (including the Bainaimiao Arc). a. During the Early Paleozoic, southward subduction of the Paleo-Asian slab resulted in the formation of the Bainaimiao Arc along the northern margin of the North China Craton. The subduction also resulted in the metasomatism of the mantle and modification of the lower crust beneath the Bainaimiao Arc; b. During Permian: the upwelling of asthenosphere mantle, probably due to the post-orogenic crustal extension, caused the partial melting of the metasomatized mantle with mixing of different amount of crust-derived magma to produce the peralkaline-alkaline intrusions, and might trigger the partial melting of the lower crustal island arc basaltic magma to generate the calc-alkaline rocks (e.g., tonalite in this study).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

a) Cambrian-Silurian

b) Permian

Table 1

Table 1. Geochronological data for the Middle Permian peralkaline-alkaline intrusions along north margin of North China Craton.

Sample no.	Location	Name of plutons	Rock type	Age (Ma)	Method	Reference
KLDR	Aohanqi	Kelidai	monzogranite	263±1	LA-ICP-MS	Luo et al., 2014
C270	W. of Chifeng	Chehugou	syenogranite porphyry	266±4	SIMS	Zeng et al., 2012
WET22	W. of Ondor Sum	Wuertagaolemiao	hornblende-syenite	271±18	LA-ICP-MS	Liu et al., 2011
WET14	W. of Ondor Sum	Wuertagaolemiao	monzogranite	256±3	LA-ICP-MS	Liu et al., 2011
WRT19	W. of Ondor Sum	Wuertagaolemiao	syenogranite	261±2	LA-ICP-MS	Liu et al., 2011
SZW07-15	N. of Siziwangqi	Xihouhaozi	monzogranite	266±2	SIMS	Meng et al., 2013
HK3	N. of Xianghuangqi	Hadamiao	granite porphyry	271±3	SHRIMP	Liu et al., 2014
BJG1	W. of Siziwangqi	Beijige	syenogranite	264±3	LA-ICP-MS	Liu et al., 2010a
XN09-203	S. of Xianghuangqi	Houerdagou	miarolitic K-feldspar granite	263±2	LA-ICP-MS	Hao, 2012
09WJ-GTHF-110	NW. of Xianghuangqi	Bilihe	K-feldspar granite porphyry	264	LA-ICP-MS	Lu et al., 2012
JN-51	NW. of Xianghuangqi	Wulanhada	K-feldspar granite	265±2	LA-ICP-MS	Jiang et al., 2013
130610-01	NW. of Xianghuangqi	Durenwuliji	quartz syenite	261±4	LA-ICP-MS	This study
130619-10	S. of Hexigten	Guangxingyuan	K-feldspar granite	257±3	LA-ICP-MS	This study
110718-07	S. of Hexigten	Guangxingyuan	syenite	265±2	LA-ICP-MS	This study
NM08-59	N. of Damaoqi		syenogranite	268±2	LA-ICP-MS	Feng et al., 2013
06B241	Bayan Obo		K-feldspar granite	266±4	LA-ICP-MS	Fan et al., 2009
06B242	Bayan Obo		K-feldspar granite	268±5	LA-ICP-MS	Fan et al., 2009
06B180	Bayan Obo		monzogranite	269±5	LA-ICP-MS	Fan et al., 2009
06B129	Bayan Obo		monzogranite	263±4	LA-ICP-MS	Fan et al., 2009

Table 2

Table 2 Lithology and mineralogy of studied intrusions

Location	Pluton name	Rock type	Age (Ma)	Texture	Structure	Mineralogy
S. Hexigten	Guangxingyuan	tonalite	267 ± 1	Midium-grained granitic	Massive	Pl (45%) + Qtz (30%) + Am (15%) + Bt (5%)
		MME		Fine-grained granitic	Massive	Pl (50%) + Am (40%) +Bt (5%) +Px (5%)
		K-feldspar granite	257 ± 3	Coarse-grained granitic	Massive	Kfs (50%) + Qtz (30%) + Pl (10%) +Am (5%)
		syenite	265 ± 2	Coarse-grained	Massive	Kfs (80%) + Pl (15%) +Qtz (5%)
NW. Xianghuangqi	Durenwuliji	Quartz syenite	261 ± 4	Coarse-grained	Massive	Kfs (70%) + Qtz (15%) +Pl (10%)
		syenite		Coarse-grained	Massive	Kfs (80%) + Pl (10%) + Qtz (5%)

Mineral: Pl=plagioclase, Kfs=K-feldspar, Qtz=quartz, Bt=biotite, Am=amphibole, Px=pyroxene.

Table 3. Comparison of main characteristics of Late Paleozoic peralkaline-alkaline rock belts in eastern CAO

	North Mongolia - Transbaikalian Belt	South Mongolia - Xing'an Belt	Northern margin of North China Craton Belt
Intrusive age	270-310 Ma	270-310 Ma	260-300 Ma
Rock types	Syenite, K-feldspar granite, peralkaline granite, A-type granite, bimodal volcanic rocks	Syenite, K-feldspar granite, peralkaline granite, A-type granite, bimodal volcanic rocks	Syenite, K-feldspar granite, peralkaline granite, A-type granite,
Sr-Nd isotope	$\epsilon_{\text{Nd}}(t) = -4.9 \sim -0.3$ $T_{\text{DM}}^{\text{C}} = 1062 \sim 1454 \text{ Ma}$	$\epsilon_{\text{Nd}}(t) = +1.2 \sim +6.5$ $T_{\text{DM}}^{\text{C}} = 429 \sim 886 \text{ Ma}$	$\epsilon_{\text{Nd}}(t) = -9.6 \sim -12.4$ $T_{\text{DM}}^{\text{C}} = 1590 \sim 2690 \text{ Ma}$
Zircon Hf isotope	No data	$\epsilon_{\text{Hf}}(t) = +4.9 \sim +17.1$ $T_{\text{DM}}^{\text{C}} = 275 \sim 988 \text{ Ma}$	$\epsilon_{\text{Hf}}(t) = -15.8 \sim +8.9$ $T_{\text{DM}}^{\text{C}} = 671 \sim 2150 \text{ Ma}$
Magma source	Enriched mantle mixing with crustal components	metasomatized mantle	Metasomatized mantle and remelting of Precambrian basement
Tectonic setting	Intracontinental rift / post-orogenic extension	Intracontinental rift / post-orogenic extension	Post-orogenic extension
Data source	Litvinovsky et al., 2002; 2011; Jahn et al., 2009	Hong, et al., 1994; 1996; Yarmolyuk et al., 2008; Zhang et al., 2015; Tong et al., 2015	This study; Zeng et al., 2012; Luo et al., 2009; Wang et al., 2009; Mo et al., 2014