SCIENCE CHINA
Earth Sciences

SPECIAL TOPIC: Origin of granites and associated mineralization
• RESEARCH PAPER •

November 2017 Vol.60 No.11: 1959–1975
doi: 10.1007/s11430-016-9069-0

Late Mesozoic magmatism and tectonic evolution in the Southern margin of the North China Craton

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Received December 13, 2016; accepted June 6, 2017; published online July 20, 2017

Abstract Late Mesozoic granitic magmatism (158–112 Ma) are widespread in the southern margin of the North China Craton (NCC), contemporary with many world-class Mo-Au-Ag-Pb-Zn polymetallic deposits. There are abrupt changes in the elements and isotopic compositions of these granites at about 127 Ma. The early stage (158–128 Ma) granites show slightly or no negative Eu anomalies, large ion lithophile elements enriched and heavy REE depleted (such as Y and Yb), belonging to typical I-type granite. The late stage (126–112 Ma) granites are characterized by A-type and/or highly fractionated I-type granite, with higher contents of SiO_2, K_2O, Y, Yb and Rb/Sr ratio and lower contents of Sr, δEu value and Sr/Y ratio than that of the early-stage granites. Moreover, the whole rock Nd and Hf isotopic compositions of the granites younger than 127 Ma show more depleted than those of the older one. The two stages of Late Mesozoic granites were derived from a source region of the ancient basement of the southern margin of the NCC incorporated the mantle material. The late stage (126–112 Ma) granites contain more fractions of mantle material with depleted isotopic composition than the early ones. The granites record evidence for a strong crust-mantle interaction. They formed in an intracontinental extensional setting which was related to lithospheric thinning and asthenospheric upwelling in this region, which was possibly caused by westward subduction of the Paleo-Pacific plate. 127 Ma is an critical period of the transformation of the tectonic regime.

Keywords Southern margin of the North China Craton, Late Mesozoic, Granite, Origin, Tectonic evolution

Citation: Gao X Y, Zhao T P. 2017. Late Mesozoic magmatism and tectonic evolution in the Southern margin of the North China Craton. Science China Earth Sciences, 60: 1959–1975, doi: 10.1007/s11430-016-9069-0

1. Introduction

Large amount of geological, geophysical and geochemical data indicate that the North China Craton (NCC) underwent craton destruction and lithospheric thinning during the Mesozoic-Cenozoic, and more than 100 km of the ancient lithosphere may have been destroyed and removed beneath the NCC (e.g. Peng et al., 1986; Basu et al., 1991; Menzies et al., 1993; Fan et al., 2000; Kusky et al., 2007; Yang et al., 2008a; Zhu et al., 2011). Tectonic regime of the NCC transformed from compression in Triassic to extensional environment in Late Jurassic-Cretaceous, accompanied by extension structure (metamorphic core complex) (e.g. Zhang and Zheng, 1999; Davis et al., 2002; Liu et al., 2005), rifted basin (e.g. Ritts et al., 2001; Ren et al., 2002), voluminous mafic to felsic magmatism and large-scale Mo-Au-Ag polymetallic mineralization (e.g. Chen et al., 1998; Mao et al., 2011; Li et al., 2012a; Zhai and Santosh, 2013; Goldfarb and Santosh, 2014).

Southern margin of the NCC also records intensive tectonic-magmatic activity during the late Mesozoic, with development of voluminous felsic igneous rocks (e.g. Mao et al., 2010; Gao et al., 2014a, 2014b; Wang X X et al., 2015; Bao et al., 2017) and many large-scale Mo-Au-Ag-Pb-Zn ore deposits (e.g. Mao et al., 2011; Deng et al., 2014; Bao et al., 2017) (Figure 1). The Late Mesozoic igneous rocks are

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important for constraining their genesis and magma source evolution, with spatial-temporal distribution and mechanism of lithospheric thinning and genetic relationship with ore deposits in the southern margin of the NCC. Therefore, petrogenesis of the Late Mesozoic granites in southern margin of the NCC has been concerned about for years.

In the last decade, study of the Mesozoic magmatism, especially origin of the granites related with ore deposits has made a great progress and accumulated relatively abundant materials about the geochronology and geochemistry (e.g. Gao X Y et al., 2010; Mao et al., 2010; Ding et al., 2011; Wang et al., 2011; Gao et al., 2012; Li N et al., 2012; Zhao et al., 2012; Gao et al., 2014a, 2014b; Wang X X et al., 2015; Bao et al., 2017). However, the magma source, geodynamics setting and its bearing on collapse of the Qinling Orogenic Belt and/or lithosphere thinning environment resulted from subduction of the Paleo-Pacific Plate are still debated.

Therefore, based on systematic summarization of petrology, geochronology, elemental and isotopic geochemistry data of the Late Mesozoic igneous rocks, we investigated their magma source and dynamic mechanism by studying the spatial-temporal evolution and rock association characteristics.

2. Geological background

The southern margin of the NCC confined by the Sanmenxia-Lushan Fault to the north and Luonan-Luanchuan Fault to the south (Figure 1b), shares the same basement-cover sequence to the NCC, namely the Archean to early Paleoproterozoic basements and the overlying late Paleoproterozoic to Phanerozoic unmetamorphosed cover sequence. The regional tectonic are dominated NE-trending superimposed NE to NNE-trending structural. The region was involved in the tectonic movement and has become a significant part of the Qinling Orogenic Belt after continental collision between the North China Craton (NCC) and the Yangtze Craton (YZC) occurred during the early Mesozoic (Wu and Zheng, 2013) (Figure 1b). As a zone of transition between stable craton and orogenic belt, its formation and evolution is closely related to the tectonic development of both the Qinling Orogenic Belt and the NCC.

The basement of the southern margin of the NCC is represented by the Neoarchean-Paleoproterozoic Taihua Group (2.26–2.84 Ga) that is composed of metamorphic rocks, such as amphibolite, felsic gneiss, migmatite, and metamorphosed supracrustal rocks (Kröner et al., 1988; Wan et al., 2006; Xu X S et al., 2009; Huang X L et al., 2010, 2012). The Taihua Group is unconformably overlain by the Xiong'er Group that is up to 7600 m thick and covers area of >60000 km^2 (Zhao T P et al., 2004). The Xiong'er Group formed in the period of 1.75–1.78 Ga (Zhao T P et al., 2004) and consists mainly of intermediate to acidic lavas and pyroclastic rocks intercalated with minor sedimentary rocks (<5%). The Xiong'er Group is covered by the Mesoproterozoic littoral facies terrigenous clastic rocks of the Guandaokou and Ruyang Groups, Neoproterozoic neritic facies clastic-carbonate rocks and alkaline volcanic rocks of the Luanchuan and Luoyu Groups, and sporadical Sinian, Cambrian and Cretaceous System strata. Since the beginning of the Cretaceous, lacustrine or alluvial sediments began to develop in the region (Figure 1b).

The Late Mesozoic magmatic rocks are mainly Triassic and Late Jurassic-Early Cretaceous (Figure 1c). The Triassic magmatic rocks, are composed of quartz monzonite, quartz diorite, monzonitic granite and syenogranite. They sporadically occurred in Xiaoqinling and Xiong'ershan area in west part of the southern margin of the NCC, including Laoniushan composite pluton (228–214 Ma, Ding et al., 2011; Qi et al., 2012), Wengyu pluton (205 Ma, Hu et al., 2012) in Xiaoqinling area and Zhaiwa granitic dyke (217.7 Ma, Li H M et al., 2012) in Xiong'ershan area.

The Late Jurassic-Early Cretaceous magmatic rocks are widespread in the southern margin of the NCC (Figure 1c), and they occur generally in forms of both large batholiths and small porphyritic bodies. The large exposed composite batholiths are produced by multi-episodes of magma, whose main rock type is porphyritic biotite monzonitic granite, biotite granite and syenogranite. The small porphyritic bodies are spatially, temporally, and genetically associated with the porphyry-skarn Mo deposits. The ore related granite porphyries are commonly small in size, with outcrop areas of less than 1 km^2. They are obviously controlled by faulted structure and distribute in groups or belts along the fault zone.

3. Geochronological framework

Numerous geochronological studies have been made for the Late Mesozoic magmatic rocks in the southern margin of the NCC. Appendix Table S1 (http:earth.scichina.com) presents a compilation of representative zircon U-Pb ages for the granitic plutons, volcanic rocks and mafic dykes in the region.

The granitic plutons have zircon U-Pb ages that range from 158 to 112 Ma, lasting for nearly 50 years (Appendix Table S1, Figure 2). There are also sporadic mafic rocks which are contemporary with granites and ore deposits. Zircon U-Pb age dates suggest that the mafic rocks were formed at about 148 to 117 Ma, with peak ages of 129–117 Ma (Xie et al., 2007; Bao et al., 2009; Zhao et al., 2010b; Gao et al., 2014a). As shown in Appendix Table S1 and Figure 2, the Late Mesozoic magmatisms in the southern margin of the NCC can be divided into two episodes: Late Jurassic to Early Cretaceous and Late Early Cretaceous.

The Late Jurassic to Early Cretaceou magmatism (158–128 Ma) are composed of 14 composite batholiths and 32 small

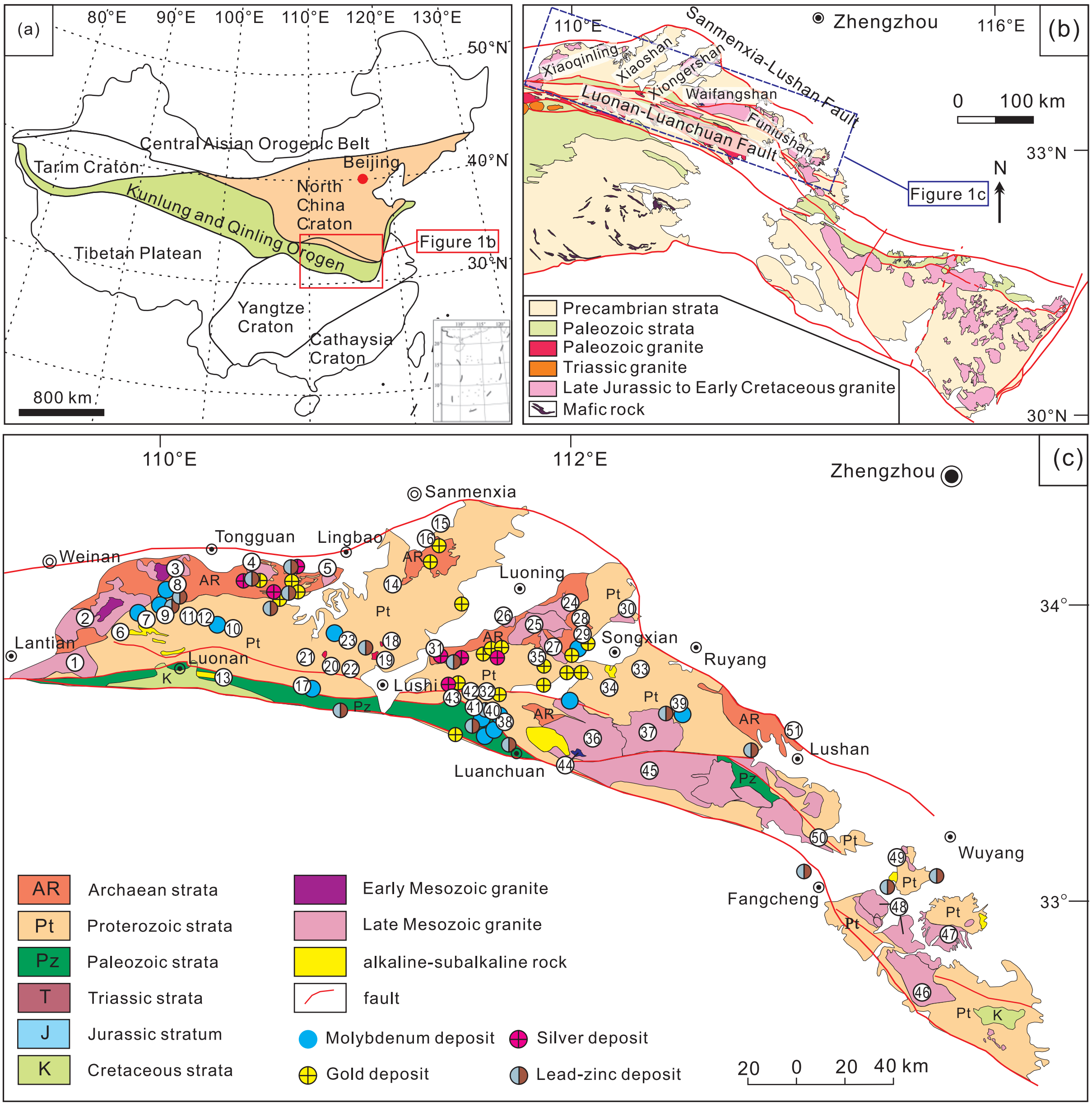

Figure 1 Distribution of the Mesozoic granitoids and deposits in the Souther margin of the the North China Craton. (a) Simplified tectonic map of China showing major tectonic phases surrounding the North China Craton and the location of the Qinling Orogen Belt. (b) Geological map of the Qinling Orogen Belt (modified from Zhang et al., 1996). (c) Distribution of the Mesozoic granitoids and deposits in the Souther margin of the the North China Craton. (NO. of the granites as same as Appendix Tables S1–4 (http://earth.scichina.com).

porphyritic granites, widely distributed all over the region (Figure 1c, Appendix Table S1). The composite batholiths are produced by multi-episodes of magma, from west to east in the region including Lantian, Huashan, Wenyu and Niangniangshan pluton in the Xiaoqinling area, Huashan, Haoping and Wuzhangshan pluton in the Xiong'ershan area, Heyu, Taishanmiao and Shibaogou in the Waifangshan area, Huangshan, Zushiding and Zhangshiying pluton in the Funiushan area (Appendix Table S1). These unmetamorphism and undeformation rocks are mainly composed of porphyritic or non-porphyritic monzonitic granite and syenogranite, and consist of K-feldspar, plagioclase, quartz, biotite and amphibole. Accessory minerals include magnetite, titanite, apatite and zircon. Formation of the batholiths always lasted for millions of years. The structure and types of different episodes intrusion of the composite batholiths show a regularly changed with time, such as the phenocryst or grain size progressively grew smaller.

The porphyritic granites, outcrop areas of less than 1.5 km^2, are composed of granite porphyry and k-feldspar granite porphyry, with typical porphyritic texture, i.e., Jinduicheng, Huanglongpu, Yechangping, Leimengou and Nannihu porphyritic granites. They are spatially, temporally, and genetically associated with the regional mineralization,

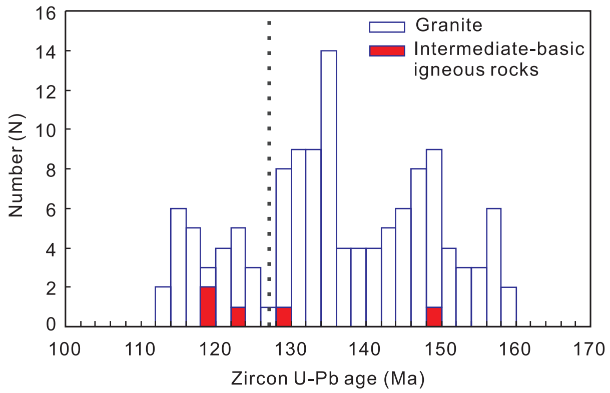

Figure 2 Zircon U-Pb age histograms of the Late Mesozoic magmatic rocks in the Southern margin of the North China Craton. Data source as same as Appendix Table S1.

especially molybdenum.

Mafic rocks, dominated by dykes or stocks, only sporadically occur in local regions such as Huanglongpu in Xiaoqinling area and Xigou lead-zinc ore district in Waifangshan area, with forming ages of 129 Ma and 148 Ma respectively (Bao et al., 2009; Zhao et al., 2010b) (Appendix Table S1).

The Late Early Cretaceous magmatism (126–112 Ma) are composed of 3 composite batholiths and 3 small porphyritic granites, and mainly outcropped in the east part of the southern margin of the NCC, including Taishanmiao, Funiushan and Jiaozishan composite batholiths, and Donggou, Zhangshiying and Shanggusi porphyritic granites (Figure 1c, Appendix Table S1). They are composed of syenogranite, monzonitic granite and quartz syenite. Mafic rocks were also developed in this period such as the Tianqiaogou diorite in Waifangshan area (122 Ma, Gao et al., 2014a), basic volcanic rock of Daying Group in the Baofeng Basin (117 Ma, Xie et al., 2007) and lamprophyre dykes intruded into the Funiushan pluton in Funiushan area (116 Ma, Gao, 2012). Moreover, the Late Mesozoic magmatic rocks in this region trend to be younger in ages from west to east according to the representative zircon U-Pb ages (Appendix Table S1).

The tectonic activity and widely developed granitic rocks exert an important influence on mineralization in the region. Besides spatially coexisting, the Late Mesozoic ore deposits in the southern margin of the NCC were dominantly formed in an interval from 157 to 115 Ma, contemporary with the magmatism (e.g., Wang et al., 2001, 2002; Mao et al., 2008; Jiao et al., 2009; Li et al., 2009; Yao et al., 2009; Gao Y L et al., 2010; Huang F et al., 2010; Liu et al., 2011; Li N et al., 2012; Li et al., 2012a, 2012b; Tang K F et al., 2013; Deng et al., 2014; Tang, 2014).

Late Mesozoic magmatic rocks crop out not only in the southern margin of the NCC but also in the vast region of eastern China. Late Jurassic to Early Cretaceous magmatic rocks occurred intensively in the Dabie-Sulu orogenic belt (e.g. Xue et al., 1997; Hacker et al., 1998; Zhao Z F et al., 2004; Yang et al., 2005; Wu et al., 2005a; Xie et al., 2006; Wang et al., 2007; Xu et al., 2007; Zhao D P et al., 2007). The Late Jurassic intrusive rocks (142–161 Ma) in the Dabie-Sulu orogenic belt sporadic crop out in the eastern part of the Sulu Orogen and are mainly composed of granodiorite, monzonitic granite and garnet-bearing leucogranite (Hu et al., 2004; Guo et al., 2005). Most of the Mesozoic magmatic rocks in the Dabie Sulu orogenic belt were formed in the Early Cretaceous, with forming ages of about 111–143 Ma and peak ages of 125–130 Ma (Zhao and Zheng, 2009). Furthermore, the Early Cretaceous magmatic rocks in the Dabie orogen also can be subdivided into two episodes with respect to their emplacement time: the early episode of rocks was emplaced principally before 130 Ma, with varying degrees of structural deformation (locally gneissic foliation) (e.g. Ma et al., 2004; Wang et al., 2007; Xu et al., 2007); the late episode of rocks was emplaced primarily during 130–111 Ma, without considerable deformation (Jahn et al., 1999; Zhao Z F et al., 2004, 2007; Xie et al., 2006; Xu et al., 2007).

In the Liaodong Peninsula, about 30000 km^2 of Mesozoic intrusive rocks have been identified, along with minor volcanic rocks. These intrusions can be mainly divided into two discrete events: Jurassic (180–156 Ma) and Early Cretaceous (131–113 Ma), although minor Triassic magmatism (233–210 Ma) is also recorded (Wu et al., 2005b; Yang et al., 2008b). The Jurassic intrusive rocks in the Liaodong Peninsula are mainly granitoids, but lack of mafic intrusions (Wu et al., 2007; Xu Y G et al., 2009). The Early Cretaceous (131–113 Ma) magmatic rocks is predominantly A-type granites with some I-type ones, alkaline rock and mafic dykes, accompanied by large scale Au ore deposits (Yang et al., 2006, 2008b).

In conclusion, Late Mesozoic magmatic rocks in the southern margin of the NCC consist with the forming ages of the magmatic rocks in the Dabie-Sulu orogenic belt and Liaodong Peninsula, suggesting same response of Late Mesozoic geological event in eastern part of NCC, and the vast region of eastern China.

4. Geochemical characteristics

4.1 Element geochemistry

The rock types of the granitic plutons consist mainly of monzogranite, granodiorite, and syenogranite. The granites are commonly alkaline rich with features of high-K calc-alkaline and shoshonitic (Figure 3) and metaluminous to peraluminous (Figure 4). The major element contents of the rocks increase with increasing SiO_2 showing linear trends on Harker diagrams (Figure 5a–f). The lack of significant compositional gaps in the Harker diagrams suggests that the main petrogenetic process operative in their origin is likely to be partial

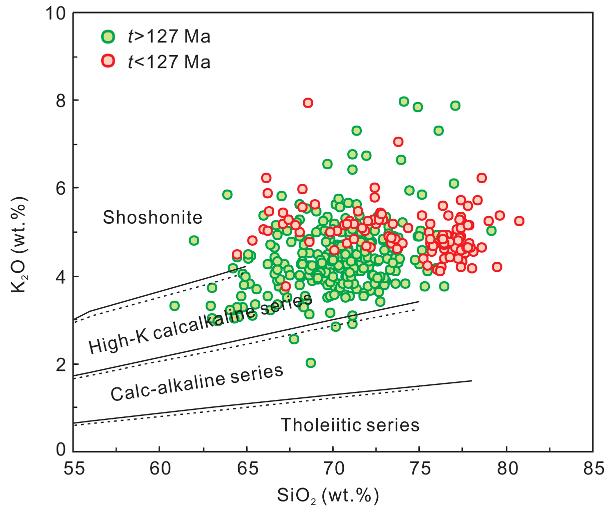

Figure 3 K_2O-SiO_2 diagram of the of the Late Mesozoic granitoids in the Southern margin of the North China Craton. Boundary line: Peccerillo and Taylor (1976), Middlemost (1985). Data sources: Ye et al. (2008), Zhou et al. (2008), Zhou (2008), Zhu et al. (2008), Bao et al. (2009, 2014), Dai et al. (2009), Guo et al. (2009), Jiao et al. (2009), Ni (2009), Xiang (2009), Xu (2009), Yao et al. (2009), Gao X Y et al. (2010), Li and Bao (2010), Zhao et al. (2010a, 2010b), Wang et al. (2011), Gao et al. (2012, 2014a, 2014b), Hu et al. (2012), Yang (2012), Zhao H X et al. (2012), Qi et al. (2012), Xiao E et al. (2012), Xiao H et al. (2012), Yang et al. (2013), Zhu et al. (2013), Ke et al. (2013), Li L et al. (2013), Li T G et al. (2013), Yang Z F et al. (2014), Li et al. (2014), Lu et al. (2014), Qi (2014), Wang C M et al. (2015), Duan et al. (2015), Lai (2015), Liang and Lu (2015), Zhang D T et al. (2015), Zhang X K et al. (2015), Wang et al. (2016).

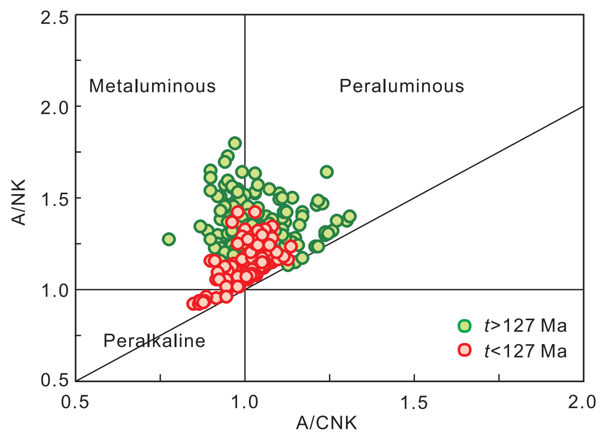

Figure 4 A/NK-A/CNK diagram of the of the Late Mesozoic granitoids in the Southern margin of the North China Craton. Boundary line: Maniar and Piccoli (1989); data sources as same as Figure 3.

melting of source rocks with widely varied chemical compositions.

In addition, it is strikingly noteworthy that there are abrupt changes in the element compositions of granites at about 127 Ma. We collected almost all available geochemical data for these Late Mesozoic granites, and the ages show two groups, at 158–128 Ma and 126–112 Ma (Figures 6 and 7), indicating two major stages of granitic magmatisms. The early stage granites (158–128 Ma) have high contents of large ion lithophile elements (LILEs) (such as K, Rb, Sr, Ba) and high field strength elements (HFSEs). They show light REE enriched, slightly or no negative Eu anomalies (δEu=0.66–1.49) (Figure 6a), and heavy REE depleted (such as Y and Yb) (Figure 8). They are typical I-type, calc-alkaline to shoshonitic, and metaluminous to slightly peraluminous granites (Figures 3 and 4).

The second-stage (126–112 Ma) are characterized by A-type and/or highly fractionated I-type, alkaline, and metaluminous to peraluminous granitoids (Figures 3 and 4). The rocks have higher contents of SiO_2 and total alkali (K_2O+Na_2O) than that of the first-stage granites. They are enriched in light REE, and show moderate to large negative Eu anomalies, enrichment of Y and Yb, and depletion of Sr and Ba (Figure 6b).

As shown, content or ratio of elements from the granitic rocks changed dramatically and rapidly in about 127 Ma, such as granitic rocks younger than 127 Ma have higher contents of Y, Yb and Rb/Sr ratio, but lower Sr, δEu and Sr/Y ratio (Figure 7a–f).

4.2 Isotope geochemistry

Whole rock Sr, Nd, Pb and zircon Hf isotopic data of the Late Mesozoic granites are listed in Appendix Tables S2 and S3, Figures 8–10. The rocks have uniform $^{87}Sr/^{86}Sr$ ratios ranging from 0.7050–0.7236, $(^{206}Pb/^{204}Pb)_i$, $(^{207}Pb/^{204}Pb)_i$ and $(^{208}Pb/^{204}Pb)_i$ values from 15.659–18.720, 15.344–15.656 and 36.110–38.707 respectively. Whole rock Nd and zircon Hf isotope compositions of the Late Mesozoic granites, which are characterized by very low $\varepsilon_{Nd}(t)$, $\varepsilon_{Hf}(t)$ and old T_{DM2} values varying mainly in the range of $\varepsilon_{Nd}(t)$=−7.5–−22.1, $T_{DM2(Nd)}$=1.55–2.74 Ga, $\varepsilon_{Hf}(t)$=−1.9–−35.7, and $T_{DM2(Hf)}$=1.29–3.38 Ga, suggest an ancient crustal origin (Appendix Table S3). Their widely variable isotopes suggest a heterogeneous source. Moreover, the whole rock $\varepsilon_{Nd}(t)$ values ($\varepsilon_{Nd}(t)$= −7.5– −17.3) of granites younger than 127 Ma are higher than those of the older ones ($\varepsilon_{Nd}(t)$=−7.6–−22.1) (Figure 8). Consistent with this, granites younger than 127 Ma have systematically higher $\varepsilon_{Hf}(t)$ values of −1.9 to −20.8 and lower crustal Hf model ages of 1.29 to 2.49 Ga than the older ones of −3.4 to −35.1 and 1.46 to 3.38 Ga (Figure 9). Thus, the younger granites contain more fractions of mantle material with depleted isotopic composition than the older ones.

5. Magma source

Voluminous Late Mesozoic magmatic rocks are spatially and genetically associated with many world-class ore deposits (Mao et al., 2008; Zhu et al., 2009; Chen and Wang, 2011; Li et al., 2012a; Deng et al., 2014). Studies concerning the magma source of these igneous rocks have important implications for tracing the ore-forming material source. Although

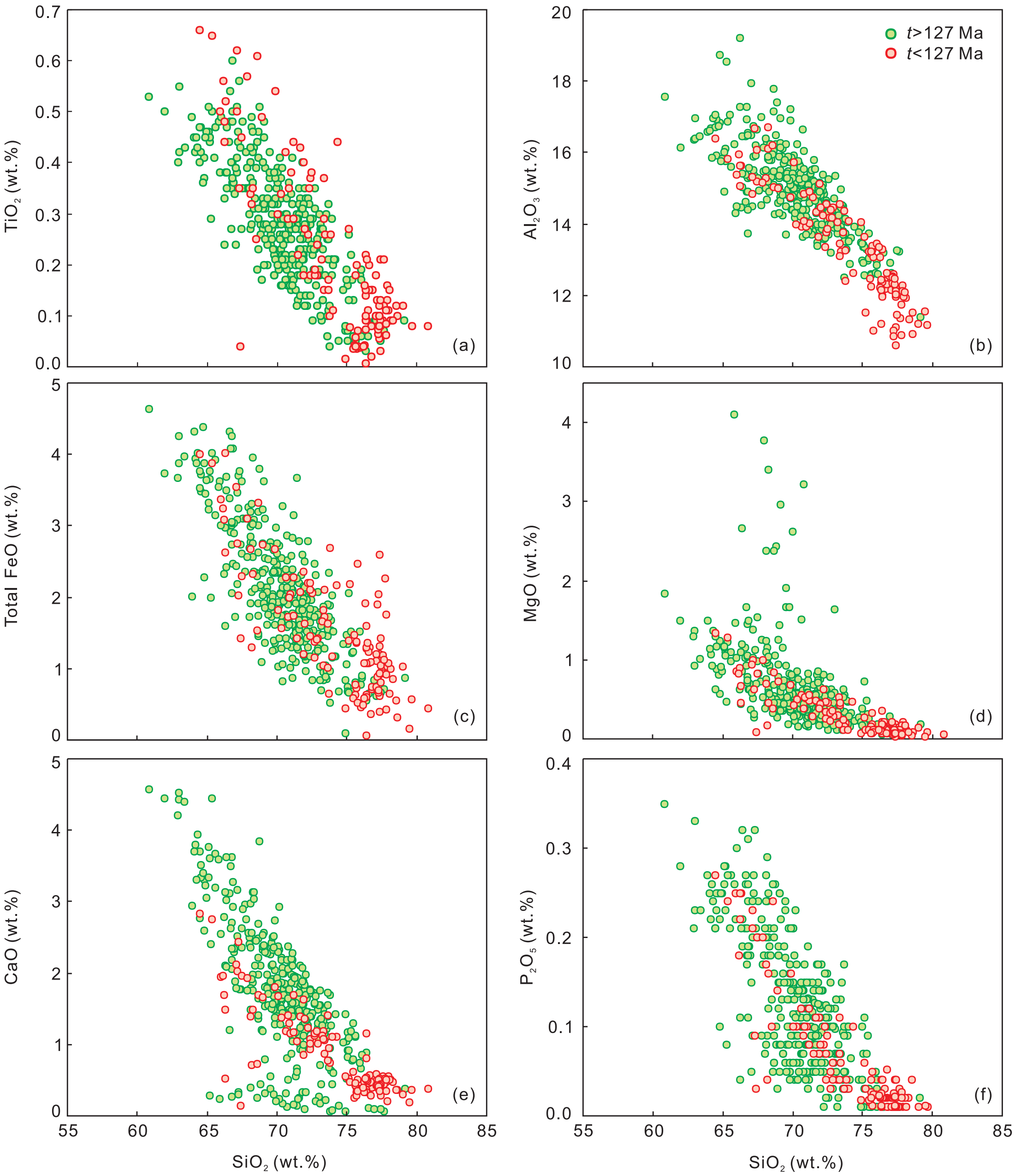

Figure 5 Major oxides vs. SiO_2 diagram of the Late Mesozoic granitoids in the Southern margin of the North China Craton. Data sources as same as Figure 3.

the Late Mesozoic granites show a large variation in chemical compositions, they have the similar Sr-Nd-Pb-Hf isotopic compositions and their magma sources are isotopically continental crust (Appendix Table S2). The granites were generally considered to be produced by partial melting of the NCC ancient crystalline basement (e.g. Taihua Group), with mixed with the juvenile lithospheric mantle or ashospheric mantle derived melts (e.g. Hu et al., 2012; Li N et al., 2012; Gao et al., 2014a, 2014b; Wang X X et al., 2015), or the subducted continental crust of the northern margin of the Yangtze Craton (e.g. Li L et al., 2013; Bao et al., 2014, 2017).

Late Mesozoic granites in the Southern margin of the North China Craton have similar initial $^{87}Sr/^{86}Sr$ values to those of the amphibolites of the Taihua Group (Xu X S et al., 2009; Ni et al., 2012) and the volcanic rocks from the Xiong'er Group at 130 Ma (Peng et al., 2008; He et al., 2010; Wang et al., 2010), but lower than those of the gneiss and quartz schists from the Taihua Group (Huang and Wu, 1990) (Figure 10). Their $\varepsilon_{Nd}(t)$ values are also close to those of the amphibolite of the Taihua Group, but obviously higher than those of gneiss and quartz schists of the Taihua Group and volcanic rocks of the Xiong'er Group (Figure 10).

The protoliths of the Taihua Group were formed in the Neoarchean and Paleoproterozoic (2.84–2.26 Ga), and were

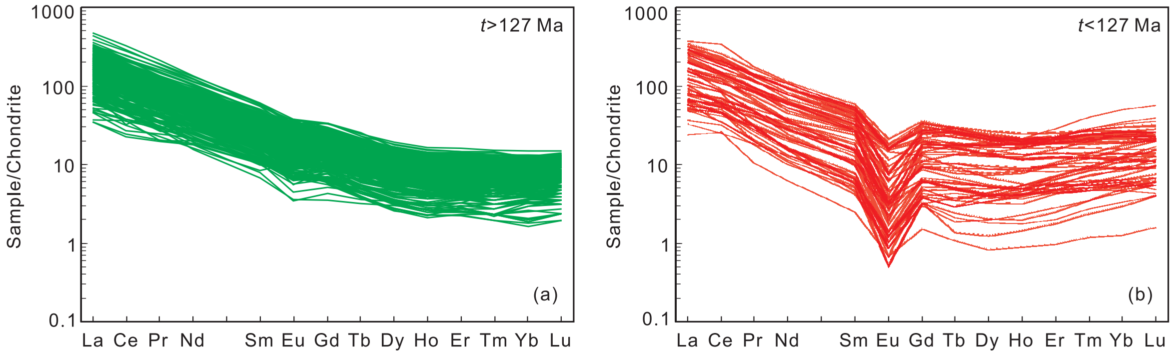

Figure 6 Chondrite-normalized REE patterns of the Late Mesozoic granitoids in the Southern margin of the North China Craton. The normalization values are from Sun and McDonough (1989); data sources as same as Figure 3.

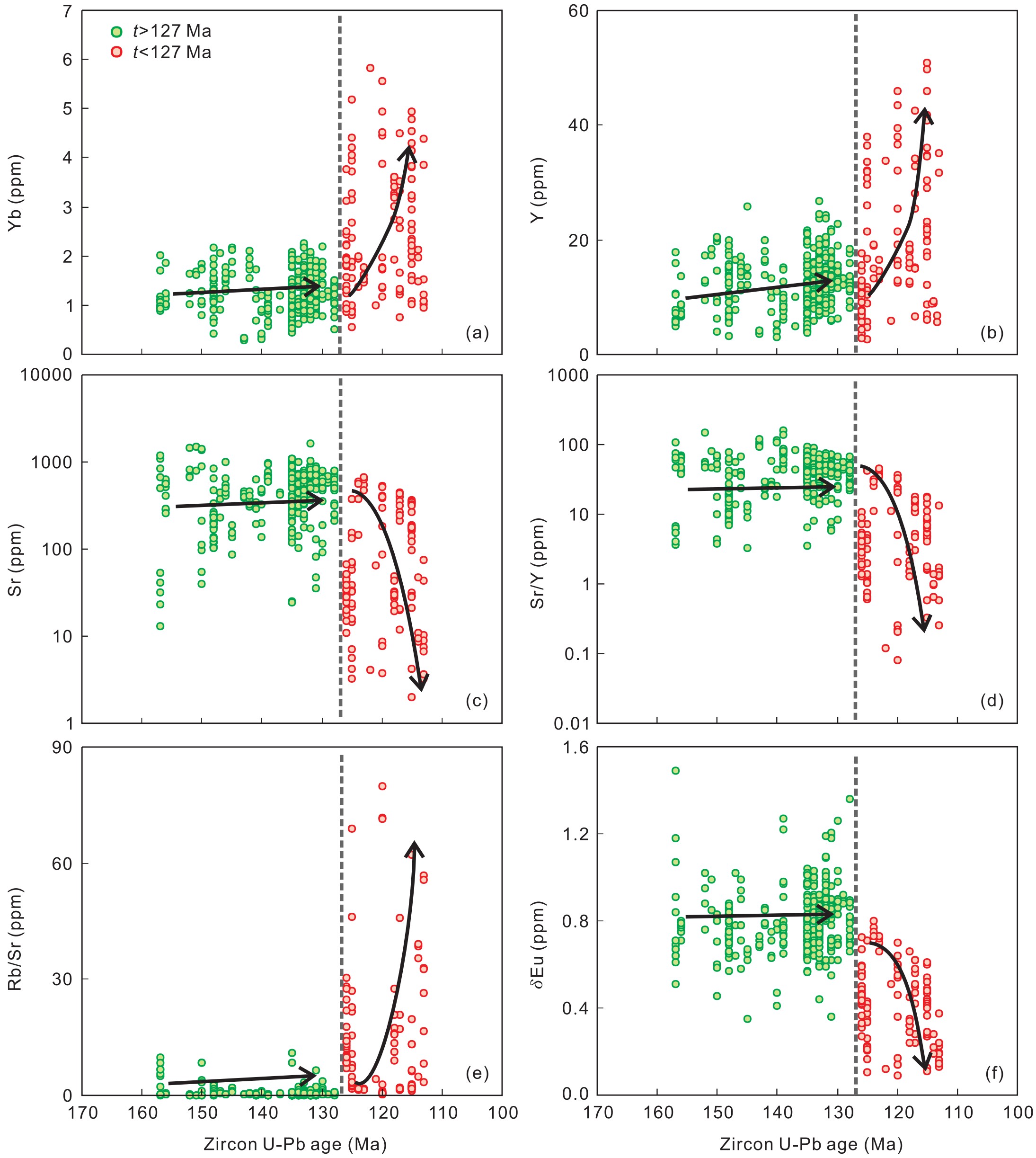

Figure 7 Bivariate plots of trace element versus U-Pb ages for the Late Mesozoic granitoids in the Southern margin of the North China Craton. Data sources as same as Figure 3.

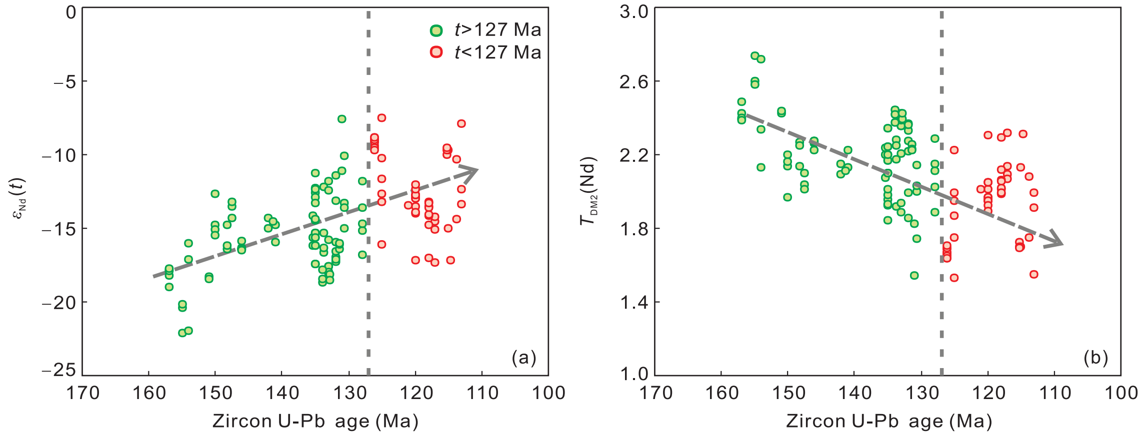

Figure 8 $\varepsilon_{Nd}(t)$ and T_{DM2}(Nd) vs. age diagrams of the Late Mesozoic granitoids in the Southern margin of the North China Craton. Data sources as same as Appendix Table S3.

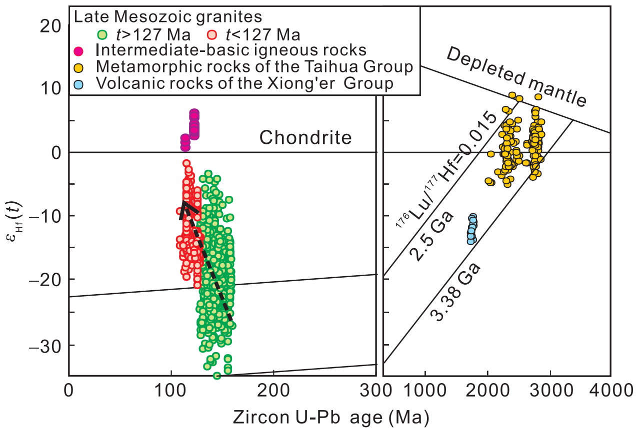

Figure 9 Zircon Hf isotopic compositions of the Late Mesozoic granitoids in the Southern margin of the North China Craton. Data sources: Dai et al. (2009), Guo et al. (2009), Yao et al. (2009), Gao X Y et al. (2010), Zhao et al. (2010a), Wang et al. (2011), Gao et al. (2012, 2014a, 2014b), Hu et al. (2012), Li H Y et al. (2012), Li N et al. (2012), Zhao H X et al. (2012), Qi et al. (2012), Xiao E et al. (2012), Yang Y et al. (2012), Cheng et al. (2013), Ke et al. (2013), Yang et al. (2013), Zeng et al. (2013), Bao et al. (2014, 2017), Wang X X et al. (2015), Wang C M et al. (2015), Duan et al. (2015), Zhang X K et al. (2015), Wang et al. (2016).

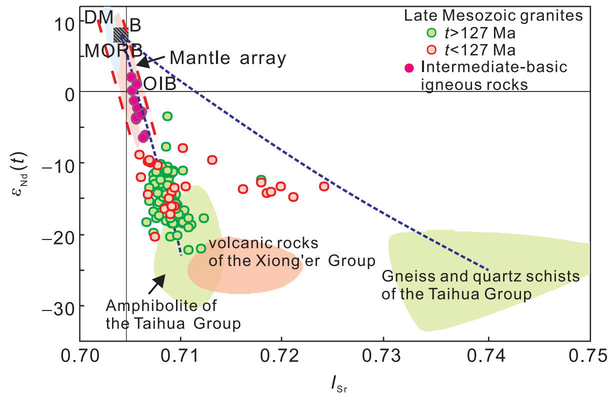

Figure 10 Whole rock Sr-Nd isotopic compositions of the Late Mesozoic granitoids in the Southern margin of the North China Craton. (The $\varepsilon_{Nd}(t)$ and I_{Sr} values of the amphibolite and gneiss and quartz schists of the Taihua and intermediate to acidic volcanic rocks of the Xiong'er Group is calculated a t=120 Ma. The mixing parameters used are: Amphibolite of Taihua Group are from Huang and Wu (1990) and Ni et al. (2012); gneiss and quartz schists of the Taihua Group are from Huang and Wu (1990); intermediate to acidic volcanic rocks of the Xiong'er Group are from He et al. (2010), Peng et al. (2008), Wang et al. (2010); mantle-derived basaltic magma (B) are from Jahn et al. (1999); DM (depleted mantle) and mantle array are after Hart and Zindler (1986); OIB and MORB data are from Sun and McDonough (1989); other data are from Appendix Table S4.

strongly deformed and metamorphosed at 2.1–1.8 Ga, with the isotopic model ages of 2.8–3.2 Ga (Kröner et al., 1988; Wan et al., 2006; Xu X S et al., 2009). Another widespread lithologic unit in the region is the Xiong'er Group that formed at 1.75 to 1.80 Ga (Zhao T P et al., 2004). Dominated age records of the NCC are similar to the two-stage model ages ($T_{DM(Nd)2}$=1.55–2.74 Ga; $T_{DM(Hf)2}$=1.29–3.38 Ga) of the Late Mesozoic granites (Figure 9). Based on the isotopic compositions and model ages, metamorphic basement rocks of the southern margin of the NCC were probably the dominant source rocks for Late Mesozoic granites. In addition, some zircons have Hf two-stage model ages of 1.6–2.5 Ga which are much younger than that of the Taihua Groups, and their $\varepsilon_{Hf}(t)$ values are also higher than those of the rocks from the Taihua Group and Xiong'er Group during the Late Mesozoic. Especially, the $\varepsilon_{Hf}(t)$ values of late stage granites almost fall above the Hf isotopic evolutionary line in Figure 9. This evidence indicates that melting of the Taihua Group metamorphic basement rocks alone cannot produce the parental magma of the Late Mesozoic granites.

High-quality zircon U-Pb data of the metamorphic basement rocks reveal that important age groups in the NCC occurred in three episodes (2.4–2.5 Ga, 1.7–1.9 Ga and 2.0–2.2 Ga), dominantly during Archean (Zhao et al., 2001; Gao et al., 2004; Xu et al., 2006). Abundant inherited zircons with Neoarchean to paleoproterozoic (2.7–1.7 Ga) U-Pb ages further support the probability that the Late Mesozoic granites are closely related to the Taihua Group in magma source (Figure 11, Appendix Table S4).

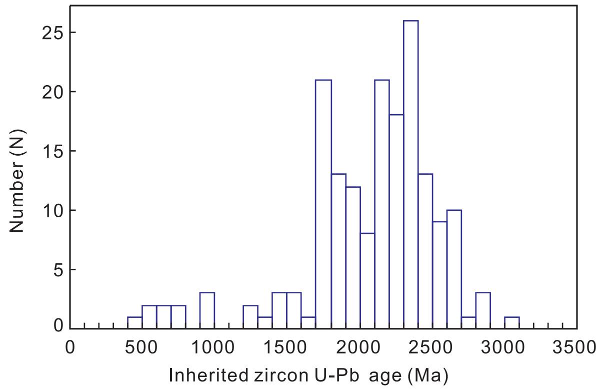

Figure 11 Inhered zircon U-Pb age histogram of the Late Mesozoic granites in the Southern margin of the North China Craton. Data are from Appendix Table S4.

Unlike the crustal growth history of the southern margin of the NCC, the northern margin of the YZC primarily exhibits Mesoproterozoic to Neoproterozoic, the Early Paleozoic and Late Triassic of crustal growth (Yang et al., 2007; Zhang et al., 2007; Ling et al., 2008; Wang et al., 2013). These ages doesn't correspond to both the Hf isotopic second-stage model ages (1.29–3.38 Ga) and major forming ages of the inherent zircon (2.7–1.7 Ga) of the Late Mesozoic granites, suggesting that the northern margin of the YZC was less likely to be the source of these rocks. Furthermore, Pb isotopic compositions of the Late Mesozoic granitiods from Dabie orogen belt which came from partial melting of the subducted lithosphere material of the northern margin of the YZC have been collected. Granites from the Dabie orogen belt and the southern margin of the NCC generally show different isotopic composition, with only a small overlap (Figure 12). In conclusion, the Late Mesozoic granites in the region was derived from a source region of the basement of the NCC incorporated the material with more depleted isotopic composition.

Many researches considered that mantle magma played an important role in the Late Mesozoic magmatism-mineralization, not only supplying heat but also materials for the formation and mineralization of the granites and ore deposits. Han et al. (2013) suggests the decrease of magma oxygen fugacity was probably associated with an increase of mantle contribution to granitic magmatism and metallogenesis, which probably gave rise to successive mineralization of Mo and Au in the eastern Qinling, by researching the zircon Ce^{4+}/Ce^{3+} ratios of ore-related porphyries. Zhu et al. (2009) conclude that the ore-forming materials of the deposits in the East Qinling molybdenum belt are derived from the deep source by the mixing of lower crust and upper mantle from the stable and Pb isotopic composition, and ore-bearing potential of the porphyry and the regional stratum.

Sporadic Late Mesozoic basic magmatic rocks have been reported, including gabbro vein (148±2 Ma) in Xigou ore district, Huanglongpu diabase vein (129±2 Ma), Tianqiaogou diorite (122±2 Ma), Daying Group andesite (117±2 Ma) and Funiushan lamprophyre dyke(117±2 Ma) (Appendix Table S1). The basic magmatic rocks, contemporary with the granites, are direct evidence for curst-mantle interaction of the Late Mesozoic magmatism in the region. Granites have the Sr-Nd isotopic data along the mixing line of the amphibolite of Taihua Group and mantle-derived basaltic magma (Figure 10), indicating the rocks underwent different degrees of crust-mantle mixing. Furthermore, there are abrupt changes in the isotopic compositions of these rocks at about 127 Ma. Nd and Hf isotopic compositions of the granites younger than 127 Ma show more depleted and younger model ages than those of the older ones, suggesting that the younger granites

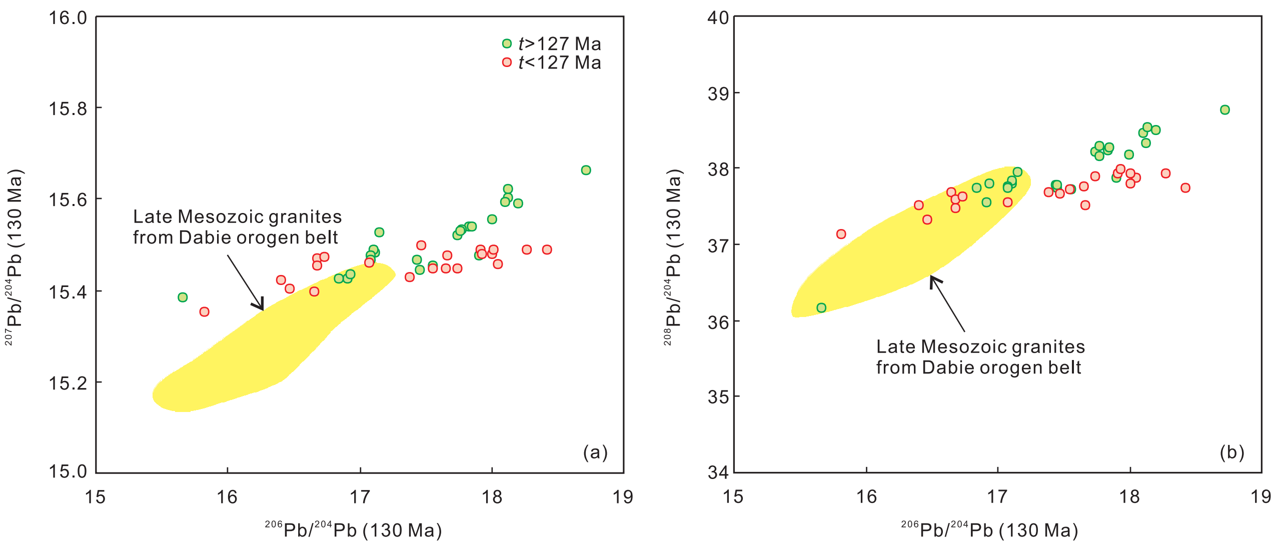

Figure 12 Pb isotopic composition of the Late Mesozoic granites in the Southern margin of the North China Craton. Data source of granites form the Dabie orogeny belt: Zhang et al. (2002), Wang et al. (2005), Hou et al. (2007), Hu et al. (2007), Huang et al. (2007, 2008), Liu et al. (2008), Liu et al. (2009), He et al. (2013).

contain more fractions of mantle material than the slightly older ones. Also, the larger scale of basic magmatism in the late stage (126–112 Ma) suggests that significant curst-mantle interaction (Figures 8 and 9). Thus, the mantle magma may have supplied both energy and materials for the generation of the granites. In Late Mesozoic, deep crust of the southern margin of the NCC had suffered significant curst-mantle interaction which get stronger with evolution of the magmatism and tectonic movement.

6. Geodynamic mechanism

As mentioned, there are abrupt changes in the element and isotopic compositions of these granites at about 127 Ma (Figures 6–9). Besides the magma source, these changes also reflect the drastic regional tectonic transformation.

The early stage (158–128 Ma) granites is predominantly typical I-type granites. However, elemental constitution of the late stage (127–112 Ma) granites changed obviously compare to the early stage, such as the moderate to large negative Eu, Sr anomalies, and higher contents of SiO_2, K_2O, and HREE than that of the early stage granites (Figures 3–7). They were consider to belong to A-type and/or highly fractionated I-type granite. The evolutional characteristics of the Late Mesozoic granites from I- to A-type and/or highly fractionated I-type, from early to late stage, suggests that the tectonic setting have been transformed into an extensional intraplate environment before 127 Ma (Ye et al., 2006; Dai et al., 2009; Li and Bao, 2010; Yang et al., 2013; Gao et al., 2014a, 2014b) (Figure 13)

Extensive melting of silicic crust requires large heat flux, which can only be supplied by mantle-derived magmas (Roberts and Clemens, 1993; Sylvester, 1998; Miller et al., 2003). Xu Y G et al. (2009) pointed out that the partial melting of crust can be triggered by thermal transmission between crust and mantle and relay on the underplating of mantle-derived magmas. Geophysical data shows that there is obviously mantle uplift trending NW under the southern margin of the NCC, with roughly similar distribution of the Late Mesozoic magmatic rocks, Mo, Au polymetallic metallogenic belt and regional deep fractures (Yuan, 1996). It was considered to be residual of the upwelling mantle material, reflecting the close relationship between mantle upwelling and magmatism-mineralization (Yuan, 1996). Early stage (158–128 Ma) granites are mainly derived from crustal source associated with the mantle-derived basaltic magma and accompanied by intrusion of sporadic mafic dikes including gabbro and dolerite dikes (147.5±1.7 Ma) from the Luanchuan, and Huanglongpu (129 Ma) from the Xiaoqinling area (Bao et al., 2009; Zhao et al., 2010b). Enriched mantle may be the predominant magma source, which is supported by their element and isotope geochemistry (Zhao et al., 2010b). Development of the basic magmatic rocks in the region implies that the upwelling asthenosphere can provide sufficient heat to melt the lithospheric mantle, resulting in voluminous mafic magmas. Underplating of the mafic magmas induced partial melting of the lower crust, and led to formation of voluminous felsic magmas which emplaced along fault belt and generated the granites. The underplated basaltic magmas may supplied both energy and materials for the formation of the granites (Figure 13b).

Isotopic compositions of the Late stage granites show more depleted than those of the early stage granites, suggesting the younger the forming age of the granite, the more mantle material in the magma source (Figure 13c). SHRIMP zircon U-Pb dating were carried out for the diabase and lamprophyre dykes of the Xiaoqinling-Xiong'ershan Au ore district, and the results show that they were emplaced at 127 and 128 Ma (Wang et al., 2008a). The rocks with the characteristics of the island arc magmatic rocks were considered to be derived from an enriched upper mantle source resulted from the potassic melt metasomatism and underwent different degrees of continental crust contamination and fractionation crystallization (Wang et al., 2008b, 2008c). Intermediate-mafic volcanic rocks of the Daying Group (117 Ma, Xie et al., 2007) were supposed to derive from partial melting of hybrid sources between subducted crust of Yangtze Craton and enriched lithospheric mantle of NCC (Li et al., 2006) or an enriched mantle source affected by subduction component (Xie et al., 2007). Several lamprophyre dykes (117 Ma) in the Funiushan granitic pluton exhibit OIB-like trace element distribution patterns and depleted radiogenic Sr-Nd-Hf isotopic compositions and were consider to derived from partial melting of hybrid sources between depleted and enriched mantle (Gao, 2012). Participation of ashospheric mantle implyintensive lithospheric extension and thinning. Emplacement of lamprophyre dykes was the important indicator of middle and upper crustal extension (Shao et al., 2003). Meanwhile, there are typical metamorphic core complex structure distribution in the Xiaoqinling region in the southern margin of the NCC. Ar-Ar and K-Ar dating shows that the extension of the detachment fault system continued from 135 to 123 Ma. The collapse represented by the extensional system within the Xiaoqinling metamorphic core complex was operative during 120–106 Ma, and its main activity occurred about 116 Ma ago (Zhang and Zheng, 1999). The basic-ultrabasic rocks and metamorphic core complex structure are the most direct evidences of the lithosphere extension and thinning.

In conclusion, the evolution from the typical I-type to A-type and/or highly fractionated I-type granites and generation of the mantle derived intermediate-basic igneous indicate the progressive lithospheric thinning and the transformation of the tectonic regime to an intensive extensional setting in the Late Mesozoic at the southern margin of the NCC. About 127 Ma is an critical period of the transformation of the tectonic region.

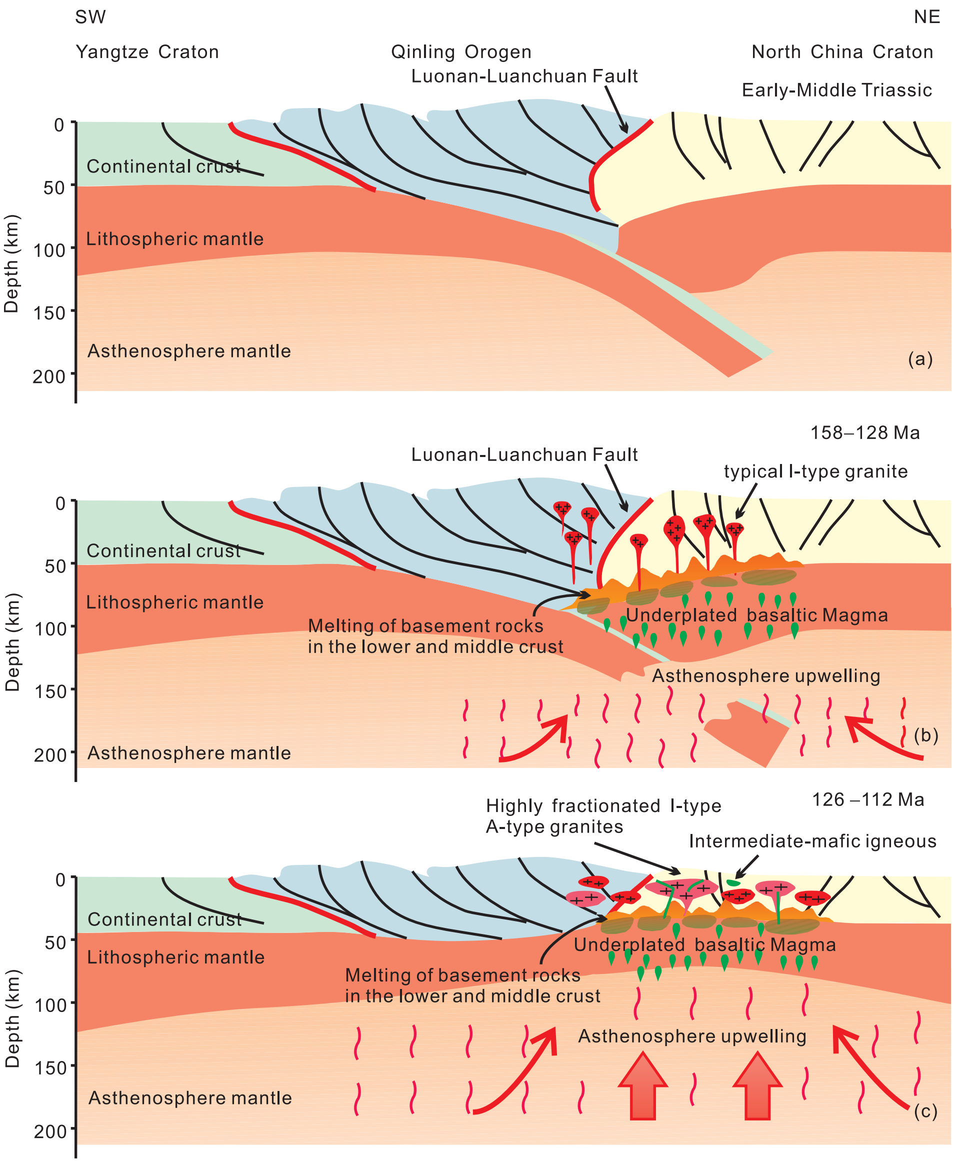

Figure 13 The geodynamic evolution and the formation and development of the magmatic activities in south margin of the NCC. Modified from Gao et al. (2014b).

It is noteworthy that continental collision between the NCC and the Yangtze craton (YZC) and the corresponding ultrahigh-pressure metamorphism occurred in Qinling Orogenic Belt during the early Mesozoic (ca. 245–235 Ma) (Zhang et al., 1996), which was almost 100 Mys older than the magmatic rocks (158–112 Ma) along the southern margin of the NCC. However, the post-collisional magmatism generally lasted within 50 mys for an orogenic cycle (e.g. Van Staal and De Roo, 1995; Finger et al., 1997; Liégeois et al., 1998; Waight et al., 1998; Bea et al., 1999; Van Wagoner et al., 2002). During the Late Mesozoic, intensive mafic to felsic magmatism, large-scale Au-Ag-Mo polymetallic deposit mineralization and extensional tectonics occurred not only in the southern margin of the NCC, but also in Jiaodong Peninsula, Taihang, Luxi, Liaodong and Dabie areas (e.g. Zhang, 2012; Guo et al., 2013; Tang Y J et al., 2013; Zhai and Santosh, 2013; Zhang et al., 2013; Goldfarb and Santosh, 2014; Yang Q Y et al., 2014), suggesting that these processes were controlled by a common geodynamic mechanism in eastern part of the NCC and even Eastern China, rather than by different independent tectonic events in southern margin of the NCC.

The late Mesozoic concurrent compressional-extensional structures, tectonic reactivation, lithospheric thinning and craton destruction of the eastern NCC coincides in time with a significant increase in the growth rate and a large change in the subduction direction of the Pacific plate (Bartolini and Larson, 2001; Sun et al., 2008). Consequently, more and more investigations have suggested that the lithospheric extension and thinning of the NCC was triggered by the long-term westward subduction of the Paleo-Pacific plate beneath the east Asian continental margin (e.g. Zhao et al.,

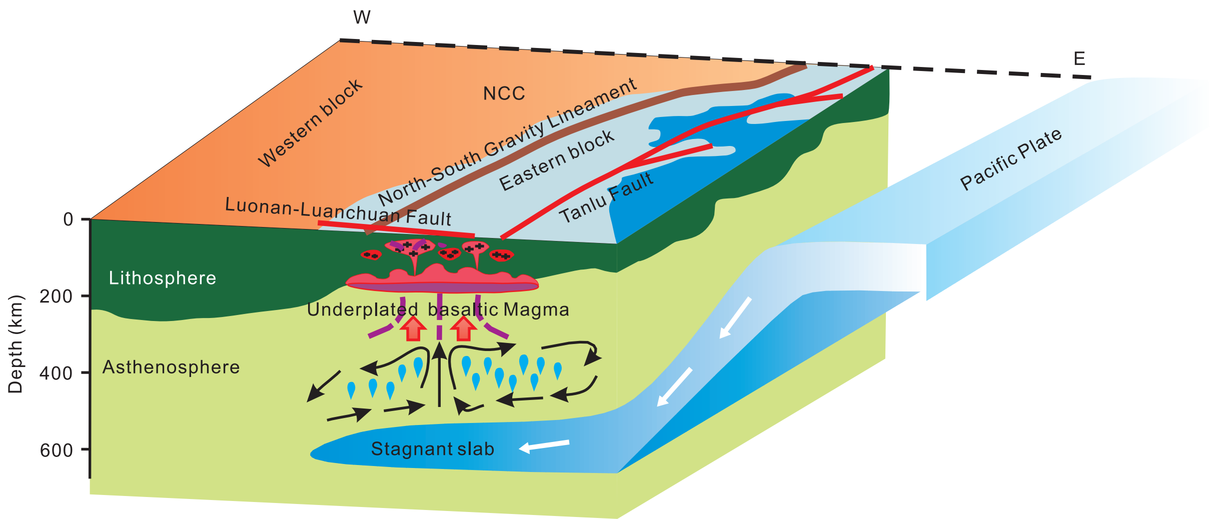

Figure 14 The geodynamic control on the thinning/destruction of the eastern NCC and the resultant magmatism. Modified from Li et al. (2012a) and Gao et al. (2014a). See text for explanation. NCC=North China Craton.

2007; Zhu G et al., 2010, 2012; Zhu et al., 2011; Zhu et al., 2013; Guo et al., 2013; Tang Y J et al., 2013; Goldfarb and Santosh, 2014). The flat-slab subduction of the paleo-Pacific plate probably reached as far as ~1300 km towards the interior of the continent and resulted in widespread late Mesozoic magmatism (Li and Li, 2007). In addition, subduction may have exerted a stronger influence on the east than the western part of the NCC, consistent with the phenomenon that widespread late Mesozoic granitic plutons are in the eastern Qinling Orogenic Belt but not in the western Qinling Orogenic Belt. Subsequently, the asthenospheric upwelling and lithospheric thinning may occurred mainly along major rupture zones that penetrated the lithospheric mantle along the margins of the NCC (Tian and Zhao, 2011; Yang W et al., 2012; Cai et al., 2013; Ma et al., 2014) (Figure 14). The influence of the long-distance subduction of the Paleo-Pacific plate, possibly reached to the Xiong'er-Xiaoqinling regions in the interior of the continent Asia (Li et al., 2012a).

7. Conclusion

Late Mesozoic magmatism are widespread in the southern margin of the NCC. Based on the zircon ages, rock associations, geochemical characteristics as well as evolution of genetic type, the evolution of magmatism lasted almost 50 Ma and can be divided into two stages. Early stage granites (158–128 Ma) are typical I-type granites. They were dominantly produced by partial melting of ancient crystallization basement of the southern margin of the NCC, with mixed with the mantle-derived basaltic magma. Late stage granites (126–112 Ma) are characterized by A-type and/or highly fractionated I-type. They are products of a strong crust-mantle interaction, and formed in an intensive intra-continental extensional setting. The genetic types of the granites change from I- to A-type and/or highly fractionated I-type from early to late, corresponding to progressive lithospheric thinning and the transformation of the tectonic regime to an intensive extensional setting in the Late Mesozoic at the southern margin of the NCC, and 127 Ma is an critical period of the transformation of the tectonic regime. The intensive magmatism-mineralization-tectonothermal event was related to lithospheric thinning and asthenospheric upwelling in this region, which was possibly caused by westward subduction of the Paleo-Pacific plate, not post-orogenic collapse process of the QOB.

Acknowledgements *We thank Professors Zhao Zhenhua, Bao Zhiwei, Yao Junming and Wang Shiyan for their help and academic advising during our study in the granites in the southern margin of the NCC. We are very grateful to the anonymous reviewers and chief editor for their valuable comments and suggestions. This work was supported by the National Key Research and Development Program of China (Grant No. 2016YFC0600106) and the National Natural Science Foundation of China (Grant Nos. 41402047 & 41373046). This is contribution No.IS-2407 from GIGCAS.*

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