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Crustal Accretion and Reworking within the Khanka Massif: Evidence from Hf Isotopes of Zircons in Phanerozoic Granitoids

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ABSTRACT: This paper presents a synthesis and analysis of geochronological, geochemical, and zircon Hf isotopic data of Phanerozoic granitoids within the Khanka massif, with the aim of revealing the accretion and reworking processes of continental crust within the massif. Zircon U-Pb dating indicates that Phanerozoic granitic magmatism within the Khanka massif can be subdivided into eight stages: Late Cambrian, Middle–Late Ordovician, Middle Silurian, Late Carboniferous, Early Permian, Middle–Late Permian to Early Triassic, Late Triassic–Early Jurassic, and Early Cretaceous. The zircon Hf isotopic compositions reveal that crustal accretionary events took place mainly in the Mesoproterozoic and Neoproterozoic. Through time, the zircon $\varepsilon_{Hf}(t)$ values gradually increase, indicating that the Phanerozoic granitic magmas were derived from the melting of progressively less ancient and more juvenile crust. The zircon $\varepsilon_{Hf}(t)$ values exhibit a gradual decrease with the increases in latitude, which implies that the amounts of ancient crustal components within the lower continental crust of the Khanka massif increased from south to north. At the same latitude range, the zircon Hf isotopic compositions also display some variations. We conclude, therefore, that significant horizontal and vertical heterogeneities existed in the lower continental crust of the Khanka massif during the Phanerozoic.
KEY WORDS: Khanka massif, Phanerozoic, granitoid, zircon Hf isotope, crustal accretion and reworking.

0 INTRODUCTION

Earth's continental crust is a unique feature among the planets of the solar system. Its formation and evolution is undoubtedly one of the most important subjects of research and debate in the Earth sciences. There is widespread agreement that appreciable volumes of continental crust were generated in the Archean (Dhuime et al., 2012, 2011; Belousova et al., 2010; Hawkesworth and Kemp, 2006; Jahn et al., 2000c; DePaolo et al., 1991; Jacobsen, 1988; Taylor and McLennan, 1985). However, the continents contain two types of tectonic unit, cratons and orogenic belts, and most previous studies on crustal growth have been focused mainly on the cratons, whereas few were concerned with crustal accretion and the reworking processes of microcontinental massifs within orogenic belts.

The Central Asian orogenic belt (CAOB) is one of the largest Phanerozoic accretionary orogens in the world (Windley et al., 2007, 1990; Xiao et al., 2004, 2003; Yakubchuk, 2004, 2002; Jahn et al., 2000a, b, c), and studies of the Phanerozoic granitoids within the CAOB have indicated that crustal accretion in this region occurred mainly in the Phanerozoic (Wu et al., 2011, 1999; Jahn et al., 2004, 2000a, b, c). However, more and more data on zircon Hf isotope compositions reveal that the Phanerozoic crustal accretion took place mainly within the Paleozoic orogenic belts of the CAOB, and not within the microcontinental massifs (Tang et al., 2015; Wang et al., 2015), indicating that the importance of Phanerozoic crustal accretion within the CAOB has been grossly overestimated (Luan et al., 2017; Kröner et al., 2014).

Northeast China and its adjacent regions, including the Russian Far East, are made up of a series of microcontinental massifs that are separated by orogenic belts, and this region has traditionally been considered the eastern part of the CAOB, located between the Siberian and North China cratons (Şengör and Natal'in, 1996; Şengör et al., 1993). Many granitoids of various ages were formed during the geological evolution of this area, and these granitoids record large amounts of information on crustal accretion and reworking processes within the CAOB (Wu et al., 2011; Rudnick, 1995; DePaolo et al., 1991). However, the answers to questions about how and when the accretion of continental crust within these microcontinental massifs took place remain unclear. The Khanka massif, as one of the microcontinental massifs within the eastern CAOB, contains numerous Phanerozoic granitoids, and it presents an op-

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timal study area for unraveling the processes of crustal accretion and reworking within these microcontinental massifs. With this in mind, we present here a case study of the processes of crustal accretion and reworking within the microcontinental massifs of the CAOB that is based on spatial and temporal variations in Hf isotopic compositions of zircons from the Phanerozoic granitoids of the Khanka massif.

1 GEOLOGICAL BACKGROUND

The Paleozoic evolution of the eastern CAOB was dominated by the closure of the Paleo-Asian Ocean and the amalgamation of microcontinental massifs, including, from southeast to northwest, the Khanka, Jiamusi, Songnen-Zhangguangcai Range, Xing'an, and Erguna massifs (Fig. 1a; Li Y et al., 2014; Cao et al., 2013; Wang et al., 2012a, b; Wu et al., 2011, 2007, 2002; Meng et al., 2010; Xu et al., 2009; Li, 2006; Li J Y et al., 1999). In contrast, the Mesozoic tectonic evolution of the eastern CAOB was characterized by overprinting of the circum-Pacific and Mongol-Okhotsk tectonic regimes (Tang et al., 2016, 2015; Dong et al., 2014; Xu W L et al., 2013; Xu M J et al., 2013; Yu et al., 2012; Meng et al., 2011).

The Khanka massif occurs mainly in the Russian Far East,

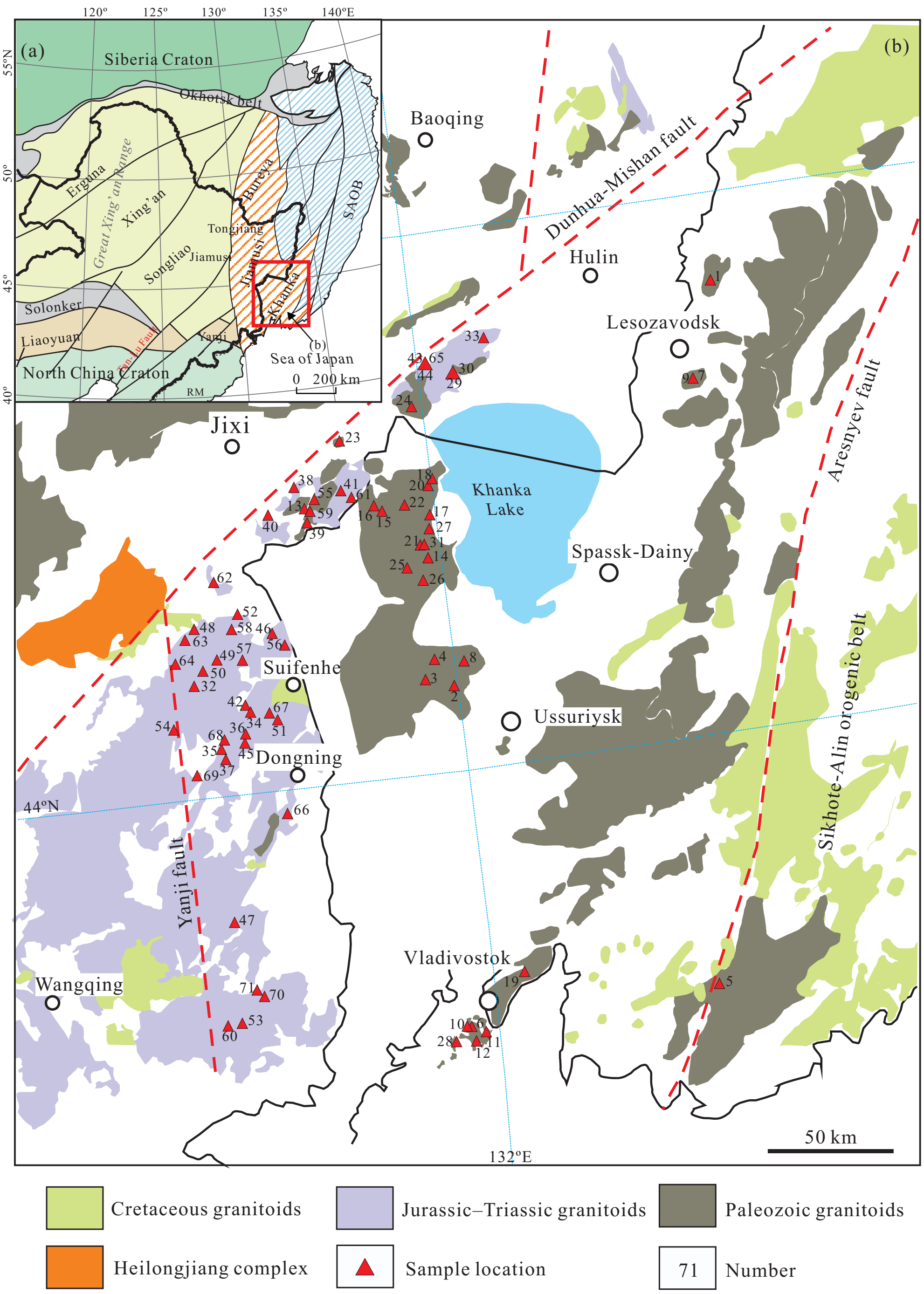

Figure 1. (a) Simplified tectonic divisions of the northeastern Asian continent (Tang et al., 2016; Sun et al., 2013; Wu et al., 2011; Sorokin et al., 2010; Barnes, 2003). (b) Distribution of Phanerozoic granitoids in the study area (modified after Jahn et al., 2015; Xu W L et al., 2013; Wu et al., 2011; HBGMR, 1993; BGMRJ, 1988).

with only a small segment cropping out in NE China. To the north of the Khanka massif is the Jiamusi massif, and to the west of that massif, bounded by the Dunhua-Mishan fault, is the Songnen-Zhangguangcai Range massif (Fig. 1a; Zhou et al., 2010; Jia et al., 2004). South of the Khanka massif is the North China Craton (Fig. 1a), bounded by the Yanji fault (Zhou et al., 2010; Jia et al., 2004), and east of the Khanka massif is the Sikhote-Alin orogenic belt, bounded by the Arsenyev fault (Fig. 1b; Wang et al., 2016; Jahn et al., 2015; Shao and Tang, 1995).

The Khanka massif mainly consists of Precambrian microcontinent and some ancient island arcs accreted to the Precambrian microcontinent. The Precambrian terrane only occurs to northeast of the Khanka massif. In addition, the Precambrian basement includes amphibolite and lower-granulite-facies metamorphic rocks, which is overlain by Paleozoic sedimentary rocks (Tsutsumi et al., 2014; Khanchuk et al., 2010; Jia et al., 2004; Khanchuk, 2001; Shcheka et al., 2001; Natal'in, 1993; HBGMR, 1993). The Precambrian basement and Paleozoic cover rocks were intruded by Paleozoic and Mesozoic granitoids, and they were overlain by Mesozoic–Cenozoic sedimentary rocks that are composed mainly of carbonates, clastic sediments, and volcanic rocks (including basalts, andesites, and rhyolites) (Kovalenko, 2006; Khanchuk, 2001; Faure et al., 1995). The intrusive rocks are exposed mainly along the eastern and western margins of the Russian part of the Khanka massif, and they include small volumes of gneissic gabbro and diorite as well as numerous Paleozoic and Mesozoic granitoid plutons (Kovalenko, 2006).

Wang et al. (2016) identified four stages of Early Paleozoic magmatic events within the Khanka massif: Middle Cambrian (~500 Ma), Early Ordovician (~480 Ma), Late Ordovician (~450 Ma), and Middle Silurian (~430 Ma). The Early Paleozoic magmatic rocks consist of a suite of gneissic granitoids found mainly in the east of Lesozavodsk (Tsutsumi et al., 2014; Khanchuk et al., 2010). The Late Paleozoic–Early Mesozoic magmatic rocks can be further subdivided into four stages (Wang et al., 2016): (1) Early Permian (~285 Ma), as represented by the Chaoxiantun pluton in the Mishan area and the Qianshan pluton in the southern part of the Hunchun area (Yang et al., 2015a; Cao et al., 2011) (2) Late Permian (~260 Ma), as represented by a suite of granitoids to the west of Khanka Lake, south of the Vladivostok area (Tsutsumi et al., 2014; Khanchuk et al., 2010), the Wudaogou pluton in the Hunchun area (Cao et al., 2011), and volcanic rocks, including dacite of the Yanggang Formation in the Jidong area, rhyolite of the Nancun Formation in the Dongning area, and pyroxene andesite of the Tuopangou Formation in the eastern part of Wangqing area; (3) Late Triassic (~202 Ma), as represented along the western margin of the Khanka massif (Wang et al., 2015; Zhao et al, 2009) by widespread volcanic rocks including pyroxene andesite of the Shuangqiaozi Formation, dacite and rhyolite of the Luoquanzhan Formation, and rhyolite of the Daxinggou Group (Xu et al., 2009); and (4) Early Jurassic (~185 Ma), represented mainly by intermediate-acidic intrusive rocks. The ages of the Late Mesozoic magmatic rocks can be subdivided into two stages (Wang et al., 2016): (1) Early Cretaceous (~108 Ma), as represented by a suite of intrusive and volcanic rocks in China (Xu W L et al., 2013); and (2) Late Cretaceous (~90 Ma), as represented by a suite of andesite and dacite in the Sunfenhe area (Xu W L et al., 2013; Ji et al., 2007).

2 GEOCHRONOLOGY, DISTRIBUTION, AND GEOCHEMISTRY OF PHANEROZOIC GRANITOIDS IN THE KHANKA MASSIF

2.1 Phanerozoic Granitic Magmatism Events

The Phanerozoic magmatic events are summarized in Supplementary Table 1. According to the U-Pb ages of zircons from granitoids in the Khanka massif, the Phanerozoic granitic activity can be subdivided into at least eight stages: Late Cambrian, Middle–Late Ordovician, Middle Silurian, Late Carboniferous, Early Permian, Middle–Late Permian to Early Triassic, Late Triassic–Early Jurassic, and Early Cretaceous (Fig. 2).

2.2 Distribution and Geochemistry of Phanerozoic Granitoids in the Khanka Massif

The Late Cambrian (~492 Ma) granitic rocks are mainly syenogranites that occur ~20 km northeast of Lesozavodsk (Xu et al., 2018). The syenogranites show enrichment in light rare earth elements (LREEs), relative depletion in heavy REEs (HREEs) ($[La/Yb]_N$=17.1–23.7), and positive Eu anomalies (Eu/Eu*=1.97–2.33). They are enriched in large ion lithophile elements (LILEs; e.g., Rb and K) and strongly depleted in high field strength elements (HFSEs; e.g., Nb, Ta, and Ti).

The Middle–Late Ordovician (461–445 Ma) granitic magmatism took place in two periods at ~460 and ~445 Ma (Fig. 2). The ~460 Ma granitic rocks are syenogranites that occur ~40 km north of Ussuriysk (Xu et al., 2018), while the ~445 Ma granitic rocks are granodiorites that occur ~111 km east of Vladivostok (Xu et al., 2018). The ~445 Ma granitic rocks are enriched in LREEs and LILEs (e.g., Rb, Ba and K), and are strongly depleted in HREEs [$(La/Yb)_N$=43.2–165] and HFSEs (e.g., Nb, Ta, Zr, and Hf), and display pronounced positive Eu and Sr anomalies (Eu/Eu*=2.22–8.35).

The Middle Silurian (431–423 Ma, with a peak at 430 Ma) granitic rocks are monzogranites and granodiorites that occur ~8 km southeast of Lesozavodsk, ~50 km north of Ussuriysk (Xu et al., 2018), and to the south of Vladivostok (Tsutsumi et al., 2014). The ~430 Ma granodiorites and biotite monzogranites exhibit depletion in HREEs ($[La/Yb]_N$=29.0–98.1) and HFSEs (e.g., Nb, Ta and Ti), along with negative Eu anomalies (Eu/Eu*=0.47–0.88).

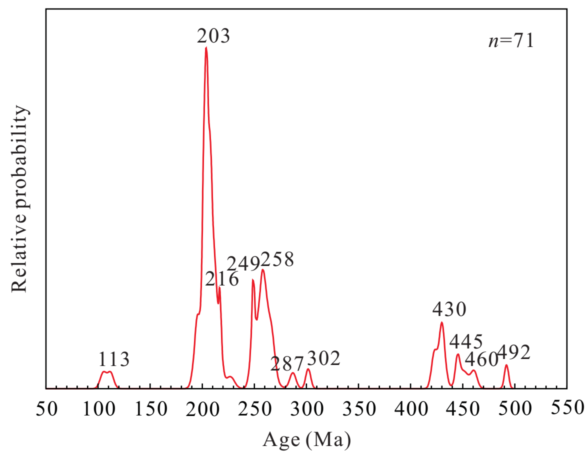

Figure 2. Relative probability plot of U-Pb ages of zircons from the Phanerozoic granitoids of the Khanka massif.

The Late Carboniferous (~302 Ma) granitic rocks are granites (Fig. 2) that occur to the south of Vladivostok (Tsutsumi et al., 2014).

The Early Permian (~287 Ma) granitic rocks are monzogranites (Fig. 2) that are found in Chaoxiantun Village (Yang et al., 2015a). The ~287 Ma monzogranites are enriched in LREEs, relative depleted in HREEs ($[La/Yb]_N$=8.11) and HFSEs (e.g., Nb, Ta and Ti), along with negative Eu anomalies (Eu/Eu*= 0.61).

The Middle–Late Permian to Early Triassic (268–249 Ma) granitic magmatism took place mainly in two periods at ~258 and ~249 Ma (Fig. 2). The ~258 Ma granitic rocks are granodiorites and granite porphyries that occur at Shuangyehu (Yang et al., 2015a), Yangtianzhai (Yang et al., 2015a), and Ryazanovka (Khanchuk et al., 2010). The ~249 Ma granitic rocks are granodiorites that occur at Vladivostok (Tsutsumi et al., 2014) and Ryazanovka (Khanchuk et al., 2010). The granodiorites show enrichment in LREEs and LILEs (e.g., Rb and K), depletion in HREEs ($[La/Yb]_N$=15.53–15.84) and HFSEs (e.g., Nb, Ta), and minor negative Eu anomalies (Eu/Eu*=0.94–1.00). The granite porphyries exhibit enrichment in LREEs, relative depletion in HREEs ($[La/Yb]_N$=7.01).

The Late Triassic–Early Jurassic (228–195 Ma) granitic magmatism took place mainly in two periods at ~216 and ~203 Ma (Fig. 2). The ~216 Ma granitic rocks are syenogranites, monzogranites, and associated rhyolites that occur in Shanhezi (Wu et al., 2011), on Daxu Mountain (Wu et al., 2011), and in Wupai Village (Yang et al., 2015b). The ~203 Ma granitic rocks are syenogranites, monzogranites, and granodiorites that occur in the Suifenhe area, along with associated rhyolites. The Late Triassic–Early Jurassic granitoids are enriched in LREEs and LILEs (e.g., Rb and K), depleted in HREEs ($[La/Yb]_N$= 4.49–6.77) and HFSEs (e.g., Nb, Ta, and Ti), and have variable negative Eu anomalies (Eu/Eu*=0.08–0.92).

The Early Cretaceous (113 Ma) granitic rocks are granodiorites (Fig. 2) that occur in the Xiaoxinancha area of Hunchun City (Sun et al., 2008).

In summary, the Phanerozoic granitoids in the Khanka massif mainly consist of a suite of granodiorites, monzogranites, and syenogranites. On the TAS diagram, they fall in the fields of granodiorite and granite, and chemically belong to the subalkaline series (Fig. 3). They have high SiO_2 (>65 wt.%) and Al_2O_3 contents (12.47 wt.%–17.11 wt.%), low $Mg^{\#}$ (4–45), Co (0.31 ppm–7.18 ppm) and Ni (0.46 ppm–7.64 ppm) contents. These geochemical characteristics suggest that the Phanerozoic granitoids in the Khanka massif could be derived from partial melting of deep crustal material (Lu and Xu, 2011).

3 Hf ISOTOPIC COMPOSITIONS OF ZIRCONS IN PHANEROZOIC GRANITOIDS OF THE KHANKA MASSIF

For this paper we compiled the recently published Hf isotopic data of zircons in Phanerozoic granitoids of the Khanka massif. We do not consider the data of inherited zircons, and we discuss only the Hf isotopic data of zircons with ages that represent the timing of crystallization of the granitoids. The Hf isotope data are listed in Supplementary Table 2. In this Table 2, depleted mantle model ages (T_{DM}) were calculated using the measured $^{176}Lu/^{177}Hf$ ratios, referred to a model depleted mantle with a present-day $^{176}Hf/^{177}Hf$=0.283 25, similar to that of average MORB (Nowell et al., 1998) and $^{176}Lu/^{177}Hf$=0.038 4 (Griffin et al., 2000). Griffin et al. (2002) presented a more realistic estimate (T_{DM2}) of the age of the source rocks for the magmas, derived by projecting the initial $^{176}Hf/^{177}Hf$ of the zircon back to the depleted mantle model growth curve, assuming a mean crustal value for $^{176}Lu/^{177}Hf$=0.015. This average crustal value was used as the standard to analyze the zircon Lu-Hf results presented in this paper.

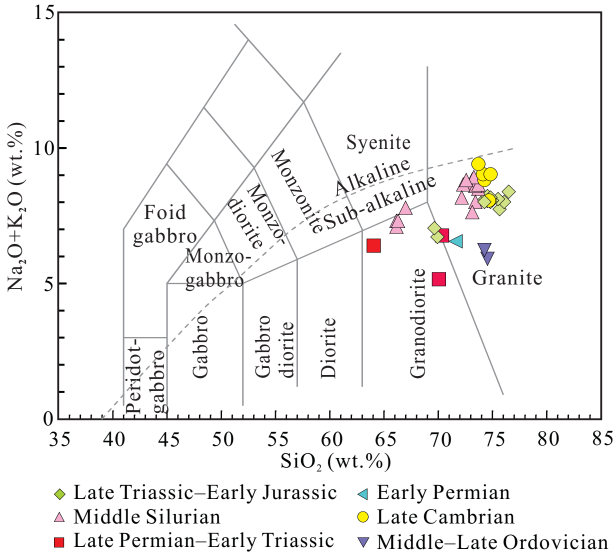

Figure 3. Plots of SiO_2 (wt.%) versus (Na_2O+K_2O) (wt.%) for the Phanerozoic granitoids of the Khanka massif (the field boundaries in the diagram are from Le Maitre, 1989).

Nearly all the Hf isotopic data of zircons in the Phanerozoic granitoids fall in the field of the CAOB (Fig. 4a), regardless of the specific area the granitoid comes from. The Hf isotopic compositions are similar to those of zircons from other Phanerozoic igneous rocks in the CAOB, but they differ from zircons of Neoarchean and Paleoproterozoic age that are found in Paleozoic–Mesozoic units of the Yanshan fold-and-thrust belt (YFTB) of the NCC (Yang et al., 2006; Xiao et al., 2004).

3.1 Hf Isotopic Compositions of Zircons from the Late Cambrian Granitoids

The $^{176}Hf/^{177}Hf$ ratios of 15 zircon grains from the Late Cambrian (~492 Ma) granitoids vary from 0.282 411 to 0.282 488, corresponding to $\varepsilon_{Hf}(t)$ values and two-stage model (T_{DM2}) ages of -2.2 to 0.5 (Fig. 4b) and 1 430 to 1 600 Ma (Fig. 4c), respectively (Xu et al., 2018). The average two-stage model (T_{DM2}) age is 1 522 Ma.

3.2 Hf Isotopic Compositions of Zircons from the Middle–Late Ordovician Granitoids

The $^{176}Hf/^{177}Hf$ ratios of 22 zircon grains from the Middle–Late Ordovician (~461 and ~445 Ma) granitoids vary from 0.282 556 to 0.282 693. Their $\varepsilon_{Hf}(t)$ values and T_{DM2} ages range from 1.8 to 6.6 (Fig. 4b) and from 1 020 to 1 311 Ma (Fig. 4c), respectively (Xu et al., 2018). The average T_{DM2} age is 1 222 Ma.

3.3 Hf Isotopic Compositions of Zircons from the Middle Silurian Granitoids

The $^{176}Hf/^{177}Hf$ ratios of 29 zircon grains from the Middle Silurian (~430 Ma) granitoids vary from 0.282 357 to 0.282 711. Their $\varepsilon_{Hf}(t)$ values and T_{DM2} ages range from -5.4 to 5.8 (Fig. 4b) and from 1 045 to 1 757 Ma (Fig. 4c), respectively (Xu et al., 2018). The average T_{DM2} age is 1 451 Ma.

3.4 Hf Isotopic Compositions of Zircons from the Early Permian Granitoids

The $^{176}Hf/^{177}Hf$ ratios of 13 zircon grains from the Early Permian granitoids vary from 0.282 582 to 0.282 652. Their $\varepsilon_{Hf}(t)$ values and T_{DM2} ages range from -0.6 to 1.8 (Fig. 4b) and from 1 189 to 1 342 Ma (Fig. 4c), respectively (Yang et al., 2015a). The average T_{DM2} age is 1 252 Ma.

3.5 Hf Isotopic Compositions of Zircons from the Late Permian–Early Triassic Granitoids

The $^{176}Hf/^{177}Hf$ ratios for 35 zircon grains from the Late Permian–Early Triassic (~258 and ~249 Ma) granitoids vary from 0.282 601 to 0.282 723. Their $\varepsilon_{Hf}(t)$ values and T_{DM2} ages range from -0.6 to 3.7 (Fig. 4b) and from 1 048 to 1 318 Ma (Fig. 4c), respectively (Liu et al., 2017; Yang et al., 2015a). The average T_{DM2} age is 1 197 Ma.

3.6 Hf Isotopic Compositions of Zircons from the Late Triassic–Early Jurassic Granitoids

The $^{176}Hf/^{177}Hf$ ratios of 130 zircons from the Late Triassic–Early Jurassic (~218 to ~199 Ma) granitoids vary from 0.282 669 to 0.282 913. Their $\varepsilon_{Hf}(t)$ values and T_{DM2} ages range from 0.8 to 9.3 (Fig. 4b) and from 720 to 1 197 Ma (Fig. 4c), respectively (Liu et al., 2017; Jing et al., 2015; Wang et al., 2015; Yang et al., 2015a, b). The average T_{DM2} age is 908 Ma.

4 SPATIAL–TEMPORAL VARIATIONS IN ZIRCON HF ISOTOPIC COMPOSITIONS AND THE ACCRETION AND REWORKING OF CONTINENTAL CRUST

4.1 Temporal Variations in Hf Isotopic Compositions of Zircons from the Phanerozoic Granitoids

The Hf isotopic compositions of zircons from the Phanerozoic granitoids show obvious trends that correlate with time. As the ages of the Phanerozoic granitoids decrease (Late Cambrian to Middle–Late Ordovician to Middle Silurian to Early Permian to Middle–Late Permian–Early Triassic to Late Triassic–Early Jurassic), the $\varepsilon_{Hf}(t)$ values of their zircons gradually increase (Fig. 4b), whereas the T_{DM2} ages gradually decrease (Mesoproterozoic to Neoproterozoic) (Fig. 4c). These trends suggest that the sources of the granitic magmas that were intruded into the Khanka massif changed gradually to an increasingly juvenile crust throughout the Paleozoic and Early Mesozoic.

4.2 Spatial Variations in Hf Isotopic Compositions of Zircons from the Phanerozoic Granitoids

The $\varepsilon_{Hf}(t)$ values of zircons from the Phanerozoic granitoids tend to decrease with increasing latitude (Fig. 5a), which implies that the components of ancient continental crust in the source area increased gradually from south to north (Fig. 5b). However, within the same range of latitude, the $\varepsilon_{Hf}(t)$ values of

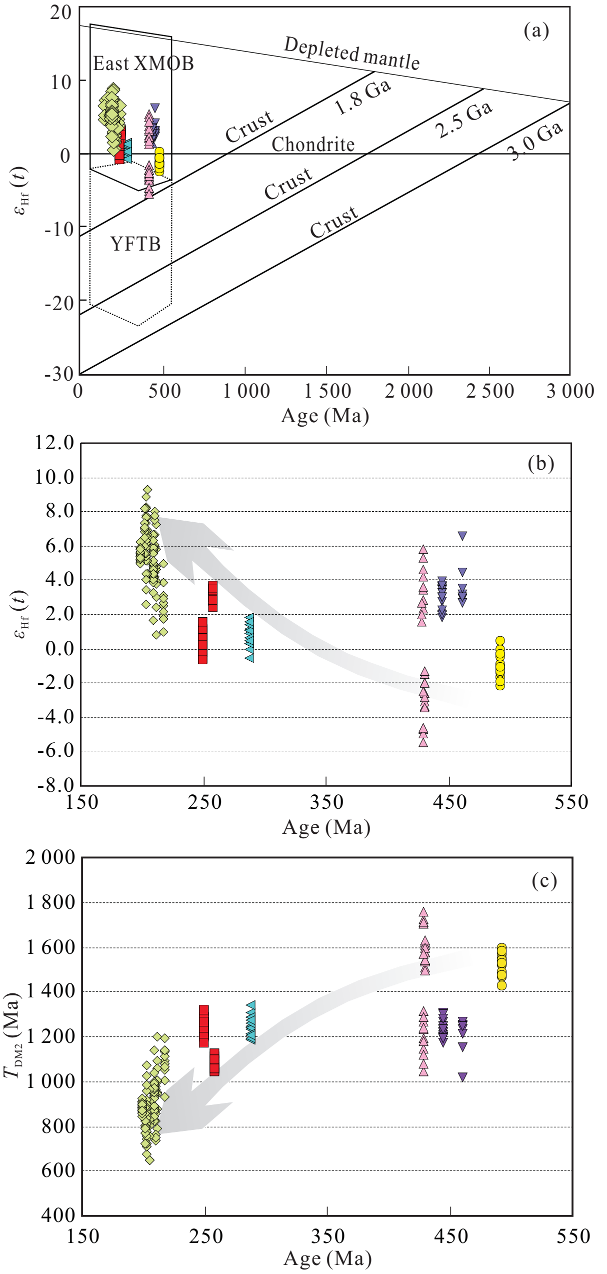

Figure 4. (a) Correlations between $\varepsilon_{Hf}(t)$ values and the ages of zircons from the Phanerozoic granitoids in the Khanka massif (CAOB. Central Asian orogenic belt; YFTB. Yanshan fold-and-thrust belt) (Yang et al., 2006). (b) Detailed diagram of the ages of zircons versus values of $\varepsilon_{Hf}(t)$ (legend as for Fig. 3). (c) Detailed diagram of the ages of zircons versus values of T_{DM2} (Ma) (legend as for Fig. 3).

zircons from the Phanerozoic granitoids also exhibit some variations (Fig. 5a). For example, the Phanerozoic granitoids located at a latitude of 45.5°N in the western part of the Khanka massif have higher zircon $\varepsilon_{Hf}(t)$ values than those in the eastern part of the Khanka massif. Moreover, as the ages of the Phanerozoic granitoids at the latitude of 45.5°N decrease, the $\varepsilon_{Hf}(t)$ values of their zircons gradually increase (gray shading in Fig. 5a), whereas their T_{DM2} ages gradually decrease (gray shading in Fig. 5b).

In addition, the $\varepsilon_{Hf}(t)$ values of zircons from the Phanerozoic granitoids tend to decrease with increasing longitude (Fig. 5c), which implies that the components of ancient continental crust in

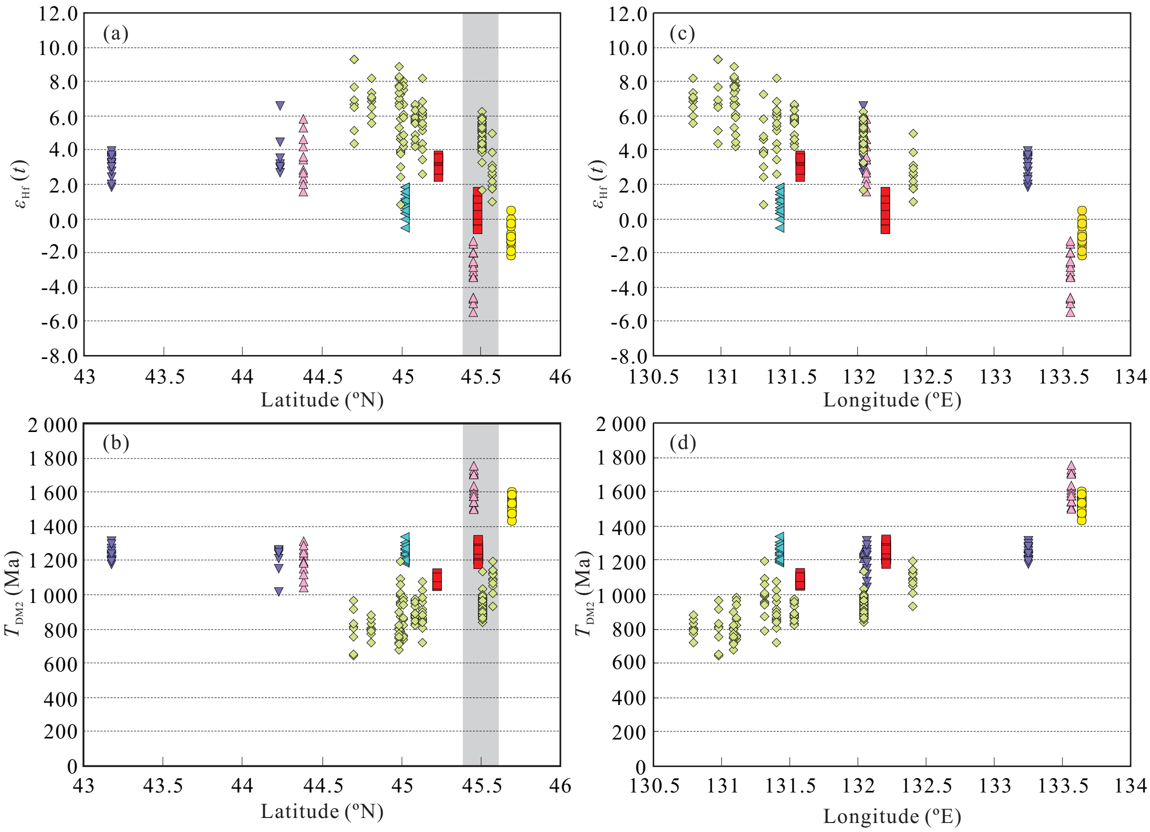

Figure 5. Plots of the latitudes and longitudes of sampling locations versus $\varepsilon_{Hf}(t)$ values and T_{DM2} ages.

the source area gradually increased from west to east (Fig. 5d).

Taking into account all these observations, we conclude that the lower continental crust within the Khanka massif exhibits heterogeneities in chemical composition in both the horizontal and vertical directions.

4.3 Accretion and Reworking of Continental Crust within the Khanka Massif

The CAOB is the largest Phanerozoic accretionary orogenic belt in the world, and this observation is consistent with the Nd isotopic and zircon Hf isotopic compositions of the Phanerozoic granitoids (Wu et al., 2011, 2003, 1999; Jahn et al., 2004, 2000a, b, c; Xiao et al., 2003). However, more and more research now indicates that the Phanerozoic crustal accretion probably took place in Paleozoic orogenic belts between the microcontinental massifs of the CAOB, rather than within the microcontinental massifs themselves, particularly in the eastern CAOB (Sun et al., 2017; Wang Z W et al., 2017; Wang F et al., 2016). In previous studies, the amount of continental crust accreted in the CAOB during the Phanerozoic has been overestimated (Kröner et al., 2014). The question then arises: when did crustal accretion within the microcontinental massifs take place? The Khanka massif, as one of the microcontinental massifs of the eastern CAOB, is an ideal site for studying the crustal accretion within the microcontinental massifs of this orogenic belt, because numerous Phanerozoic granitoids occur within the massif (Xu et al., 2018).

The reconstruction of crustal growth curve is based mainly on the detrital zircon Hf isotope (Dhuime et al., 2012; Condie et al., 2011; Condie and Aster, 2010), especial those from rivers could reflect the crustal growth of the blocks that the rivers occur (Liu et al., 2017; Wang et al., 2011, 2009; Belousova et al., 2010). However, the detrital mineral suffered from physical-chemical weathering, and transportation of river or wind. Finally, they deposited in the sedimentary area, were buried and formed rock. There are many uncertain factors in the long and complicated geological history, which produce some deviation about the age of detrital zircon (Guo et al., 2017). Additionally, the some crustal growth curves are smooth in part because these models are typically based on radiogenic isotope ratios (whole-rock Sr-Nd-Pb isotopes) of sediments and sedimentary rocks (McLennan, 2001; Davies et al., 1985; Allègre and Rousseau, 1984; O'Nions et al., 1983; Armstrong, 1981). Such samples reflect the history of the crust over long periods of time, but they may also result in hybrid crust generation ages that are the result of mixing processes rather than real magmatic events. Igneous rocks preserve the ages of the specific events in which new continental crust may have been generated, although this record may not be complete (Hawkesworth and Kemp, 2006). Taken together, we consider that because these granitoids are chiefly derived from partial melting of the lower crust, the Hf isotopic compositions of magmatic zircons from these granitoids basically record the growth and reworking history of the lower continental crust within the Khanka massif.

The two-stage model (T_{DM2}) ages of zircons in the Phanerozoic granitoids of the Khanka massif indicate that crustal accretion took place mainly during three stages: 1) Mesoproterozoic, 2) Neoproterozoic, and 3) to a lesser extent, Late Paleoproterozoic (Fig. 6).

We calculate the cumulative growth curve of continental crust for the Khanka massif by the Hf isotopic compositions of zircons from the Phanerozoic granitoids (Fig. 7). The curve indicates that the accretion of continental crust within the Khanka massif took place during the Proterozoic, which differs from the traditional viewpoint that the accretion of continental crust within the CAOB took place mainly in the Phanerozoic (Jahn et al., 2004, 2000a, b, c; Wu et al., 2011, 1999) as well as continental growth models within cratonic regions (Cawood et al., 2013; Wang et al., 2011, 2009) (Fig. 7). These results also indicate that the Khanka massif has a Precambrian basement, and more obviously so during the Early Paleozoic.

The Hf isotopic compositions of zircons from the Phanerozoic granitoids not only reveal the nature of accretionary process in the lower continental crust of the microcontinental massifs, but also reflect the processes of reworking of the lower continental crust. The formation of granitoids results mainly from the reworking of the lower continental crust (Sun et al., 2017). How, then, did these Phanerozoic granitoids form, and how was the lower crust reworked during the formation of these granitoids?

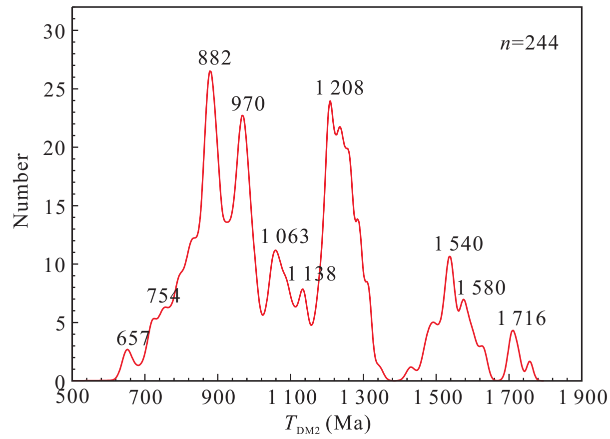

Figure 6. Relative probability plot of two-stage model (T_{DM2}) ages of zircons from the Phanerozoic granitoids in the Khanka massif.

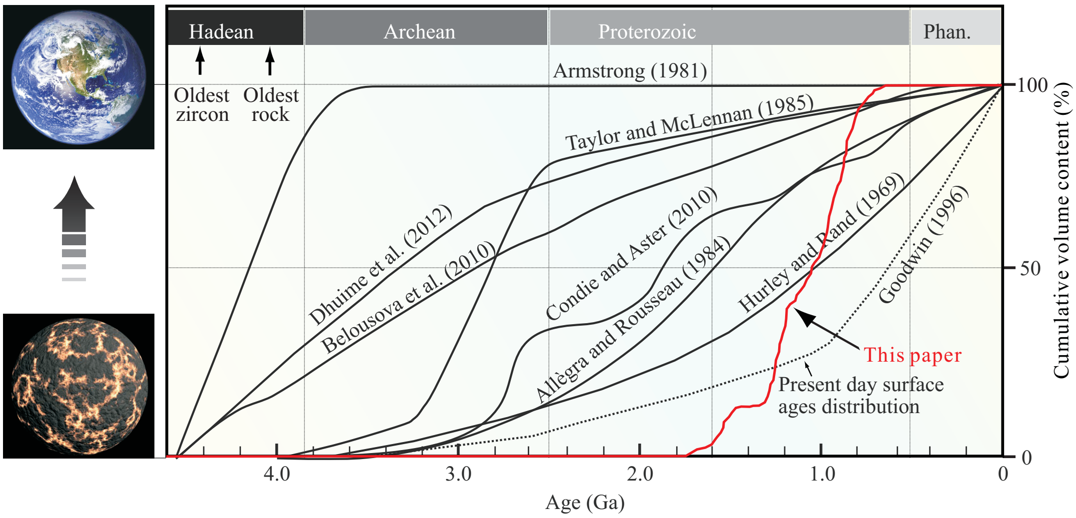

Figure 7. Crustal growth curve of the Khanka massif (modified after Cawood et al., 2013).

The zircon two-stage model (T_{DM2}) ages (Fig. 4c), together with the changes in $\varepsilon_{Hf}(t)$ values with latitude (Fig. 5), suggest that the Late Cambrian and Middle Silurian granitoids in the northeastern part of the Khanka massif originated mainly from the reworking of a Late Paleoproterozoic–Early Mesoproterozoic (1 430–1 757 Ma) lower crust, whereas the Middle–Late Ordovician and Middle Silurian granitoids in the southern part of the Khanka massif resulted from the reworking of a Mesoproterozoic (1 020–1 313 Ma) lower crust. The Early Permian–Early Triassic granitoids along the western margin of the Khanka massif were derived chiefly from the reworking of Late Mesoproterozoic lower crust, whereas the Late Triassic–Early Jurassic granitoids were derived mainly from the reworking of a Neoproterozoic lower crust (Fig. 4c; Supplementary Table 2). We conclude, therefore, that the Phanerozoic granitoids of the Khanka massif were generated by the reworking of lower continental crustal material with different ages, and that the crustal material that was reworked decreased in age progressively throughout the Phanerozoic.

5 CONCLUSIONS

(1) The periods of Phanerozoic granitic magmatism in the Khanka massif can be subdivided into at least eight stages: Late Cambrian, Middle–Late Ordovician, Middle Silurian, Late Carboniferous, Early Permian, Middle–Late Permian to Early Triassic, Late Triassic–Early Jurassic, and Early Cretaceous.

(2) The Hf isotopic compositions of zircons from the Phanerozoic granitoids reveal that the accretion of the lower continental crust in the Khanka massif took place mainly in the Mesoproterozoic and Neoproterozoic, and to a lesser extent in the Paleoproterozoic.

(3) The Khanka massif is an ancient microcontinent with a Precambrian basement.

(4) The repeated reworking of the lower crust of the Khanka massif resulted in the source of the Phanerozoic granitoids becoming progressively less ancient and more juvenile over time.

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