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Eoarchean ultra-depleted mantle domains inferred from ca. 3.81 Ga Anshan trondhjemitic gneisses, North China Craton

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ABSTRACT

Early mantle differentiation is yet to be well constrained because isotopic systems recorded in many ancient rocks are arguably susceptible to later disturbances. Although refractory zircon is of singular importance in deciphering early Earth history, a growing body of work on ancient zircons indicates that interpretations of their U–Pb ages and Hf–O isotopes are neither straightforward nor unique. Owing to these complexities, the question of whether the Anshan Complex of North China Craton (NCC) really preserves 3.8 Ga rocks remains controversial. To better understand these issues, we conducted a systematic in situ zircon U–Pb, Hf and O isotopic study guided by detailed field mapping (1:50 scale) and sampling at Guodishan, northern Anshan Complex. Three rock units were recognized and precisely dated: a ca. 3.13 Ga massive trondhjemitic gneiss that dominates the outcrop, a ca. 3.36–3.30 Ga migmatite complex that is intruded by the trondhjemitic gneiss, and a ca. 3.81 Ga massive to weakly-banded trondhjemitic gneiss that is enclosed by the migmatite complex.

U abundances, U–Pb discordances, apparent $^{207}Pb/^{206}Pb$ ages and $\delta^{18}O$ values of a single generation of magmatic zircons reveal that only low-U (generally U < 500 ppm), concordant zircons can preserve magmatic oxygen isotopes. High-U zircons generally tend towards lower $\delta^{18}O$ values, possibly due to secondary alterations facilitated by strong metamictization. Concordant ca. 3.81 Ga oscillatory zoned zircons from the oldest unit give $\varepsilon_{Hf}(t) = -0.7$ to 6.2 and $\delta^{18}O = 5.2–7.0‰$. These data combined with whole-rock geochemistry suggest that this Eoarchean trondhjemitic geniss was either formed by magma mixing or probably derived from a heterogeneous basaltic source at ca. 13–14 kbar, 950–1000 °C. The highest initial ε_{Hf} value of 6.2 at ca. 3.81 Ga exceeds those recorded by contemporaneous zircons worldwide and the modeled depleted mantle value. This provides new isotopic evidence for the existence of an Eoarchean ultra-depleted mantle domain underlying NCC. A literature survey reveals that this Eoarchean ultra-depleted signature was not registered in younger zircons worldwide, suggesting that this ultra-depleted mantle signature may be transient, possibly erased by subsequent mantle re-homogenization processes.

1. Introduction

There is a general consensus that continental crust is a mantle extract and therefore, ancient crustal rocks can serve as direct archive of early mantle differentiation. Evidence for early mantle differentiation depends largely on isotopic studies (e.g. Sm–Nd and Lu–Hf systematics) of ancient rocks and zircons. Whole-rock Sm–Nd isotope systems of ancient rocks have been widely used to decipher early mantle differentiation, but some rocks were arguably susceptible to later geological disturbances, thus may not preserve primary signatures (e.g., Gruau et al., 1996; Kamber et al., 2001; Moorbath et al., 1997; Vervoort and Blichert-Toft, 1999; Vervoort et al., 1996). As an alternative, zircons have been intensively studied to unravel early Earth processes (e.g., Amelin et al., 1999; Harrison et al., 2005). Among Hadean to Eoarchean zircons, most show chondritic to enriched Hf isotopes (e.g., Amelin et al., 2000; Blichert-Toft and Albarède, 2008; Harrison et al., 2008; Iizuka et al., 2009; Kemp et al., 2009, 2010; Nebel-Jacobsen et al., 2010; Vervoort and Blichert-Toft, 1999), which are of limited use for directly tracking mantle depletion history, and only rare zircons exhibit depleted Hf isotope signatures, mainly from West Greenland (e.g., Guitreau et al., 2012), Antarctica (Choi et al., 2006) and North China (e.g., Liu et al., 2008; Wu et al., 2008). It is noteworthy that the extremely positive $\varepsilon_{Hf}(t)$ values for Jack Hills detrital zircons are very rare, and these data have been debated (Bell et al., 2011; Blichert-Toft and Albarède, 2008; Harrison et al.,

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2008; Kemp et al., 2010). Eoarchean metabasalts in West Greenland yielded highly variable depleted Hf isotopes (Hoffmann et al., 2010), together with zircon $\varepsilon_{Hf}(t)$ values up to 5.6 at 3.85 Ga in Eoarchean gneisses from the Napier Complex, Antarctica (Choi et al., 2006), indicating the possible existence of a highly depleted Archean mantle. These zircon analyses, however, were conducted by the solution MC-ICPMS technique on highly reversely-discordant single-grain zircons with complex age patterns and overgrowth rims, making their interpretations ambiguous. The major problem is whether the isotopic signatures obtained from ancient zircons truly represent primary magmatic signatures or result from secondary alteration, since the interpretation of isotopic compositions of ancient zircons is frequently clouded by: (1) the strong U–Pb discordant nature of zircons, which are susceptible to later disturbances, potentially obliterating their pristine isotopic compositions; (2) the complex age patterns even within a single zircon grain; (3) the difficulty of reliably associating Hf isotope values with the crystallization ages for structurally complex zircons, particularly when obtaining Hf isotopic data by large beam sizes laser-ablation or solution chemistry techniques (e.g., Guitreau et al., 2012; Kemp et al., 2010; Valley et al., 2006). These complexities have resulted in fundamental controversies about early Earth processes, from the crystallization ages of ancient continental rocks (e.g., Kamber et al., 2001) to Hadean tectonics (e.g., Harrison et al., 2005; Kemp et al., 2010).

The Archean Anshan Complex (AAC) in the northeastern segment of North China Craton (NCC) (Fig. 1A), is considered as one of a few documented localities worldwide that may have preserved crustal remnants as old as 3.8 Ga (e.g., Liu et al., 1992; Nutman et al., 2001). Substantial amounts of zircon U–Pb and Hf–O isotopic data of AAC have been accumulated in the past two decades (e.g., Liu et al., 1992, 2008; Song et al., 1996; Wan et al., 2005, 2012, 2013; Wu et al., 1998, 2008; Zhang et al., 2013). Results show that zircons within previously reported oldest rocks have complex structures (e.g., recrystallization and overgrowth) and are characterized by the coexistence of a wide range of ages associated with radiogenic Pb loss to varying degrees even within a single sample. Geological interpretation of such ancient, complicated zircons is difficult, resulting in controversy over whether there are any ca. 3.8 Ga rocks existing in Anshan (Liu et al., 2008; Nutman et al., 2009; Wu et al., 2008, 2009).

In light of these issues, we carried out a systematic in situ zircon U–Pb, O and Hf isotopic study and detailed field mapping and sampling on outcrops in Guodishan, northern AAC. The new results demonstrate that: (1) there exists a ca. 3.81 Ga trondhjemitic gneiss enclave overprinted by a ca. 3.36–3.30 Ga migmatization event. The younger zircon $^{207}Pb/^{206}Pb$ ages within this enclave are attributed to subsequent radiogenic Pb loss and to the injection of ca. 3.36 Ga leucosome veins; (2) only low-U, concordant zircons can best preserve primary $\delta^{18}O$ isotope signatures, while high-U, strongly discordant zircons generally record lower $\delta^{18}O$ values; and (3) pristine ca. 3.81 Ga zircons within this Eoarchean trondhjemitic gneiss recorded highly depleted ε_{Hf} values, arguing for a significant mantle differentiation in the early Eoarchean–Hadean time.

2. Regional geology

The AAC consists of several Archean rock suites, with a total exposed area over 80 km^2 in the northeastern segment of NCC (Fig. 1B). These rock units include: (1) Eoarchean Baijiafen, Dongshan and Shengousi gneisses previously dated at ca. 3.78–3.81 Ga (Liu et al., 1992, 2008; Song et al., 1996; Wan et al., 2005; Zhang et al., 2013); (2) Paleoarchean gneissic trondhjemites and porphyritic to fine-grained granites dated at ca. 3.45–3.30 Ga with associated supracrustal rocks (Song et al., 1996; Wan et al., 2013); (3) Mesoarchean Lishan trondhjemitic gneiss and Tiejiashan granite dated at ca. 3.1 and 3.0 Ga, respectively (Wu et al., 1998); (4) ca. 2.45 Ga Qidashan alkali-feldspar granite that intrudes Neoarchean Anshan Group metasedimentary rocks (Wu et al., 1998). It is, however, noteworthy that crystallization ages for some of these rock suites, particularly of the Eoarchean and Paleoarchean rocks, are still a subject of considerable debate, because of the coexistence of several generations of zircons within a single sample (e.g., Liu et al., 2008; Nutman et al., 2009; Wu et al., 2008, 2009). In this paper, we document and report results for the newly-discovered North Guodishan Complex, another occurrence of very ancient rocks in the Anshan area (Fig. 1).

3. North Guodishan Complex

3.1. Field geology

The Guodishan outcrop (41°08′14″N, 123°03′16″E-WGS-84 datum) in northern AAC has a boomerange shape and three major lithologic units are identified based on detailed field mapping (1:50 scale) (Fig. 1C). (1) A fine-grained massive trondhjemitic gneiss (Unit 1) dominates the outcrop (Fig. 2A). It is locally crosscut by granitic, pegmatitic and quartz veins several centimeters in width. (2) A migmatite complex (Unit 2), consisting of layered migmatite, with paired leucosome and melansome-biotite schist (Fig. 2B and C). This unit is highly deformed and shows phlebitic, stromatic and ptygmatic structures in the field. Leucosomes occur as thin straight and ptygmatic veins, or accumulate to form clots, which cut across the layered migmatite. Biotite-rich layers, however, are spatially closely related to leucosome, occurring either as dark bands of the layered migmatite and thus maybe restitic, or as small rounded blocks within the migmatites. (3) Massive to weakly-banded trondhjemitic gneiss (Unit 3) occurs as enclaves within Unit 2. This unit is bounded by the migmatite complex (Figs. 1C and 2D).

Based on field relationships, the Unit 3 trondhjemitic gneiss is the oldest rock. However, it does contain minor leucosome veins of Unit 2 (Fig. 2E and F). The Unit 1 trondhjemitic gneiss intrudes the Unit 2, and is in turn cut by younger granitic veins.

3.2. Petrography

Samples C209-4 and C209-6 from Unit 1 show hypidiomorphic textures, consisting of quartz (~35%), plagioclase (~50%), biotite (10%), microcline (<5%) and accessory apatite and zircon (Fig. 3A and B). Plagioclase forms subhedral to anhedral, polysynthetic twinned crystals that are partly or entirely sericitized. Quartz is present as anhedral, medium-grained aggregates. Small tabular biotites occur as interstitial crystals among major rock-forming minerals. Biotite was partly replaced by small prismatic clinozoisites.

Unit 2 migmatite complex consists of layered migmatite (sample C209-1), coarse-grained trondhjemitic leucosome (sample C209-3) and biotite schist (sample C209-2). C209-3 is composed of subhedral plagioclase (50%) and anhedral quartz (40%), with minor biotite, apatite and zircon (Fig. 3C). C209-2 consists mainly of biotite (80%), quartz (15%) with accessory apatite, zircon. Biotite is partly replaced by epidote (Fig. 3D). C209-1 consists of alternating medium-grained light layers and fine-grained dark layers (Fig. 3E). The light layer consists of plagioclase (60%), quartz (35%) and minor biotite (5%) with accessory zircon, apatite and secondary muscovite; whereas the dark layer consists mainly of biotite (55%) and quartz (40%), and some secondary muscovite (<5%) and epidote.

Unit 3 samples C209-8(1) and C209-8(3) consist of plagioclase (55%), quartz (30%), biotite (5–10%) and accessory minerals apatite, zircon (Fig. 3F). Subhedral polysynthetic twinned plagioclase grains are strongly sericitized. Anhedral quartz grains in size of 0.5 to 1.5 mm occur frequently as aggregates. Biotite occurs as small