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Geochronological and geochemical constraints on the petrogenesis of the 2.6–2.5 Ga amphibolites, low- and high-Al TTGs in the Wangwushan area, southern North China Craton: Implications for the Neoarchean crustal evolution

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ABSTRACT

The crustal evolutionary processes of the North China Craton (NCC) during the late Neoarchean (ca. 2.6–2.5 Ga) are still under large debate. The systematic investigations of widespread ca. 2.6–2.5 Ga meta-volcanic basalts and TTG assemblages can provide a better understanding of tectonic evolution at this period. The Wangwushan Neoarchean amphibolites, high- and low-Al TTGs in southern NCC were formed at 2.57–2.52 Ga. The amphibolites are tholeiitic in composition. They have whole-rock $\varepsilon_{Nd}(t)$ values of −2.8–+4.0 (T_{DM1} = 3.7–2.6 Ga), and zircon $\varepsilon_{Hf}(t)$ values of +1.2–+7.2 (T_{DM1} = 2.81–2.57 Ga), indicative of a depleted mantle source with involvement of older crustal materials. Their compositional spectrum accords with those in island-arc field, or straddles the boundary between MORB and island-arc fields, suggesting significant contributions from subduction zone-derived fluids during magma formation. The high-Al TTGs contain high Mg#, Cr and Ni contents, and $(La/Yb)_N$ and Sr/Y ratios, together with positive whole-rock $\varepsilon_{Nd}(t)$ values (−0.6–+5.2) (T_{DM2} = 2.95–2.48 Ga), indicating that they derived from partial melting of a subducted oceanic slab with older crustal materials. Their geochemical features are corresponding to 'slab-melt' identification criterion in an arc setting, and illustrate a deep source (> 45 km) with garnet amphibolite in the residue without rutile. The low-Al TTGs show low Mg# and $(La/Yb)_N$ ratios, negative Eu anomalies, relatively flat HREE (and Y) patterns. Their zircon $\varepsilon_{Hf}(t)$ (+2.2–+8.8 and +1.3–+6.9) and whole-rock $\varepsilon_{Nd}(t)$ values (ca. +2.23) are positive. All the evidences support that the low-Al TTGs derived from a low degree partial melting of basaltic crust with the residue lack of garnet, consistent with a shallower depth (about < 30 km). It is likely that the underplated basaltic or high-Al magmas gave rise to re-melting newly formed lower crust to form the low-Al TTGs. Combined with ca. 2.52 Ga diorites and high-K granites in this area, which were formed in a subduction process and post-collisional setting, respectively, we propose that all of these igneous rocks record multi-stage processes in a convergent plate margin.

1. Introduction

Archean crust is mainly composed of TTG (Tonalite-Trondhjemite-Granodiorite) assemblages, and supracrustal meta-volcanic-sedimentary rocks. Dioritic and high-K granite plutons/batholiths also occur, frequently representing late-tectonic phases that heralded craton stabilization (e.g., Taylor and Mclennan, 1985; Hawkesworth and Kemp, 2006; Rollinson, 2007). In the past decades, however, although a lot of systematic investigations have been done on supracrustal meta-volcanic rocks and TTGs, their properties and petrogenetic processes are still under large debate. Geochemical studies have documented two major types of volcanic rock associations in global Archean cratons (e.g., Xie et al., 1993; Sandeman et al., 2004; Polat et al., 2005; Smithies et al., 2005): (1) Mg- to Fe-rich tholeiitic basalts and komatiites, possibly erupted from mantle plumes; and (2) tholeiitic to calc-alkaline basalts, andesites, dacites, and rhyolites typical of convergent margin volcanic rocks. In addition, there are volumetrically minor boninites, picrites, low-Ti and Nb-enriched series in the magmatic arc association (e.g., Hollings and Kerrich, 2000; Wyman et al., 2000, 2002; Polat and Kerrich, 2006). On the other hand, the onset of TTG magmatism

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represents the transition from dominantly mafic crust to crust with a significant felsic component (Glikson, 1979). Although the issue of tectonic setting in the Archean Era remains disputed, it has been noted that the physio-chemical processes that gave rise to the evolution of felsic magmatism in Archean cratons follow a similar differentiation trend with time, which starts with early sodic TTG suites and ending with medium- and high-potassium granite-granodiorite suites of the late-tectonic regime (e.g., Champion and Smithies, 2001; Martin and Moyen, 2002; Smithies et al., 2003).

Since the 1980s, the TTGs have been widely studied with two main focuses: Understanding the tectonic regime of the early Earth and constraining the processes of differentiation of the continental crust. The TTGs are commonly considered to be a product of partial melting of subducted slabs, oceanic plateaux, root zones of volcanic arcs related to subduction (e.g., Martin and Moyen, 2002; Condie, 2005) or hydrous thickened basaltic crust in the lowest crust (e.g., Smithies, 2000, 2002). Meanwhile, there is also considerable debate concerning both the depth of melting and the mineralogy of the source, i.e. amphibolite— < 15 kbar (Foley et al., 2002), or eclogite— > 15–20 kbar (Rapp et al., 2003). However, most studies discussing the origin of the Archean TTG series suggest they should be formed in only one tectonic setting with little consideration for intermediate or mixed models. This results in models for Archean crustal growth and generally geodynamics in which the continents form in one single site. For instance, subduction zones (Martin, 1994; Foley et al., 2002; Rapp et al., 2003) with high Mg# and Cr and Ni concentrations (Martin, 1999; Smithies and Champion, 2000; Martin and Moyen, 2002; Martin et al., 2005; Moyen, 2009) by the interaction of the slab-derived melt with the overlying mantle wedge during ascent process (Rapp et al., 1999, 2010). Other possibilities include sites unrelated to plate boundaries but more likely modern intraplate situations such as oceanic plateaus (Stein and Goldstein, 1996; Smithies, 2000; Bédard, 2006; Willbold et al., 2009) with low Mg#, and Cr and Ni concentrations (Atherton and Petford, 1993; Rapp and Watson, 1995; Petford and Atherton, 1996; Rapp et al., 1999), or variations on either end-member. Yet, many studies identify distinct types or subseries of TTG in one region with clearly different geochemical features. For instance, TTGs developed in the Zimbabwe Craton (Luais and Hawkesworth, 1994), Western Superior Province (Whalen et al., 2004), Barberton granite-greenstone terrane (Clemens et al., 2006; Moyen et al., 2007), Pilbara (Champion and Smithies, 2007) and Karelian and Kola cratons of Finland (Halla et al., 2009). The differences between various TTG types, particularly in Al_2O_3 (high-Al and low-Al types), HREE and Sr concentrations, are interpreted as reflecting distinct depths of melting with corresponding variable mineral assemblages, more or less garnet and plagioclase-rich (Luais and Hawkesworth, 1994; Halla et al., 2009). In turn, this suggests that "TTGs" are actually a diverse group, that can be formed by distinct petrogenetic as well as geodynamic processes. Therefore, systematic investigations of Precambrian greenstone belts and TTG assemblages have greatly improved our understanding of early history of the Earth, including possible role of plate tectonics during the Archean (e.g., Chown et al., 2002; Martin and Moyen, 2002; Smithies et al., 2003; Kusky et al., 2013).

The North China Craton (NCC) is the largest and oldest known cratonic block in China, containing rocks as old as 3.8 Ga (Liu et al., 1992; Zhao, 1993; Windley, 1995; Zhai, 2004), with widespread Archean to Paleoproterozoic basement (Fig. 1a), which records secular changes in tectonics and metallogeny. In contrast to many other cratons around the world that behaved as stable crustal blocks by 2.7 Ga (e.g., Lodge, 2016), the NCC is dominated by the late Neoarchean ($\sim$2.6–2.5 Ga) granitoid gneisses and metamorphosed volcano-sedimentary sequences that experienced strong tectono-thermal overprinting close to the Archean-Proterozoic boundary (Zhai and Liu, 2003; Zhao et al., 2005; Wan et al., 2011a; Zhai and Santosh, 2011; Zhao and Zhai, 2013). Despite recent significant advances in understanding Neoarchean tectonics of the NCC, the crucial issues remain unresolved on discriminating inherent crustal evolutionary scenarios of crustal reworking versus major crustal growth, and in determining geodynamic driving mechanisms at this period (mantle plume versus plate tectonics; e.g., Liu et al., 2004; Zhao et al., 2005).

The Wangwushan area is located in the southern NCC (Fig. 1a). The Neoarchean Linshan Complex in this area preserves extensively 2.6–2.5 Ga amphibolites, low- and high-Al TTGs, diorites and high-K granites (Fig. 1b), making it an ideal place to broaden the existing knowledge of the evolution of the NCC. However, the Neoarchean sequences in the Wangwushan area are complicated constituents including biotite plagioclase gneisses, amphibolites, granites, marbles and banded iron formations. They were all lumped together and generally thought to be para-metamorphic rocks and thus were termed as Neoarchean Linshan "Group" before 1990s (Bureau of Geology and Mineral Resources of Henan Province (BGMRHP, 1981)). Therefore, unclear rock types, formation ages, petrogenesis and tectonic implications hamper a better understanding of the Precambrian crustal evolution of the southern NCC.

In this contribution, we present new field investigations, integrated zircon U-Pb and Hf isotope data, as well as whole-rock major and trace elements and Nd isotope data of the Neoarchean amphibolites and TTG gneisses (high- and low-Al subsuites) in the Wangwushan area. The data set is used to discuss the crystallization ages and origin of these rocks and investigate their petrogenetic relationships. The ultimate aim is to provide a better understanding of the Precambrian crustal evolution in the southern NCC.

2. Geological background

The North China Craton is bounded by the late Paleozoic Central Asian orogenic belt to the north, the early Paleozoic Kunlun-Qilian orogenic belt to the west and the Mesozoic Qinling-Dabie-Sulu ultrahigh-pressure metamorphic belt to the south (Fig. 1a). Long-term studies have shown that the NCC was formed by the assembly of several micro-continental blocks (Zhao et al., 2001; Zhai and Liu, 2003; Zhai et al., 2005; Zhai and Santosh, 2011; Zhai, 2014). According to one prevailing view, it was tectonically divided into Eastern and Western blocks by the Trans-North China Orogen (e.g., Zhao et al., 2001, 2005). In this model, the Eastern Block underwent a Paleoproterozoic (2.20–1.90 Ga) rifting event along its eastern margin to form the Jiao-Liao-Ji Belt at ca. 1.90 Ga (Li et al., 2004; Luo et al., 2004; Li and Zhao, 2007). The Western Block was formed by amalgamation of the Yinshan Block in the north and the Ordos Block in the south at 1.95–1.92 Ga (Zhao et al., 2005; Santosh et al., 2007a,b, 2009a,b). The Trans-North China Orogen was believed to be a collision zone between the Eastern and Western blocks formed at ca. 1.85 Ga (e.g., Zhao et al., 2005, 2006; Kröner et al., 2005), yet others (e.g., Kusky et al., 2007) call this belt the Central Orogenic Belt and suggest that it is an Archean orogen overprinted by younger events. The other prevailing view is that the main body of the NCC was formed through the amalgamation of seven microblocks at the end of the Neoarchean (ca. 2.50 Ga) (Kusky et al., 2007; Wan et al., 2011a; Zhai and Santosh, 2011). Subsequently, the NCC underwent Paleoproterozoic rifting (2.35–1.95 Ga) followed by subduction-accretion-collision tectonics (1.95–1.82 Ga) to form a uniform block (Kusky and Li, 2003; Zhai and Liu, 2003), which subsequently underwent plume-triggered extension and rifting at ca. 1.78 Ga (Zhao et al., 2002). In a recent review, Kusky et al. (2016) suggest that the Eastern Block formed by the assembly of an archipelago-like series of microblocks between 2.70 and 2.50 Ga, then a composite oceanic arc system collided with this system at 2.50 Ga, followed by progressive outward accretion of the Western Block, then the Yinshan Block (or Inner Mongolia-Northern Hebei Orogen), converted to an Andean margin, followed by terminal collision with the Columbia Supercontinent at ca. 1.85 Ga.

The basement of the NCC is mainly composed of Neoarchean TTG gneisses, metamorphosed supracrustal rocks, and sparse Paleoarchean