Lithos 113 (2009) 673–690

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Geochemical and Nd–Hf isotopic constraints on the origin of the ~1.74-Ga Damiao anorthosite complex, North China Craton

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ARTICLE INFO

Article history:
Received 5 April 2009
Accepted 3 July 2009
Available online 18 July 2009

Keywords:
Massif-type anorthosite
Mangerite
High-Al gabbro
Post-collisional magmatism
Proterozoic
North China Craton

ABSTRACT

The ~1.74-Ga Damiao complex in the North China Craton consists of anorthosite (85%), norite (10%), mangerite (4%) and minor troctolite (<1%), all of which are cut by gabbroic and ferrodioritic dikes. The complex hosts abundant Fe–Ti–P oxide ores and has an emplacement sequence from anorthosite and norite to Fe–Ti–P oxide ores to mangerite. All of the different lithologies in the complex have similar light rare earth element (LREE)-enriched patterns and Nd isotopic compositions with $\varepsilon_{Nd}(t)$ values mostly within the range of −5.0 to −4.0. Average $\varepsilon_{Hf}(t)$ values of zircon are −4.7 for mangerite and −5.9 for norite. Plagioclase and clinopyroxene show a continuous range of composition from anorthosite and norite to Fe–Ti–P oxide ores to mangerite, suggesting that these lithologies formed by differentiation from a common parental magma. Gabbroic dikes in the Damiao complex are characterized by high Al_2O_3 (14.5–17.1 wt.%), Sr (~1000 ppm) and Mg#s [100 Mg/(Mg + Fe^{2+})] = 56–73), similar to the high-Al gabbros parental to the Harp Lake and Laramie anorthosite complexes in North America. The high-Al gabbroic dikes of the Damiao complex may reflect the parental melt from which the complex formed, whereas the ferrodioritic dikes may represent residual melts after anorthosite crystallization from the high-Al gabbroic magma. The high-Al gabbros have incompatible element ratios (Zr/Nb = 14–24; La/Nb = 3.6–4.8), which differ significantly from those of nearby coeval, mantle-derived, mafic dike swarms and volcanic rocks but are similar to those of the lower crust. Their zircon $\varepsilon_{Hf}(t)$ and whole-rock $\varepsilon_{Nd}(t)$ compositions plot along the evolution lines of the ~2.5 Ga Archean rocks in the North China Craton, suggesting that the Damiao complex was derived from an ancient lower crust. Exceptionally high temperatures and high-degrees of melting (>75%) would have been required to form the parental high-Al gabbroic magma from the lower crust. We propose that the crustal rocks were dragged into the upper mantle during amalgamation of the North China Craton, where the ambient temperature was high enough (>1271 °C at 12 kbar) to cause extensive melting, producing a deep-seated magma chamber. The melt then evolved through polybaric crystallization, producing anorthositic magmas with abundant suspended plagioclase that were finally injected at mid-crustal depth to form the Damiao complex.

1. Introduction

Massif-type anorthosites are mostly Proterozoic in age (2.1–0.9 Ga) and generally hosted in high-grade metamorphic terranes in Archean and Proterozoic shield areas (Wiebe, 1992). They are typically associated with contemporary rapakivi granite and charnockite in addition to mafic rocks such as troctolite, norite and gabbro to form anorthosite–mangerite–charnockite–granite suites (Emslie, 1991). Thus, they are important for understanding the secular evolution of Proterozoic mantle and crust (Emslie, 1991; Ashwal, 1993; Duchesne, 1999; Duchesne et al., 1999). However, the petrogenesis of massif-type anorthosites is still not fully understood. In particular, controversies exist with regard to the nature of the parental magmas, the nature and extent of differentiation, the relationship between the mafic and associated silicic rocks and the tectonic settings in which anorthosites form (Emslie, 1978; Ashwal, 1993; Longhi, 2005). For example, petrological and experimental observations have shown that magmas parental to anorthositic complexes can range in composition from high-Al basaltic (Fram and Longhi, 1992), to jotunitic (Fe–Ti–P-rich hypersthene monzodiorite) (Vander Auwera et al., 1998) to ferrodioritic (Ashwal, 1993). These magmas are considered to have originated by melting of either lower crust (Longhi et al., 1999) or upper mantle (Ashwal, 1993).

The common association of anorthosite with mangerite or charnockite has also not yet been satisfactorily explained (Markl, 2001). These rocks are thought to be comagmatic and to have formed by continuous fractionation (Emslie, 1985; Mitchell et al., 1995; Scoates and Frost, 1996). Alternatively, these rocks, as well as the

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doi:10.1016/j.lithos.2009.07.002

associated Fe–Ti–P oxide ore deposits, have been linked to liquid immiscibility (Philpotts, 1981). It is also suggested that the rocks may be coeval but not comagmatic (Duchesne, 1990; Icenhower et al., 1998; Longhi et al., 1999).

The Damiao anorthositic complex in the North China Craton contains a typical anorthosite–ferrodiorite–mangerite association. It has been known for decades because of mining for Fe–Ti–P oxide ores (Cao, 1988; Ye et al., 1996; Zhao et al., 2004a), and numerous geological, petrological and geochemical studies are available mostly in Chinese (Zhai, 1965; Wang, 1979; Xie and Wang, 1988; Xue et al., 1988; Hu et al., 1990; Ye et al., 1996; Zhang et al., 2007). However, neither the nature of the parental magma nor the relationship between different types of rocks in the complex is fully understood. Likewise, it is not clear what controlled the emplacement of the Damiao complex along with spatially and temporally associated alkali granitoids (Yu et al., 1993; Yang et al., 2005; Zhang et al., 2007). For example, Zhao (2001) proposed that post-collisional extension of the crust and lithospheric thinning caused decompressive melting of the subcontinental lithospheric mantle. Others argue that the melting was produced by a mantle plume (Zhai and Liu, 2003), which was also responsible for the formation of the coeval rapakivi granites (Ramo et al., 1995), bimodal volcanic rocks (Zhao et al., 2002) and mafic dike swarms (Hall et al., 2000).

This paper presents new major and trace element data, Nd isotopic compositions, zircon U–Pb dating results and Hf isotope analyses for rocks from the Damiao complex. The objectives are to examine the field and genetic relationships between different types of rocks in the complex, and to provide geochemical constraints on the nature of its source, its parental magma and the role of differentiation in its formation. With the new dataset, we further discuss the significance of the complex in the tectonic evolution of the North China Craton.

2. Regional geology

The North China Craton, extending from North Korea to the Tarim Basin in NW China, is separated from the Yangtze Block by the Qinling Orogenic Belt to the south and is bounded to the north by the Central Asian Orogenic Belt. The craton is divided into the Eastern and Western Blocks, separated by the Trans-North China Orogenic Belt (Fig. 1A; inset) which was formed by collision between the two blocks at 1.80–1.85 Ga (Zhao et al., 2000; Zhao, 2001). The cover sequences include the Proterozoic Xiong'er and Changcheng Groups (Zhao et al., 2002; Peng et al., 2008). The Xiong'er Group is widely distributed in the southern part of the North China Craton and consists of a volcanic sequence including basalt, andesite and rhyolite that formed at about 1.75–1.80 Ga (Zhao et al., 2004b). The Changcheng Group in the central and northern parts of the craton consists of a 3.5-km-thick sedimentary sequence of quartz conglomerate, sandstone, siltstone and illite shale with intercalated dolomitic limestone and lavas, which formed at ~1.68 Ga (Li et al., 1995). Mafic dike swarms with ages of ~1.77 Ga are also common (Hall et al., 2000). In addition, ~1.70-Ga rapakivi granites have been documented in the northern part of the craton (Ramo et al., 1995).

The Damiao anorthosite complex is located in the northern part of the Trans-North China Orogenic Belt (Fig. 1A; inset). The complex is spatially and temporally associated with alkali granitoids (Yu et al., 1993) and rapakivi granites (Yang et al., 2005) (Fig. 1A), and hence is part of a typical anorthosite–mangerite–charnockite–granite suite (Zhang et al., 2007). This igneous suite has ages ranging from 1.75 Ga to 1.68 Ga (Yang et al., 2005; Zhang et al., 2007).

3. Geology of the Damiao anorthosite complex

The Damiao anorthosite complex, which is exposed over ~120 km^2, intrudes Archean migmatitic granite and gneiss to the northwest and Archean metamorphic rocks along a high-angle E–W-trending fault (Damiao Fault) to the south (Fig. 1B). The complex is, in turn, intruded by a Mesozoic dioritic pluton to the northwest, and is uncomformably overlain by Jurassic strata to the east and northeast. The complex consists of two lobes, known as the West and East Bodies which have outcrop areas of 88 km^2 and 32 km^2, respectively (Fig. 1A). Our current study is focused on the West Body.

The West Body consists of anorthosite (85%), norite (10%), mangerite (4%), and minor troctolite (<1%), accompanied by gabbroic and ferrodioritic dikes (Ye et al., 1996). The norite and troctolite intrude the anorthosite in places along NE- and NW-trending faults (Fig. 2A), but in other locations they grade into anorthosite. The mangerite locally intrudes the anorthosite in the northwestern part of the complex (Fig. 1B). The ferrodioritic and gabbroic dikes occur mainly at the margins of the complex where they intrude the anorthosite. The Fe–Ti–P oxide ore deposit consists of numerous ore bodies occurring as dikes, veins or sheets scattered throughout the anorthosite (Figs. 1B and 2B).

The ore bodies consist of noritic gabbro, Fe–Ti–P oxide-rich gabbro and massive ores. These lithologies generally occur in the upper, middle and lower parts of the ore bodies, respectively. The massive ores can be broadly divided into Fe–Ti oxide and Fe–Ti–P oxide types (Fig. 2C). The massive ores in the lower parts of ore bodies are locally in sharp contact with the host anorthosite (Fig. 2D), and they grade upward into Fe–Ti–P oxide-rich gabbro with increasing abundance of silicate minerals. The noritic gabbros, at the margins and upper parts of the ore bodies, commonly show a preferred foliation parallel to the contact with the host anorthosite. The foliation is characteristic by the orientation of tabular plagioclase, indicating a magmatic origin. Locally, lenses of massive ore are enclosed in Fe–Ti–P oxide-rich gabbro or noritic gabbro with transitional contacts (Fig. 2E and F).

4. Petrography

Anorthosite and norite are mainly composed of plagioclase (50%–95%) and orthopyroxene (5%–40%) megacrysts as cumulus minerals (Figs. 2A and 3A). The plagioclase crystals are typically tabular, ranging from 1 to 20 cm long. The plagioclase megacrysts contain abundant exsolution lamellae of K-feldspar and fine inclusions of mafic minerals (Fig. 3B). Most plagioclase megacrysts exhibit high-temperature deformation with curved polysynthetic twinning (Xie and Wang, 1988). The orthopyroxene megacrysts contain abundant exsolved lamellae of plagioclase on the {100} plane (Fig. 3C). Other interstitial minerals include plagioclase and orthopyroxene with minor magnetite, ilmenite and apatite, which do not show exsolution features. Mangerite consists of perthite phenocrysts in a groundmass of plagioclase, K-feldspar and quartz with minor but variable Fe–Ti oxides, apatite, olivine, biotite, hornblende and clinopyroxene (see Fig. 3D).

The noritic gabbros are composed of variable amounts of plagioclase (20–70%), clinopyroxene (10–50%) and olivine (~5%) with minor Fe–Ti oxides, apatite (<5%) and perthite. They also contain a few megacrysts of antiperthite and hypersthene (<5%). Fe–Ti–P oxide-rich gabbros generally consist of clinopyroxene (10–30%), plagioclase (10–20%), variable Fe–Ti oxides (20–50%) and apatite (1–20%) with minor olivine, orthopyroxene and sulphides. Some rocks contain only trace amounts of apatite (<1%). Fe–Ti oxides and apatite occur either as interstitial fillings between silicate minerals or as euhedral to anhedral crystals enclosed in silicate minerals (Fig. 3E and F). Clinopyroxene crystals commonly show two sets of exsolved lamellae marked by ilmenite laths oriented parallel to the prismatic cleavage.

The massive ores include Fe–Ti oxide and Fe–Ti–P oxide types. The massive Fe–Ti oxide ore consists chiefly of magnetite and ilmenite (>70%) accompanied by minor olivine (~Fo_{64}), mostly altered to chlorite, whereas the massive Fe–Ti–P oxide ore contains more apatite (15–50%) (Fig. 3G). The magnetite contains abundant lamellae of