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Chemical composition and ultrahigh-P metamorphism of garnet peridotites from the Sulu UHP terrane, China: Investigation of major, trace elements and Hf isotopes of minerals

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ABSTRACT

The Zhimafang peridotite body recovered by a pre-pilot borehole (PP1) of the Chinese Continental Scientific Drilling Project occurs in gneiss from the southern Sulu ultrahigh-P (UHP) terrane, east-central China. Detailed petrographic observation of the freshest lherzolites reveals the existence of pre-peak mantle relics, rare enstatite inclusions (Opx1) in garnet, and coarse-grained diopside (Cpx1) in the peridotites. Matrix phases Ol+Grt+Opx+Cpx±Phl represent the assemblage of the peak-stage. At least >1.5 GPa pressure increase is recognized from the mantle setting to the peak-stage of subduction-zone UHP metamorphism at ~800 °C and 6.8 GPa for the peridotites. All peridotitic minerals have high Mg# (Ol, 91–93, Cpx, 93–94 and Opx, 92–94). Garnets are depleted in LREE, and have increased abundances from Pr through the MREE to a plateau of heavy REE (HREE) at about 10 times chondrite. In contrast, clinopyroxenes display humped REE patterns with high $(La/Yb)_N$ values of 27–68. Phlogopite is a major carrier of Ba (5205 ppm) and Th (5.5 ppm). Partition coefficients ($D_{Cpx/Grt}$) for REE between clinopyroxene and garnet decrease from LREE (~100) to HREE (<1 but >0.1), suggesting that clinopyroxene and garnet equilibrated at low-T (<1100 °C). Zircons from three phlogopite and/or magnesite-bearing peridotites show very low $^{176}Lu/^{177}Hf$ values (between 10^{-3} and 10^{-6}), and a wide range in $^{176}Hf/^{177}Hf$ ratios (0.28221–0.28250). The zircons with low $^{176}Hf/^{177}Hf$ and relatively high $^{176}Lu/^{177}Hf$ document that metasomatism affected the peridotite protolith. The model ages (T_{DM}) of zircons mostly cluster around 1.3–1.4 Ga, which probably reflects the metasomatic source. These chemical data combined with previous published bulk-rock major and trace element data indicate that the Zhimafang peridotites probably represent depleted and metasomatized subcontinental lithospheric mantle (SCLM) beneath the Sino-Korean craton. Investigation of the Sulu UHP metamorphic garnet peridotites provides additional insights into the Earth's geochemical and tectonic evolution, and enlarges our understanding of the exhumation of orogenic peridotites.

1. Introduction

Orogenic peridotites of various sizes occur in high-pressure (HP) and ultrahigh-pressure (UHP) metamorphic belts worldwide (Medaris, 1999). Petrochemical and tectonic investigations of these peridotites provide additional insights into processes related to the upper mantle and plate tectonics (Brueckner and Medaris, 1998, 2000; Zhang et al., 2000, 2005a,b, 2007). P–T estimates and mineral microstructures of garnet peridotites suggest that some garnet peridotites may have been derived from initial mantle depths of 180–300 km (Dobrzhinetskaya et al., 1996; Van Roermund et al., 2000; Zhang and Liou, 2003; Spengler et al., 2006) or were subducted to ~200 km depths (Ye et al., 2000a; Zhang et al., 2000). Isotopic and trace element data for bulk rocks and minerals are essential in order to understand the processes that have produced the secular and spatial variations in composition of subcontinental lithospheric mantle (SCLM).

The northern edge of the Yangtze craton was subducted northward to >150 km depth beneath the Sino-Korean craton, creating the Dabie–Sulu diamond- and coesite-bearing eclogites (e.g., Hacker et al., 2004). Garnet peridotites are widespread and are subdivided into mantle-derived peridotites (Type A), which are thought to represent SCLM beneath the Sino–Korean craton, and crust-hosted peridotites (Type B), which have been emplaced into continental crust of the Yangtze craton (Zhang et al., 2000). Zircon as a rare accessory mineral was successfully separated recently from Sulu garnet peridotites. Isotopic compositions of zircons from Type A peridotites were analyzed by SHRIMP, and their U–Pb ages are nearly identical to that

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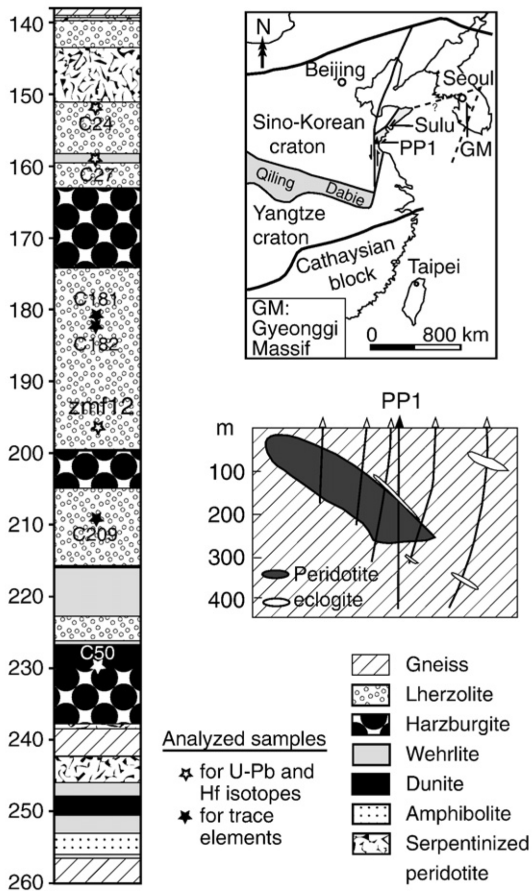

Fig. 1. Schematic map of the Zhimafang peridotite body and its lithological profile recovered from the CCSD-PP1 drill hole, southern Sulu, eastern China.

of the UHP metamorphic event (Zhang et al., 2005b; Zhao et al., 2006; Zheng et al., 2006a). U–Pb data combined with Lu–Hf isotopic compositions of peridotitic zircons are critical in order to decipher the nature and evolution of the Earth mantle. So far only a small number of zircon grains from one Sulu peridotite sample have been devoted to the study of the Lu–Hf system (e.g., Zheng et al., 2006a).

Zhimafang garnet peridotites with characteristics of a mantle origin were selected for the present study for the following reasons. (1) Numerous sparsely zircon-bearing peridotite core samples were recovered from the first pre-pilot borehole (PP1) of the Chinese Continental Scientific Drilling (CCSD) Project (Fig. 1). This drilling operation has opened a unique opportunity to study unaltered mantle samples of this UHP terrane. (2) Although the mantle origin of this peridotite has been accepted (Zhang et al., 2000; Yang et al., 2003; Zhang et al., 2007; Yang et al., 2007), a long-standing debate focuses on whether the peridotite was subjected to UHP metamorphism, as well as its travel path from mantle depths to the surface. In the present study we provide new petrologic evidence documenting that the garnet peridotite experienced subduction-zone UHP metamorphism; we also identify its travel path. New major and trace element data are provided for coexisting garnet, diopside and phlogopite from the freshest garnet lherzolite cores, and Hf isotope compositions of zircons from phlogopite- and magnesite-bearing peridotites. These data, combined with petrologic characteristics, are employed to constrain the compositions and evolution of the SCLM.

2. Geological background

A curvilinear, EW-trending orogenic chain extends for more than 4000 km between the Sino–Korean and Yangtze cratons. The early Paleozoic (~460–500 Ma) Altyn, northern Qaidam and Qinling terranes resulted from episodic subduction and collision of micro-continents during closure of the paleo-Tethys ocean prior to the well-documented Triassic continent–continent collision between the Sino-Korean and Yangtze cratons (Fig. 1). The easternmost Sulu terrane contains a faulted-bounded UHP coesite-bearing eclogite belt and an HP belt consisting of quartz-mica schist, chloritoid–kyanite–mica–quartz schist, marble, and rare blueschist. The UHP belt consists of various UHP metamorphic gneiss, marble, and quartzite typified by the common presence of coesite inclusions in zircon (Ye et al., 2000b; Liu et al., 2002, 2005), although these rocks exhibit retrograde amphibolite-facies overprint. Blocks, boudins and layers of coesite-bearing eclogite occur as enclaves in gneiss, peridotite and marble.

Most garnet peridotites with minor garnet clinopyroxenites and coesite-bearing eclogites in the Sulu terrane occur as bocks or lenses of m to km in felsic gneiss, and are mantle-derived (Type A). A few garnet peridotites are crust-hosted (Type B), such as those recovered in the CCSD-main hole, and occur as interlayers within coesite-bearing eclogites. The supracrustal and mafic-ultramafic rocks were subjected to Triassic (220–240 Ma) (Hacker et al., 2000; Yang et al., 2003; Jahn et al., 2003; Liu et al., 2004; Zhang et al., 2005b; Leech et al., 2006) *in situ* subduction-zone UHP metamorphism at 750–950 °C and 4–6.5 GPa, followed by granulite- to amphibolite-facies retrogression. Minerals from these peridotites exhibit various exsolution textures suggesting deep subduction ≥200 km (Liou et al., 1998; Zhang and Liou, 1999; Ye et al., 2000a; Zhang and Liou, 2003; Chen and Xu, 2005).

3. Sample description

The Zhimafang ultramafic body enclosed in gneisses (34°30′ N, 118°58′ E) from Donghai, southern Sulu UHP belt is ~790 m long, 70–170 m wide, and has a maximum thickness of 118 m. The PP-1 hole of 432 m depth was drilled through the SE part of this body, and recovered continuous core samples of mainly peridotites with minor gneisses between the depths of 138.5 to 256.4 m (Fig. 1). Most peridotites are fresh except for those adjacent to the contacts with the country rock gneiss. PP-1 peridotites consist of lherzolite, harzburgite, wehrlite and minor dunite. In addition to Ol, Opx, Cpx, Grt and Phl (mineral abbreviations are after Kretz, 1983), some layers contain magnesite and Ti-clinohumite (Ti-Chu). The peridotites are depleted in some major elements (such as CaO, Al_2O_3, and Na_2O), and are anomalously enriched in incompatible elements (e.g., LREE and LILE) and low HFSE elements, through metasomatism (Yang et al., 2007; Zhang et al., 2007); these ultramafic rocks were subjected to subduction-zone UHP metamorphism (Yang et al., 1993; Zhang et al., 2000, 2005b). Garnet, clinopyroxene and phlogopite of three of the freshest garnet lherzolites (C181, C182 and C209) were selected for analyses of trace elements. Zircons from Phl- and Mgs-bearing peridotite samples (C24, 151 m depth, C27, 159 m, and C50, 279.8 m) were chosen for Hf isotope analyses, their U–Pb ages having been previously determined. Modal proportions of these samples are listed in Table 1. Brief sample descriptions are presented below.

Garnet lherzolites show porphyroblastic textures (Fig. 2a). Rounded or subrounded, coarse-grained garnets 4–10 mm across

Table 1
Mineral modal proportions of the studied peridotites

	Ol	Cpx	Opx	Grt	Phl	Ti-Chu	Mgs	Dol	Crm
C180	69	9	6	13	3				
C181	74	7	8	11					Trace
C182	78	5	6	10	1				Trace
C209	72	5	6	12	5				Trace
C216	71	5	8	16	3	Trace			
C24	74	5	7	7	5	1.5		0.5	Trace
C27	71	8	1		18	1	1.5	trace	1
C50	90	0.5	2		4	1	0.5		2