Dual origin of garnet peridotites of Dabie-Sulu UHP terrane, eastern-central China

Two distinct types of garnet peridotite blocks or layers occur within quartzofeldspathic gneiss in the Dabie-Sulu ultrahigh-pressure (UHP) terrane of eastern-central China. Type A mantle-derived peridotites are fragments of mantle wedge that have been sequestered into subducted continental lithosphere whereas type B crustal-hosted peridotites are portions of mafic-ultramafic complexes emplaced into continental crust prior to subduction. Type A lherzolites have lower CaO, Al₂O₃, TiO₂ and REE contents than primitive mantle, and pyroxenites preserve mantle O isotope values (δ¹⁸O: 5.0–5.6‰) and ⁸⁷Sr/⁸⁶Sr ratios (0.7032–0.7036). In contrast, Type B peridotites, including pyroxenites, show a wide range in CaO, Al₂O₃, TiO₂ and REE; some possess extremely [(La/Yb)N = 17386] to moderately fractionated LREE-enriched REE patterns. Type B peridotites have relatively low δ¹⁸O values of +1.5 to +4.1‰, and high ⁸⁷Sr/⁸⁶Sr ratios (0.707–0.708), and were subjected to crustal contamination and/or metasomatism prior to UHP metamorphism.

Garnet peridotites of both types have experienced four distinct stages of recrystallization: (I) primary formation, (II) peak UHP metamorphism, (III) granulite and amphibolite facies retrogression during decompression, and (IV) greenschist facies overprint. P-T estimates of UHP metamorphism are 800 to 1000 °C and pressures of 35–60 kbar. These garnet peridotites provide a window into geochemical characteristics of mantle wedge and deep subduction processes involving the role of different fluids (surficial vs. juvenile) sequestered within a subducting continental lithosphere plate.

Introduction

Garnet peridotites occur in Caledonian, Variscan, and Alpine orogenic belts in Europe and in the Triassic Dabie-Sulu ultrahigh-pressure (UHP) terrane in eastern-central China. They have been considered to either be mantle-derived tectonically emplaced into crustal sequences or products of subduction-zone metamorphism previously emplaced into the crust (Medaris and Carswell, 1990). In the first hypothesis, whether the garnet peridotites were incorporated into the continental crust prior to subduction has not always been made clear (Jamtveit et al., 1991). Some garnet peridotites have been recently considered to be mantle wedge garnet peridotites that were incorporated into subducted continental crust and were subsequently subjected to UHP metamorphism together with the continental sequences at depths >100 km (Zhang et al., 1994; Bruckner, 1997).

Garnet peridotites of both crustal-hosted and mantle-derived origins have been recognized in the Dabie-Sulu UHP terrane marking the collision zone between the Sino-Korean and Yangtze cratons. They are garnet-bearing lherzolite, harzburgite, wehrlite, websterite and pyroxenites that occur as layers and blocks within an UHP paragneiss. This paper compares and contrasts their petrochemical features, mineral parageneses and distribution in the Dabie-Sulu terrane, and proposes a tectonic model for their formation and exhumation.

Two types of garnet peridotites

The spatial distribution of a high-P belt to the south and a UHP belt to the north with progressive metamorphic zones in the Dabie-Sulu collision zone is well documented (Figure 1). The mapped distribution suggests Triassic northward subduction of the Yangtze continental lithosphere beneath the Sino-Korean craton prior to the collision. Garnet peridotites are ubiquitous in the Dabie-Sulu UHP terrane (Figure 1), where inclusions of coesite have been identified in eclogitic minerals and in zircons from gneisses (Sobolev et al., 1994; Zhang et al., 1996; Tabata et al., in press). Garnet peridotites occur as meter to kilometer size blocks and thin layers in quartzofeldspathic gneiss; many have been partially to completely serpenitized and strongly deformed. Relict assemblages of garnet peridotite are preserved in the core of ultramafic bodies. Many of these garnet peridotites contain eclogite lenses (or nodules) and layers with rare inclusions of coesite or quartz pseudomorphs after coesite in garnet and/or omphacite. Diamond has been reported in heavy mineral separates of the Donghai garnet lherzolite (Xu, Z, personal communication, 1997). The occurrence of coesite and possible diamond is consistent with the extremely low Al₂O₃ content of orthopyroxene in all Dabie-Sulu garnet peridotites (e.g., Zhang et al., 1994, 1995; Liou and Zhang, 1998). These petrologic data suggest that the garnet peridotites, regardless of origin, have been subjected to UHP metamorphism at mantle depths of >100 km.

The garnet peridotites of the Dabie-Sulu terrane can be divided into two types based on their spatial association with other rocks, petrochemical features and metamorphic history. Type A peridotites are fragments of the mantle wedge that have been tectonically inserted into the subducted continental lithosphere but have not been exposed to the crust prior to subduction, whereas type B peridotites include crustal mafic-ultramafic complexes of various origins. Gar- net peridotites of type A are mainly distributed in the Sulu UHP terrane, whereas type B garnet peridotites occur mainly in the Dabie UHP terrane (Figure 1). Some representative garnet peridotites of these two types are described below.

Type A garnet peridotites (lherzolite, harzburgite, wehrlite and minor websterite and clinoptyroxenite) in the Sulu region are massive, and strongly serpenitized. Garnet lherzolites (Opx+Grt±Phl±Amp) are near-equiгранular (e.g. Rongcheng) or porphyroblastic (e.g. Donghai). Most garnet has a thin kelyphitic rim consisting of radial aggregates of Opx and Cpx. Olivine exhibits unusual
exsolution rods of ilmenite (Hacker et al., 1997). Donghai harzburgite contains minor Ti-clinohumite and magnesite (Yang et al., 1993). In addition, a unique assemblage of garnet-enstatite-magnesite-Ti-magnetite was found in Donghai. Many garnet clinopyroxenite masses in Rizhao occur within serpentinite and exhibit porphyroblastic or equigranular textures. Garnet occurs both as a porphyroblast (2 mm in size) and as a fine-grained matrix phase (<0.5 mm in size). Rare garnet megacrysts (about 2.5 cm) contain inclusions of green spinel, diopside, hornblende, and ilmenite with hematite lamellae (Zhang et al., 1994; Hiramatsu et al., 1995). Most garnet peridotites from the Sulu region do not contain spinel inclusions; instead, spinel is a common retrograde phase. The clinopyroxene inclusions display exsolved amphibole lamellae, garnet blebs and ilmenite.

Type B garnet peridotites consist mainly of pyroxenite, herzolite, wehrlite and minor harzburgite; they are distributed in the Dabie and rarely in the Sulu terranes, and are characterized by well-developed ultramafic layers of various compositions. Those in the Dabieshan include the Bixiling mafic-ultramafic complex and the Maowu layered garnet pyroxenite with minor harzburgite. The Bingliling complex consists predominantly of eclogite of various assemblages and about 20 thin garnet peridotite layers. The ultramafic rocks include garnet lherzolite, wehrlite and websterite, and consist mainly of olivine, enstatite, and diopside with a variable amount of chlorite, Ti-clinohumite (Ti-Chu) and magnesite. Ti-clinohumite is replaced by olivine-ilmenite sylmeltcite and magnesite is replaced by fine-grained aggregates of dolomite at their rims (Zhang et al., 1993).

The Maowu complex is a large lenticular mass consisting of banded garnet orthopyroxenite, clinopyroxenite and harzburgite, and minor mafic layers of eclogite and omphacite (Okay, 1994; Liou and Zhang, 1998). Many hydrous phases such as talc, chlorite, mica and amphibole occur as inclusions in garnet and pyroxenes. Minor

harzburgite consists of olivine + enstatite with minor fine-grained clinohumite, garnet, chrome, and magnesite; both olivine and clinohumite contain magnetite lamellae. Garnet orthopyroxenite is composed of enstatite, variable amounts of garnet (5 to >20 vol%), and subordinate clinohumite, chlorite, chrome, and apatite, with or without magnesite. Garnet clinopyroxenite sample (54°C) contains minor monazite and rutile as matrix and inclusion phases in garnet and diopside. A thin omphacite layer 5–10 cm thick consists mainly of oscillatory zoned omphacite (Jd60–68 Acn5–15 Aug63), rare rutile and monazite; coesite inclusions occur in omphacite.

**Type B garnet peridotites at Yangkou Beach in the Sulu terrane are associated with a metagabbro-eclogite body of 100 × 200 m², and show a discordant contact with the host gneiss. Most of the ultramafic rocks are strongly serpentinized with minor garnet peridotite and pyroxenite relics.**

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**Petrochemical characteristics**

Figure 1  Distribution of garnet peridotites in the Dabie-Sulu ultrahigh-pressure metamorphic terrane, eastern-central China. A – type A; B – type B.

Table 1. Major, trace and REE data of some garnet peridotites from the Dabie-Sulu ultrahigh-pressure metamorphic terrane, eastern-central China.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Type A</th>
<th>Type B</th>
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<tr>
<td>Al₂O₃ (wt%)</td>
<td>2.2–3.8</td>
<td>2.1–3.1</td>
</tr>
<tr>
<td>CaO (wt%)</td>
<td>2.0–7.7</td>
<td>0.07–0.11</td>
</tr>
<tr>
<td>TiO₂ (wt%)</td>
<td>0.11–0.53</td>
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REE patterns of type A and B garnet peridotites are shown in Figure 2. Type A garnet lherzolites lie within the field of typical mantle-derived garnet peridotites from the Western Gneissic Region of Norway (Garmann et al., 1975). The lherzolites from Rongcheng [RC(Z)] show a relatively flat pattern (see Figure 2A) with REE abundances close to or slightly higher than the chondritic values. Peridotites from Jiangzhuang of the Donghai area [DH(ZC)] have moderately fractionated REE patterns with slight HREE depletion (Zhai et al., 1991; Li et al., 1993) (Figure 2A); such concave patterns may be related to garnet and clinopyroxene cumulates. Type B peridotites from Bixiling [BX(CJ)] also have lower total REE contents similar to the type A peridotites and show unusual REE patterns with positive Eu anomalies, different from common Alpine-type peridotites (Figure 2B); these patterns have been interpreted to represent a more advanced crystal cumulation or depleted peridotite (Chavagnac and Jahn, 1996). The positive Eu anomalies may be attributed to the presence of plagioclase in the protoliths (Zhang et al., 1995). However, most type B ortho- and...
clino-pyroxenites from Maowu [MW(LZ)] are characterized by extremely high total REE contents and LREE-enrichment with two distinct REE patterns. The clinopyroxenites possess an extremely (54C, (La/Yb)N = 17386) to moderately fractionated and LREE-enriched REE pattern (see Figure 2B) whereas the orthopyroxenites have concave REE patterns. This feature implies that the Maowu pyroxenites were metasomatized by LREE-enriched fluid or melt prior to UHP metamorphism in the upper mantle (Zhang et al., in review).

The discovery of negative 18O-isotope values and unusually low deuterium contents in silicate minerals in eclogites, interlayered quartzites and felsic gneisses from Qinglongshan and adjacent areas of the Donghai region (Yui et al., 1995; Rumble and Yui, in review) indicate that fluid was not free to infiltrate across lithologic contacts during UHP metamorphism at mantle depths and subsequent exhumation. Although oxygen isotope data for the UHP peridotites and pyroxenites in the Dabie-Sulu terrane are limited, type A and B exhibit significantly different δ18O values. Type A pyroxenites from Rizhao have δ18O values of +5.5 to +5.6‰ (Yang, 1991) and 87Sr/86Sr ratios of 0.7032–0.7036 (Jahn, 1998); these values are typical for mantle rocks. On the other hand, one type B harzburgite and six pyroxenites from Maowu and Bixiling have low δ18O values ranging from -1.5 to +4.1‰ (Zhang et al., 1998). Moreover, the Maowu garnet pyroxenites have relatively high 87Sr/86Sr of 0.707–0.708 (Jahn, 1998), but very low 87Rb/86Sr (< 0.1) ratios. Such geochronological characteristics may have resulted from complex metasomatic exchanges of the protoliths with meteoric waters and crustal contamination, and may have suffered no significant change during subduction because of limited fluid/rock interaction. The Bixiling mafic-ultramafic complex has been considered to be a mantle-derived melt-cumulate association based on Sr isotopic (87Sr/86Sr ratios: 0.7036–0.7042) and petrological data (Chavagnac and Jahn, 1996; Zhang et al., 1995). Thus, the Maowu and Bixiling mafic-ultramafic complexes evidently were emplaced into continental crust and experienced crustal contamination and/or metasomatism prior to Triassic UHP metamorphism.

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**Metamorphic evolution and P-T conditions**

Mineral parageneses of the Dabie-Sulu garnet peridotites indicate a complex metamorphic history of subduction and exhumation. At least four distinct stages were identified: (I) crystallization of precursor minerals trapped in inclusions, (II) peak UHP metamorphism, (III) early decompression and development of granulite and amphibolite facies assemblages, and (IV) late decompression greenschist facies recrystallization. Suggested P-T positions of these stages are shown in Figure 3. Constraints for the P-T paths are based on a detailed study of type A garnet peridotites from the Sulu UHP terrane (e.g., Zhang et al., 1994) and Type B garnet peridotites from Bixiling (Zhang et al., 1995). As Type B peridotites were subducted along with supracrustal rocks and share the same P-T path, the prograde P-T path is constrained based on the observed parageneses of transformation from metagabbro to coesite eclogite in a single block (Zhang and Liou, 1997) in the Sulu UHP terrane. This prograde P-T path is similar to the Dora Maira Massif of the western Alps (e.g., Schertl et al., 1991).
**Type A peridotites**

The protoliths of UHP peridotites from the Dabie-Sulu terrane could have contained primary assemblages characteristic of spinel lherzolite, or garnet lherzolite depending on their depth of genesis. These primary relics are barely preserved because these ultramafics have been subjected to extensive recrystallization at various stages. Rare inclusion associations of Sp→Cpx±Opx±Ilm±Amp in porphyroelastic garnets of clinopyroxenite from Rizhao suggest that its protolith could be spinel peridotite (Zhang et al., 1994). The primary clinopyroxene included in garnet are highly aluminous (＞1.80 wt%) and have been modified by exsolution. Exsolved garnet and host clinopyroxene pairs yield a breakdown temperature for stage I clinopyroxene of about 920 ± 50 °C, and the primary assemblage may have crystallized at even higher temperatures. Garnet peridotite from greater depths in a mantle wedge could also have been a protolith for the type A garnet peridotite.

**Type A garnet lherzolites of the Sulu UHP terrane carry stage II assemblage Ol+Opx+Cpx+Grt±Phl.** During the UHP metamorphism, primary Al-bearing phases such as spinel reacted with Opx and Cpx to form garnet in response to increasing pressure. P-T estimates of UHP metamorphism by several geothermobarometers yield temperatures ranging from 800 to 1000 °C and pressures of 35–60 kbar (Yang et al., 1993; Zhang et al., 1994, 1995; Hiramatsu et al., 1995). During exhumation, these UHP rocks were retrogressed. In an early decompression stage, garnet was replaced by a kelyphitic assemblage of Opx±Cpx±Sp around the rims, or by minute granules of green spinel. The assemblage Ol±Opx±Cpx±Sp±Par-Amp suggests a granulite overprint. In other garnet peridotites, garnet and clinopyroxene were replaced by pargasitic amphibole, suggesting an amphibolite facies retrograde event. P-T conditions for this stage were constrained by the maximum stability limit of tremolite + forsterite in the CMASH system at T less than 750 °C at 12 kbar and 800 °C at 4 kbar but above the tremolite-chlorite stability at 600±70 °C and about 5 kbar. In a later decompression stage, orthopyroxene was replaced by chlorite, talc or serpentine, pargasitic amphibole by tremolite, and olivine by serpentine and minor talc. The mineral assemblages of this stage suggest greenschist-facies metamorphism at 300–500 °C (Zhang, et al., 1994).

**Type B peridotites**

Various stages of metamorphic recrystallization of garnet peridotites and their P-T conditions were previously described (Zhang et al., 1995; Liou and Zhang, 1998). Most representative peak assemblages for peridotite and pyroxenite are Grt±En±Di±Ol±Mgs±Ti-clinohumite. Peak pressures of 47–60 kbar and temperatures of 790–1000 °C and 840–860 °C were estimated for Bixiling garnetiferous lherzolite and websterite, respectively; similar P-T estimates were obtained for Maowu harzburgite and pyroxenite (Okay, 1994; Liou and Zhang, 1998). In the early decompression stage, diopside and enstatite were replaced by tremolite and by talc and magnetite respectively, whereas Ti-clinohumite was replaced by symplectic intergrowths of secondary olivine+ilmenite, and magnesite by dolomite. Later stage recrystallization is characterized by an overprint of chlorite and serpentine.

**Dual origin of garnet peridotite — A tentative model**

All evidence described above indicates that type A and B garnet peridotites possess significantly different petrochemical and isotopic characteristics in spite of their shared retrograde P-T path shown in Figure 3. The Type A peridotites (mainly lherzolite) were derived from the mantle wedge near a subduction zone, and prior to UHPM, were never at the surface. Hence, they preserve a mantle signature for major, REE and isotopic (O, Sr) compositions. The transformation of stage I spinel to stage II garnet requires a tectonic process to decrease temperature and/or increase pressure. These factors suggest that fragments of mantle wedge ultramafics were inserted into subducting lithosphere, and subsequently recrystallized together with...
the supracrustal materials at depths greater than 100–180 km (Figure 4A). Depending on the thickness of the mantle wedge above the subduction zone, both spinel and garnet peridotites could have been sequestered into subducting materials and subsequently subjected to coeval UHP metamorphism. Bruckner (1997) recently proposed a "sinking intrusion model" to explain the occurrence of garnet peridotites in the Western Gneiss Region of the Norwegian Caledonides. He noted that a denser mantle wedge above less dense subducting supracrustal material is gravitationally unstable; mixing of mantle ultramafics in deep subduction zone occurred at the interface between crust and mantle.

Type B peridotites, which contain considerable pyroxenite and more hydrous and carbonate phases, have low δ18O values (+1.5–+4.1‰) and high 87Sr/86Sr (such as 0.707–0.708 for Maowu pyroxenite) suggesting distinct crustal contamination and metamatism. The protoliths of these mafic-ultramafic complexes crystallized near the surface before Triassic subduction and UHPM; hence they share the same prograde and retrograde P–T–t path and oxygen isotopic characteristics with the adjacent eclogites and enclosing quartzofeldspathic gneisses.

A schematic model for the dual origin of the garnet peridotites from the Dabie-Sulu UHP terrane is shown in Figure 4. Figure 4A illustrates the original settings of type A and B peridotites before and during Triassic subduction of the Yangtze craton beneath the Sino-Korean craton and the coeval nature of UHP and retrograde events with the surrounding gneissic rocks. Because of their different setting, type A and B garnet peridotites possess different isotopic and metamorphic signatures. Figure 4B shows the exhumation of the UHP slab which initially could be mainly due to buoyant return after slab breakoff and later by doming processes (for details see Ernst et al., 1997; Maruyama et al., 1996). These peridotites share similar retrograde overprints by granulate through amphibolite to greenschist facies assemblages.

The dual origin of Alpine-type garnet peridotites has long been described (e.g., Medaris and Carswell, 1990) and such rocks are common in most HP and UHP subduction complexes. Those from the Dabie-Sulu UHP terrane are unique in that they contain inclusions of coesite in the enclosing eclogite or omphacite and ilmenite rods and magnetite plates in olivine. Moreover, because of the limited fluid/rock interaction during for the UHP event, type A and B garnet peridotites preserve their primary geochemical and isotopic signatures. Systematic investigation of these garnet peridotites from this terrane provides a window into geochemical characteristics of mantle wedge and deep subduction processes involving the role of different fluids (subaerial vs juvenile) sequestered within subducting continental lithosphere plate.

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Hutchison ‘Young Scientist’ Fund

William Watt Hutchison, "Hutch" to his many friends around the world, was a Scots-born Canadian geologist who served Canada and the IUGS in myriad dynamic and creative ways. Most notably, he served as the IUGS Secretary General (1976-1980) at a pivotal time in its history, and as IUGS President (1984-1987). The same boundless energy, enthusiasm, skill in communications, and ability to foster teamwork that characterized his work with the IUGS also carried him to preeminent scientific administrative positions in the Canadian Government, where he served as Director General of the Geological Survey of Canada and as Assistant Deputy Minister of Earth Sciences. His distinguished career was terminated in 1987 by his untimely death at the age of 52, following a painful struggle with cancer.

One of Hutch's last wishes was to establish under IUGS auspices a memorial foundation intended to promote the professional growth of deserving, meritorious young scientists from around the world by supporting their participation in important IUGS-sponsored conferences. The first 3 beneficiaries of the Hutchison "Young Scientist Foundation" attended the 28th International Geological Congress (IGC) in Washington, D.C., in 1989.

Currently, income earned as interest on the Hutchison fund is insufficient to sustain comparable grants every four years without seriously eroding the principal. For that reason, the IUGS made no grants from the fund for the 30th IGC, preferring instead to strengthen the fund by allowing it to earn interest for a longer period of time and by appealing for donations from the international geologic community. It is expected that grants from the fund will again support deserving young scientists to attend the 31st IGC in the year 2000. The Hutchison "Young Scientist Foundation" is a worthy cause that honors a fine, caring man and a distinguished, public-spirited scientist and administrator. The foundation also celebrates and promotes those things that gave Hutch the most professional satisfaction: geology, international scientific collaboration, and stimulating young minds.

The IUGS welcomes contributions to the Hutchison "Young Scientist Foundation." Please send donations to:

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