DEEP SUBDUCTION OF SU-LU GARNET PERIDOTITES

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Summery

Garnet peridotites from the Chinese Su-Lu ultra-high-pressure metamorphic terrane contain garnet with aligned inclusions comprising a low P-T mineral assemblage (chlorite, hornblende, Na-gedrite, Na-phlogopite, talc, spinel, and pyrite). Orthopyroxene and clinopyroxene show exsolution lamellae from each other. Matrix pyroxene and garnet crystallized at the expense of olivine, as a result of metasomatism by SiO_2-rich melt. The Mg/(Mg+Fe) ratio of garnet decreases from core to rim, while compositions of pyroxenes are similar in terms of Ca-Mg-Fe. The Mg-rich core of garnet and reconstructed compositions of pyroxenes record high T-P (~1000 °C, ≥5.1 GPa), whereas the matrix minerals record much lower T-P (~760 °C, ~4.2 GPa). Sm-Nd data give ages of ~380 Ma, which are meaningless because isotopic disequilibrium between garnet cores and the rest of the rocks was caused by melt/fluids from crustal materials. The Rb-Sr systems of phlogopite and clinopyroxene reached equilibrium and record cooling ages of ~205 Ma. It is suggested that the garnet peridotites were originally emplaced into a shallow level prior to the ~220 Ma continental collision, during which they were subducted together with crustal rocks to mantle depth. An important corollary is that at least some of the coevally subducted crustal rocks have been subjected to metamorphism at P-T much higher than presently estimated (≥2.7 GPa, ≤800 °C).

Introduction

Garnet lherzolites resembling mantle peridotites occur as an important rock type in most coesite-bearing eclogite terranes. However, it has not been easy to assess whether such rocks were emplaced directly from the mantle, or whether, together with the crustal rocks (e.g., coesite-bearing eclogites), they were also subjected to ultra-high-pressure metamorphic (UHPM) conditions of ≥ 2.5 GPa with a high P/T ratio appropriate to a deeply subducted slab.

In the Su-Lu and Dabie UHPM terranes, eastern China, garnet lherzolite lenses with modal and mineral chemical compositions resembling mantle rocks are mostly recognized in Donghai County. Mineral compositions of some fresh garnet peridotites are very similar to those of garnet peridotite xenoliths in kimberlites, suggesting that these Su-Lu garnet peridotites were originally derived from mantle source. In the present study, however, we document the occurrence of a low P-T mineral assemblage as inclusions in garnet porphyroblasts, which indicates that the peridotites had a subduction history. Based on petrologic, mineral chemical and isotopic data we discuss the P-T path of these garnet peridotites and implications for the peak metamorphic P-T conditions of the coevally subducted coesite-bearing eclogites.

Field relations and petrography

The peridotites at the village of Zhimafang, Donghai County, are enclosed in quartzofeldspathic gneiss and are serpentinized at the surface. The assemblage talc + magnesite was observed along the margins of the peridotite bodies. Garnet peridotite samples obtained from old drill-cores are very fresh and nearly free of serpentinization. They contain large (up to 2.5 cm) deep violet garnets and apple green clinopyroxenes (up to 5 mm).

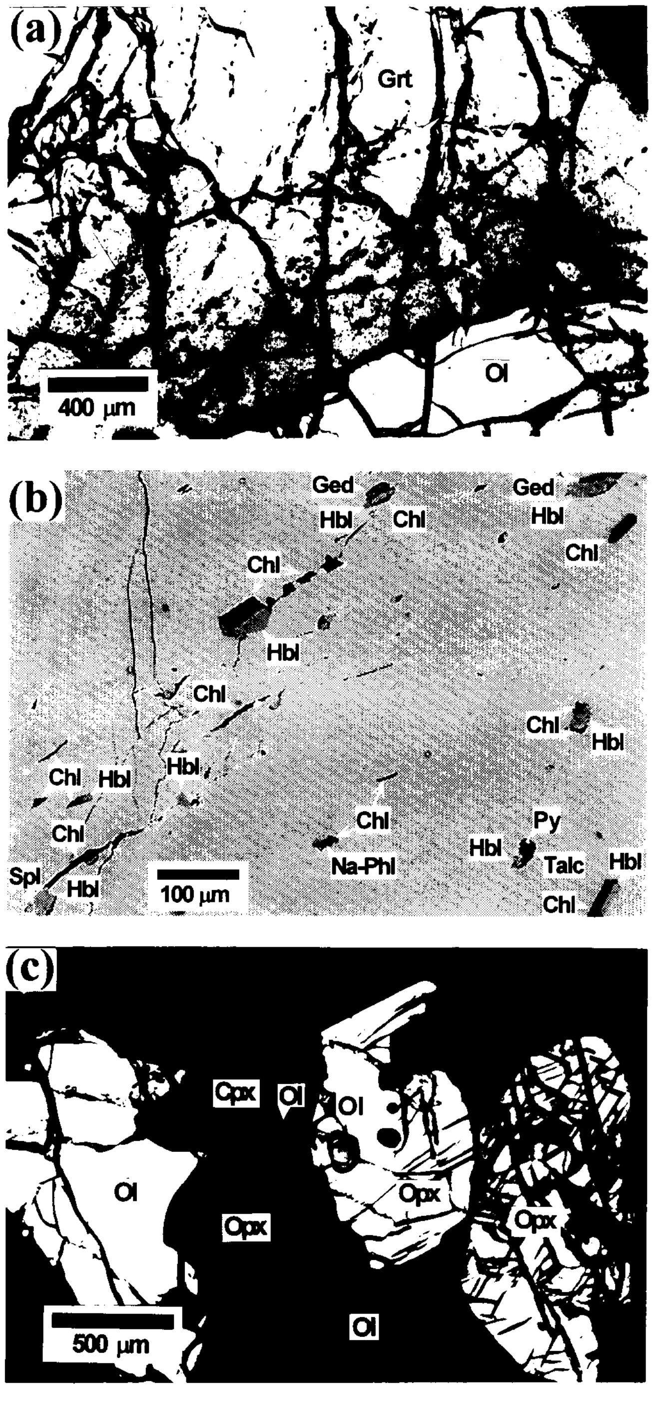

Fig. 1. **(a)** Photomicrograph of mineral inclusions in garnet. Arrowheads indicate (trails of) the inclusions. Plane-polarized light. **(b)** Back-scattered electron image of the inclusions in garnet. **(c)** Triple-junctions of matrix pyroxenes including rounded olivines (DZ10b). Cross-polarized light.

Many garnet porphyroblasts contain abundant minute inclusions (Fig. 1a, b). They are mostly chlorite, hornblende, and Na-gedrite, with rare talc, Na-phlogopite, spinel, and pyrite. Garnet rims are free of inclusions and are in most cases not corroded by amphibole and/or chlorite. The hydrous mineral inclusions in the cores of large garnet are mostly aligned in one or more directions, which are not related to the present fractures in the garnets. Some inclusion trails in garnet cut across each other. While the rims of the porphyroblastic garnet may have simply overgrown on hydrous minerals, the straight and crosscutting trails of such mineral inclusions in the cores of garnet porphyroblasts require pre-existence of garnet. They probably represent former fractures in the garnet, and were likely formed due to fluid infiltration through broken garnets, followed by reaction between fluids and garnet and fracture healing due to later reheating. Thus, the mineral inclusions in garnet were formed early in the metamorphic history of the peridotites, prior to UHP metamorphism, but later than the cores of the porphyroblastic garnet.

Small rounded olivine grains also occur in some garnets. In micaceous part of the peridotite body, some garnet grains also include euhedral titanian clinohumite and magnesite in their rims or even cores, but these occur in separate groups from the hydrous mineral inclusions described above. Discontinuous chromian garnet overgrowths (up to 180 μm wide) on the rims of garnet are observed in all the fresh samples, indicating a further growth of the garnet.

Olivine porphyroblasts (up to 6 mm) contain oriented opaque needles and tablets in their cores. The tablets are magnetite with some ulvospinel and chromite in solid solution. The needles are probably $FeTiO_3$. Orthopyroxene porphyroblasts (up to 3 mm) contain up to 3.33 vol% of clinopyroxene and 0.42 vol% of chromite as exsolution lamellae. A clinopyroxene inclusion (~1 mm) in a garnet porphyroblast contains 1.41 vol% of orthopyroxene lamellae, whereas discrete clinopyroxene porphyroblasts are free of orthopyroxene exsolution but contain fine phlogopite flakes in their cores.

The rims of porphyroblastic clinopyroxene are free of phlogopite inclusions; however, they almost invariably include rounded olivine. Matrix pyroxenes exclusively include rounded olivine; they are closely associated and recrystallized to form triple-junctions (Fig. 1c). These features suggest that the matrix minerals, including parts of the porphyroblastic minerals, are newly crystallized phases at the expense of olivine, due to metasomatism of the garnet peridotites by SiO_2-rich melt/fluids at UHP conditions during exhumation.

In the rock matrix, phlogopite and magnesite are texturally later than the major phases. Only trace chromite occurs. Minor amphibole and chlorite appear around garnet and phlogopite, respectively. Other inclusion minerals in garnet, such as orthoamphibole, talc, Na-phlogopite, and Mg-Al spinel are not observed in the matrix.

The garnet websterite sample DG01 is an well-equilibrated equigranular Grt+Opx+Cpx±Chr assemblage (Yang et al., 1993), it may be taken as metasomatic product of the garnet peridotites at high pressure. Garnets in this sample are free of low P-T mineral inclusions, but contain titanian clinohumite.

Mineral chemistry

The porphyroblastic garnet is zoned, with decreasing Mg and increasing Fe toward the rim (Table 1). Such zoning is obviously not prograde, as commonly found in eclogite garnet containing low P-T mineral inclusions. Small garnet is homogeneous in composition. Apart from the chromian overgrowth, the

Table 1. Selected electron microprobe analyses of major minerals.

Mineral	*Clinopyroxene*					*Orthopyroxene*							*Olivine*		*Garnet*						
Occurrence	*in garnet*			*matrix*		*porphyroblast*					*matrix*		*matrix*		*porphyroblasts*					*small blast*	
Position	**Opx lam**	**host**	**rec.**	**core**	**rim**	**Cpx lam**	**Chr lam**	**core**	**rim**	**rec.**	**core**	**rim**	**core**	**rim**	**core**	**rim**	**Cr-rim**	**core***	**rim**	**core**	**Cr-rim**
Sample No.	DZ06			DZ10b		DZ06					DZ10b				DZ06			DZ10b			
Remark	*1.49 mol%*	2	1	3	3	*3.32 mol%*	*0.92 mol%*	3	3	1	3	3	5	3	3	11	5	1	1	50	3
SiO2	58.32	55.10	55.15	54.38	54.48	54.31	0.17	58.53	57.83	57.86	57.56	58.01	41.11	40.80	41.97	40.81	40.84	40.62	41.52	40.91	40.90
TiO2	0.00	0.04	0.04	0.04	0.08	0.04	0.23	0.00	0.01	0.00	0.01	0.02	0.00	0.03	0.04	0.05	0.00	0.03	0.00	0.03	0.01
Al2O3	0.24	1.64	1.62	1.32	1.84	1.56	4.08	0.09	0.17	0.18	0.18	0.20	0.00	0.00	22.71	22.15	21.15	21.74	22.62	22.50	20.85
Cr2O3	0.13	1.70	1.68	1.79	1.36	1.81	43.69	0.06	0.06	0.52	0.03	0.05	0.01	0.06	2.18	2.41	3.58	1.80	1.56	1.63	3.28
FeO	4.71	1.66	1.71	2.17	2.58	2.59	42.52	5.17	5.58	5.43	4.99	5.06	8.00	7.83	8.04	10.72	11.48	9.19	10.57	10.73	11.60
MnO	0.14	0.05	0.05	0.01	0.03	0.05	0.38	0.00	0.10	0.01	0.06	0.07	0.10	0.05	0.37	0.59	0.68	0.33	0.72	0.60	0.68
NiO	0.00	0.02	0.02	0.04	0.03	0.07	0.24	0.04	0.19	0.04	0.02	0.05	0.32	0.33	0.00	0.06	0.00	0.07	0.00	0.00	0.00
MgO	35.85	16.17	16.46	15.61	15.37	15.57	4.80	36.35	36.19	35.37	36.17	36.12	50.74	50.70	20.26	18.46	18.34	20.51	20.09	19.16	18.67
CaO	0.93	22.09	21.77	21.87	21.66	21.58	0.05	0.02	0.09	0.74	0.10	0.09	0.00	0.03	4.96	4.97	4.45	4.81	4.75	4.65	4.23
Na2O	0.07	1.91	1.88	1.99	2.12	2.19	0.02	0.02	0.03	0.09	0.00	0.00				0.04		0.02	0.02	0.03	
K2O	0.01	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.03	0.00	0.00	0.00									
Total	100.40	100.38	100.38	99.22	99.55	99.80	96.18	100.28	100.29	100.24	99.12	99.67	100.28	99.83	100.53	100.26	100.52	99.11	101.85	100.24	100.22

*: Garnet including hydrous minerals; Cr-rim: chromian garnet overgrowth.

compositional profiles of the interiors of the large garnet may be explained as a result of cooling from peak metamorphic temperature.

Olivine compositions in different samples vary from Fo_{90} to $Fo_{91\sim92}$. Orthopyroxene is very low in Al. The reconstructed compositions of the exsolution-bearing pyroxenes differ significantly from those of the matrix pyroxenes in their Fe/Mg ratios, the reconstructed orthopyroxene composition is also higher in Ca, Cr, and Na than the matrix orthopyroxene (Table 1).

The mineral inclusions in garnet porphyroblasts are characterized by high Al contents. The hornblende is a solid solution between pargasite, tschermakite, and tremolite, different from the texturally latest tremolitic amphibole in the matrix. The orthoamphibole is Na-gedrite. The Na-phlogopite forms solid solution with some clintonite. The talc is aluminous talc. The spinel is the Mg-Al type.

Sm-Nd and Rb-Sr isotopic compositions

The Rb-Sr data of phlogopite, whole-rock and clinopyroxene define isochron ages of 205 ± 4 and 201 ± 4 Ma for two garnet peridotite samples (DZ04, DZ08) from Zhimafang. These ages are slightly younger than the commonly accepted age for the UHP metamorphism (ca. 220 Ma) in the Dabie and Su-Lu regions, and may represent the time when the garnet peridotites were cooled to the phlogopite closure temperature of ~500 °C during the exhumation process.

By contrast, the data of garnet, whole rock and clinopyroxene give an age of 378±24 Ma for sample DZ04 and 376±16 Ma for DZ08. These are substantially greater than the commonly accepted UHP metamorphic age of about 220 Ma.

The Sm-Nd isotope data of a coesite-bearing eclogite from Lanshantou define a mineral isochron age of 208±4 Ma, which is in the range of those obtained by the same method for most eclogites occurring in the Dabie and Su-Lu terranes.

The I_{Sr} values of about 0.709-0.710 and the negative $\varepsilon_{Nd}(T)$ values of -4 to -5 (even lower if recalculated to 220 Ma) clearly indicate that the garnet peridotites have been "enriched" in Rb/Sr and Nd/Sm ratios for a significant length of time or they have been contaminated by continental material. This resulted in the low $^{147}Sm/^{144}Nd$ ratios (0.07 and 0.13) for whole-rock samples, which are much lower than that for the depleted mantle reservoir (ca. 0.214). Such isotopic compositions indicate that the peridotites were not pristine mantle slices that were emplaced tectonically into the continental crust during the 220 Ma collision between the Sino-Korean and Yangtze cratons.

Metasomatism of the rocks at high P-T conditions by SiO_2-rich melt/fluids is manifested by the rounded olivine in the matrix pyroxenes and garnet, and by the occurrence of phlogopite and magnesite. It is likely that the garnet peridotites were also subjected to UHP metamorphism at ca. 220 Ma together with the coesite-bearing eclogites. The SiO_2 and LREE-rich melt/fluids derived from the subducted crustal rocks gave rise to metasomatism of the peridotites deep in the subducted slab (Yang & Jahn, unpublished data), resulting in isotopic disequilibrium between the Mg-rich cores of garnet and the rest of the rocks. Consequently, both $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios of the matrix phases were lowered, leading to the older Sm-Nd isochron age values.

Discussion

Parageneses and origin of the garnet peridotites

The mineral parageneses for the different metamorphic stages experienced by the garnet peridotites are summarized as the following:

I. Initial stage (>>220 Ma):
Ol + Opx + Grt + Cpx

II. Low P-T stage (>220 Ma):
Ol + Opx + Grt + Cpx + fluids → Chl + Hbl + Ged + Tlc + Spl + Na-Phl + Py + Ol ± Opx ±Cpx + fluids

III. Subduction to UHPM stage (~220 Ma):
Chl + Hbl + Ged + Tlc + Spl + Na-Phl + Py + Ol ± Opx ± Cpx + fluids → Ol + Opx + Grt + Cpx + Ti-Chu + primary Phl + Mgs ± Chr + fluids

IV. Exhumation stage (≤205 Ma):
Ol + Opx + Cpx + Grt + Ti-Chu + primary Phl + Mgs ± Chr + fluids → Tr + Dol ± secondary Phl + fluids

V. Doming stage (? Ma):
Chl + Prg + Tlc + Mgs + Cal + Per + Srp + fluids

P-T estimates

The stability of chlorite + orthoamphibole + Ca-amphibole + talc + forsterite + H_2O in the system CMASH was experimentally located at ≤ 0.8 GPa and <750 °C by Jenkins (1981). Schmädicke & Okrusch (1997) calculated the stability of chlorite + orthoamphibole + Ca-amphibole + talc in the system CMFASH to be <550-650 °C and 0.1-1.4 GPa. The occurrence of Na-gedrite, instead of anthophyllite, in the inclusion assemblage in garnet was apparently related to the Al-rich chemical environment in garnet.

Using the core compositions of porphyroblastic garnet, olivine, and the reconstructed compositions of pyroxene (Table 1), and taking all Fe as Fe^{2+}, the Cpx-Grt, Opx-Grt, Ol-Grt, and Ca-in-Opx thermometers yield high T estimates (830~1100 °C at 4.0 GPa), whereas the two-pyroxene thermometer yields 780 °C. Pressure estimates are obtained by the Al-in-Opx barometers as 5.1~5.3 GPa at 1000 °C. An independent pressure estimate is made by calculating the equilibrium:

$$2\ Ca_3Al_2Si_3O_{12} + Mg_3Al_2Si_3O_{12} = 3\ CaMgSi_2O_6 + 3\ CaAl_2SiO_6$$

which is a potential geobarometer very sensitive to the solution model of garnet (Eric Essene, person. commun.). It is found that the ideal mixing-on-sites models for both garnet and clinopyroxene yield P values very close to those by the Al-in-Opx barometers for all the samples.

The compositions of the porphyroblastic garnet inner rims and small garnet cores (less Mg-rich and least chromian) are considered to be in equilibrium with the matrix pyroxenes because they all crystallized/recrystallized during metasomatism. Close intersections of the Cpx-Grt and Opx-Grt thermometers with the Al-in-Opx barometers based on the core compositions of the matrix pyroxenes and small garnet in sample DZ10 (Table 1) yields 760 °C and 4.2 GPa. For the texturally and chemically well-equilibrated garnet websterite (DG01), the thermometers and barometers employed above tightly intersect at around 760 °C and 4.2 GPa.

The enigmatic problem in P-T estimation

Some problems arise when the high-T estimates (~1000 °C) for the porphyroblastic mineral assemblages in the peridotite samples are taken to be the peak T of the UHP metamorphism. Firstly, it is not known whether the hydrous mineral inclusions are able to exist in garnet at such high T. Secondly, estimates for the peak T of coesite-bearing eclogites and garnet-orthopyroxene rock in the Su-Lu and Dabie terranes are mostly ≤800 °C. Therefore, another interpretation is that the most pyropic cores of large garnet porphyroblasts represent the composition of the initial stage garnets, whereas the P-T estimates for the matrix mineral assemblage are the peak conditions of UHP metamorphism. It follows that the cores of garnet porphyroblasts retain their initial Sm-Nd memories, as diffusion rates of Sm-Nd are lower than that of Mg in garnets.

However, the high-T and hence high-P estimates obtained from the reconstructed composition of porphyroblastic orthopyroxene and clinopyroxene are difficult to be attributed to the early garnet peridotite stage (Stage I), which should be much more aluminous as being characteristic of pyroxenes at low P/T conditions appropriate to mantle environment. Unlike the exsolutions in relict pyroxenes that survived subsequent metamorphism, the fine exsolutions in the porphyroblastic pyroxenes are more likely resulted from rapid cooling after the peak of UHP metamorphism. In addition, the very flat Ca profile of the porpyroblastic garnet is unlikely intact from UHP metamorphism if the initial Ca composition of the garnet core was different from that at UHP conditions. Therefore, higher T (≥1000 °C) and P (≥5.1 GPa) conditions for the peak of UHP metamorphism must be envisaged. This necessarily implies that the hydrous mineral inclusions are able to metastably persist in garnets through such high P-T metamorphism while the composition of the garnet was changed. More importantly, this also implies that the peak P-T conditions of at least some coevally subducted crustal materials (e.g., coesite-bearing eclogites, country gneisses) were substantially higher than estimated to date (≤800 °C and ≥2.7 GPa).

P-T path

The P-T path for the metamorphic evolution of the garnet peridotites is outlined in Fig. 2. The lack of prograde zoning, the crosscutting nature of the inclusion trails, and the very aluminous compositions of the inclusion minerals in garnets suggest that garnet existed in the peridotite before they were first emplaced into a low P-T environment at a time >>220 Ma. A quantitative P-T estimate for the initial stage is not possible due to the lack of information about the compositions of the minerals at this early stage. The P-T estimates for the equilibrium of the hydrous mineral assemblage included in garnet are only an approximation. Very high T and P (≥1000 °C and ≥5.1 GPa) conditions must be envisaged, although not yet accurately determined, for the peak metamorphic stage. The P-T estimates (~4.2 GPa, ~760 °C) for the matrix mineral assemblages in the peridotites and the garnet websterite are considered accurate. Thus, the metasomatism responsible for crystallization of these assemblages is a remarkable event during cooling from the peak of UHP metamorphism. The late exhumation stages are deduced from the assemblages of chlorite + tremolitic amphibole and calcite ± periclase observed in different domains of the rocks (Yang et al., 1993), and the talc + magnesite assemblage at the boundaries between the peridotite bodies and the surrounding gneiss.

The early high-T and depleted nature (Yang & Jahn, unpublished data) of the garnet peridotites may suggest that the initial stage was a diapiric upwelling of mantle material from below the continental lithosphere into the crust. Alternatively, mantle convection may have led to uplift of garnet peridotites to shallow mantle where the rocks retrogressed to chlorite–Na-gedrite-hornblende-talc peridotites. Subduction of the continental lithosphere may have dragged the hydrous peridotites of the mantle wedge into the subducting slab and the rocks recrystallized back to garnet lherzolite assemblages. In the present case, however, garnet must have persisted throughout the metamorphic history. This requires that the convection process to be very fast

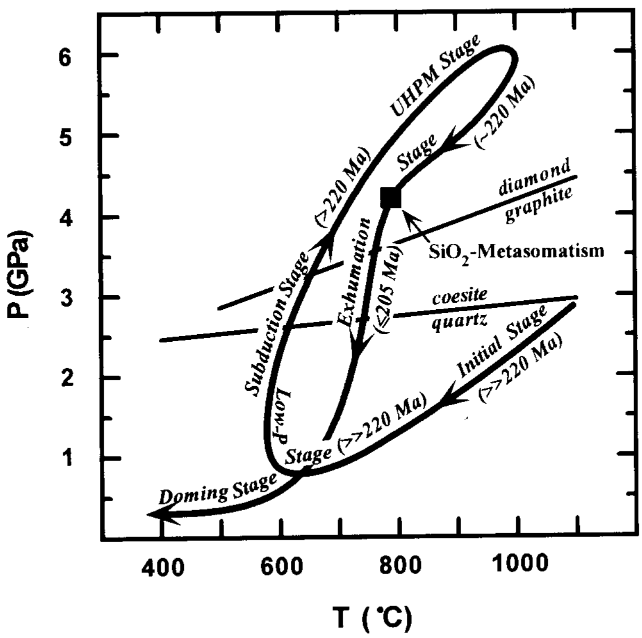

Fig. 2. P-T path of the Su-Lu garnet peridotites.

and that the shallow mantle to be at sufficiently low T, such that the alteration of garnet into Chl + Amp + Tlc + Spl was very sluggish. The low P-T conditions for the hydrous mineral assemblage may only be possible in the uppermost hydrated mantle wedge, if not in the continental crust.

Conclusions

1 The garnet peridotites from Zhimafang at the southern end of Su-Lu UHPM terrane were initially mantle slices emplaced into a low P-T environment earlier than ca. 220 Ma, when they were brought back to mantle depths (≥ 5.1 GPa) due to the Triassic continental collision between the Sino-Korean and the Yangtze cratons. During post-collisional relaxation, the garnet peridotites were exhumed again to a crustal level, followed by exposure on the surface due to doming and erosion of the terrane.

2 Rb-Sr isotope analyses on 2 garnet peridotites at Zhimafang and Sm-Nd isotope analyses on an eclogite at Lanshantou provide ages of ~210 Ma, largely consistent with the previous age determinations of the UHP eclogites in the Su-Lu – Dabie orogen. However, the Sm-Nd data on the 2 garnet peridotites yielded apparent isochron ages of ~380 Ma and negative $\varepsilon_{Nd}(0)$ values ~ -9. These ages are meaningless because isotopic disequilibrium between garnet cores and the rest of the rocks was likely resulted from interaction between the garnet peridotites and external SiO_2-rich melt/fluids during early cooling from UHP metamorphism.

3 P-T estimates for the peak of UHP metamorphism of the garnet peridotites indicate temperature of ~1000 °C and pressure over 5.1 GPa. The large difference between these P-T estimates and those of the coesite-bearing eclogites in this terrane implies that the present P-T estimates for the coevally subducted eclogites are not peak metamorphic conditions. On the other hand, the P-T estimates (4.2 GPa and 760 °C) for the metasomatic crystallization of the matrix assemblages of the peridotites and the garnet-websterite are compatible with those (2.7~≥4.0 GPa and ≤800 °C) of the coesite-bearing eclogites and garnet-pyroxene rocks in the Su-Lu and Dabie terrane.