Compositional heterogeneity in subduction-related mantle peridotites, Troodos massif, Cyprus

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ABSTRACT

Geochemical mapping has revealed the presence of two distinct units within the mantle section of the Troodos massif, Cyprus. The first unit (U1) is composed of spinel lherzolite (Cr# [Cr/(Cr+Al)] of chrome spinels = 0.22–0.28), which contains numerous dunite bodies accompanied by zones of clinopyroxene-bearing harzburgite (U1-harzburgite). The second unit (U2) mainly consists of refractory clinopyroxene-poor harzburgite (U2-harzburgite; Cr# of chrome spinels = 0.51–0.70). The U1 spinel lherzolite is interpreted as residue after mid-ocean ridge basalt extraction, which was tectonically juxtaposed with U2. It was not involved in production of suprasubduction-type Troodos magmas, but has subsequently been modified by their percolation. The dunite bodies and related zones of U1-harzburgite might represent pathways of these melts in the mantle. The U2-harzburgite could have resulted from reaction between host rock and melts.

Keywords: lherzolite, harzburgite, clinopyroxene, trace elements, SIMS, modeling.

INTRODUCTION

It is generally accepted that the composition of the upper mantle is the result of complex processes involving melting in the convecting mantle as well as interactions with migrating melts. Studies of mantle peridotites from suprasubduction ophiolite complexes could provide important information on physical processes of melting, melt extraction, and melt migration in the mantle wedge above subduction zones. Here we report the results of detailed mapping, electron- and ion-microprobe studies, and numerical simulation for mantle peridotites from the Troodos ophiolite, which represents a classical type locality of lithosphere formed in a suprasubduction environment (e.g., Robinson and Malpas, 1990). Contrary to the idea that the Troodos peridotites are homogeneous and highly refractory (e.g., Hebert and Laurent, 1990), we show that more than half of the exposed peridotitic basement consists of less refractory abyssal-type peridotite, which was not involved in production of Troodos suprasubduction magmas.

GEOLOGIC BACKGROUND

It has been accepted (e.g., Allen, 1975; Hebert and Laurent, 1990) that the ultramafic basement of the Troodos ophiolite consists of refractory harzburgite with high Cr# of spinel (0.51–0.71) and major heterogeneity caused by degree of serpentinization (Wilson, 1959). The east-central part of the peridotite body (Fig. 1) is occupied by a zone of intense serpentinization that is characterized by a large scatter in tectonite fabrics and an apparent northeast trend of the dunite bodies (Wilson, 1959; George, 1978). The west margin harzburgite is less serpentinized. It shows northwest-trending tectonite fabrics and evidence of high-temperature deformation together with overlying dunites and layered cumulates (George, 1978; Malpas, 1990). Harzburgite with less refractory composition (Cr# of spinel 0.25) was previously reported only for a single locality within the east-central part (Duncan and Green, 1987).

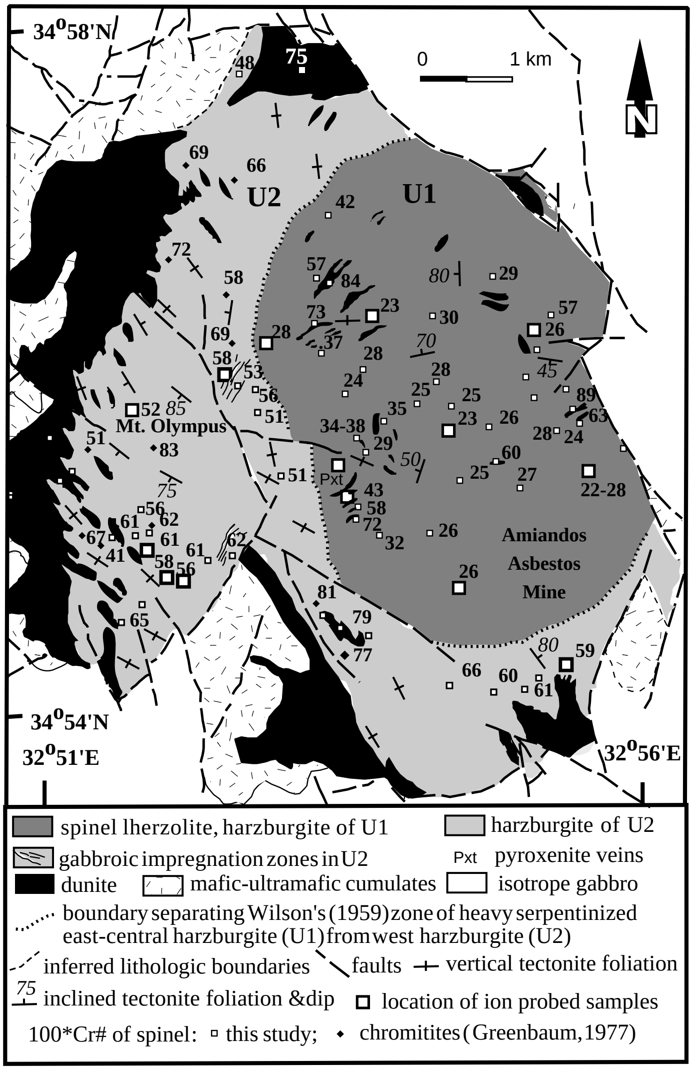

Figure 1. Geologic sketch map of Mount Olympus area (modified after Wilson, 1959; George, 1978), showing Cr# of spinels in mantle peridotite.

Our detailed geochemical mapping of the mantle peridotite section in the Troodos massif has revealed a kilometer-scale compositional heterogeneity. On the basis of Cr# of spinel and the modal abundance of clinopyroxene (cpx), we subdivided the mantle section into two units. Unit one (U1) occupies the east-central part of the peridotite body (Fig. 1). It is composed of spinel lherzolite with a Cr# of 0.22–0.28 and 5–7 modal percent of cpx. This lherzolite contains numerous dunite bodies, which vary in width from a few centimeters to 10–50 m, and in length from 1 to about 500 m. Zones of cpx-bearing harzburgite are located between the spinel lherzolite and the dunite bodies and have higher Cr# values of spinel (0.32–0.51) and lower modal cpx (1.5%–4.5%) than surrounding spinel lherzolite. We refer to cpx-bearing harzburgite zones as U1-harzburgite. The dunites display the highest Cr# of spinel (between 0.70 and 0.84). Contacts between spinel lherzolite and U1-harzburgite are gradational. Contacts between U1-harzburgite and dunite are sharp. Although cpx is present in the contact zone between U1-harzburgite and dunite, the dunites are cpx free. Clinopyroxenite and orthopyroxenite veins are associated with dunite bodies.

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Data Repository item 200010 contains additional material related to this article.

Unit two (U2) is located in the western part of the peridotite body. It consists of refractory cpx-poor harzburgite (U2-harzburgite) with a Cr# of 0.51–0.70 and 0.5–1 modal percent of cpx. The U2-harzburgite is located between U1 rocks and a thick layer of chromite-bearing dunite (Fig. 1), which is below layered mafic-ultramafic metacumulates representing the petrologic Moho (e.g., Allen, 1975; George, 1978; Malpas, 1990).

The boundary between U1 and U2 coincides (Fig. 1) with that separating Wilson's (1959) zone of intense serpentinized east-central harzburgite from the less serpentinized western harzburgite. Thus, the divided units also differ in their structural features and degree of late-stage alteration.

TRACE ELEMENT CONCENTRATIONS IN CPX

Rare earth element (REE), Ti, Sr, Y, and Zr concentrations in cpx from mantle rocks of the Troodos massif were determined by secondary-ion mass spectrometry (SIMS) on the Cameca IMS 4f ion probe at the Institute of Microelectronics, Yaroslavl, Russia (Batanova et al., 1998). Energy filtering with –100 eV offset was used in order to eliminate complex ion interference (Shimizu and Hart, 1982; Bottazzi et al., 1992). Major and trace element contents of cpx are listed in Table 1.

Spinel lherzolite of U1 display a narrow compositional range over the entire unit, well within compositional variations of abyssal peridotites (Johnson et al., 1990; Johnson and Dick, 1992; Dick, 1989) in respect to both trace element concentrations of cpx and mineral chemistry (Figs. 2A and 3). The incompatible element patterns of cpx are very close to those of abyssal peridotites; the only difference is a slight upward inflection of La and Ce in the former.

Clinopyroxenes from U1-harzburgite surrounding the dunite bodies within the U1 spinel lherzolite have lower heavy REE concentrations and extremely low (close to SIMS detection limit) middle REE concentrations (Fig. 2B). They show very significant upward inflection of La and Ce relative to Nd. Clinopyroxene from the clinopyroxenite veins differs from cpx of U1-harzburgite in that it has a higher middle REE concentration (Fig. 2B). In addition, the vein cpx contains abundant small (10–15 μm) melt inclusions, which strongly suggest a magmatic origin of the cpx. All these rocks are close in their cpx trace element composition and mineral chemistry (Figs. 2B and 3) to forearc peridotites (Parkinson and Pearce, 1998), to the most depleted Oman harzburgite (Kelemen et al., 1995), and to depleted harzburgite from Hess Deep (Fig. 3) (Dick and Natland, 1995).

Clinopyroxenes from the U2-harzburgite are extremely depleted in heavy REE (Figs. 2 and 3). Their middle REE concentrations are below the detection limit of SIMS (around 0.003 ppm for Sm). The cpx grain morphologies suggest that cpx formed by exsolution from orthopyroxene (opx) during recrystallization accompanying solid-state deformation (Sobolev and Batanova, 1995). This fact precludes our using the cpx composition from U2-harzburgite in modeling because its trace element equilibrium with bulk opx cannot be easily proved.

ORIGIN OF TROODOS PERIDOTITES

U1 Spinel Lherzolite

We modeled partial melting by using the critical melting formulation of Sobolev and Shimizu (1992).[1] The modeling suggests that the spinel lherzolite represents the residue of 12% critical melting of a depleted (mid-ocean ridge basalt, MORB-like) mantle source (Fig. 4A) with a low residual mantle porosity (0.1%). The produced integrated melts are similar to normal MORB and are significantly less depleted than any Troodos primary magmas (Fig. 4A). This strongly suggests that U1 spinel lherzolite was not involved in production of Troodos suprasubduction magmas. The upward inflection of La and Ce (Fig. 4A) could be explained by a subsequent melt percolation event. A

TABLE 1. MAJOR AND TRACE ELEMENT COMPOSITIONS OF CLINOPYROXENE FOR THE TROODOS PERIDOTITES

	1	2	3	4	5	6	7	8	9	10	11	12	13
	tv220-1	tv271	tv225/4	tv225/5	tv225/6	tv225/7	tv225/8	tv225/9	tv225/10	tv279	tv280	tv283	tv301
SiO_2	51.40	50.36	52.12	52.54	52.90	52.92	53.00	53.37	53.57	53.41	54.07	53.44	52.63
TiO_2	0.15	0.14	0.07	0.13	0.07	0.06	0.07	0.03	0.06	0.01	0.01	0.04	0.03
Al_2O_3	5.28	5.39	3.75	2.77	2.29	3.00	2.53	2.71	1.68	2.19	2.28	2.73	2.80
FeO	2.39	2.44	2.21	2.25	2.01	2.48	1.96	2.77	3.31	2.31	2.33	2.77	2.51
MnO	0.07	0.09	0.08	0.10	0.04	0.08	0.09	0.08	0.10	0.05	0.14	0.10	0.09
MgO	15.98	16.01	17.15	16.98	17.50	16.88	17.26	18.14	17.81	17.44	17.68	18.07	17.47
CaO	23.35	23.20	23.62	23.67	24.12	23.10	23.72	22.86	22.21	23.13	23.03	21.93	22.59
Na_2O	0.21	0.21	0.13	0.13	0.13	0.08	0.17	0.06	0.17	0.01	0.17	0.03	0.04
Cr_2O_3	1.24	1.27	1.20	0.88	0.76	1.17	0.95	1.00	0.81	1.09	1.01	1.13	1.21
Mg#	92.25	92.13	93.26	93.07	93.95	92.38	94.02	92.11	90.55	93.08	93.13	92.08	92.54
Ti	794	662	424	456	312	312	430	354	401	66	78	129	95
Sr	0.7	0.6	1.2	0.8	2.3	0.6	0.7	1.1	1.4	0.4	0.9	0.6	4.7
Y	7.7	6.7	3.5	2.5	1.8	1.6	1.9	1.8	2.5	0.4	0.5	0.7	0.5
Zr	0.25	0.25	0.14	0.17	0.19	0.16	0.20	0.21	0.30	0.10	0.13	0.13	0.13
La	0.019	0.011	0.018	0.026	0.015	0.012	0.019	0.019	0.017	0.008	0.017	0.014	0.017
Ce	0.03	0.02	0.06	0.07	0.05	0.03	0.04	0.05	0.05	0.016	0.07	0.05	0.06
Nd	0.07	0.05	0.015	0.020	0.020	0.011	0.021	0.029	0.10	0.013	b.d.l.	0.011	0.015
Sm	0.14	0.13	0.047	0.006	0.013	b.d.l.	0.014	0.017	0.09	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Eu	0.08	0.08	0.027	0.006	0.015	0.005	0.018	0.008	0.05	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Dy	1.21	1.02	0.47	0.32	0.23	0.19	0.21	0.20	0.41	0.03	0.06	0.05	0.05
Er	0.85	0.78	0.39	0.31	0.22	0.19	0.24	0.24	0.24	0.08	0.05	0.11	0.07
Yb	0.78	0.67	0.41	0.36	0.26	0.22	0.30	0.30	0.25	0.12	0.13	0.16	0.14
Fo in Olivine	90.69	91.24		91.57	91.16	91.14	91.62	91.27		91.20	91.67	91.35	91.21
Cr# in Spinel	0.23	0.24	0.43	0.43	0.48	0.51	0.52	0.51	0.57	0.61	0.58	0.56	0.59

Note: 1, 2—U1 spinel lherzolite; 3, 4—U1-harzburgite, 10 m from contact with dunite; 5—orthopyroxenite vein; 6—U1-harzburgite in contact with orthopyroxenite; 7, 8—U1-harzburgite in contact with dunite; 9—clinopyroxenite vein; 10–13—U2-harzburgite. Oxides are in weight percent, trace elements are in ppm; b.d.l.—below detection limit.

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[1] GSA Data Repository item 200010, Details of modeling, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.

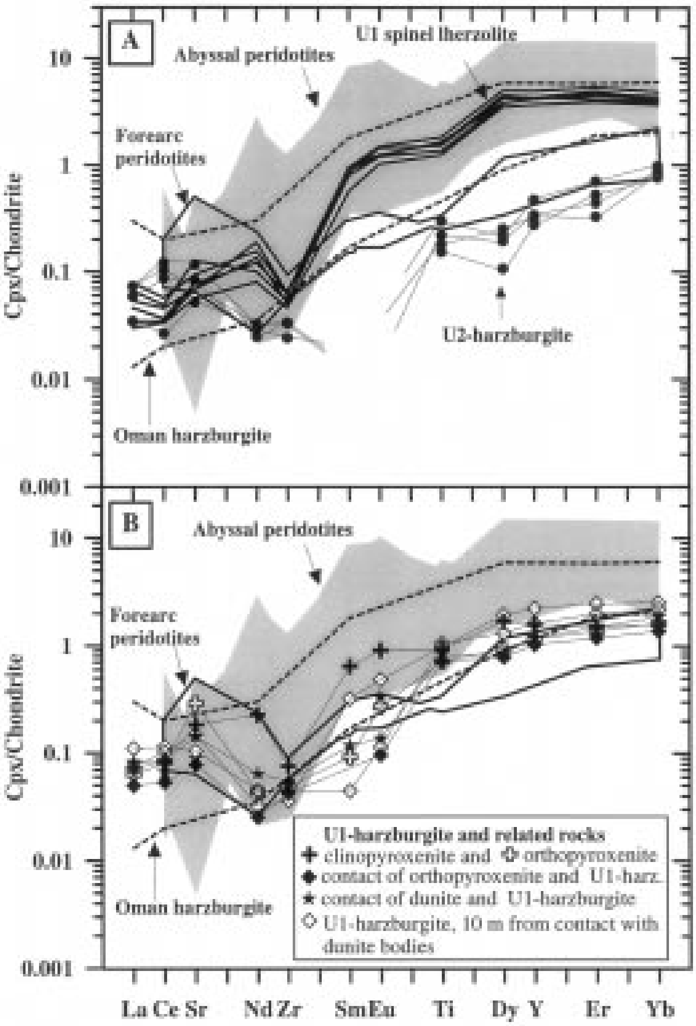

Figure 2. Trace element contents in clinopyroxene (cpx) from Troodos. A: U1 spinel lherzolite and U2-harzburgite. B: U1-harzburgite and associated pyroxenites. Both are compared to observed concentration in cpx from abyssal peridotite, Oman, and forearc harzburgite. All concentrations are normalized to those of C1 chondrite (Anders and Grevesse, 1989). Field of abyssal peridotites is after Johnson et al. (1990) and Johnson and Dick (1992), field of Oman harzburgite is after Kelemen et al. (1995), and field of forearc harzburgite is after Parkinson and Pearce (1998).

percolation-controlled model (Bodinier et al., 1990) was used to model the trace element exchange between peridotite and melts (see footnote 1). The La and Ce patterns can be matched by using a composition of typical Troodos Upper pillow lava (Sobolev et al., 1993) as infiltrating melt and mantle column parameters allowing minor changes in matrix peridotite (Fig. 4A).

U1 Harzburgite and Dunite

U1-harzburgite is located within the spinel lherzolite and occurs as zones surrounding dunite bodies. The structure of these zones is very similar to the reaction zones described in the Trinity peridotite (Kelemen et al., 1992). These zones are symmetrical about a plane, composed of dunite (or rarely pyroxenite), and they vary in size from tens of centimeters to hundreds of meters. The occurrence of melt inclusions in clinopyroxenite is direct evidence of melt transport in the central plane of such zones. Thus, the structure of U1-harzburgite and dunite zones, their position within the spinel lherzolite, and their association with magmatic pyroxenite veins allow us to suggest that these zones could be produced by reaction of spinel lherzolite with percolating melts. Therefore dunite bodies mark zones where melts passed through the shallow mantle, dissolved pyroxene, and precipitated olivine in porous melt channels. Pyroxenite veins were formed after production of the surrounding reaction zone (e.g., Kelemen et al., 1992). Clinopyroxene crystals in U1-harzburgite may have reequilibrated with percolating melts or could be formed directly by crystallization from melt during cooling. Thus the trace element composition of cpx may indicate the composition of the magmas migrating through the Troodos mantle. On the basis of cpx compositions, some of these melts may have been close to ultradepleted boninites from Troodos Upper pillow lavas (Fig. 4B). However, most of the cpx crystals suggest a percolation of melts significantly more depleted in middle REEs than any melt known so far on Cyprus or anywhere else. Such melts could form as a result of 3%–7% second-stage melting of residual lherzolites (Fig. 4B), but require an additional light REE– and Zr-enriched component, which presumably originated from the subduction zone.

U2 Harzburgite

A lack of correlation between the forsterite contents of olivine and the Cr# of spinel in U1 spinel lherzolite and U2-harzburgite (Table 1; Sobolev and Batanova, 1995) precludes their genetic relationship by different degree of partial melting of the same mantle source. Moreover, a typical subduction-related harzburgite of Torishima forearc seamount, considered to have formed by 20%–25% fractional melting (Parkinson and Pearce, 1998), contains olivine with higher forsterite content than in Troodos U2-harzburgite (Fig. 3), but still has 2% primary cpx. In contrast, most Troodos U2-harzburgite was likely to have been cpx free during melting (Sobolev and Batanova, 1995). Thus, a more plausible mechanism for the production of the U2-harzburgite is an open-system reaction between infiltrating melt and the initial spinel lherzolite, similar to what has been demonstrated to occur on a smaller scale within the spinel lherzolite body.

Relation Between U1 and U2

The peridotite of U2 has a refractory composition. It was affected by high-temperature deformation processes that were the same as those in overlying dunites and layered cumulates of the Troodos massif. Peridotites of U1 differ from those of U2 in composition, structure, and degree of second-stage

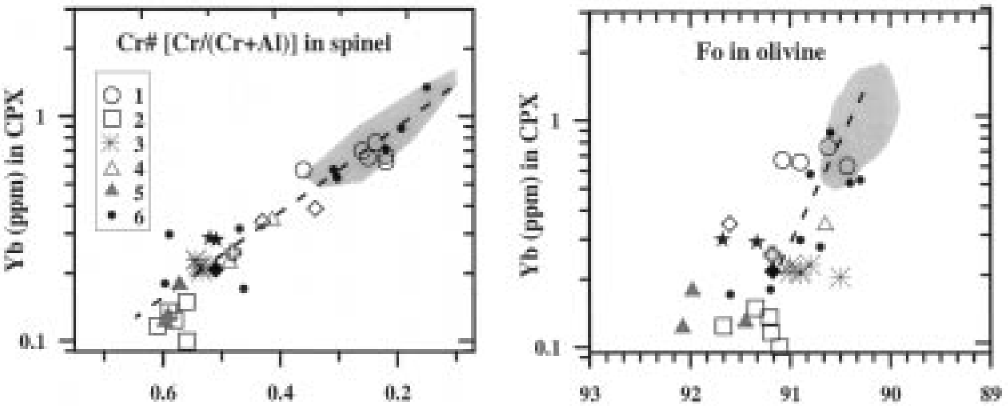

Figure 3. Correlation between Yb (ppm) in clinopyroxene (cpx) and mineral chemistry of peridotites from Troodos massif, compared with abyssal, forearc, and ophiolite peridotites. 1—U1 spinel lherzolite and 2—U2-harzburgite of Troodos massif; 3—Ocean Drilling Program Site 895 Hess Deep residual harzburgite (Dick and Natland, 1995); Forearc harzburgites: 4—Conical Seamount and 5—Torishima Seamount (Parkinson and Pearce, 1998); 6—peridotite from Bay of Islands ophiolite (Batanova et al., 1998); shaded field—abyssal peridotite after Johnson et al. (1990), Johnson and Dick (1992), and Dick (1989). Symbols are as in Figure 2.

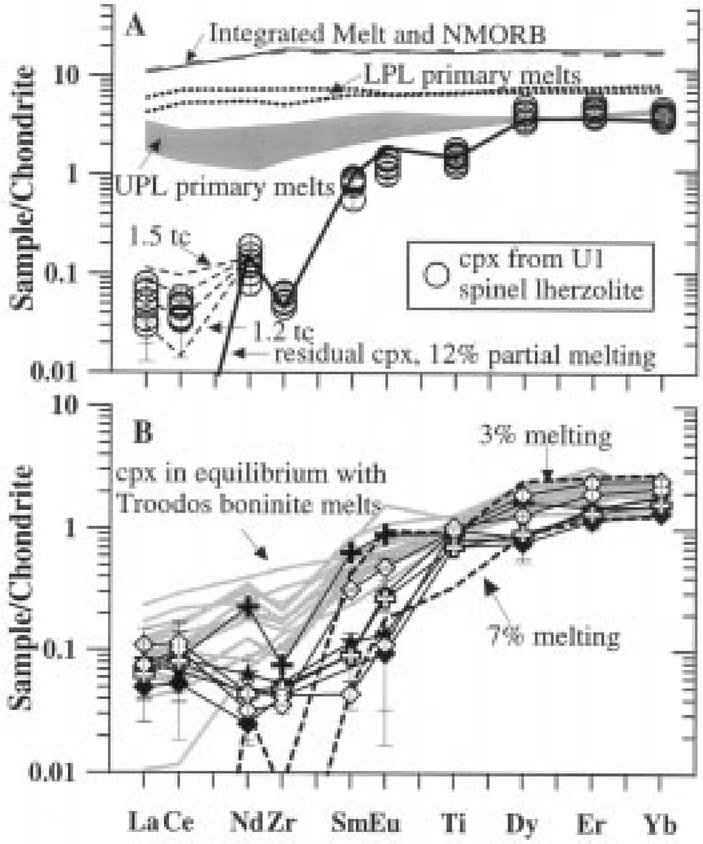

Figure 4. A: Critical melting and melt percolation models for U1 spinel lherzolite. Heavy line represents residual clinopyroxene (cpx) concentration calculated from Sobolev and Shimizu (1992). Dashed lines show light rare earth element enrichment in cpx due to percolation of melts (Bodinier et al., 1990) through residue. Tc—time required for melt to pass column. Integrated fractional liquid after 12% near fractional melting, average normal mid-ocean ridge basalt (N-MORB) (Hofmann, 1988), and primary melts of Troodos Lower pillow lava (LPL) and Upper pillow lava (UPL) (Portnyagin et al., 1997; Sobolev et al., 1993) are also plotted. B: Cpx from U1-harzburgite and associated pyroxenites (individual symbols as in Fig. 2) compared with calculated cpx in equilibrium with boninite melts from Troodos UPL (shaded lines) (Cameron, 1985; Sobolev et al., 1993; Portnyagin et al., 1996). Heavy dashed lines represent cpx in equilibrium with melts formed by 3%–7% of second-stage melting of refractory lherzolite at low residual porosity (0.1%).

alteration. It was not involved in the production of suprasubduction magmas of the Troodos crust, but does show evidence of percolation of such magmas. This suggests that U1 peridotites actually represent a relict block of a mantle wedge above the zone of generation of suprasubduction Troodos melts, which was tectonically juxtaposed with U2 during serpentinite diapirism after ophiolite emplacement (e.g., Allen, 1975; Robinson and Malpas, 1990).

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