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Os mobilization during melt percolation: The evolution of Os isotope heterogeneities in the mantle sequence of the Troodos ophiolite, Cyprus

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Abstract—This study focuses on the origin of the Os isotope heterogeneities and the behaviour of Os and Re during melt percolation and partial melting processes in the mantle sequence of the Troodos Ophiolite Complex. The sequence has been divided into an eastern (Unit 1) and a western part (Unit 2) (Batanova and Sobolev, 2000). Unit 1 consists mainly of spinel-lherzolites and a minor amount of dunites, which are surrounded by cpx-bearing harzburgites. Unit 2 consists of harzburgites, dunites, and contains chromitite deposits.

Unit 1 ($^{187}Os/^{188}Os$: 0.1169 to 0.1366) and Unit 2 ($^{187}Os/^{188}Os$ 0.1235 to 0.1546) peridotites both show large ranges in their Os isotopic composition. Most of the $^{187}Os/^{188}Os$ ratios of Unit 1 lherzolites and harzburgites are chondritic to subchondritic, and this can be explained by Re depletion during ancient partial melting and melt percolation events. The old Os isotope model ages (>800 Ma) of some peridotites in a young ophiolitic mantle show that ancient Os isotopic heterogeneities can survive in the Earth upper mantle. Most harzburgites and dunites of Unit 2 have suprachondritic $^{187}Os/^{188}Os$ ratios. This is the result of the addition of radiogenic Os during a younger major melt percolation event, which probably occurred during the formation of the Troodos crust 90 Ma ago.

Osmium concentrations tend to decrease from spinel-lherzolites (4.35 ± 0.2 ng/g) to harzburgites (Unit 1: 4.06 ± 1.12 ng/g; Unit 2: 3.46 ± 1.38 ng/g) and dunites (Unit 1: 2.71 ± 0.84 ng/g; Unit 2: 1.85 ± 1.20 ng/g). Therefore, this element does not behave compatibly during melt percolation as it is observed during partial melting, but becomes dissolved and mobilized by the percolating melt. The Os contents and Re/Os ratios in the mantle peridotites can be explained if they represent mixing products of old depleted mantle with cpx- and opx-veins, which are crystallization products of the percolating melt. This mixing occurred during the melting of a continuously fluxed mantle in a supra-subduction zone environment.

This study shows that Unit 1 and Unit 2 of the Troodos mantle section have a complex and different evolution. However, the Os isotopic characteristics are consistent with a model where the harzburgites and dunites of both units belong to the same melting regime producing the Troodos oceanic crust.

1. INTRODUCTION

The Re/Os isotopic system is a unique tool to investigate melting and differentiation processes in the Earth mantle. This is due to the compatible behaviour of Os and the moderately incompatible behaviour of Re during partial melting. Therefore Os, un-like all other commonly used isotopic tracers, remains mostly in the mantle during crust-mantle differentiation. Osmium and Re distribution in mantle peridotites is mainly controlled by sulfides (e.g., Morgan and Baedekker, 1983; Hart and Ravizza, 1996; Burton et al., 1999; Lorand and Alard, 2001). Nevertheless, the petrology and physical behaviour of sulfide melts during mantle processes is still poorly understood. Recent studies indicate that two types of sulfides appear in mantle rocks: silicate-enclosed sulfides thought to represent residues of partial melting processes and interstitial sulfides suggested to be crystallisation products of sulfur-bearing fluids (Alard et al., 2000; Pearson, 2002). However, many interstitial sulfides may be primary, while intracrystalline sulfides could be metasomatic microphases incorporated during recrystallization (Lorand, 1989b).

The composition of mantle peridotites is modified by partial melting processes and the interaction with melts percolating through it. Although these processes are spatially and temporally linked, they produce chemically and mineralogically distinct mantle lithologies. Thus, the formation of dunites in the Earth upper mantle cannot be explained by partial melting, because of their high liquidus temperatures. Instead, they can be formed during melt percolation (Quick, 1981; Kelemen et al., 1995).

It is commonly accepted that Os behaves compatibly during partial melting (e.g., Morgan, 1986; Walker et al., 1989). However, recent studies indicate that Os behaves incompatibly during melt percolation, because it is dissolved and mobilized together with the sulfides by the melt (Becker et al., 2001; Büchl et al., 2002). Büchl et al. (2002) observed that dunites in one single melt channel from the mantle sequence of the Troodos Ophiolite Complex have lower Os concentrations than surrounding harzburgites. The present study addresses the behaviour of Os in harzburgites and dunites during melt percolation on a regional scale in the mantle of the Troodos Ophiolite Complex. In addition, the regional variation of $^{187}Os/^{188}Os$ ratios of the peridotites provides new constraints on the origin of Os isotope heterogeneity and the history of the mantle sequence of the Troodos Ophiolite Complex.

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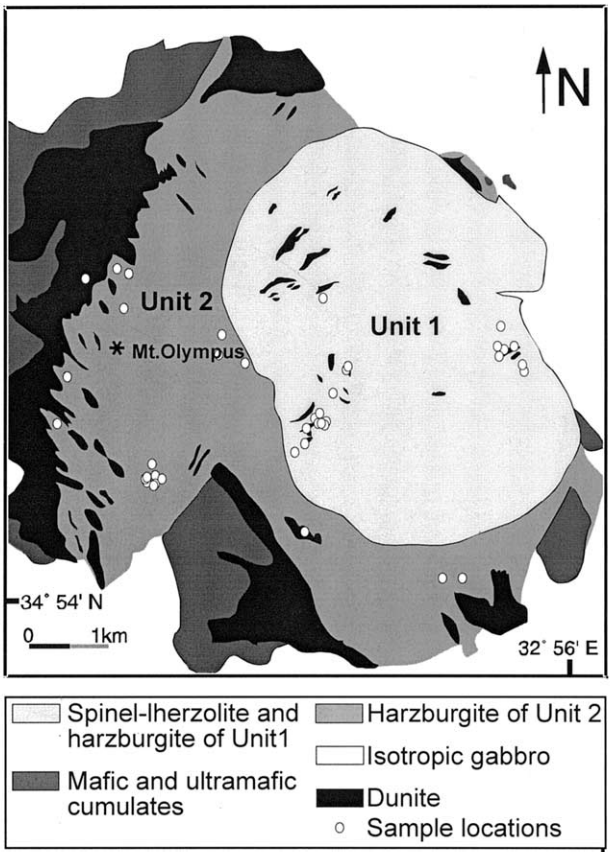

Fig. 1. Geological map of the mantle sequence from the Troodos Ophiolite Complex. The mantle sequence can be divided into two parts. Unit 1 consists of spinel-lherzolites, cpx-bearing harzburgites and dunites. In contrast, Unit 2 contains harzburgites, dunites and chromitite deposits. Representative samples were taken from all lithologies and are shown with white dots.

2. GEOLOGICAL BACKGROUND AND SAMPLES

2.1. Geological Background

The Troodos Ophiolite on Cyprus is a well studied ophiolite complex, and it is viewed by the scientific community as a classical example. The Troodos Ophiolite Complex represents an uplifted segment of Mesozoic oceanic lithosphere from the ancient Tethys ocean, and was formed 90 Ma ago (Mukasa and Ludden, 1987). Geological and geochemical data indicate its origin in a spreading center above an actively subducting lithospheric plate (e.g., Robinson and Malpas, 1990).

The mantle section of the complex has been divided into two parts (Unit 1 and Unit 2) based on the mineralogical and geochemical composition of the peridotites (Batanova and Sobolev, 2000) (Fig. 1). The eastern part (Unit 1) is mainly composed of spinel-lherzolites with subordinate cpx-bearing harzburgites and dunites. In contrast the western part (Unit 2) is composed of refractory harzburgites, dunites and chromitite deposits. Both Units have been affected by a different degree of melt percolation (Batanova and Sobolev, 2000). In Unit 1 melt percolation was restricted to the narrow zones composed of cpx-bearing harzburgites and dunites. The harzburgites of Unit 2 could be the result of open-system reaction between infiltrating melt and spinel-lherzolite. This suggestion was supported and extended to the dunites of Unit 2 by a detailed investigation of a single melt channel (Büchl et al., 2002).

2.2. Samples

The Os isotopic compositions and Os and Re abundances of 34 peridotites from the mantle sequence of the Troodos Ophiolite Complex (Fig. 1) were analysed during this regional study. The sampling covers the major lithologies of both units: 3 spinel-lherzolites, 7 cpx-bearing harzburgites (1.5—4 modal percent cpx) and 7 dunites from Unit 1, and 9 harzburgites (0.5—1 modal percent cpx) and 8 dunites from Unit 2. In addition, two clinopyroxenite veins (one of each Unit) and three orthopyroxenite veins (two of Unit 1 and one of Unit 2) were analysed. The degree of alteration of the samples does not exceed 80%.

Batanova and Sobolev (2001) investigated the mineral chemistry and the distribution of sulfides in the mantle section of the Troodos Complex. The sulfide assemblage originated from upper-mantle monosulfide solid solution during subsolidus equilibration. The primary sulfide association contains pentlandite, pyrrhotite and chalcopyrite and is observed in samples showing minor serpentinization. At higher degrees of serpentinization occur native metal, alloy and oxide phases, such as heazlewoodite, native copper, awaruite and magnetite.

Unit 1 represents a zone of intense serpentinization that is characterized by a variety of tectonite fabrics and an apparent northeast trend of the dunite bodies (Wilson, 1959; George, 1978). Unit 1 harzburgites are located within the spinel-lherzolites and occur as zones surrounding dunite bodies. Contacts between spinel-lherzolite and U1 harzburgite are gradational. Contacts between U1 harzburgites and dunites are sharp. Although cpx is present in the contact zone between U1 harzburgite and dunite, the dunites are cpx free (Batanova and Sobolev, 2000). Unit 2 is less serpentinised. It shows northwest-trending tectonite fabrics and evidence for high temperature deformation (George, 1978; Malpas, 1990). U2 harzburgite is located between U1 rocks and thick layer of chromite bearing dunite, which is below layered mafic-ultramafic metacummulates representing the petrologic Moho (e.g., George 1978; Malpas, 1990). Clinopyroxenite and orthopyroxenite veins are associated with dunite bodies.

3. ANALYTICAL METHODS

Major and trace element concentrations were determined on glass and powder pellets with a Phillips PW 1404 X-ray fluorescence spectrometer at the University of Mainz. Electron microprobe (Jeol JXA 8900 RL) analyses of spinel were made at the University of Mainz using the routine standard procedure.

For Re-Os analysis, 2g of the sample powder, together with a Re-Os isotope tracer (^{185}Re, ^{190}Os), conc. HCl and conc. HNO_3 (2:3), were digested in a quartz vessel for 16 h in a high-pressure asher at 100 bar and 300°C. Osmium was separated from the sample solution by solvent extraction with bromine and purified by microdistillation (Birck et al., 1997; Meisel et al., 2003). Afterwards, Re was separated using anion exchange columns. Osmium and Re measurements were done by *N*-TIMS with a Finnigan MAT 262 mass spectrometer at the Max-Planck Institut für Chemie in Mainz. Fourteen procedural blanks (determined by isotope dilution) ranged from 67 fg to 558 fg for Os and from 1 pg to 18 pg for Re. The 2σ external precision (the reproducibility of the isotopic ratios used in isotope dilution calculations) of the ^{187}Os/^{188}Os was 0.3% based on repeated measurements of an in-house

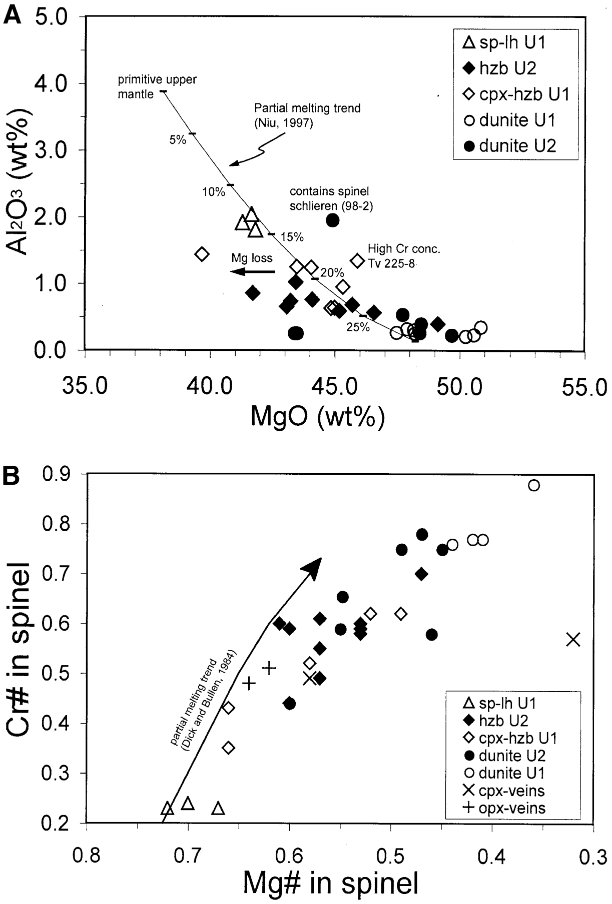

Fig. 2. Variation in lithophile elements (a) Al_2O_3 vs MgO concentrations, (b) Cr number against Mg number in spinels. (a) Unit 1 and Unit 2 peridotites show a negative correlation between Al_2O_3 and MgO. Al_2O_3 contents decrease in the sequence of lherzolites, harzburgites and dunites. Unit 2 harzburgites tend to be more refractory than those of Unit 1. (b) Unit 1 spinels define a trend with increasing Mg and Cr number. Unit 2 peridotites do lie on this trend and harzburgites and dunites overlap each other.

Os standard solution (n = 77) containing 35–70 pg Os. The estimated external reproducibility for $^{187}Os/^{188}Os$ based on 9 complete digestions of a fresh aliquant of sample was better than 0.8% and for the Os concentration it was better than 13%. Forty-seven repeated measurements of a Re standard solution gave a 2σ external precision of 0.5% for the $^{185}Re/^{187}Re$ ratio. The estimated reproducibility of the Re concentration based on 8 duplicated samples is better than 25%; only in one case it is 43%. The analytical uncertainties of Os are likely due to a heterogeneous distribution of the HSE on a small scale, the so-called nugget effect (Mitchell and Keays, 1981, Ellam et al., 1992, Reisberg et al., 1993).

4. RESULTS

4.1. Lithophile and Chalcophile Elements

The spinel-lherzolites of Unit 1 represent the least refractory peridotites in the mantle sequence of the Troodos Ophiolite Complex, but they are nevertheless depleted in Al_2O_3 and other incompatible elements when compared with the primitive mantle composition (Fig. 2a; Table 1). Most peridotites from Unit 1 and 2 show a typical range in the concentrations of lithophile elements and appear to follow the melting trend proposed by Niu (1997) (Table 1; Fig. 2a). One cpx-bearing harzburgite sample (TV-224) of Unit 1 and some samples of Unit 2 lie off the trend to lower MgO concentrations, most probably because of MgO loss during alteration. One cpx-bearing harzburgite sample (TV-225/8, Unit 1) and one dunite sample (98-2, Unit 2) have unusually high Cr concentration of 6536 ppm and 42600 ppm. These samples contain schlieren of spinel visible in hand specimen. They also have high Al_2O_3 contents, which is due to accumulation of spinel (Fig. 2a).

The Cr (Cr/(Cr+Al)) and Mg number (Mg/(Mg+Fe)) in spinels define a negative correlation (Fig. 2b; Table 1). Compared with the partial melting trend from Dick and Bullen (1984) the spinels from the Troodos peridotites are displaced toward lower Mg numbers because of re-equilibration at low temperatures. The Cr number of spinel from Unit 1 systematically increases from lherzolite to harzburgite and dunite. However, the Cr and Mg numbers of the spinels in the dunites of Unit 2 show a large variation, which partly overlaps with that of the harzburgites.

4.2. Os Isotopic Compositions and Os Concentrations

The spinel-lherzolites of Unit 1 have $^{187}Os/^{188}Os_{t=0}$ ratios (0.1255–0.1276) similar to carbonaceous chondrites (0.127 after Shirey and Walker, 1998) (Table 1; Fig. 3a). Most of Os isotopic ratios of the cpx-bearing harzburgites and dunites from Unit 1 are similar to or lower than those of the spinel-lherzolites (Table 1; Fig. 3a). In contrast, most of the harzburgites and dunites of Unit 2 have carbonaceous chondritic to suprachondritic $^{187}Os/^{188}Os$ ratios (Table 1; Fig. 3a). Overall the range of $^{187}Os/^{188}Os$ of the harzburgites of Unit 2 is smaller than that observed in harzburgites of Unit 1 or the dunites of both units.

Unit 1 spinel-lherzolites contain 4.35 ± 0.20 (2 sigma) ng/g Os (Table 1, Fig. 4), which is comparable to Os concentrations in orogenic massifs (Reisberg and Lorand, 1995), but higher than those of most ultramafic xenoliths (Meisel et al., 2001). With the exception of two cpx-harzburgites which have a high Os concentration the Os concentration tend to decrease from the spinel-lherzolites to the harzburgites of both units (Unit 1: 4.06 ± 1.12 (2 sigma) ng/g Os, Unit 2: 3.46 ± 1.38 (2 sigma) ng/g Os) although the average values agree within error. However, Re concentrations decrease by a factor of 3 (sp-lherzolites: 0.31 ± 0.07 (2 sigma) ng/g Re, harzburgites: 0.18 ± 0.16 (2 sigma) ng/g Re; Figure 5. The Os concentration of dunites from both Units (Unit 1: 2.71 ± 0.84 (2 sigma) ng/g Os—with the exception of one sample (259/1) which contains 7.35 ng/g Os-, Unit 2: 1.85 ± 1.20 (2 sigma) ng/g Os) are significantly lower than those of the harzburgites (Fig. 4), whereas the Re concentrations are comparable (dunites: 0.12 ± 0.12 (2 sigma) ng/g Re; Figure 5. The Re concentration of two dunites (0.43 and 0.4 ng/g) (Fig. 5) is similar to boninites from the Troodos Complex (Re: 0.54 ng/g, Büchl et al., 2002).

It has been suggested that clinopyroxenite and orthopyroxenite veins represent crystallization products of percolating melts (e.g., Kelemen et al., 1992; Kelemen et al., 1997). The clinopyroxenite veins from the Troodos mantle sequence have low, but variable concentrations of Os (0.74 ng/g and 0.074 ng/g; Fig. 5) and radiogenic $^{187}Os/^{188}Os_{t=0}$ ratios of 0.130 and 0.133 (Fig. 3b, c). Despite the high Os (4.86 ng/g to 7.84 ng/g)

Table 1A. Major and trace elements, Os isotopes and mineral data in Unit 1.

Sample	TV-271 sp-lh U1	TV-220/5 sp-lh U1	TV-220/1 sp-lh U1	TV-225/8 cpx-hzb U1	TV-225/5 cpx-hzb U1	TV-224 cpx-hzb U1	TV-225/4 cpx-hzb U1	TV-261 cpx-hzb U1	TV-259/3 cpx-hzb U1	TV-231 cpx-hzb U1
SiO_2	44.61	44.59	44.79	40.88	43.54	48.26	43.26	43.89	43.85	43.46
Al_2O_3	2.03	1.91	1.81	1.34	0.95	1.43	1.23	0.63	0.64	1.25
Fe_2O_3	8.52	9.20	8.98	9.50	8.76	8.34	9.28	9.16	8.98	9.47
MgO	41.67	41.30	41.82	45.92	45.35	39.69	44.07	44.86	45.01	43.49
CaO	2.25	2.11	1.70	0.34	0.57	1.35	1.28	0.56	0.67	1.50
TiO_2	0.05	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.02
LOI	12.66	10.96	6.23	12.06	10.10	10.31	14.37	11.36	11.88	14.01
V (ppm)	64	53	62	32	29	56	43	29	35	45
Cr (ppm)	2995	2533	2922	6536	2117	3215	2303	2279	2304	2295
Co (ppm)	102	105	112	121	112	100	104	111	111	107
Ni (ppm)	1874	1930	2126	2463	2240	1902	1899	2073	2015	1915
Cu (ppm)	14	15	10	4	5	35	7	4	12	8
S (ppm)	191	163	153	147	106	203	249	108	147	98
Os (ng/g)	4.19	4.64	4.23	8.12	7.47	5.66	4.22	2.30	4.59	3.53
Duplicate			4.26		7.46					
Re (ng/g)	0.348	0.371	0.212	0.063	0.118	0.676	0.339	0.071	0.276	0.187
$^{187}Os/^{188}Os$	0.12731	0.12755	0.12552	0.12411	0.11694	0.13689	0.12562	0.12575	0.12687	0.12486
Duplicate			0.1258		0.1167					
2 SE (M)	0.00021	0.00014	0.00017	0.00024	0.00021	0.00042	0.00031	0.00019	0.00021	0.00018
$^{187}Re/^{188}Os$	0.398	0.383	0.240	0.015	0.030	0.573	0.385	0.148	0.288	0.254
γOs	0.2	0.4	−1.2	−2.3	−7.9	7.8	−1.1	−1.0	−0.1	−1.7
T_{Ma}			547	446	1602			294	71	861
Cr# in spinel	0.24	0.23	0.23	0.52	0.43	0.44	0.43	0.62	0.62	0.35
Mg# in spinel	0.7*	0.72**	0.67*	0.58*	0.66*	0.60**	0.66*	0.49**	0.52**	0.66**

Abbreviations: U1: Unit 1; U2: Unit 2; sp-lh: spinel-lherzolite; cpx-hzb: cpx-bearing harzburgite; hzb: harzburgite.
Major (wt%) and trace (ppm) element concentrations determined by XRF, Os isotopes by N-TIMS, mineral data by electron microprobe.
Major elements (wt%) corrected for LOI (loss of ignition).
Cr# = Cr/(Cr + Al), Mg# = Mg/(Mg + Fe).
γOs: $((^{187}Os/^{188}Os)_{90Ma}/(^{187}Os/^{188}Os)_{Tchur} - 1)*100$, $(^{187}Os/^{188}Os)_{Tchur}$: 0.12641.
TMa: $\lambda = 1.666*10^{-11}$; $^{187}Os/^{188}Os_{chon} = 0.127$; $^{187}Re/^{188}Os_{chon} = 0.40186$.
* Data from Batanova and Sobolev (2000); ** unpublished data of V. Batanova.

and low Re (0.03 ng/g to 0.35 ng/g) (Fig. 5) concentrations, the orthopyroxenites have extremely radiogenic Os isotopic compositions as they have the highest $^{187}Os/^{188}Os$ ratios ranging from 0.1666 to 0.1846 (Table 1, Fig. 3b, 3c).

5. DISCUSSION

5.1. Melt Percolation in the Troodos Mantle

It has been proposed that the dunites and harzburgites of Unit 1 and Unit 2 do not simply represent residues of partial melting processes, but have been chemically overprinted during melt percolation (Sobolev and Batanova, 1995; Batanova and Sobolev, 2000). This is supported by several observations:

The two mantle units of the Troodos Ophiolite Complex were distinguished on the basis of the Cr number in spinel and cpx abundances in the peridotites (Batanova and Sobolev, 2000). In Unit 1, the Cr number in spinel increases from the spinel-lherzolites to harzburgites and dunites (Fig. 2b). This trend can be explained by partial melting (Dick and Bullen, 1984), but such mantle dunites and harzburgites can also form from lherzolites during melt percolation processes by cpx dissolution and incongruent melting of opx, and precipitation of olivine from the melt (Kelemen et al., 1995; Kelemen et al., 1997; Suhr, 1999).

Unit 2 peridotites lie along the trend of Unit 1 peridotites but the Cr numbers of spinels from Unit 2 dunite and harzburgite overlap with each other (Fig. 2b). This can be explained if the spinels in harzburgite and dunite have equilibrated with a percolating melt and are not residual phases of partial melting. Büchl et al. (2002) observed identical REE patterns - characterized by strong light REE depletion—in clinopyroxenes of dunites and harzburgites from a single melt channel from Unit 2 of the Troodos Ophiolite Complex. Indeed, the REE patterns of clinopyroxenes from harzburgites from all over Unit 2 are similar to those of the single melt channel (Batanova and Sobolev, 2000). This suggests that harzburgites and dunites of the entire unit are products of melt percolation and that they have reacted with the same melt. The trace element composition of the cpx from a websterite vein, a clinopyroxenite from Unit 1 and that of cpx phenocrysts from a boninite of the Troodos volcanic succession are also very similar (Büchl et al., 2002). This observation suggests that a melt with the composition similar to that of the upper pillow lava boninites has percolated through the mantle section of the Troodos Ophiolite.

5.2. Behaviour of Os and Re during Melt Percolation

The spinel-lherzolites of Unit 1 experienced 12% of MORB extraction (Batanova and Sobolev, 2000). Thus, we suggest that before the formation of the dunite-harzburgite channels and at the onset of melt percolation, the Troodos mantle is believed to have had an Os concentration similar to that of the spinel-

Table 1B. Major and trace elements, Os isotopes and mineral data in Unit 1.

Sample	TV-225/1 dunite U1	T16a dunite U1	TV-262 dunite U1	TV-259/1 dunite U1	TV-259/2 du-hzb U1	T21a dunite U1	T21b dunite U1
SiO_2	40.57	41.50	41.64	40.20	41.42	38.76	39.66
Al_2O_3	0.26	0.27	0.33	0.22	0.31	0.36	0.24
Fe_2O_3	9.79	9.89	8.94	8.27	8.88	8.76	8.50
MgO	48.20	47.47	47.88	50.22	48.16	50.83	50.56
CaO	0.32	0.28	0.25	0.23	0.22	0.26	0.30
TiO_2	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LOI	15.91	15.31	15.35	15.37	15.43	16.46	16.11
V (ppm)	12	9	16	13	12	12	12
Cr (ppm)	1174	530	2062	1961	1678	1592	1897
Co (ppm)	122	127	117	115	111	110	116
Ni (ppm)	2315	2356	2128	2365	2151	2390	2311
Cu (ppm)	3	4	b.d.	2	4	4	4
S (ppm)	88	158	81	57	64	168	264
Os (ng/g)	2.73	0.87	3.16	7.35	3.11	3.40	2.98
Duplicate						4.00	2.32
Re (ng/g)	0.064	0.055	0.109	0.068	0.068	0.059	
$^{187}Os/^{188}Os$	0.13098	0.13659	0.12057	0.12342	0.13103	0.12253	0.12551
Duplicate						0.1227	0.1255
2 SE (M)	0.00017	0.00031	0.00033	0.00027	0.00036	0.00012	0.00020
$^{187}Re/^{188}Os$	0.112	0.306	0.166	0.045	0.104	0.071	
γOs	3.1	7.6	−5.1	−2.8	3.2	−3.5	−1.2
T_{Ma}			1613	599		805	223
Cr# in spinel	0.76		0.88	0.77	0.77		
Mg# in spinel	0.44**		0.36**	0.42**	0.41**		

Abbreviations: U1: Unit 1; U2: Unit 2; sp-lh: spinel-lherzolite; cpx-hzb: cpx-bearing harzburgite; hzb: harzburgite.
Major (wt%) and trace (ppm) element concentrations determined by XRF.
Os isotopes by N-TIMS, mineral data by electron microprobe.
Major elements (wt%) corrected for LOI.
Cr# = Cr/(Cr + Al), Mg# = Mg/(Mg + Fe).
* Data from Batanova and Sobolev (2000); ** unpublished data of V. Batanova.

lherzolites of Unit 1 (4.35 ng/g; Fig. 4). The model of melt percolation requires that the dunites formed at high melt/peridotites ratios, whereas the harzburgites reacted with lower amounts of melt (Kelemen et al., 1997). The on average only slightly lower Os concentration in the harzburgites in Unit 2 and some cpx-harzburgites of Unit 1 compared with the spinel-lherzolites suggests that Os is not significantly mobilized during melt percolation with a low melt/rock ratio. This has also been observed by Becker et al. (2001). Some harzburgites, however, have rather low Os concentrations (<3.5 ng/g). This implies that in these samples during melt/rock interaction with an increasing melt/rock ratio from harzburgite to dunite Os behaves incompatibly (Fig. 4). In addition, the amount of sulfides decreases from the spinel-lherzolites (0.01 vol.%–0.02 vol.%) to the harzburgites and dunites (<0.001 vol.%; Batanova and Sobolev, 2001) by at least a factor of 10. Most dunites are virtually free of sulfides and the tiny amount of sulfides now present in some dunites could also represent precipitates from the percolating melt. However, the covariation of decreasing sulfide and Os contents suggests that sulfide controls the variation of Os (Table 1). The sulfides are likely not simply physically removed or added to the peridotites. Büchl et al. (2002) showed that the PGE become systematically fractionated across a melt channel during melt percolation, which would not be expected if a physical process controls the PGE distribution. But fractionation should be anticipated if mantle sulfides and Os are dissolved by the percolating melt. Sulfide-silicate melt partition coefficients for Os, though not well constrained, are thought to be extremely high (Fleet et al., 1999). Thus, sulfides control the bulk peridotite/melt partition coefficient of Os. As the sulfide content decreases with increasing melt percolation, this bulk partition coefficient will decrease, and eventually becomes less that 1, at which point Os could behave as an incompatible element. In particular, the dunites contain little or no mantle sulfides and in this case Os cannot be efficiently retained in the residue and is mobilized along with the percolating melt. Unfortunately, the threshold value for the amount of residual mantle sulfide at which Os becomes incompatible is difficult to determine. This depends on the sulfide-partition coefficient and on the Os solubility in high-temperature fluid-melt systems, which are believed to have reacted with the Troodos mantle. Both variables are not well constrained. Therefore, we can only present a semiquantitative description of the Os behaviour in Section 5.4.

The decrease in Re from spinel-lherzolites to harzburgites and dunites (Fig. 5) indicates that Re behaves incompatibly during the melt percolation process as well as during partial melting. Therefore, Re cannot be used to distinguish between melt percolation and partial melting.

5.3. Evolution of $^{187}Os/^{188}Os$ Heterogeneities in the Troodos Mantle

The Os isotopic composition of the spinel-lherzolites and most of the harzburgites (except 2) from the mantle sequence of the Troodos Ophiolite Complex varies within a small range,

Table 1C. Major and trace elements, Os isotopes and mineral data in Unit 2.

Sample	98-8 hzb U2	TV-279 hzb U2	TV-298 hzb U2	TV-241 hzb U2	TV-291 hzb U2	98-15 hzb U2	T4a# hzb U2	T4ba# hzb U2	T4ca# hzb U2
SiO_2	45.66	43.27	43.24	44.76	42.12	39.87	44.28	46.41	44.59
Al_2O_3	0.74	0.59	0.68	1.02	0.56	0.40	0.76	0.85	0.65
Fe_2O_3	9.45	9.42	8.98	8.87	9.48	9.29	9.18	9.44	10.45
MgO	43.25	45.20	45.71	43.44	46.58	49.14	44.11	41.72	43.08
CaO	0.03	0.64	0.54	0.98	0.39	0.17	0.87	0.81	0.37
TiO_2	0.01	0.01	0.01	0.02	0.01	0.02	b.d.	b.d.	b.d.
LOI	12.52	13.22	7.51	11.71	9.93	9.71	12.19	10.60	13.59
V (ppm)	39	32	26	43	24	20	b.d.	b.d.	b.d.
Cr (ppm)	2598	2259	2179	2744	2542	3452	2460	2300	2220
Co (ppm)	116	114	113	108	118	131	b.d.	b.d.	b.d.
Ni (ppm)	2144	2067	2251	1982	2180	2156	2056	2157	2265
Cu (ppm)	7	1	b.d.	11	b.d.	b.d.	b.d.	b.d.	b.d.
S (ppm)	b.d.	108	101	73	78	b.d.	102	82	92
Os (ng/g)	4.21	3.52	2.08	3.76	3.55	0.21	4.69	4.61	4.56
Duplicate						0.15			
Re (ng/g)	0.084	0.150	0.039	0.262	0.186	0.019	0.050	0.170	0.130
$^{187}Os/^{188}Os$	0.12739	0.12709	0.12460	0.12825	0.12651	0.12830	0.12920	0.13130	0.12880
Duplicate						0.1302			
2 SE (M)	0.00016	0.00016	0.00021	0.00032	0.00028	0.00020	0.00130	0.00200	0.00120
$^{187}Re/^{188}Os$	0.096	0.081	2.081	0.334	0.251	0.214	0.050	0.179	0.143
γOs	0.3	0.1	−1.9	1.0	−0.4	1.0	1.4	3.6	1.7
T_{Ma}					196				
Cr# in spinel	0.6	0.61	0.59	0.49	0.55	0.70	0.58	0.59	0.6
Mg# in spinel	0.61	0.57*	0.60**	0.57**	0.57**	0.47	0.53	0.53	0.53

Abbreviations: U1: Unit 1; U2: Unit 2; sp-lh: spinel-lherzolite; cpx-hzb: cpx-bearing harzburgite; hzb: harzburgite; b.d.: below detection limit.
Major (wt%) and trace (ppm) element concentrations determined by XRF.
Os isotopes by N-TIMS, mineral data by electron microprobe.
Major elements (wt%) corrected for LOI; b.d. = below detection limit.
Cr# = Cr/(Cr + Al), Mg# = Mg/(Mg + Fe).
* Data from Batanova and Sobolev (2000); ** unpublished data of V. Batanova; # data from Büchl et al. (2002).

with $^{187}Os/^{188}Os_{t=0}$ ranging from 0.1241–0.1313 (Table 1 and Fig. 3a). The dunites, however, show a very large variation of the $^{187}Os/^{188}Os_{t=0}$ ratios, ranging from 0.1205 to 0.1546 (Table 1; Fig. 3a). Such a variation is much larger than that observed so far in abyssal peridotites (Martin, 1990; Roy-Barman and Allègre, 1994; Snow and Reisberg 1995; Brandon et al., 2000).

Several processes could be responsible for the large variation of the Os isotopic composition in the peridotites from Troodos:

1. Os exchange between seawater and peridotite

The addition of seawater-derived Os during hydrothermal alteration could have increased the $^{187}Os/^{188}Os$ ratio of the peridotites because 90 Ma ago seawater had a very radiogenic $^{187}Os/^{188}Os$ of 0.51 to 1.1 (Sharma et al., 2000; Ravizza et al., 2001). However, this cannot explain the suprachondritic isotopic composition of some peridotites, because peridotites (~3 ng/g) have much higher Os concentrations than seawater (8–10 fg/g; Sharma et al. (2000), Peucker-Ehrenbrink and Ravizza (2000), Levasseur et al., (1998)). To elevate the $^{187}Os/^{188}Os$ ratios of the peridotites significantly the seawater/peridotite ratio must be >98:2. This is not consistent with the degree of alteration observed in the peridotites (<80%.) In general, the peridotites of Unit 1 are more serpentinised than the peridotites of Unit 2. Assuming that the radiogenic Os isotopic compositions are due to an influence of seawater the peridotites of Unit 1 should therefore have higher $^{187}Os/^{188}Os$ ratios than those of Unit 2. However, the opposite trend is observed and this implies that the radiogenic $^{187}Os/^{188}Os$ ratio cannot fully be accounted by the influence of seawater.

2. Re gain or loss during secondary processes

Re is mobile during serpentinization or hydrothermal alteration, and Re gain/loss may change the Re/Os ratios and therefore the isotopic evolution of the peridotites. Serpentinization of the Troodos peridotites is a young event, because it occurred in the course of the exhumation of the Troodos Complex during the Pleistocene (<2Ma; Robertson, 1977c). Such a recent (<90 Ma) Re gain/loss would not have a noticeable influence on the Os isotopic ratios, because of the high Os and low Re concentrations of mantle peridotites. Therefore, serpentinization should not have had a major influence on the Os isotopic composition of the peridotites which implies that the radiogenic and unradiogenic Os isotopic compositions of the Troodos peridotites are primary igneous features. Mantle processes that could have caused the isotopic heterogeneity are partial melting and/or melt percolation.

3. Partial melting and melt percolation

Re behaves moderately incompatibly and Os compatibly during partial melting. Partial melting lowers the Re/Os ratios and, therefore, reduces the growth of $^{187}Os/^{188}Os$ with time. Thus, subchondritic $^{187}Os/^{188}Os$ ratios in the peridotites could be explained by ancient partial melting processes. Peridotites of the Troodos Complex have Os isotope model ages which range up to 1.6 Ga (Table 1). Such old ages

Table 1D. Major and trace elements, Os isotopes and mineral data in Unit 2.

Sample	98-2 dunite U2	TV-247 dunite U2	TV-287 dunite U2	T4cb$^{\#}$ dunite U2	T4d$^{\#}$ dunite U2	TV-295 dunite U2	T19 dunite U2	TV-299 dunite U2
SiO_2	35.19	40.38		44.17	44.38	40.28	39.46	39.51
Al_2O_3	1.96	0.27		0.26	0.26	0.24	0.40	0.54
Fe_2O_3	11.32	10.11		11.22	11.23	8.80	10.51	10.83
MgO	44.89	48.40		43.48	43.39	49.68	48.45	47.71
CaO	0.16	0.23		0.23	0.12	0.16	0.25	0.21
TiO_2	0.03	0.01		b.d.	b.d.	0.01	0.01	0.02
LOI	9.59	9.02		14.27	14.07	12.01	13.51	14.17
V (ppm)	123	12		b.d.	b.d.	14	20	19
Cr (ppm)	42588	595		640	700	1833	3359	3424
Co (ppm)	99	136		b.d.	b.d.	124	127	129
Ni (ppm)	2706	2617		2514	2505	2400	1477	2057
Cu (ppm)	b.d.	b.d.		b.d.	b.d.	b.d.	b.d.	9
S (ppm)	b.d.	55		63	89	78	251	79
Os (ng/g)	2.20	2.23	3.69	1.95	0.58	3.30	0.10	0.75
Duplicate								
Re (ng/g)	0.108	0.016		0.430	0.400	0.017	0.085	0.135
$^{187}Os/^{188}Os$	0.12592	0.15464	0.12723	0.13900	0.13840	0.12346	0.13120	0.12761
Duplicate								
2 SE (M)	0.00013	0.00027	0.00021	0.0014	0.0016	0.00037	0.00026	0.00024
$^{187}Re/^{188}Os$	0.235	0.034		1.065	3.246	0.024	3.902	0.864
γOs	−0.9	21.8	0.2	9.4	9.0	−2.8	3.3	0.5
T_{Ma}	387			1076	240	560	72	79
Cr# in spinel	0.75	0.44	0.78	0.58	0.58	0.75	0.66	0.59
Mg# in spinel	0.49	0.60**	0.47**	0.46	0.46	0.45**	0.55	0.55**

Major elements (wt%) corrected for LOI; b.d.: below detection limit.
* Data from Batanova and Sobolev (2000); ** unpublished data of V. Batanova; # data from Büchl et al. (2002).

imply that the Troodos mantle had already experienced fractionation processes long before the Troodos crust was formed. However, partial melting cannot raise the Re/Os ratio in residual peridotites and, therefore, cannot explain the observed suprachondritic $^{187}Os/^{188}Os$ ratios.

A melt percolation model assuming reactive chemical exchange with low melt/peridotite ratios would fractionate Re and Os, too. Under such conditions the percolating melt would not mobilize Os but would dissolves Re, leaving behind a Re-depleted peridotite. Thus, subchondritic $^{187}Os/^{188}Os$ ratios can also be explained by old melt percolation events. In this case the percolating melt itself has no detectable influence on the Os isotopic composition of the peridotite, because the Os-bearing mantle sulfides dominate the Os isotopic signature of the peridotite. The Os component of the melt could have a detectable influence on the isotope composition of the peridotite if most of the mantle sulfides—and with it the Os component of the mantle—are removed during the percolation process. Such peridotites could inherit a radiogenic Os isotopic composition if a ^{187}Os-rich melt is percolating through it.

Most of the harzburgites and dunites of Unit 2 have chondritic or suprachondritic Os isotopic compositions, whereas most of Unit 1 harzburgites have chondritic or subchondritic $^{187}Os/^{188}Os$ ratios (Fig. 3a). This suggests that the two units of the Troodos mantle have seen different mantle processes and therefore followed different evolution paths.

5.3.1. *The evolution of unit 1: partial melting and locally restricted melt percolation*

The spinel-lherzolites of Unit 1 represent residues of partial melting. The cpx-bearing harzburgites and dunites with subchondritic Os isotopic composition could have been formed during several old melt extraction processes ranging in age to at least 1.6 Ga based on the calculated Os isotope model ages (T_{Ma}) (Table 1 and Fig. 6). The old ages imply that the Troodos mantle has already experienced fractionation processes long before the Troodos crust was formed. This is surprising, because these old ages appear in a young ophiolitic mantle. It shows that ancient Os isotope heterogeneities can survive in the ophiolite mantle, which has also been observed in abyssal and fore-arc peridotites (Parkinson et al., 1998; Esperança et al., 1999; Brandon et al., 2000).

The suprachondritic Os isotopic ratios in some peridotites from Unit 1 should reflect melt percolation processes where the melt removed the mantle sulfides and left its own signature behind. This provides an alternative explanation for the variable subchondritic $^{187}Os/^{188}Os$ in Unit 1: this part of mantle has experienced one old melt extraction event, at least 1.6 Ga ago, and most of the observed variation in the Os isotopic composition could be due to a younger, spatially restricted reaction with a radiogenic melt. Becker et al. (2001) also explained suprachondritic $^{187}Os/^{188}Os$ ratios in dunite-pyroxenite rocks from the Bohemian massif in Austria by addition of radiogenic Os.

5.3.2. *The evolution of unit 2: pervasive melt percolation*

An important feature of Unit 2 is that the Cr number in spinel and the REE patterns of clinopyroxene from harzburgites and dunites are similar. Thus, spinels and clinopyroxenes are reaction products of the percolating melt with

Table 1E. Major and trace elements, Os isotopes and mineral data in pyroxenite veins.

Sample	TV-225/10 cpx-vein U1	TV-292 cpx-vein U2	T4bb# opx-vein U2	TV-225/6 opx-vein U1	TV-225/7 opx-vein U1	Prim. Mantle***
SiO_2	53.40	51.56	49.42	51.99	51.85	
Al_2O_3	1.82	2.02	1.83	2.40	2.43	
Fe_2O_3	4.92	5.55	8.55	7.16	7.19	
MgO	21.10	21.78	37.65	35.26	35.38	
CaO	17.72	18.23	1.40	1.73	1.72	
TiO_2	0.07	0.08	0.02	b.d.	b.d.	
LOI	1.22	0.90	9.18	3.83	4.28	
V (ppm)	175	175	b.d.	b.d.	b.d.	82
Cr (ppm)	5139	3978	5170	6807	7122	2625
Co (ppm)	41	48	b.d.	b.d.	b.d.	105
Ni (ppm)	736	327	1514	1290	1299	1960
Cu (ppm)	b.d.	b.d.	b.d.	b.d.	b.d.	30
S (ppm)	77	80	134	68	84	250
Os (ng/g)	0.74	0.07	7.84	5.72	4.86	3.4
Duplicate	0.11	0.06				
Re (ng/g)	0.153	0.060	0.030	0.300	0.350	0.28
$^{187}Os/^{188}Os$	0.13039	0.13310	0.16660	0.18300	0.18460	
Duplicate	0.1315	0.1331				
2 SE (M)	0.00031	0.00032				
$^{187}Re/^{188}Os$	0.990	3.918	0.018	0.260	0.350	
γOs	2.7	4.8	31.2	44.1	45.4	
T_{Ma}	345	104				
Cr# in spinel	0.57		0.49	0.48	0.51	
Mg# in spinel	0.32**		0.58	0.64**	0.62**	

Abbreviations: U1: Unit 1; U2: Unit 2; b.d.: below detection limit.
Major (wt%) and trace (ppm) element concentrations determined by XRF.
Os isotopes by N-TIMS, mineral data by electron microprobe.
Major elements (wt%) corrected for LOI; Cr# = Cr/(Cr + Al), Mg# = Mg/(Mg + Fe).
* Data from Batanova and Sobolev (2000); ** unpublished data of V. Batanova; # data from Büchl et al. (2002).
*** Data from McDonough and Sun, 1995.

the mantle peridotite. In addition, most of the harzburgites and dunites of Unit 2 have chondritic or suprachondritic Os isotopic compositions (Fig. 3a), implying the involvement of a radiogenic melt component. This suggests that the peridotites from Unit 2 did not experience locally restricted partial melting and melt percolation events like those observed in Unit 1, but have seen a pervasive melt percolation event. However, harzburgites and dunites with very unradiogenic Os isotopic compositions could also represent relicts of an ancient partial melting event. No clear linear relationships can be identified in the isochron diagrams for samples from Unit 1 and 2 (Fig. 3b, c), so that the age of the pervasive percolation event cannot be determined using the Os isotopes. However, during the formation of the Troodos crust 90 Ma ago very likely a large amount of melt percolated through the Troodos mantle. Batanova and Sobolev (2000) have shown that the dunites and harzburgites of Unit 1 formed as a result of percolation of melts close to the composition of ultradepleted boninites occurring in the Troodos Ophiolite. In addition, the close spatial relationship of the mantle section with the basalts of the oceanic crust in the Troodos ophiolite provides a reasonable logic for a hypothesis relating the formation of the Troodos crust to mantle processes observed in the mantle part.

5.4. Quantitative Description of Melt Percolation in the Troodos Mantle

Our hypothesis suggests that the mantle sections of the Troodos Ophiolite represent fragments of depleted upper mantle, which were invaded by melts during the formation of the Troodos crust in a suprasubduction zone environment. Before ocean crust formation the mantle had already been depleted in Re by at least 1.6 Ga old melt extraction processes. Depending on the age and the extent of partial melting and melt percolation the old melt extraction events left behind spinel-lherzolites with chondritic and subchondritic $^{187}Os/^{188}Os$ ratios and even harzburgites and dunites with very low $^{187}Os/^{188}Os$ ratios. At the time the Troodos crust formed, this "old," isotopically heterogeneous mantle melted again due to the release of fluids from a subducted ocean lithosphere. These produced fluid-rich melts which reacted with the mantle peridotite on their way to the ocean floor and formed harzburgites and dunites. In this scenario Unit 1 of the Troodos mantle could represent a part of the melting regime, where a relatively small amount of melt is formed, and therefore only isolated melt channels form in a lherzolite host. Unit 2 could represent a part of the melting regime where, due to higher degrees of partial melting and accumulation of melts rising from deeper zones, the mantle lherzolite became pervasively invaded by large amounts of melts.

The following discussion should provide a quantitative framework of the hypothesis outlined above constraining the behaviour of Os during the formation of harzburgite and dunite and the isotopic heterogeneity in the Troodos mantle.

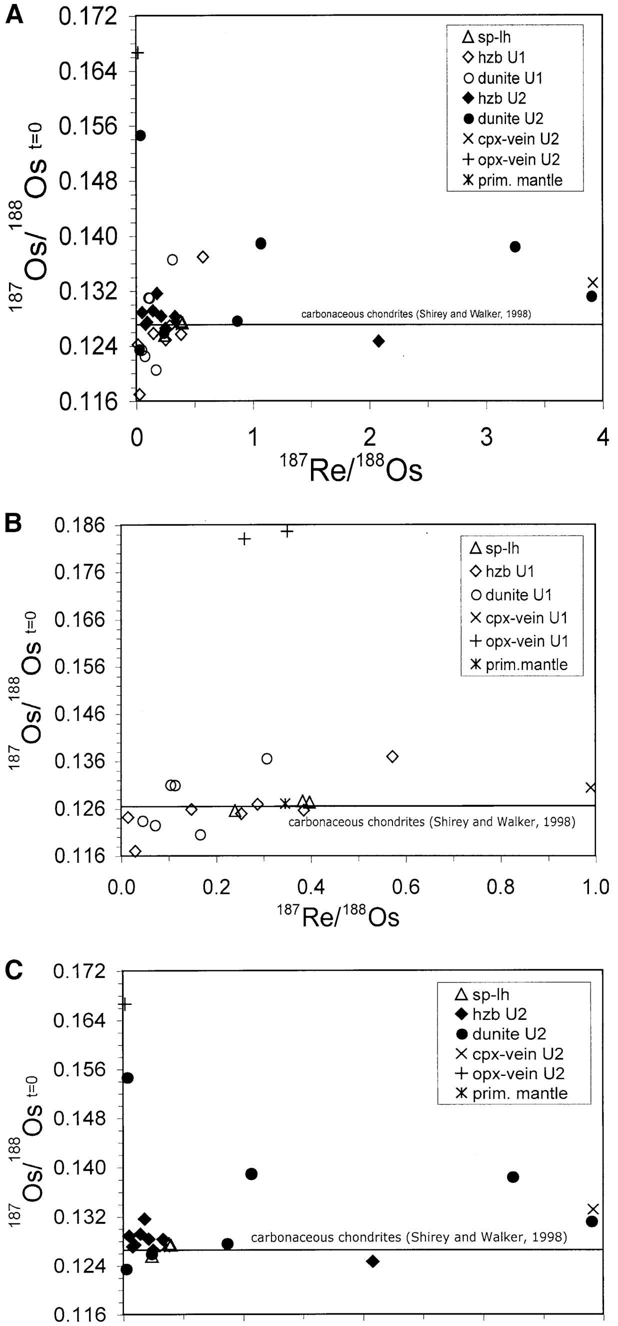

Fig. 3. Isochron diagram (a) for mantle peridotites of both Units, (b) for mantle peridotites of Unit 1, (c) for mantle peridotites of Unit 2. (a) The peridotites of both Units show a large range in their Os isotopic composition. The variation is mainly caused by the dunites. (b) Most harzburgites of Unit 1 are subchondritic in their Os isotopic composition. This can be explained by old partial melting and melt percolation events. (c) In contrast, most harzburgites of Unit 2 have suprachondritic Os isotopic compositions. This is probably due to a young major melt percolation event.

5.4.1. *Formation of harzburgites and dunites by open-system melting*

Melt percolation is the main mechanism forming the harzburgites and dunites in both units. Our data (Fig. 4) suggest that at a certain melt/rock ratio Os does not behave compatibly anymore. It is possible to calculate minimum melt/rock ratios for our dunites if one assumes a certain ^{187}Os/^{188}Os ratio for the dunites at the onset of melt percolation—for example the Os isotopic composition of the spinel-lherzolites (0.127). However, it is likely that some of the dunites experienced a partial melting event before the melt percolation process and this would imply lower ^{187}Os/^{188}Os ratios at the time melt percolation begins. Most (7) of the minimum melt/rock ratios of the dunites lie between 10 to 200 and agree with the range observed by Kelemen et al. (1997) and Becker et al. (2001). In

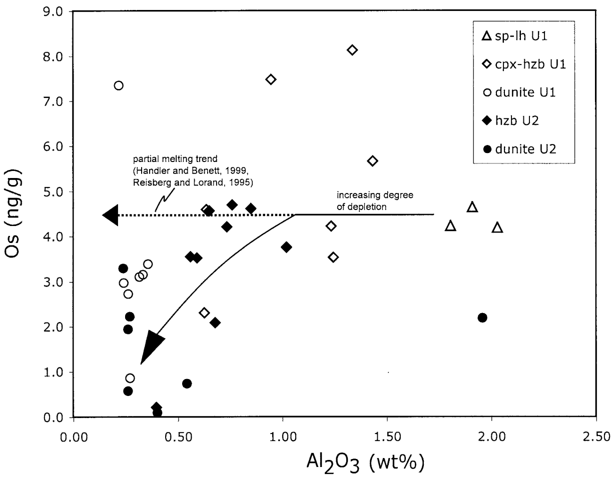

Fig. 4. Variation of the Os concentration with Al$_2$0$_3$. Apart from four samples with high Os abundances, the Os concentration stays constant or decreases in the peridotites with increasing depletion degrees of the peridotites.

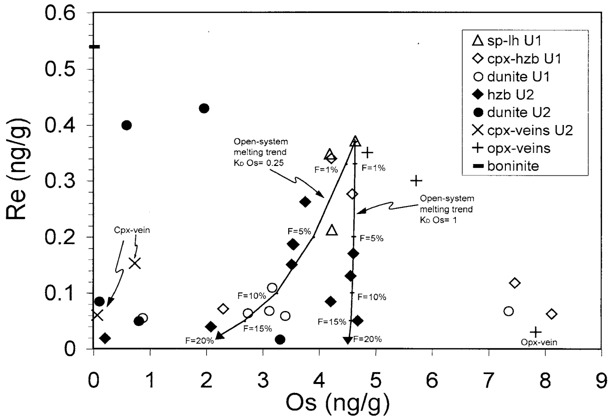

Fig. 5. Variation in Os and Re concentrations in Unit 1 and Unit 2. Re and Os concentrations decrease slightly from spinel-lherzolites to harzburgites and enormously to the dunites. Most of the peridotites lie between the spinel-lherzolites and the cpx-veins. Only three samples lie off this trend and match the opx-veins. Two dunites of Unit 2 have higher Re concentrations, which are similar to boninites from the Troodos Complex (Büchl et al., 2002). The errors of the Re and Os analyses lie in the symbol size. The Re and Os concentrations of Unit 1 and Unit 2 harzburgites and Unit 1 dunites can be modeled by open-system melting. Trend 1: $K_{DOs} > 1$; Trend 2: $K_{DOs} < 1$. The dunites of Unit 2 lie on mixing arrays between the harzburgites and the cpx- and opx-veins.

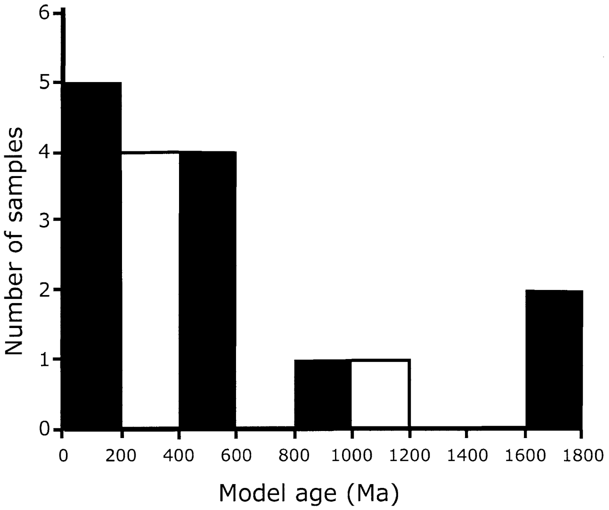

Fig. 6. Os isotope model ages of the peridotites from both units. The Os isotope model ages in the mantle sequence range between 71 Ma and 1.6 Ga. This shows that in a young ophiolitic mantle (90 Ma) ancient Os isotopic heterogeneities can survive in the Earth upper mantle.

Table 2. Parameters and results of the open-system melting model.

	Bulk silicates	Sulphides
Mantle source*	0.9994	0.0006
Melting modes*	0.9964	0.0036
alpha (porosity)	0.002	
beta (mass fluxing rate)	0.1	
F (degree of melting)	0-20%	

P (bulk part. coeff. weighted for the proportions of phases entering the melt) = K_{D1}*melting mode_1 + K_{D2}*melting mode_2 + . . .

D_o (initial bulk solid part. coeff.) = K_{D1}*proportion mantle source_1 + K_{D2} + proportion mantle source_2 + . . .

	Os	Re
C_o (conc. in protolith, sp-lherzolite of Troodos) (ng/g)	4.64	0.37
C_a (conc. in fluxing fluid) (ng/g)	0.01	0.54

Results	Os		Re
Partition coefficient	1	0.25	0.08
F = 1%	4.64	4.48	0.33
F = 5%	4.62	3.9	0.2
F = 10%	4.59	3.25	0.1
F = 15%	4.57	2.68	0.05
F = 20%	4.54	2.19	0.02

* After Rehkämper et al., 1999.

addition one dunite sample has a melt/rock ratio of 2 and one of 1330. We can also estimate the relative mantle source/melt distribution coefficients (K_D) for Os at different melt/rock ratios. In a suprasubduction zone environment, melt-mantle interaction can be described by a model of open-system melting, which considers non-modal melting in a continuously-fluxed mantle (Ozawa and Shimizu, 1995; Zhou, 1998). The higher fluid content of the melt causes enhanced partial melting if compared with the degree of partial melting in abyssal peridotites (Hirose and Kawamoto, 1995; Gaetani and Grove, 1998). Such a model has been developed to explain the behaviour of highly siderophile elements in a single melt channel from Unit 2 of the Troodos Ophiolite Complex (Büchl et al., 2002). We use the model parameters of Büchl et al. (2002) in the present study (Table 2). The concentrations of Re and Os in the mantle residue can be calculated if one knows the mantle source/melt partition coefficients (K_D) and the concentration of the elements in the instantaneous melt (C_l) produced during open-system melting: $C_{res} = C_1 * K_D$

The concentration of the element in the instantaneous melt (Cl) can be calculated using the equation describing open-system melting (Zhou, 1998):

$$\begin{aligned} C_l = {} & 1/(P - \beta - 1)*(-C_a * \beta + ((D_o * C_a * \beta \\ & + C_o * (P - \beta - 1))/(D_o + F_c * (1 + \beta - P))) \\ & \times ((D_o + \alpha - F * (P + \alpha))/(D_o + \alpha - F_c * (P + \alpha))) \\ & \times \exp((1 + \beta - P)/(P + \alpha))) \end{aligned}$$

where C_o is the concentration of the element in the protolith (here the spinel-lherzolite of Unit 1, which is the most primitive mantle peridotite from the Troodos Ophiolite), and C_a is the concentration of the element in the in fluxing fluid (here assumed to be a melt in equilibrium with a boninite from the Troodos Ophiolite). Batanova and Sobolev (2000) have shown that in the mantle section of the Troodos Ophiolite the percolating melts may have been similar to ultra-depleted boninite from the Troodos upper pillow lavas. Comparison of the trace element composition of the cpx from a websterite vein with that of the cpx phenocrysts from the boninite shows a close match (Büchl et al., 2002). α is the porosity of the harzburgite and was assumed to be 1%. β, the mass fluxing rate was assumed to be 0.001. F_c is defined as $\alpha/(\alpha + \beta + 1)$. F is the degree of melting or melt/rock ratio and is varied from 1 to 30%. P is the bulk partition coefficient weighted for the proportions of phases entering the melt, and D_o is the initial bulk solid partition coefficient.

The result of this study indicates that Os behaves differently during melt percolation and during partial melting in abyssal and orogenic peridotites. The amount of sulfides in harzburgite critically determines the bulk partition coefficient of Os. Os appears to behave compatibly when harzburgites form during melt percolation, and the partition coefficient for Os $\approx$ 1 can be used to describe this process (Fig. 5). As described above, if the melt/rock ratio (F) increases during melt percolation Os appears to become incompatible and this phase of the process is described by using a partition coefficient for Os$<$1 for the calculations. Rhenium behaves moderately incompatibly during partial melting and melt percolation and mantle source/melt partition coefficients between 0.2 and 0.08 seem to fit best with our data. The residue has rather constant Os concentrations if the partition coefficient for Os $\geq$1, whereas Re decreases as the degree of melting increases. A few harzburgites from both units lie along this open-system melting trend (Fig. 5). However, most harzburgites from both units and dunites from Unit 1 follow a melting trend assuming a partition coefficient for Os $<$1. This suggests that in most peridotites the threshold value for the amount of sulfides below which Os behaves incompatibly is undershot. Figure 5 shows that most dunites from Unit

2 have low Os concentrations similar to those of cpx-veins from Unit 2 or the boninite from the Troodos Ophiolite. Most dunites are virtually free of sulfides. We therefore suggest that the tiny amount of sulfides now present could represent precipitates from the percolating melt. This would imply that samples with low Os abundance could have exchanged Os with that of a radiogenic source, like the melt.

Probably, the percolating melts had variable Os concentrations and isotopic compositions. The ultimate source of the radiogenic Os is the oceanic crust. During its subduction it dehydrates, and Os can be mobilized and transported into the overlying mantle wedge (Brandon et al., 2000; Walker et al., 2002). This process would cause isotopic heterogeneities in the mantle, depending on the amount of fluid and on the Os concentration and the isotopic composition of Os in the fluids. Therefore, partial melting in the mantle wedge would produce melts with variable Os isotopic compositions. Thus, the isotopic heterogeneity observed in the Troodos mantle appears to be the result of old partial melting events and the mobilization and addition of radiogenic Os during melt percolation related to the formation of the Troodos crust.

6. CONCLUSIONS

This study investigates the behaviour of Os and Re and the origin of Os isotopic heterogeneities during melt percolation in the mantle sequence of the Troodos Ophiolite Complex, Cyprus. Unit 1 and Unit 2 show a large variation in Os isotopic compositions in harzburgites and dunites. The range is large compared to that of abyssal peridotites. This study let us suggest that a large heterogeneity in their Os isotopic composition is a typical feature of mantle peridotites from above subduction zones.

We suggest that subchondritic ^{187}Os/^{188}Os ratios reflect old partial melting and melt percolation events. Suprachonditic ^{187}Os/^{188}Os ratios necessitate the addition of radiogenic Os during melt percolation. The ultimate source of the radiogenic Os isotopic signature in the melt is most probably the dehydration phase of subducted oceanic crust.

Most harzburgites of Unit 1 have subchrondritic Os isotopic ratios and experienced at least one old melt extraction event as inferred from Os isotope model ages in the range of 90 Ma to 1.6 Ga. These old ages appear in a young ophiolitic mantle and it shows that ancient mantle heterogeneities can survive in the mantle. In contrast, most of the peridotites of Unit 2 have suprachondritic ^{187}Os/^{188}Os values implying that a younger melt percolation event overprinted the Os isotopic composition of the mantle sequence. This major event could have been the formation of the Troodos crust 90 Ma ago.

The Os concentrations and Re/Os ratios in the mantle peridotites can be explained if they represent mixing products of old depleted mantle and cpx- and opx-veins, which are crystallization products of the percolating melt. This mixing occurred during the melting of a continuously- fluxed mantle.

During melt percolation the distribution of Os is controlled by sulfide. At low melt/rock ratios Os behaves compatibly, like during partial melting processes. However, during the formation of harzburgites and dunites at high melt rock ratios the sulfide content and the Os content of the mantle peridotites decrease. Thus, Os is mobilized and becomes incompatible.

Unit 1 and Unit 2 harzburgites and dunites probably belong to the same melting regime, which eventually produced the Troodos oceanic crust 90 Ma ago.

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