16. PETROLOGY AND GEOCHEMISTRY OF NODULAR WEBSTERITE INCLUSIONS IN HARZBURGITE, HOLE 920D¹

Pamela D. Kempton² and Christopher J. Stephens³

ABSTRACT

Two nodular websterite inclusions (3-4 cm in diameter) were identified in the predominantly harzburgitic core in Hole 920D. These inclusions and a representative harzburgite from the same drill hole have been analyzed for their Sr-, Nd-, and Pbisotope ratios along with major-element mineral compositions to better understand their origin and significance. Elevated Srand Pb-isotope ratios provide abundant evidence for seawater interaction; ²⁰⁸Pb/²⁰⁴Pb ratios are higher for a given ²⁰⁶Pb/²⁰⁴Pb than those of normal (i.e., away from plume/hotspot influences) mid-ocean ridge basalt (N-MORB) from the North Atlantic and are consistent with a model for alteration involving a component of pelagic sediment. In contrast, Nd isotopes are largely unaffected by alteration processes. The pyroxenes separated from the Site 920 peridotites have higher ¹⁴³Nd/¹⁴⁴Nd ratios than most North Atlantic N-MORB, and higher than any measured abyssal peridotite to date. Nodular websterites have slightly higher Nd-isotope ratios than the analyzed harzburgite. Both websterites and harzburgite are isotopically distinct from all magmatic rocks in the Mid-Atlantic Ridge south of the Kane Fracture Zone (MARK) area, including gabbros, diabase dikes, and recent basalts. Thus, in terms of their isotopic compositions, the analyzed peridotites are not representative of the mantle source of the MARK magmatic rocks. High aluminum, iron, and titanium contents in the websterite pyroxenes suggest a vein origin, possibly as a result of decompression melting in an upwelling diapir. These veins preceded the more numerous clinopyroxenite veinlets and gabbroic dikes observed throughout the Site 920 core and probably formed in the asthenosphere. These inclusions may thus be analogous to Type I/Type I composite relationships found in alpine peridotites and alkali-basalt hosted xenolith suites. They provide evidence that interaction between basaltic melts and peridotite residues is a common and varied occurrence in the genesis of oceanic lithosphere.

INTRODUCTION

Studies of mantle-derived ultramafic xenoliths and peridotite massifs have highlighted the significance of magmatic veins in modifying the composition of the mantle. In particular, it is now commonly accepted that vein emplacement constitutes one of the most effective ways of refertilizing mantle previously depleted by partial melting processes. Conversely, the veins also provide information on the mechanisms of melt segregation and migration in the mantle, and may be physical evidence for the commonly postulated polybaric melting scenarios proposed to explain the compositions of primary mantle melts (MacKenzie, 1984; Klein and Langmuir, 1987; Salters and Hart, 1989; Langmuir et al., 1992).

Numerous studies of peridotite xenoliths in alkalic basalts, as well as alpine peridotite massifs, have indicated that such veins are variable in composition, ranging from Fe-Ti-Al-rich assemblages of pyroxene \pm amphibole and mica (Type II) to Mg-Cr-rich pyroxenites and websterites (Type I). Adapting the classification of Frey and Prinz (1978) for ultramafic xenoliths, Kempton (1987) referred to these different composite relationships as Type II/Type I and Type I/ Type I, depending on whether the vein was Type II or Type I in composition. Note that, in this classification, Type I compositions are characterized by high Mg and Cr contents and the clinopyroxene is typically Cr diopside. In contrast, Type II lithologies are characterized by Fe-, Al-, and Ti-rich compositions and are typified by the presence of Al augite \pm amphibole and/or phlogopite. In most composite samples, the vein minerals are compositionally distinct from the wallrock peridotite, and there is clear evidence that the assemblage represents the crystallization of magma in mantle conduits (Irving, 1980; Spray, 1989). Type I/Type I assemblages are more ambiguous in origin because the vein mineral phases are virtually indistinguishable in composition from those in the wallrock lherzolite or harzburgite; the veins are often only recognized by the concentration of green pyroxene in bands relative to the olivine-rich lherzolite or harzburgite. It has been argued that these may be either more ancient veins that later reequilibrated with the ambient mantle or veins that crystallized at greater depths in the mantle (Sinigoi et al., 1983; Kempton, 1987; Scribano, 1987). Alternatively, they may simply be metamorphic segregations of pyroxene (Dick and Sinton, 1979; Spray, 1989).

Abundant evidence for magmatic intrusion into depleted peridotite mantle is observed in the Leg 153 core at Site 920. These range from cm-wide gabbroic dikelets to mm-wide clinopyroxenite veins. These rocks, and the chemical consequences of their interaction with the peridotite wallrock, are the subject of several studies in this volume (Casey, this volume; Stephens, this volume; Niida, this volume; Cannat, Chatin, et al., this volume). The gabbroic dikelets are probably most directly analogous to the Type II/Type I composite relationships observed in basalt-hosted ultramafic xenoliths.

Two nodular concentrations of pyroxene that may be analogous to Type I/Type I composite relationships were also identified in Hole 920D. These websterite inclusions are the subject of this paper. Although websterites are extremely rare among abyssal peridotites, they are not unknown. Dick et al. (1984) reported the mineral modes of two websterite samples recovered by dredging, one from the Kane Fracture Zone and one from the Islas Orcadas Fracture Zone. A websterite sample was also recovered during drilling on Leg 109 at Site 670, just 20 km south of Site 920. Major-element mineral chemistry as well as modal information are available for this sample (Fujii, 1990; Juteau et al., 1990). More recently, the petrography and major-

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²NERC Isotope Geosciences Laboratory, Kingsley Durham Centre, Keyworth, NG12 5GG, United Kingdom. P.KEMPTON@NIGL.NERC.AC.UK

³Department of Earth Sciences, The University of Queensland, Brisbane, 4072, Australia. (Present address: School of Geology, Queensland University of Technology, 2 George Street, Brisbane, 4000, Australia.)

element mineral chemistry of three clinopyroxenites from the Tereveka transform fault (located on the western rift of the Easter microplate) have been described by Constantin et al. (1995). We have analyzed the Site 920 websterites for Sr, Nd, and Pb isotopes along with major-element mineral compositions to characterize these unusual features. Our new data will be discussed in conjunction with the data on Cr diopside websterites and clinopyroxenites from other localities to further our understanding of the origin and significance of these rare lithologies.

SAMPLE DESCRIPTION

Two pyroxene-rich nodular inclusions were observed in the Leg 153 core (Samples 153-920D-13R-2, 65-68 cm, and 15R-3, 18-21 cm). Section 153-920D-13R-2 consists predominantly of porphyroclastic serpentinized harzburgite to dunite. Modal proportions of the harzburgite are variable: olivine ranges from 75% to 98%, orthopyroxene from 2% to 23%, and clinopyroxene from 0% to 1%. Spinel occurs in abundances of less than 1% throughout. Total alteration (principally serpentinization) of the harzburgite is high, and it increases with decreasing pyroxene content from 70% to greater than 95% of the rock. Piece 2 in Section 13R-2 contains an oval-shaped (3 ×4 cm) inclusion or band of olivine websterite. Contacts with the surrounding harzburgite are sharp and smooth. In contrast to the rest of the core, the inclusion consists of 57% orthopyroxene, 30% clinopyroxene, 10% olivine, and 3% spinel; opaque minerals occur in trace amounts. The pyroxenes are also significantly more coarse grained than the pyroxenes typically found in the lherzolites and harzburgites. Alteration of the inclusion is significantly less than that of the surrounding harzburgite, although the olivine in the websterite is partially altered to serpentine in a mesh texture analogous to that seen in the surrounding harzburgite. The shipboard assessment of the inclusion is that "it may either be a xenolith or a vein" (Shipboard Scientific Party, 1995).

Similar to that of Section 13R-2, a pyroxene-rich nodular inclusion occurs in Piece 2 of Section 153-920D-15R-3. This section is also predominantly serpentinized porphyroclastic harzburgite. However, the clinopyroxene content may be slightly higher than it is in Section 13R-2. Visual estimates from the core suggest that, on average, the harzburgite in this section consists of 80% olivine, 14% orthopyroxene, 5% clinopyroxene, and less than 1% spinel. In general, alteration of Section 15R-3 is also slightly less than that of Section 13R-2, averaging about 60% throughout. However, petrographic description of a thin section taken approximately 20 cm below the websterite nodule indicates that in this interval the rock originally consisted of 80%-87% olivine, 10%-17% orthopyroxene, <2% clinopyroxene and <1% spinel; this interval is also more than 95% altered to serpentine, chlorite, talc, and/or tremolite. Modal proportions of the websterite inclusion were not noted during the shipboard core description, but shore-based analysis indicates than this nodule is more clinopyroxene rich than the websterite in Section 13R-2, with clinopyroxene approximately twice as abundant as orthopyroxene. Similar to the nodular inclusion in Section 13R-2, the pyroxenes are significantly more coarse grained than pyroxenes found in the lherzolites and harzburgites elsewhere in the core. The contact between the

websterite and harzburgite in this section is complicated by the presence of a 6- to 8-mm-wide band of altered pyroxene adjacent to the websterite. A second trail of secondary pyroxene crystals branches from this vein and runs along the length of Piece 2. These trails are oblique to the foliation and are interpreted as magmatic veins (Shipboard Scientific Party, 1995). They are clearly later in origin than the nodular inclusion.

Pyroxenes from the nodular websterites in Sections 13R-2 and 15R-3 are similar petrographically to the pyroxenes that occur in lherzolites and harzburgites throughout the core at Site 920 (Stephens, this volume). In particular, they contain exsolution lamellae of pyroxene, consistent with low-temperature re-equilibration, and similar structural characteristics (e.g., kink-banding and recrystallization of porphyroclasts).

The modal proportions of mineral phases in the websterites from Section 13R-2 are similar to those in other abyssal websterites (Table 1). In particular, clinopyroxene is typically less than or equal to orthopyroxene in modal abundance. However, note that the modal mineralogies of adjacent samples of the websterite from Site 670 differ significantly. In one sample, orthopyroxene and clinopyroxene occur in roughly equal amounts (Juteau et al., 1990); in the other, orthopyroxene is three times more abundant than clinopyroxene (Fujii, 1990). This highlights the problem of determining accurate modes for these samples because they tend to be both small in size and coarse grained. The websterite from Section 15R-3 is more clinopyroxene rich than most reported websterites, but nonetheless contains significant amounts of orthopyroxene. In contrast to the websterites, clinopyroxenites from the Tereveka transform consist of greater than 90% clinopyroxene, with only minor enstatite (Constantin et al., 1995).

Contacts between websterite and harzburgite were not described for the sample from Site 670, but the websterites dredged from the Kane and Islas Orcadas Fracture Zones are described as occurring in bands (Dick et al., 1984). Similarly, two of the clinopyroxenites from Tereveka (Constantin et al., 1995) are described as veins, one occurring as a layer subparallel to foliation, the other recording a complex sequence of multiple melt injections with mineral assemblages ranging from Cr diopside at the vein margins to gabbroic in the core. A third clinopyroxenite bears some physical similarities with the Site 920 websterites in that it is described as a "cluster" 2 cm in diameter, enclosed in harzburgite (Constantin et al., 1995). The cluster is >90% clinopyroxene with fine-grained interstitial orthopyroxene + spinel \pm olivine. The contact with the harzburgite is described as sharp. Analogous to the Site 920 websterites, all of the clinopyroxenites and websterites described above are significantly less altered (i.e., less serpentinized) than the surrounding harzburgites.

In addition to the websterite inclusions, a sample of more typical peridotite from Site 920 was analyzed for comparative purposes. Sample 153-920D-22R-7, 45–49 cm, was taken from one of the more clinopyroxene-rich intervals of the core where the assemblage is borderline lherzolite/harzburgite, containing 4%–5% clinopyroxene, 15%–17% orthopyroxene, and 81%–83% olivine. The harzburgite exhibits an elongate porphyroclastic texture typical of the Site 920 core. The section is 80%–90% altered to serpentine.

Approximately 50 cm below the harzburgite sample analyzed in this study, a 1-cm-wide metagabbro vein crosscuts the peridotite. Iso-

Table 1. Modal analyses of olivine websterites.

Sample	Olivine	Orthopyroxene	Clinopyroxene	Spinel
153-920D-13R-2, 65-68 cm (this study)	10	57	30	3
109-670A-9R-1, 19-20 cm (1)	12	42.2	45.7	0.1
109-670A-9R-1, 22-24 cm (2)	20	60	20	1
AII 96-1-3 (Kane FZ) (3)	20.8	43.1	34.3	1.8
1011/76-60-52 (Islas Orcadas FZ) (3)	28.8	53.2	17.3	0.7

Notes: Data from (1) Fujii (1990), (2) Juteau et al. (1990), (3) Dick et al. (1984). FZ = Fracture Zone.

topic analyses of these metagabbro veins is the subject of a separate study (Kempton and Hunter, this volume). Here, however, we include a high-temperature brown amphibole (Sample 153-920D-12R-1, 128-134 cm) separated from a vein that crosscuts the peridotite and is oblique to the high-temperature crystal-plastic foliation. Visual core descriptions (Shipboard Scientific Party, 1995) indicate that the vein was originally in excess of 5 cm thick. The vein is composed of three distinct bands: a zone (15-20 mm wide) of brown amphibole, chlorite, zeolite, and clay minerals, bounded by a band (10-15 mm wide) of chlorite and serpentine, which in turn abuts a white band of tremolite. It is unclear whether the vein was originally magmatic hornblende or a pyroxenite/gabbro that was subsequently replaced, first by hornblende, and later by lower-temperature alteration phases (e.g., tremolite and chlorite). Several small altered magmatic veins are observed elsewhere in the core, but these do not contain hornblende.

ANALYTICAL TECHNIQUES

Mineral separates for isotopic analyses of strontium, neodymium, and lead were hand-picked from crushed and sieved splits of the whole-rock sample. Because of the small size of the nodular websterites, orthopyroxene and clinopyroxene were combined for analysis. For Sample 153-920D-15R-3, 18-21 cm, the analyzed split contained approximately 80% clinopyroxene and 20% orthopyroxene; for Sample 13R-2, 65-68 cm, the analyzed split was approximately 45% clinopyroxene and 55% orthopyroxene. In addition, serpentine separated from Sample 15R-3, 18-21 cm, was analyzed to determine the effect of alteration/serpentinization on the peridotites. It was possible to separate sufficient quantities of both clinopyroxene and orthopyroxene from the harzburgite in Section 22R-7 so these phases were analyzed separately for this sample. The brown amphibole is from an altered vein, and we separated the white alteration phase(s) to investigate this form of alteration; the material analyzed is predominantly tremolite.

The mineral separates were cleaned ultrasonically in Milli-Q brand H₂O to remove surface contaminants acquired through drilling or handling. They were then hand-picked in methanol using a binocular microscope to ensure the highest purity possible for each sample. Note that the silicate phases in Sample 153-902D-13R-2, 65-68 cm, contained abundant tiny opaque inclusions that could not be entirely eliminated. This precluded separation of a totally pure pyroxene mineral separate. We therefore analyzed two splits of this sample-one with opaque inclusions and a high-graded split in which inclusions were avoided as much as possible. We estimate that this latter split contained <1% inclusions. Except for the serpentine and the white alteration phase(s) separated from the amphibole vein, all samples were leached prior to dissolution in 6-M HCl on a hot plate at ~100°C for ~30 min. The leachates were removed and the mineral grains rinsed in Milli-Q H2O. The leachates and the Milli-Q H2O rinses were combined and processed for isotopic analysis along with the cleaned mineral separates. The samples were then crushed in an agate mortar.

Because the concentrations of Pb, Sr, and Nd are so low, relatively large sample sizes (250–650 mg) were used where possible. For total sample sizes greater than 250 mg, dissolutions were performed on multiple splits of the same sample, with each split not exceeding 250 mg. Further details of the geochemical procedures used are given in Kempton and Hunter (this volume). Sr, Nd, and Pb were run as the metal species on single Ta, double Re + Ta, and single Re filaments, respectively, using a Finnegan MAT 262 multicollector mass spectrometer in static mode at the NERC Isotope Geosciences Laboratory (NIGL). Blanks for Sr, Nd, and Pb are typically less than 400 pg, 300 pg, and 200 pg, respectively. However, a Nd blank of 2.6 ng was measured for one batch of samples. Nevertheless, the ¹⁴³Nd/¹⁴⁴Nd of most blanks is lower than the sample values measured here, and we believe it is unlikely that there has been a serious effect on our sample data. Reference standards throughout the course of analysis averaged values of 87 Sr/ 86 Sr = 0.710184 ± 14 for the NBS987 standard, and 143 Nd/ 144 Nd = 0.511106 ± 10 for the Johnson Matthey (J&M) Nd standard. 87Sr/86Sr was normalized to 86Sr/88Sr = 0.1194; 143Nd/144Nd was normalized to a value of 146Nd/144Nd = 0.7219. Samples for this and related studies were analyzed over a period of 18 months; to minimize the effects of machine drift, sample results are further normalized to accepted values for NBS 987 and J&M of 0.71024 and 0.51111, respectively. Minimum uncertainties are derived from external precision of standard measurements, and these average 27 ppm for 143Nd/144Nd and 18 ppm for 87Sr/86Sr. Based on repeated runs of NBS981 common Pb standard, the reproducibility is better than $\pm 0.1\%$ per a.m.u. Pb-isotopic ratios were corrected relative to the average standard Pb-isotopic compositions of Todt et al. (1984). The Pb-isotope analyses were particularly difficult to perform, and beam currents were often less than 1 pA on ²⁰⁸Pb; this means that the ²⁰⁴Pb intensity is typically <0.03pA. This low intensity on ²⁰⁴Pb adds considerably to the uncertainty of the Pb-isotope ratios involving this isotope, and it is particularly apparent on diagrams involving 207Pb/ ²⁰⁴Pb because the range is already very small for this ratio. Errors quoted for samples are one standard deviation from measured or calculated values.

Major-element mineral analyses were performed at the University of Queensland. Details of analytical techniques can be found in Stephens (this volume).

RESULTS

Major-Element Mineral Chemistry

Average compositions of the four primary mineral phases present in the two nodular inclusions are presented in Table 2. Although there is no statistically significant chemical zonation evident within the individual grains of the websterites, the presence of exsolution complicates interpretation of the major-element mineral analyses because much of it is on a micron scale. Therefore, average compositions have been calculated from multiple broad beam analyses (Table 2). Pyroxenes from the websterites are similar in their major components (Ca-Mg-Fe), both to each other and to Site 920 peridotite pyroxenes (Fig. 1). Pyroxene from the websterite in Section 15R-3 is, nonetheless, slightly more Fe rich and has a lower Mg# (i.e., 100 · Mg/Mg + Fe2+) than the average for Site 920 peridotites (Table 2). Olivine compositions from the websterites, however, are similar to average Site 920 peridotite. Fujii (1990) and Juteau et al. (1990) noted a similar overlap in olivine and pyroxene compositions between the Site 670 websterite and associated harzburgites.

However, differences in minor-element concentrations mirror the small differences in major mineral components of the pyroxenes from Sample 15R-3, 18-21 cm. In particular, pyroxenes from Sample 15R-3, 18-21 cm, have higher TiO2 and Na2O contents (Table 2), and pyroxenes from both websterite samples have higher Cr2O3 for a given Al₂O₃ content compared with other Site 920 peridotites (Fig. 2). Relative to other peridotites from or near the Mid-Atlantic Ridge, south of the Kane Fracture Zone (MARK) area (i.e., Sites 670 and 395), the Site 920 pyroxenes have intermediate Al₂O₃ contents, but the range of Cr₂O₃ is similar for each site. Recall that Site 670 is located only about 18 km south of Site 920 and is also from the rift valley wall, so it is presumably of a similar age and has a similar petrogenetic history to peridotites from Site 920. Peridotites from Site 395 are located approximately 100 km west of Site 670 in 7-m.y.-old crust. Also shown for comparison are the highly depleted pyroxenes from peridotites dredged along the Mid-Atlantic Ridge at 43°N (Shibata and Thompson, 1986) and harzburgites from the Tereveka transform (Constantin et al., 1995). The extremely low Al contents of peridotites from 43°N are interpreted as evidence of extensive depletion as a result of partial melting processes, possibly melting beyond the

		Clinopyroxer			Orthopyroxer	ne				
	13R-2, 65-68 cm		15R-3, 18-21 cm	Site 920	13R-2, 65-68 cm		15R-3, 18-21 cm		Site 920	
	<i>n</i> = 54	s.d.	n = 41	s.d.	n = 365	n = 37	s.d.	n = 23	s.d.	n = 282
SiO ₂	51.25	0.83	50.99	0.51	51.77	55.36	0.68	55.27	0.46	55.13
TiO ₂	0.11	0.03	0.14	0.03	0.11	0.04	0.02	0.07	0.02	0.04
Al ₂ Ô ₂	4.83	0.63	5.05	0.23	4.72	3.82	0.49	3.86	0.23	4.11
Cr ₂ O ₂	1.19	0.19	1.37	0.08	1.12	0.76	0.16	0.92	0.06	0.82
FeO	2.38	0.21	2.84	0.26	2.52	6.10	0.22	6.00	0.16	5.96
MnO	0.08	0.02	0.10	0.02	0.09	0.14	0.02	0.14	0.02	0.14
NiO	0.05	0.03	0.05	0.03	0.05	0.09	0.03	0.11	0.03	0.10
MgO	16.37	0.73	16.63	0.79	16.75	32.88	0.67	32.28	0.60	32.64
CaO	23.68	1.07	22.29	1.25	22.87	1.10	0.52	1.79	0.47	1.48
Na ₂ O	0.04	0.03	0.10	0.04	0.09	0.01	0.01	0.01	0.01	0.01
K ₂ Ô	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mg#	92.5		91.3		92.3	90.7		90.6		90.8
			Olivine					Spinel		
	13R-2, 65-68 cm		15R-3, 18	-21 cm	Site 920	13R-2, 65-	-68 cm	15R-3, 18	-21 cm	Site 920
	<i>n</i> = 22	s.d.	<i>n</i> = 8	s.d.	n = 346	n = 15	s.d.	<i>n</i> = 7	s.d.	n = 364
SiO	41.33	0.22	41.22	0.52	41.16	0.02	0.01	0.03	0.01	0.04
TiO2	0.01	0.52	0.02	0.02	41.10	0.02	0.02	0.03	0.02	0.07
AL 0	0.01	0.01	0.02	0.02	0.01	43.70	0.02	41.37	131	42.45
CrO_3	0.01	0.07	0.02	0.01	0.01	24.13	0.40	26.22	0.52	25.75
EaO	0.01	0.02	0.02	0.07	0.01	12 20	0.43	13 73	0.20	14.04
MnO	0.14	0.02	9.20	0.20	9.15	0.16	0.03	0.16	0.02	0.17
NiO	0.14	0.02	0.15	0.02	0.15	0.10	0.03	0.22	0.04	0.20
MaO	40.80	0.65	50.04	0.02	50.08	17.40	0.28	17.06	0.34	16.01
CaO	49.00	0.05	0.04	0.00	0.04	0.02	0.20	0.04	0.01	0.01
NaO	0.05	0.01	0.04	0.02	0.04	0.02	0.01	0.02	0.02	0.01
K O	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.01
R20	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00
Mg# Cr#	90.7		90.7		90.8	70.3 27.0		69.1 29.8		68.4 28.9

Table 2. Average compositions of primary phases in Site 920 websterites.

Notes: n = the number of analyses used to calculate the average. The standard deviation (s.d.) quoted is 1σ. Mg # calculated on the basis of cation proportions as Mg/(Mg+Fe⁺²) · 100; Cr# calculated as Cr/(Cr+Al) · 100. Averages for Site 920 are from Stephens (this volume).



Figure 1. Compositions of pyroxene from websterite nodules in Sections 153-920D-13R-2 and 15R-3 shown in a pyroxene quadrilateral and compared with the total range of pyroxene compositions for Site 920 (Stephens, this volume).

diopside-out equilibria (Hess, 1992); this high degree of partial melting has been attributed to the proximity of the Azores hotspot. In contrast to the websterites from Site 920, the websterite from Site 670 has a lower Cr_2O_3 concentration for a given Al_2O_3 , not only relative to the Site 920 peridotites, but also to the Site 670 harzburgites. Clinopyroxenites from Tereveka have both higher and lower Cr_2O_3 contents relative to Tereveka harzburgites, but the clinopyroxenite cluster has the highest Al_2O_3 of the Tereveka Cr diopsides. Constantin et al. (1995) also note that the Tereveka clinopyroxenites have high TiO₂ contents relative to most harzburgites from the same area.

Although both spinels from Site 920 websterites fall within the total range for Site 920 peridotites (see Stephens, this volume), spinel in Sample 15R-3, 18–21 cm, is one of the most Cr rich of the suite (Fig. 3; Table 2). Analogous to the pyroxene results, spinel in the Site 670 websterite has low Cr# (i.e., $100 \cdot Cr/Cr + Al$) for a given Mg# relative to the associated harzburgites. In contrast, abyssal peridotites from Mid-Atlantic Ridge 43°N and Tereveka have the highest Cr numbers and extend to the lowest Mg numbers. Site 920 peridotite



Figure 2. Cr_2O_3 vs. Al_2O_3 (wt%) in clinopyroxene (cpx) from websterite Samples 153-920D-13R-2, 65–68 cm, and 15R-3, 18–21 cm. Shown for comparison are data for websterites from Site 670 (Fujii, 1990; Juteau et al., 1990) and clinopyroxenites (cpxenite) from the Tereveka transform (Constantin et al., 1995). Also shown are fields for harzburgite clinopyroxenes from Site 920 (Stephens, this volume), Site 670 (Fujii, 1990; Juteau et al., 1990; Komor et al., 1990; Hébert et al., 1990), Site 395 (Fujii, 1990), Mid-Atlantic Ridge (MAR) 43°N (Shibata and Thompson, 1986), and the Tereveka transform (Constantin et al., 1995).

spinels are intermediate in composition between those from Sites 670 and 395. Spinels from Tereveka clinopyroxenites have both lower and higher Cr contents compared with spinels from Tereveka harzburgites. In general, increasing Cr# in spinel reflects increasing degrees of partial melting in the mantle (Dick and Bullen, 1984). However, Dick (1989) also notes that whole-rock chromium contents in abyssal peridotites decrease rather than increase with proximity to the Bouvet hotspot, correlating inversely with the abundances of compatible elements magnesium and nickel. This suggests that chromium behaves incompatibly during mantle melting.

Isotopes

Results from isotopic analyses are summarized in Table 3. Sr- and Nd-isotope data are shown in Figure 4 relative to fields for North Atlantic mid-ocean ridge basalt (MORB) and Leg 153 gabbros from Sites 920 to 924. Also shown is the field for recent MARK basalts. In general, the Sr-isotope compositions of the peridotite pyroxenes and brown amphibole are significantly higher than Leg 153 gabbros from Sites 920 to 924 and higher than North Atlantic MORB. The lowest 87Sr/86Sr ratio occurs in the clinopyroxene separated from the harzburgite in Section 153-920D-22R-7. Some gabbro dikes from Site 920 have ⁸⁷Sr/86Sr ratios that overlap the low end of the peridotite range. The high-temperature brown amphibole has a similar isotopic composition to that of the clinopyroxene from the harzburgite in Section 22R-7. In contrast, the split of the websterite from Section 13R-2 that contains abundant inclusions has the highest Sr-isotope ratios of the peridotites. The high-graded split of this sample and the websterite from Section 15R-3 have intermediate 87Sr/86Sr ratios, but Ndisotope compositions are indistinguishable within analytical error.



Figure 3. Mg# vs. Cr# for spinels from websterite Samples 153-920D-13R-2, 65–68 cm, and 15R-3, 18–21 cm. Shown for comparison are data for spinels in websterites from Site 670 and in clinopyroxenites (cpxenite) from Tereveka. Also shown are fields for harzburgite spinels from Site 920, Site 670, Site 395, Mid-Atlantic Ridge (MAR) 43°N, and the Tereveka transform. Data sources and abbreviations as in Figure 2.

The serpentine and mineral leachates have the highest ⁸⁷Sr/⁸⁶Sr ratios measured for the sample set.

The ¹⁴³Nd/¹⁴⁴Nd ratios of the peridotites overlap the high end of the MORB field, but are higher than the values measured for the gabbros from Sites 920 to 924. The Nd-isotope compositions of the secondary amphibole and the serpentine overlap those of the Leg 153 gabbros. Few leachates had sufficient Nd to analyze, but those that did indicate the leachable component has a relatively low ¹⁴³Nd/¹⁴⁴Nd value (Table 3).

Pb-isotope results are shown in Figure 5. Similar to the Sr-isotope results, the amphiboles and peridotite pyroxenes have more radiogenic Pb-isotope values than the Leg 153 gabbros. Indeed, the peridotites have significantly higher 206Pb/204Pb, 207Pb/204Pb, and 208Pb/204Pb. The data are shown relative to the fields for North Atlantic MORB and Atlantic sediments, as well as the field for recent MARK basalts. The peridotites and secondary amphibole lie in the middle of the range of ²⁰⁶Pb/²⁰⁴Pb shown by MORB and on the low end of the range of Atlantic sediments. In ²⁰⁸Pb/²⁰⁴Pb, they lie above and parallel to the field of Mid-Atlantic Ridge basalts, and overlap the field of Atlantic sediments at higher 206Pb/204Pb, but have significantly higher 207Pb/204Pb than all MORB. The brown amphibole also has slightly higher 207Pb/ 204Pb than MORB, although it lies within the field of MORB in 208Pb/ 204Pb vs. 206Pb/204Pb. Surprisingly, the serpentine separated from Sample 15R-3, 18-21 cm, has a Pb-isotope composition more similar to the vein amphiboles than to the peridotites.

The leachates from the peridotite pyroxenes show a wide range of compositions. Most unusual are the relatively unradiogenic ²⁰⁶Pb/²⁰⁴Pb values of the leachates from the harzburgite pyroxenes in Section 22R-7; these leachates have significantly higher ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb than MORB for a given ²⁰⁶Pb/²⁰⁴Pb. We would emphasize, however, that some of these data have a relatively high error associated with them because of the small amount of Pb being analyzed (e.g., the orthopyroxene from Section 22R-7). In addition, we have yet to determine the concentrations of Sr, Nd, and Pb in the various mineral separates. Therefore, we are unable to make blank corrections at this time. These analyses are currently in progress. Similarly, we are attempting to duplicate the analyses for the harzburgite pyroxenes in Sample 22R-7, 45–49 cm. Unfortunately, we are unable to duplicate the analyses for the websterite nodules because all available material was consumed in completing the initial analyses.

DISCUSSION

Alteration—A Role For Sediment?

Peridotites from Site 920 have Sr- and Pb-isotope compositions significantly more radiogenic than normal unaltered MORB. These

Table 3. Sr, Nd, and Pb isotopes of websterite and harzburgite pyroxenes, vein amphibole, serpentine, and leachates.

Sample name	Sample type	⁸⁷ Sr/ ⁸⁶ Sr	s.e.	143Nd/144Nd	s.e.	²⁰⁶ Pb/ ²⁰⁴ Pb	s.e.	²⁰⁷ Pb/ ²⁰⁴ Pb	s.e.	²⁰⁸ Pb/ ²⁰⁴ Pb	s.e.
153-920D-											
12R-1, 128-134	Hornblende	0.703046	12	0.513230	3	18.275	11	15.586	10	37.877	25
12R-1, 128-134	Tremolite	0.705437	13	0.513204	5	18.374	10	15.620	9	38.057	21
12R-1, 128-134	Hornblende leachate			0.513203	4	18.066	8	15.594	7	37.832	17
13R-2, 65-68	Pyroxene w/ inclusions	0.705526	64	0.513303	10	18.400	42	15.713	36	38.155	87
13R-2, 65-68	Pyroxene w/o inclusions	0.704266	58	0.513268	28	18.444	25	15.696	21	38.305	50
13R-2, 65-68	Pyx w/ inclusions leachate	0.708942	17			18.571	3	15.645	3	38.246	7
13R-2, 65-68	Pyroxene leachate			0.511613	162	18.381	3	15.630	3	38.103	7
15R-3, 18-21	Pyroxene	0.704412	32	0.513285	7	18.553	21	15.690	17	38.265	41
15R-3, 18-21	Pyroxene leachate					18.569	4	15.644	3	38.223	7
15R-3, 18-21	Serpentine	0.706826	51	0.513231	7	18.385	74	15.560	61	38.007	149
22R-7, 45-49	Orthopyroxene	0.704854	14	0.513149	32	18.734	108	15.911	94	38.792	217
22R-7, 45-49	Orthopyroxene	0.704847	29								
22R-7, 45-49	Clinopyroxene	0.702886	7	0.513243	8	18.504	19	15.649	15	38.425	39
22R-7, 45-49	Orthopyroxene leachate	0.708492	11			17.896	3	15.600	3	37.741	7
22R-7, 45-49	Clinopyroxene leachate	Constant of the Party of the Pa		0.512967	160	17.839	7	15.610	6	37.723	15

Note: All samples were leached in 6-M HCI except tremolite from Sample 153-920D-12R-1, 128-134 cm, and serpentine from Sample 15R-3, 18-21 cm. Errors quoted are 1σ standard error (s.e.). Pyx = pyroxene.



Figure 4. Plot of ⁸⁷Sr/⁸⁶Sr vs. ¹⁴³Nd/¹⁴⁴Nd for Leg 153 peridotites. Shown for comparison are fields for massif gabbros from Sites 920 to 924 and gabbroic dikes from Site 920 (Kempton and Hunter, this volume), diabase dikes from Sites 920 and 921 (Kempton and Casey, this volume), amphibolitized microgabbro from Site 920, recent MARK basalt glasses from the neovolcanic zone (Kempton and Hunter, this volume), and North Atlantic N-MORB (indicated as NA-MORB on figure). Data for NA-MORB field from Cohen et al. (1980), Cohen and O'Nions (1982), Dosso et al. (1991, 1993), Frey et al. (1993), Ito et al. (1987), and White and Hofmann (1982). Data from Machado et al. (1982) are shown separately; these data have been normalized using Machado's published value for BCR (0.512679 \pm 20) to make them consistent with NIGL measured value for this rock standard (0.512602). Data for MARNOK sediment from P.D. Kempton (unpubl. data). The 1 σ error bar for ¹⁴³Nd/¹⁴⁴Nd shown in the lower left corner is based on replicate analyses of J&M Nd standard solution; 1 σ error for ⁸⁷Sr/⁸⁶Sr is within the size of the symbols for most samples. Where the 1 σ error exceeds these ranges, the errors are as shown for the individual samples. Br. = brown, Sec. = secondary, cpx = clinopyroxene, opx = orthopyroxene, incl = inclusion.

values are a clear indication that the Sr and Pb isotopes have been disturbed by hydrothermal alteration and serpentinization. Until recently, the isotopic composition of the fluids involved in these processes has been assumed to be that of average seawater or some mixture between seawater and oceanic basalts. However, Snow et al. (1994a) have shown that there can be a significant component of 87Sr derived from continental crust in oceanic sediments, and the same is almost certainly true for Pb. Although the Sr-isotope composition of seawater (0.7092) is well known by direct measurement of seawater samples, the Pb-isotope composition is usually inferred from the compositions of sediments and Mn nodules because of its low concentration in seawater. Based on the results of leaching experiments on Leg 153 gabbros, Kempton and Hunter (this volume) have suggested that the compositions of average seawater and local sediments for the MARK area are not the same, at least with respect to Pb isotopes. These authors suggest that, for most gabbro samples from Leg 153, the hydrothermal fluids responsible for alteration involved only seawater, but in a few cases local sediments were also involved-the principal consequence being elevated 206Pb/204Pb and 208Pb/204Pb. Thus, although hydrothermal fluids in the ocean crust may be dominated by seawater, the Pb-isotope composition of that fluid may locally be more or less radiogenic than average seawater if pelagic sediments are involved.

For Leg 153 peridotites, 208Pb/204Pb vs. 206Pb/204Pb systematics for peridotites show a clear linear trend from the MORB field toward pelagic sediment. Although we have not analyzed a sample of the sediment from the MARK area specifically, we have analyzed pelagic ooze and a manganese encrustation on basalt from the MARNOK area immediately north of the Kane Fracture Zone. The MARNOK sediment data are clearly consistent with the hypothesis that sediments are involved in the alteration. 207Pb/204Pb vs. 206Pb/204Pb systematics are less convincing because most of the peridotites have higher ²⁰⁷Pb/²⁰⁴Pb than the analyzed sediments. However, given the large error on the measured 207Pb/204Pb ratios, we would argue that the sediment hypothesis cannot be ruled out on the basis of the 207Pb/ ²⁰⁴Pb data. Indeed, the fact that serpentine separated from Sample 15R-3, 18-21 cm, has near-seawater values for Sr isotopes, but lower ²⁰⁸Pb/²⁰⁴Pb than the leached pyroxenes, suggests that (1) seawater, on average, has lower ²⁰⁸Pb/²⁰⁴Pb than the local sediment, and (2) alteration of the peridotites involved a range of fluid compositions in which the proportion of seawater to sediment Pb varied.

The trend toward low ²⁰⁶Pb/²⁰⁴Pb for the leachates from harzburgite Sample 22R-7, 45–49 cm, is enigmatic and we have no explanation for it at this time, particularly because the leachates from the nodular websterites lie within the main trend of data. Similar unradiogenic values were found in leachates from most Leg 153 gabbros



Figure 5. Plot of ${}^{206}Pb/{}^{204}Pb$ vs. (A) ${}^{207}Pb/{}^{204}Pb$ and (B) ${}^{208}Pb/{}^{204}Pb$. Data for North Atlantic N-MORB (NA-MORB) field are from Dupré and Allègre (1980), Dupré et al. (1981), Hamelin et al. (1984), Sun (1980), and sources listed in Figure 4. Data for Atlantic sediment field from Ben Othman et al. (1989), Sun (1980), and White et al. (1985). Abbreviations as in Figure 4.

(Kempton and Hunter, this volume). Kempton et al. (1993) also found unradiogenic compositions for leachates from basalt glass dredged from MARNOK, and suggested that this component may be caused by contamination with anthropogenic Pb. We are currently investigating this possibility along with analytical alternatives.

Origin of Nodular Websterites at Site 920

One of the original objectives of this study was to determine the relationship between the nodular websterites and the predominantly harzburgitic core at Site 920. Clearly the high modal proportion of pyroxenes observed in the websterite nodules is in marked contrast to the average state of depletion of the rest of the core. Major-element mineral data indicate that the primary silicate phases in the nodular websterites are similar to average Site 920 peridotite in major components (i.e., Ca, Mg, and Fe), but differ in the concentrations of some minor elements. In particular, concentrations of Cr_2O_3 at a given Al_2O_3 are higher in websterite pyroxenes than they are in average Site 920 peridotite (Fig. 2). Concentrations of Fe and Ti are also higher than the average in pyroxenes from Sample 15R-3, 18–21 cm (Table 2).

One obvious possibility is that these inclusions are remnants of veins. Dick et al. (1984) interpreted abyssal websterites from the Kane and Islas Orcadas Fracture Zones as evidence for "in situ" crystallization of partial melt trapped in peridotite matrix. The Leg 153 core provides ample evidence for melt infiltration processes in mantle peridotite, ranging from mm-size veinlets of Mg-rich clinopyroxene (± spinel ± plagioclase) to cm- and m-size dikes of gabbro and diabase, respectively. Of these, the Mg-rich clinopyroxene veinlets are the most similar to the websterites. However, the precise nature of the relationship between these and the websterites is uncertain. Clearly, they differ in mineralogy in that the nodular websterites contain high modal proportions of orthopyroxene as well as clinopyroxene, whereas the veinlets are composed predominantly of clinopyroxene ± spinel or plagioclase. The presence of orthopyroxene and absence of plagioclase in the websterites suggests a slightly higher pressure origin for the websterites.

One of the more intriguing observations made from the Site 920 core is that cyclic variations in modal mineral proportions occur on a scale of centimeters to tens of meters, and clinopyroxenite and/or gabbroic veins are frequently associated with the most depleted portions of these cyclic variations. This has been interpreted as evidence for interaction between basaltic melts and peridotite wallrock in the Site 920 core (Shipboard Scientific Party, 1995). Therefore, it might be argued that if the websterites are remnants of veins, there should be a depletion zone adjacent to them. In Section 15R-3, the modal proportion of pyroxene is lower in the harzburgite, relative to the rest of the section, within 20 cm of the websterite. However, the presence of a clinopyroxenite veinlet adjacent to the websterite makes it difficult to establish whether or not the depletion in this interval is related to either of the veins. Furthermore, in a detailed study of websterite veins in alpine peridotites, Rivalenti et al. (1995) identified two types of peridotite to websterite transition. In one type, depletion of the peridotite increases and clinopyroxene fertility decreases towards the contact; Al is lower and Cr higher in the websterite clinopyroxene with respect to the adjacent peridotite. In the second type of transition, as the contact is approached, there is an increase in modal clinopyroxene. The wallrock depletion in the first transition type is interpreted to be caused by melt extraction induced by intrusion of melts derived from deeper mantle. The second transition type is interpreted in terms of melt infiltration and re-equilibration of the melt with the peridotite matrix. Therefore, depletion adjacent to the websterite is not a prerequisite for a vein origin.

Compositional similarities between the nodular websterites and the clinopyroxenite veinlets, nevertheless, support a vein origin for the websterites. Cannat, Chatin, et al. (this volume) found that the compositions of pyroxenes in the veinlets largely overlap those of residual clinopyroxene in the harzburgites, except that clinopyroxene in thicker veins has slightly higher Fe and Na contents. Niida (this volume) also notes elevated Fe in veinlet clinopyroxene as well as elevated Ti and depletions in Mg. These compositional characteristics are similar to those of the Site 920 websterites (Table 2). Cannat et al. (1994) also suggested that the thin clinopyroxene veinlets are evidence for trails of melt infiltration that occurred in the peridotite at high temperatures, possibly close to the solidus, which in turn implies that this event took place in the asthenospheric mantle. If so, given the structural and textural similarities between the websterite and harzburgite minerals, the websterites must also be asthenospheric in origin, possibly as a result of decompression melting in an upwelling diapir.

Compositional characteristics of residual peridotites associated with increasing partial fusion (in the pressure range of spinel peridotite facies) include the following: an increase of Mg#, a decrease of wt% alumina in orthopyroxene, and a decrease of Al along with an increase of Cr in spinel (Michael and Bonatti, 1985). Conversely, if the websterites and clinopyroxenites represent the complementary partial melt to the depleted peridotite in which they are enclosed, they should be more Fe, Ti, Na, and Al rich than the residua.

However, Niida (this volume) notes depletions in Al and Cr in vein clinopyroxene relative to residual clinopyroxene. Although this relationship is analogous to that of the Site 670 websterite and associated harzburgites, it contrasts with the Site 920 websterites which have higher Cr and relatively high Al contents (Fig. 2). Similarly, the Tereveka clinopyroxenites have both higher and lower Cr and Al than the Tereveka harzburgites. Rivalenti et al. (1995) observed higher Cr and lower Al in websterite pyroxenes in alpine peridotites relative to the peridotite away from the veins, but Kempton (1984, 1987) found the reverse situation for Type I/Type I composite xenoliths. In addition, olivines in the websterites and clinopyroxenites have high Ni contents indistinguishable from the surrounding harzburgites (Table 2; Fuji, 1990; Juteau et al., 1990; Constantin et al., 1995). It therefore seems unlikely that these assemblages represent the direct crystallization product of trapped liquid extracted from surrounding peridotite during partial melting.

Many workers now interpret websterites and clinopyroxenite layers and clusters to be crystal cumulates derived by the interaction of partial melt with host peridotite rather than representing the actual partial melt itself (Sinigoi et al., 1983; Frey, 1984; Spray, 1989; Shervais and Mukasa, 1991; Rivalenti et al., 1995). Some of the compositional complexities observed may thus be a function of varying proportions of cumulus and/or residual minerals relative to trapped melt. Furthermore, based on studies of alpine peridotite massifs, Scribano (1987) suggests that Cr diopside websterites form at the start of the fractionation path of such melts and that more Al-Ti-Fe augite websterites occur at an evolved stage. This agrees with the observation that the websterites, both from Site 670 and Site 920, are plastically deformed, similar to the surrounding harzburgite. However, the high Nd-isotope ratios of the websterite pyroxenes indicate high time-integrated Sm/Nd ratios (i.e., greater depletion of light relative to heavy rare-earth elements), suggesting that they may be more depleted in trace-element terms than the surrounding peridotite. This is inconsistent with the pyroxene-rich modes of the websterites and suggests that the concentration of pyroxene in the veins is a fairly recent process. Trace-element analyses in progress should help resolve this problem and give us a better understanding of the mechanisms of melt migration represented by the websterites.

Relationship Between Leg 153 Peridotites and Magmatic Rocks

As previously discussed, Sr- and Pb-isotope systematics of Leg 153 peridotites have been strongly affected by secondary processes. Even after strong acid leaching, it is not possible to obtain Sr- or Pbisotope values that unambiguously reflect the primary composition. Instead, all values must be considered maximum estimates of the primary composition. For example, the websterite sample containing inclusions has a higher ⁸⁷Sr/⁸⁶Sr ratio (Fig. 4) than does the cleaner split of the same sample, a result consistent with greater alteration.

In contrast to the Sr- and Pb-isotope compositions, the rare-earth elements (REE) are significantly less mobile during seawater alteration and/or serpentinization (Humphris and Thompson, 1978). Peridotite analyses by many authors have shown no correlation between increasing degree of serpentinization and REE pattern shape or REE concentrations (Bodinier et al., 1990; Frey et al., 1985; Gruau et al., 1991). However, we observe a significant difference in the Nd-isotope composition between pyroxenes and serpentine separated from the same sample (Fig. 4). Therefore, we have analyzed only clean, hand-picked pyroxenes separated from the peridotites rather than whole-rock samples to identify the primary compositions if possible. We are confident that extrapolation of the pyroxene data to the whole-rock system is justified for the following reasons. For the websterite samples, both clinopyroxene and orthopyroxene are included in the analyzed sample. Thus, less than 15% of the original mineral assemblage (i.e., the olivine and spinel) is excluded, and the concentration of Nd in these phases is extremely low. Even for the harzburgites, it is a simple calculation to show that if we assume standard distribution coefficients for REE in mantle minerals (e.g., Keleman et al., 1992), the coexisting olivine, orthopyroxene and spinel contain <10% of all the REE, and less than 5% of the Sm and Nd. Thus, clinopyroxene is by far the main reservoir for the REE in abyssal peridotites. For this reason, its 143Nd/144Nd is almost certainly representative of the original whole-rock composition, and given the degree of serpentinization of the orthopyroxene and olivine in most samples, it is clearly the best estimate available.

The pyroxene data from the websterites and the clinopyroxene from harzburgite Sample 22R-7, 45-49 cm, are consistent with this assumption. The relatively high Nd-isotope values of these samples are unlikely to be the product of alteration or serpentinization because seawater and local sediments have significantly lower ¹⁴³Nd/¹⁴⁴Nd values. Serpentinization would therefore only serve to lower the Ndisotope ratios of the peridotites. This is consistent with the lower 143Nd/144Nd value of the serpentine separated from Sample 15R-3, 18-21 cm. One clear exception is the orthopyroxene from harzburgite Sample 22R-7, 45-49 cm. This sample has a low 143Nd/144Nd value, consistent with partial exchange with seawater and/or sediment. This low value contrasts with the composition of the coexisting clinopyroxene, but it is not really surprising in that the Nd concentration in orthopyroxene is significantly lower than that in clinopyroxene and thus more easily affected by alteration. Pb isotopes suggest that alteration of the orthopyroxene involves pelagic sediment as well as seawater because the Pb-isotope ratios of the serpentine are lower than those of the peridotites, whereas the sediments have higher Pbisotope ratios.

Based on these data, it is interesting that the peridotite pyroxenes have higher ¹⁴³Nd/¹⁴⁴Nd than the Leg 153 gabbros (Fig. 4; Kempton and Hunter, this volume). Thus, if the nodular inclusions represent veins, as suggested in the previous section, they clearly did not originate from the same source as that giving rise to either the gabbro veins at Site 920 or the gabbro massif at Sites 921–924. They are even less like the recent basalts from the neovolcanic zone. This indicates that the peridotite pyroxenes analyzed are not representative (at least isotopically) of the source for the magmas which produced the MARK gabbros (Kempton and Hunter, this volume).

Although the Leg 153 peridotites overlap the high Nd-isotope end of the MORB array (Fig. 4), this end of the field is defined by basaltic samples dredged from the Kane Fracture Zone (Machado et al., 1982). Note that these values are higher than any other data reported for the Kane Fracture Zone area. We have analyzed samples of plagiogranite and diabase (P.D. Kempton, unpubl. data) dredged from localities near to those sampled and analyzed by Machado et al. (1982), and these samples yield Nd-isotope values identical to those of Leg 153 gabbros. We therefore suspect that there is an interlaboratory bias and that the Machado et al. (1982) data may need revision to be internally consistent with our own data.

If the Machado data are systematically too high, as suggested by our data for Kane Fracture Zone samples, the Nd values measured for the Leg 153 peridotites are higher than most previously published analyses of North Atlantic MORB. Only two unusual basalts from 17°N (Dosso et al., 1993) have higher ¹⁴³Nd/¹⁴⁴Nd ratios (0.51335–0.51336). The Site 920 peridotites also have higher Nd-isotope ratios than any analyzed abyssal peridotites known to the authors.

How do we explain the apparent incongruity that the Site 920 peridotites have more depleted Nd-isotope ratios than the magmatic rocks from the same area? One possibility proposed by Snow et al. (1994b) is that enriched veins in the mantle source have a lower melting point and are sampled by the first fractions of melting. This results in relatively enriched melts in the early fractions, followed by more depleted melts. Residues of melting that have lost their vein components would then have more depleted isotopic compositions than basalts derived from both early and later melting. However, the highest Nd-isotope values at Site 920 are found in assemblages interpreted as veins rather than the residues from partial melting, and both websterites have higher Nd-isotope values than pyroxenes from the harzburgite in Section 22R-7. Admittedly, it is unclear whether the nodular websterites are distinct from the analyzed harzburgite, because (1) the compositional range of the Site 920 peridotites has not been established on the basis of the one harzburgite sample analyzed here, and (2) one of the nodular inclusions overlaps the clinopyroxene from Sample 22R-7, 45-49 cm, within analytical error. Nevertheless, Spray (1989) argues that veins devoid of hydrous phases are unlikely to be parental to MORBs. If this is correct, the websterite veins may not be representative of types of veins that would contribute to the early melting events proposed by Snow (1994b). More data will need to be collected on Site 920 peridotites to establish the range of compositions before further interpretations are possible.

CONCLUSIONS

- The pyroxenes from the two websterites and clinopyroxene from one harzburgite sample analyzed from Leg 153 peridotites are isotopically distinct from all magmatic rocks in the MARK area (i.e., gabbros, diabase dikes, and recent basalts). They are, therefore, not representative of the mantle source of these magmatic rocks, at least with respect to its isotopic composition. The Nd-isotope ratios of the peridotites are higher (i.e., more depleted) than most N-MORB from the North Atlantic and higher than any measured abyssal peridotite known to the authors.
- High alumina, iron, and titanium contents in the websterite pyroxenes suggest a vein origin, possibly as a result of decompression melting in an upwelling diapir. These veins preceded the more numerous clinopyroxenite veinlets observed throughout the Site 920 core and probably formed in the asthenosphere.
- Sr and Pb isotopes provide evidence for seawater interaction and ²⁰⁸Pb/²⁰⁴Pb ratios suggest a component of pelagic sediment. Even after extensive leaching, it is not possible to obtain Sr- or Pb-isotope ratios that unambiguously reflect the primary composition.

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PETROLOGY AND GEOCHEMISTRY OF WEBSTERITE INCLUSIONS

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