**Geochemistry of serpentinized and multiphase altered Atlantis Massif peridotites (IODP Expedition 357): Petrogenesis and discrimination of melt-rock vs. fluid-rock processes**

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# Abstract

International Ocean Discovery Program (IODP) Expedition 357 drilled 17 shallow sites distributed ~ 10 km in the spreading direction (from west to east) across the Atlantis Massif oceanic core complex (Mid-Atlantic Ridge, 30 ºN). Mantle exposed in the footwall of the Atlantis Massif oceanic core complex is predominantly nearly wholly serpentinized harzburgite with subordinate dunite. Peridotites are subdivided into three types: (I) serpentinized peridotites, (II) melt-impregnated peridotites, and (III) metasomatic peridotites. Type I peridotites show no evidence of melt-impregnation or metasomatism apart from serpentinization and local oxidation. Type II peridotites have been intruded by gabbroic melts and are distinguishable in some cases on the basis of macroscopic and microscopic observations, e.g., mm-cm scale mafic-melt veinlets, rare plagioclase (˂0.5 modal % in one sample) or by the local presence of secondary (replacive) olivine after orthopyroxene; in other cases ‘cryptic’ melt-impregnation in peridotite is inferred on the basis of incompatible element enrichments. Type III peridotites are characterized by silica metasomatism manifested by alteration of orthopyroxene to talc and amphibole, and by anomalously high anhydrous SiO2 concentrations (59-61 wt.%) and low MgO/SiO2 ratios (0.48-0.52). While many chondrite-normalized rare earth element (REE) and primitive mantle-normalized incompatible trace element anomalies, e.g., negative Ce-anomalies, are attributable to serpentinization, other compositional heterogeneities are due to melt-impregnation. On the basis of whole rock incompatible trace elements, a dominant mechanism of melt-impregnation is distinguished in the central and eastern peridotites from fluid-rock alteration (mostly serpentinization) in the western peridotites, with increasing melt-impregnation manifest as a west to east increase in enrichment in high-field strength elements and light REE. High degrees of melt extraction are evident in low whole-rock Al2O3/SiO2 ratios and low concentrations of Al2O3, CaO and incompatible elements. Estimates of the degree of melt extraction based on whole rock REE patterns suggest a maximum of ~ 20 % non-modal fractional melting, with little variation between sites. As some peridotite samples are *ex situ* rubble, the magmatic histories observed at each site are consistent with a local source (from the fault zone) rather than rafted rubble that would be expected to show more heterogeneity and no spatial pattern. In this case, the studied sites may provide a time-record of enhanced melt-rock interactions with time, consistent with proposed geological models. Alternatively, sites may signify heterogeneities in these processes at spatial scales of a few km.

# *Keywords*: IODP Expedition 357; Atlantis Massif; mantle peridotite; fluid-rock interaction; melt- rock interaction

# 1. Introduction

Spreading rate exerts a profound influence on the geometry and architecture of the oceanic crust. Slow-spreading ridges (≤ 5 cm/year), as exemplified by the Mid-Atlantic ridge (MAR), are characterized by wide (up to 30 km) and deep (1–2 km) axial valleys bounded by uplifted shoulders and transient magma reserves. In contrast, fast-spreading ridges (≥ 9 cm/year), as characterized by the East Pacific Rise, exhibit much narrower to absent axial troughs (a few hundred meters wide) and a more continuous magma supply (e.g., Macdonald, 1982; Karson, 2002; Stewart et al., 2005). Analogous with ‘metamorphic core complexes’ found in extended continental regions (e.g., John, 1987), ‘oceanic core complexes’ (OCCs), such as the Atlantis Massif (30 °N, Fig. 1a) along the MAR, represent segments of a slow spreading ridge comprised of elevated seafloor massifs that display flat or gently curved upper surfaces with prominent corrugations or ‘megamullions’ (Escartin et al., 2017; Tucholke et al., 1998). OCCs comprise segments of lower crustal and upper mantle rocks exposed at the seafloor (Cann et al., 1997; Blackman et al., 1998; Tucholke et al., 1998) and represent uplifted footwalls of large-offset low-angle normal faults, commonly referred to as detachment faults. Mantle rocks of OCCs characteristically comprise olivine-rich peridotite (i.e., harzburgite, dunite) that interacted with seawater to produce serpentinite over a range of temperatures (Andreani et al., 2007; Blackman et al., 1998; Boschi et al., 2006a; Boschi et al., 2006b; Cann et al., 1997; Cannat, 1993; Früh-Green et al., 2004; Karson et al., 2006; Kelemen et al., 2007; Rouméjon et al., 2015; Rouméjon et al., 2018a; Schroeder et al, 2002).

Four OCCs have been drilled by the Ocean Drilling Program (ODP), the Integrated Ocean Drilling Program (IODP) and the International Ocean Discovery Program (IODP). The Atlantis Massif is one of the best studied and well-known OCC as it hosts the off-axis, peridotite-hosted Lost City hydrothermal field (Kelley et al., 2001) on its southern wall (Fig. 1b). Other drilled OCCs include the Atlantis Bank, SW Indian Ridge (ODP Hole 735B, Dick et al., 2000), the MARK (Mid-Atlantic Ridge Kane fracture zone) at 23°32′ N (ODP Leg 153, Sites 921–924, Cannat et al., 1995), and an OCC on the MAR at 15°44′ N (ODP Leg 209, Site 1275, Kelemen et al., 2004). The Atlantis Massif (30 °N, Fig. 1a) was drilled during IODP Expeditions 304/305 (Blackman et al., 2006), at Site U1309 and Expedition 357 (Früh-Green et al., 2017, 2018; Roumejon et al., 2018a, 2018b; Akizawa et al., 2020).

# Research on detachment faulting at OCCs implies that oceanic spreading is closely linked to the development of hydrothermal circulation patterns and encompasses a wide variety of fluid flow and hydrothermal regimes (McCaig et al., 2007; Escartin et al., 2008). High-temperature fluid circulation both within the footwall and along the fault zone is well documented on the basis of mineralogy and geochemistry (Schroeder and John, 2004; Boschi et al., 2006a; McCaig et al., 2010, Picazo et al., 2012, Verlaguet et al., 2021). Importantly, uplift along detachment faults appears to promote circulation and alteration within the footwall. Several studies propose a temporal evolution in the style of hydrothermal circulation associated with OCC formation. High-temperature systems are hosted in the basaltic hanging wall within the rift valley, whereas high-temperature ultramafic-hosted systems occur within the OCC footwall. Ultimately, hydrothermal circulation transitions to off-axis ultramafic-hosted systems within the footwall (Andreani et al., 2007; McCaig et al., 2007; Fouquet et al., 2010). In ultramafic and mafic systems, metasomatic assemblages of talc-tremolite-chlorite or quartz form at > 350 °C (Boschi et al., 2006a, 2008; McCaig et al., 2010; Verlaguet et al., 2021), typical of black smoker discharge zones, whereas serpentine-prehnite-hydrogarnet assemblages form at lower temperatures (Frost et al., 2008; Bach and Klein, 2009).

Cores recovered during IODP Expedition 357 have highly heterogeneous rock types, and are variably altered and deformed. Ultramafic rocks are dominated by harzburgite with intervals of dunite and minor pyroxenite veins; gabbroic layers occur as melt impregnations and veins. Dolerite dikes and basalts are the latest phase of magmatism. Overall, the peridotites show a high degree of serpentinization (> 80 %) and are locally oxidized. In cores with gabbroic intrusions, metasomatic overprinting, which forms talc-amphibole-chlorite assemblages, is common and post-dates an early phase of serpentinization.

The petrogenesis of mantle peridotites recovered during IODP Expedition 357 is the subject of this communication. In this paper we use whole rock trace and rare earth element (REE) chemistry of Expedition 357 peridotites to discriminate dominant melt-impregnation vs. fluid-dominated processes (i.e., serpentinization, Si metasomatism) and constrain the degrees of partial melting recorded in the peridotites. Peridotites are subdivided into Type I serpentinized peridotites, Type II melt-impregnated peridotites and Type III metasomatic peridotites. Type I peridotites show no evidence of melt-impregnation or metasomatism apart from serpentinization and local oxidation. Type II peridotites are distinguishable in some cases on the basis of macroscopic or microscopic evidence and in other cases, are inferred on the basis of incompatible element enrichment in the case of ‘cryptically’ melt-impregnated peridotites. Type III peridotites are characterized by silica metasomatism and the formation of talc-rich alteration assemblages and anomalously high anhydrous SiO2 concentrations and low MgO/SiO2 ratios. In so doing, we geochemically characterize the evolution of mantle lithosphere at a slow-spreading ridge associated with OCC formation, and document spatial compositional variations.

# 2. Geological setting

# The dome-shaped Atlantis Massif OCC is located at 30 °N on the western edge of the MAR axial valley where it intersects the Atlantis Fracture Zone (Fig. 1b). The OCC stretches 15-20 km N–S parallel to the ridge and is 8-12 km wide. Exhumation occurred via low-angle detachment faulting (Cann et al., 1997; Blackman et al., 2002; Schroeder and John, 2004; Karson et al., 2006; Ildefonse et al., 2007). On the basis of its distance from the spreading axis and a calculated spreading half-rate of 12 mm/yr (Zervas et al., 1995), the lithosphere of the massif is considered to be 2.0 to 0.5 Ma (Blackman et al., 2006), a span which encompasses eighteen SHRIMP U/Pb zircon ages of oxide gabbro and felsic dike melt intrusions recovered from Hole U1309D, which range from 1.28 ± 0.05 to 1.08 ± 0.07 Ma (Grimes et al., 2008). Dredging and submersible dives at the massif revealed the dominance of serpentinized peridotite (Blackman et al., 2002; Boschi et al., 2006a; Karson et al., 2006) concentrated primarily along the southern and most elevated portion of the detachment. Samples recovered during IODP Expeditions 304/305, with a drill hole reaching ~ 1500 m depth, consisted almost entirely of olivine-rich mafic intrusive rocks of gabbro and troctolite (Drouin et al., 2009; Ferrando et al., 2018; Godard et al., 2009; Suhr et al., 2008). These geological observations suggest a compositional change of the footwall, with peridotites decreasing in abundance from the segment end towards the north, and also reflecting in time the emplacement of magma in the footwall (Ildefonse et al., 2007).

# IODP Expedition 357 cored seventeen shallow holes at nine sites (Fig. 1b) along the detachment fault surface of the Atlantis Massif (Früh-Green et al., 2016). The two eastern sites (M0075, M0068) and one western site (M0071) recovered fault scarp deposits whereas the central sites yielded *in situ* sequences. Most of the sites are aligned along the southern edge of the detachment fault by the Atlantis Fracture Zone wall, with the northernmost hole (M0074) located ~ 6 km north of the detachment’s southern edge, and ~ 1 km to the southwest of U1309D. In terms of igneous lithologies and their metamorphosed equivalents, IODP Expedition 357 recovered primarily serpentinized peridotite comprising harzburgite with subordinate dunite (Fig. 1c) and wehrlite with lesser amounts of variably altered mafic inclusions of basalt, gabbro and dolerite (Früh-Green et al., 2018; Rouméjon et al., 2018a; Akizawa et al., 2020). Core lengths range from approximately 1.3 to 16.5 m. Recovery was ~ 75 %.

# 3. Samples and petrography

#  Except for one talc schist, the protolith of which was mafic, all rocks chosen for study are peridotites, and from holes immediately adjacent to the transform fault scarp and drilled at the southern edge of the detachment fault surface (Figs. 1b, c). All peridotites were subjected to high degrees of serpentinization of the order of > 80 %. On the basis of collective macroscopic, microscopic and whole rock chemistry evidence, the studied samples are divided into three types: Type I are serpentinized peridotites, Type II peridotites are melt-impregnated peridotites, and Type III are metasomatic peridotites. Type I peridotites are ones primarily subjected to serpentinization, and Types II and III peridotites have been subjected to mm- to cm-scale mafic melt intrusions and subsequent silica metasomatism, respectively. In the case of melt-impregnation, this is evident in Type II peridotites by the presence of small veinlets of dolerite (as reported in Expedition 357 petrology logs), and in one case by the presence of rare plagioclase and in another case, by the presence of recrystallized olivine along the peripheries of dissolving orthopyroxene (see Fig. 2). Further details regarding evidence for classification of Types II and III are provided in Table 1.

All samples were studied by polarization microscopy. Representative thin section images are given in Figure 2. Sample numbers and rock type names are taken directly from Früh-Green et al. (2017, Supplementary material). Below, we describe the petrography of each sample type. The mineralogy and mode of the peridotites are summarized in Table 2.

*3.1. Type I Serpentinized peridotites*

Serpentinized peridotites (Fig. 2a-d) consist of dominant harzburgite (14 of 20 samples) and lesser dunite. Outlines of olivine are generally clear under plane-polarized light (PPL) as serpentinization is most intense around grain boundaries, and decorating fractures cutting olivine (e.g., Fig. 2a). Classic mesh-textures are commonly observed. In the harzburgite, orthopyroxene is always altered to bastite, but nonetheless recognizable under crossed polars by remnant and deformed (curved) cleavage, and parallel extinction. Orthopyroxene is typically ˂ 2 mm and olivine is 2-4 mm. Reddish-orange to brown spinel is easily identifiable under PPL and is typically less than 0.5 mm but in some cases up to 4 mm. Spinel occurs both as isolated, angular grains and as subangular and rounded grains commonly arranged in masses or trails of multiple grains. Clinopyroxene was not observed in any samples and reflects the high degrees of partial melting and melt extraction that many of these peridotites have undergone (see Fig. 3). Modal percentages of the volumetrically dominant serpentinized harzburgite lie in the range of 75-90 % for olivine and 10-25 % for orthopyroxene; spinel ranges from 0-3 % (Table 2). In the serpentinized dunite, orthopyroxene is absent and spinel is less common (0 to <1 %) than in the harzburgite.

Four Type I peridotites exhibit anomalously high CaO contents ranging from 6-13 wt.% (see Table 3). Microscopic inspection reveals that the Ca-rich peridotites exhibit an extensive and densely concentrated, anastomosing network of ~ 0.1 mm thick carbonate veinlets (Fig. 2d).

*3.2. Type II Melt-impregnated peridotites*

Melt-impregnated peridotites consist of harzburgite only and comprise six of the studied 29 samples (Table 1). Type II peridotites in most cases are observed to have mm to cm-scale mafic veins at the scale of the drill core (Table 2) although these are not obvious in thin section. Orthopyroxene ranges from ~ 1-5 mm. Modal percentages of olivine and orthopyroxene are 70-90 % and 10-30 %, respectively, with spinel typically absent but reaching 2-3 % in one sample (Table 2).

In some Type II peridotites, other petrographic evidence is present to confirm melt-impregnation. For example, one central harzburgite (76B-7R1-81-83) is the only one in which rare 0.5-0.7 mm plagioclase (˂ 0.5 % of the mode) is present (Fig. 2e). Plagioclase is highly altered (epidote, sericite) but preserves relict twinning. In another harzburgite from eastern Site M0068B, fresh, 0.5-1 mm olivine constitutes ~ 5 % of the mode, and is observed mantling orthopyroxene (Fig. 2f), which we interpret as replacive following dissolution of orthopyroxene accompanying melt injection.

*3.3. Type III Metasomatic peridotite*

 Type III peridotites from this study include two harzburgites that are restricted to the eastern sites (Fig. 1c), and are distinguishable on the basis of talc-amphibole alteration of orthopyroxene (Fig. 2e) and whole rock chemistry (see Section 5.1). Orthopyroxene ranges from 1-6 mm and brown spinel ranges from 0.5-2 mm, the latter are always embedded in orthopyroxene. Modal percentages of olivine and orthopyroxene are ~ 70 % and 30 % respectively, with spinel occupying around 2 % (Table 2).

**4. Analytical methods and data compilation**

*4.1. Whole rock geochemistry*

Major and trace element contents of peridotite were determined by inductively coupled plasma mass spectrometry (ICP-MS) and atomic emission spectroscopy (ICP-AES) at ALS Geochemistry, North Vancouver, Canada. Prior to shipping to ALS, samples for whole-rock analysis were trimmed to remove weathered surfaces. Samples sent to ALS were crushed to > 70 % passing through a 2 mm mesh, and a 250-g split was pulverized to > 85 % of the material being < 75 µm in diameter. Powders were then analyzed for whole rock major and trace element determinations. For major element oxides, 100 mg of powered sample was added to lithium metaborate/lithium tetraborate flux, mixed well and fused in a furnace at 1000 °C. The resulting melt was dissolved in 100 mL of 4 % HNO3/2 % HCl. This solution was then analyzed by ICP-AES (ALS Geochemistry method ME-ICP06) and the results were corrected for spectral inter-element interferences. Major element detection limits were 0.01% for all oxides except Cr2O3, which was 0.002 % (Supplementary Table S1). For loss on ignition (LOI), 1 g of sample powder was heated at 1000° C for one hour, cooled and then reweighed, with percent LOI calculated by the difference in weight.

For trace and rare earth elements, the ME-MS61L Super Trace and MS61L-REE methods ([https://www.alsglobal.com/](https://can01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.alsglobal.com%2F&data=04%7C01%7Cm.leybourne%40queensu.ca%7Cb7f131199e0044d3d3fe08d90d399661%7Cd61ecb3b38b142d582c4efb2838b925c%7C1%7C0%7C637555363260752989%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C1000&sdata=2zYXCnAMEP%2FFr%2B8CrHH7DX%2FnjwSFZv%2FnZZwcnZK0scI%3D&reserved=0)) were employed, which combines a four-acid digestion with ICP-MS instrumentation utilizing collision/reaction cell technologies to provide the lowest detection limits available. In the first method, analyzed elements include Ba, Cd, Ce, Co, Cr, Cs, Cu, Ga, Hf, La, Li, Mo, Nb, Ni, Pb, Rb, Sc, Sn, Sr, Ta, Te, Th, U, V, W, Zn and Zr; in the second method, analyzed elements include Dy, Er, Eu, Gd, Ho, Lu, Nd, Pr, Sm, Tb, Tm and Yb. This trace method has been optimized for long-term robust ICP-MS signal stability, in particular for samples with high Ca content. The prepared samples (nominal weight 0.25 g) were digested with 1.5 mL concentrated HNO3 and HClO4, followed by concentrated HF. Subsequently, the mixture was heated at 185 °C until incipient dryness, leached with 50 % HCl and diluted with weak HCl. The final solution was then analyzed by ICP-MS with results corrected for spectral inter-element interferences. Apart from Ba, Cr, Sn, V, W and Zr with detection limits that range from 0.3-5 µg/g, detection limits of the remaining trace elements ranged from 0.001-0.2 µg/g (Supplementary Table S1).

Results of duplicate analyses and analytical standards used are provided in Supplementary Table S2. Reproducibility of these reference samples is generally better than 5 % for concentrations more than 10 x above the detection limit, and typically 5-20 % closer to the detection limit.

*4.2. Data compilation*

The stratigraphic location of samples analyzed for whole rock chemistry in this study are shown in Fig. 1c. The new whole rock geochemical data of 29 whole rock ICP-MS and ICP-AES geochemical analyses from this study (Table 3) are compared with the ten Expedition 357 peridotite samples of Früh-Green et al. (2018) and the four Atlantis Massif peridotite samples of Godard et al. (2009) from Site 1309 in Figs 3-10. We also compare these data with whole rock geochemical data compiled from global abyssal peridotites of Niu (2004), Paulick et al. (2006) and Godard et al. (2008).

# 5. Results

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# *5.1. Whole rock chemistry major elements and Ni and Cr abundances*

# In MgO/SiO2 vs. Al2O3/SiO2 space (Fig. 3) the ‘terrestrial array’ represents the successive magmatic depletion (or melt extraction) trend of primitive mantle. Highly depleted compositions are characterized by low Al2O3/SiO2 of < 0.01 (Jagoutz et al., 1979; Hart and Zindler, 1986). Verification of this melt extraction trend is reflected by a global data set of MOR peridotites (compilation of Niu, 2004; Paulick et al., 2006; Godard et al., 2008). In general, the Atlantis Massif peridotites record Al2O3/SiO2 that range from ~ 0.01-0.04 indicating moderate to high degrees of magmatic depletion, with the exception of two Type I serpentinized dunites from the central sites (M0076B-3R1-78-82, M0076B-5R1-59-61, Table 1), and one dunite (1309D-31R-25-28) from Site U1309 reported by Godard et al. (2009) that exhibit Al2O3/SiO2 ˂ 0.01. Very low Al2O3/SiO2 ratios can alternatively be caused by replacive melt-rock interaction. Vertical deviations from the terrestrial array are indicative of Mg-Si mass transfer; peridotites that exhibit MgO/SiO2 below the terrestrial array may reflect magnesium loss or silica addition during serpentinization or magnesium loss during seafloor weathering (Snow and Dick, 1995; Niu, 2004). A trend defined by increasing Al2O3/SiO2 with most samples offset to moderately low MgO/SiO2, as seen in the Atlantis Massif peridotites (Fig. 3), can also be partially attributed to melt-impregnation processes (Niu, 2004). Half of the eight Type II melt-impregnated peridotites of the eastern and central sites from this study and the study of Früh-Green et al. (2018) exhibit MgO/SiO2 of ˂ 0.9, consistent with this process; nonetheless, all melt-impregnated peridotites plot within the range of the Type I serpentinized peridotites. Two central serpentinitized peridotites yield MgO/SiO2 ratios of ~ 0.76-0.86, within the lower range of the melt-impregnated peridotites, which suggests that these two samples may also have been subjected to processes associated with melt-impregnation. Silica-metasomatism is characterized by low MgO/SiO2 (˂ 0.55) and low Al2O3/SiO2 (˂ 0.025). One exception is the talc schist, which exhibits low MgO/SiO2 (~ 0.4) but high Al2O3/SiO2 of 0.11, which suggests the addition of silicic melt (Paulick et al., 2006).

# In Fig. 4 we plot MgO vs. selected major element oxides and loss on ignition (LOI) to illustrate the effects of serpentinization and multiphase alteration processes on major element chemistry. In terms of MgO and other major element oxides, the Type I serpentinized peridotites generally plot similarly to global MOR peridotites. Apart from two serpentinized harzburgites, which exhibit anomalously high Al2O3 and CaO, the remaining serpentinized peridotites have MgO contents that ranges from 41.25 to 46.06 wt.% and Mg# (Mg/Mg+Fe2+) of 87.6-91.8 (Table 3). In SiO2 vs. MgO space (Fig. 4a) the serpentinized peridotites and melt-impregnated peridotites fall almost completely within the range of global abyssal peridotite and plot similarly to, but with slightly lower SiO2 contents than the bulk composition of serpentine. In contrast, the Type III talc-altered harzburgites and talc schists plot near the bulk composition of talc and ODP Leg 209 talc-altered peridotites, but with slightly lower SiO2 and MgO. The Ca-rich Type I serpentinized peridotites (6.66-13.30 wt.% CaO) plot off the linear array of the serpentinites and melt-impregnated peridotites in SiO2 vs. MgO space with significantly lower SiO2 at similar MgO. Fe2O3, Al2O3 and CaO contents (Figs. 4b-d) of the talc-altered harzburgites and talc schists generally fall within the range of the serpentinized peridotites. Apart from two melt-impregnated harzburgites, which exhibit slightly higher Al2O3 contents than the serpentinites, other major element oxide concentrations of the melt-impregnated peridotites are similar to those of the serpentinized peridotites. CaO contents in the western site peridotites (Fig. 4d) record lower concentrations (0.05-0.30 wt.%) than those of the central and eastern sites. Similar to the SiO2 vs. MgO plot, significant differences exist in LOI values between the Ca-rich serpentinized peridotites, the remaining serpentinized peridotites, melt-impregnated peridotites, and talc-altered peridotites (Fig. 4e). While the bulk of the peridotites exhibit LOI of ~ 12-14 wt.%, similar to those of global MOR peridotites, the talc-altered harzburgites and schists have low LOI ranging from ~ 4-6 wt.%, similar to ODP Leg 209 talc-altered peridotites, and the Ca-rich serpentinized peridotites have high LOI of ~ 16-20 wt.%. The melt-impregnated peridotites have LOI that are up to ~ 9 wt.%, intermediate between those of the talc-altered harzburgites and schists and the serpentinized peridotites.

# The majority of the Expedition 357 peridotites have Ni and Cr concentrations of ~ 1000-3000 µg/g (Table 3), similar to that of primitive mantle (PM), and which fall within the range of global MOR peridotites (Supplementary Fig. S1). Exceptions are two central and two western peridotite samples from Früh-Green et al. (2018), which range to Ni ˃ 10000 µg/g and Cr ˃ 30000 µg/g, two central serpentinized dunites and two eastern melt-impregnated harzburgites, which exhibit low Cr (˂ 400 µg/g), and a single talc schist from the eastern site, which has relatively low Ni of ~ 700 µg/g.

# *5.2. Whole rock trace element concentrations*

# Significant differences in the relative degree of depletion, pattern morphology, and the existence of prominent element anomalies, are apparent in peridotites on the basis of chondrite-normalized REE and PM-normalized incompatible trace element patterns (Fig. 5). Patterns range from those similar to and significantly more depleted than depleted MORB mantle (DMM) and mean abyssal peridotite in western Site M0071, central Sites M0069 and M0076, and Atlantis Massif IODP Site U1309 (Godard et al., 2009) to patterns enriched relative to DMM and mean abyssal peridotite as shown by central Site M0072 and most of eastern Site M0068. The peridotites from eastern Site M0068 are atypical to other Expedition 357 peridotites in that they exhibit LREE enrichments but HREE concentrations intermediate to that of DMM and mean abyssal peridotite. Central Site M0072 and eastern Site M0068 peridotites typically exhibit REE concentrations that are more enriched than DMM and range from ~ 1-10 x chondrite; two M0068 talc schists are atypical in exhibiting high REE concentrations of ~ 20 x chondrite.

# Serpentinized peridotites sampled at western Site M0071, and central Sites M0069 and M0076 exhibit low Yb as well as low abundances of other incompatible elements, for example the high-field strength elements (HFSE) Nb and Zr (Table 3). Apart from one central Site M0072 serpentinized dunite with similarly low Yb, Nb and Zr, the remaining central Site M0072 and eastern site peridotites, many of which are Type II melt-impregnated or Type III metasomatic peridotites, exhibit comparatively higher concentrations of these incompatible elements (Table 1). As we show in Section 6.2.3, the melt-impregnated peridotites, in particular in central Site M0072 and eastern Site M0068, show high concentrations of most incompatible elements relative to other sites.

# While the highly depleted serpentinized peridotites from the western and central sites exhibit mostly concave upwards REE patterns with a steady decrease in REE abundances from the HREE to LREE, central Site M0072 peridotites exhibit flatter patterns; the eastern serpentinites are atypical relative to the peridotites to the west in that they exhibit an LREE enrichment. Excluding the lone, Ca-rich (12.46 wt.% CaO) serpentinized dunite with La/SmCN (CN denotes chondrite-normalized) of 4.70 and La/YbCN of 2.39, the western serpentinites from Site M0071 exhibit mostly moderate but variable LREE/MREE fractionation (La/SmCN of 0.40-3.03) but extreme LREE/HREE fractionation with La/YbCN ranging from 0.11-0.68. In contrast, the two eastern serpentinized peridotites exhibit relatively minor LREE enrichment with La/SmCN and La/YbCN ranging from 1.08-1.17 and 1.13-1.30, respectively; the eastern melt-impregnated peridotites have higher LREE enrichments with La/SmCN = 1.72-2.15 and La/YbCN = 1.43-1.68 and the talc-altered peridotites have LaSmCN = 0.41-1.41 and La/YbCN = 0.48-1.36.

# 6. Discussion

# On the basis of trace and rare earth element chemistry, we address differences in the compositions of the different peridotite types to discriminate dominant fluid-rock interaction processes associated with serpentinization, from processes associated with mafic melt-rock interaction . We then provide estimates of degrees of partial melting (melt extraction) recorded in peridotites sampled across the Atlantis Massif (IODP Exp. 357), before linking the geochemistry to processes associated with oceanic core complex formation.

# *6.1. Evidence of fluid-dominated serpentinization processes*

# Significant observations from the chondrite-normalized REE and PM-normalized patterns are: (1) prominent negative Ce-anomalies (i.e., Ce/Ce\* where Ce\* = √(LaCN\*PrCN) and Ce = CeCN) in the western serpentinized peridotites and two serpentinized central peridotite, and positive Ce-anomalies in almost all eastern peridotites (the vast majority of other central peridotites show Ce/Ce\* ~ 1); (2) extreme U-enrichment in many peridotites with values that range to nearly 300 x PM; and (3) extreme Sr-anomalies with enrichments of up 100 x PM in most Ca-rich serpentinized peridotites and depletion to below 0.1 x PM in the peridotites of Sites M0072 and M0068.

# With respect to the negative Ce-anomalies exhibited mostly by the western serpentinized peridotites (site M0071), such anomalies in peridotites have been attributed to seawater-peridotite interaction (e.g., Frisby et al., 2016a, b) and indeed, (oxygenated) seawater itself exhibits a negative Ce-anomaly (e.g., Elderfield and Greaves, 1982).

# The western site serpentinized peridotites range to the highest U concentrations (5.05 µg/g), whereas the melt-impregnated peridotites of central site M0072 and eastern site M0068 range to the lowest U concentrations (0.01 µg/g) (Fig. 6a, Table 3), which suggests that U enrichment is associated with serpentinization and oxidation, and not melt-impregnation. U enrichment in serpentinites is common as U is hosted by serpentine phases (e.g., Deschamps et al., 2010). Frisby et al. (2016a, b) have shown that U enrichments correlate with Ce anomalies and the amount of Nd derived from seawater, which is a proxy for water/rock ratios. Thus, U enrichments have been shown explicitly to reflect fluid-rock interaction in abyssal peridotites.

# In the case of Sr enrichment (Fig. 6b), evidence is not as clear. However, we note that the melt-impregnated central site M0072 and eastern site M0068 peridotites range to the lowest Sr concentrations, with the former exhibiting the lowest concentrations of Sr (1.02-4.01 µg/g) of all sites, whereas the other sites locally show distinct Sr enrichments. This suggests that Sr is not associated with melt-impregnation.

# *6.2. Evidence for melt-impregnation processes: Enrichment in incompatible elements, LREE, LREE fractionations and ΣREE*

#  As explained above, we infer melt-impregnation in central site M0072 peridotites on the basis of compositional similarities with melt-impregnated peridotites constrained on the basis of macroscopic and microscopic evidence, even though site M0072 peridotites lack observable evidence of melt-impregnation at the scale of core and thin section. Hence, due to the absence of such mineralogical evidence, we term these M0072 peridotites ‘cryptically melt-impregnated’.

#  The HFSE, e.g., Th, Hf, Zr (Figs. 7a-c), Nb and Ti are highest in Type II melt-impregnated peridotites at central Site M0072 and eastern Site M0068 and lowest in western sites Type I serpentinized peridotites. In addition, Figures 7d and e show an increase in LREE and ΣREE, and possibly LREE fractionation from Type I serpentinized peridotites to Types II and III peridotites, and from west to central to east. For example, apart from a lone Ca-rich serpentinized dunite, which exhibits anomalously high La and anomalously low Ce and La/YbCN of 2.39, the remaining western serpentinized peridotites yield La/YbCN of 0.11-0.68 and (including the Ca-rich peridotite) mean ΣREE of 0.8 µg/g. The central peridotites yield a range of La/YbCN of 0.15-1.31 and mean ΣREE of 3.3 µg/g, and the eastern peridotites yield a range of La/YbCN of 0.48-1.68 and mean ΣREE of 22.63 µg/g. Thus, melt impregnation produces less LREE fractionation and more elevated ΣREE compared to processes dominated by fluid-rock interaction.

# *6.3. Evidence of silica metasomatism*

Talc and amphibole-rich fault rocks form as the result of silica metasomatism and have been recovered from detachment fault surfaces along slow and ultra-slow spreading mid-ocean ridges including oceanic core complexes (e.g., Escartín et al., 2003; Schroeder and John, 2004; Boschi et al., 2006b; McCaig et al., 2007; Picazo et al., 2021). These rocks record heterogeneous deformation under greenschist-facies conditions and are commonly restricted to localized shear zones (< 200 m), which are associated with intense talc-amphibole metasomatism (Escartín et al., 2003; Boschi et al., 2006b). Talc, serpentine and chlorite are mechanically weak and thus may be critical to the development of such fault zones and may enhance unroofing of upper mantle peridotites and lower crustal gabbroic rocks during seafloor spreading. In the case of the Atlantis Massif, talc metasomatism is associated with serpentinite dehydration (Boschi et al., 2008). Strontium isotope compositions of talc-rich fault rocks indicate that talc metasomatism along detachment faults occurs at low water/rock ratios (0.2–0.7) and reflect interaction with Si-rich, evolved fluids with a mafic component derived from interaction with gabbro lenses within a peridotite-dominated ridge segment (Boschi et al., 2008).

In our study, silica metasomatism is reflected by plots of MgO/SiO2 vs. Al2O3/SiO2 (Fig. 3) and MgO vs. SiO2 (Fig. 4a). These figures demonstrate the distinct whole rock geochemistry of the talc-altered harzburgites and talc schists from the eastern site M0068: In MgO vs. SiO2 space (Fig. 4a), the talc-bearing peridotites and talc schists are clearly distinct from all other Exp. 357 peridotites by much lower MgO and much higher SiO2 contents. These low MgO/SiO2 and Al2O3/SiO2 values of < 0.02 are indicative of silica metasomatism and are close to compositions of talc-bearing harzburgites recovered during ODP Leg 209 (Paulick et al., 2006).

# *6.4. Discrimination of fluid-rock vs. melt-dominated processes*

# *6.4.1. Comparison with global abyssal peridotites*

# Figure 8a highlights trace element variations of mean global abyssal peridotites with compositions interpreted as dominated by melt-rock interaction vs. those dominated by fluid-rock interaction associated with serpentinization (Paulick et al., 2006). Peridotites subjected to mafic melt-impregnation exhibit enrichments in incompatible elements relative to those that have not been affected by melt-impregnation (Fig. 8a). In Figure 8b, we have plotted the mean peridotite composition of each Expedition 357 location (i.e., west, central, east) vs. the mean compositions of melt-dominated and fluid-dominated global abyssal peridotites as shown in Fig. 8a. In Fig. 8c, we have parsed the mean peridotite compositions according to borehole of the central sites only. There are clear differences in incompatible element concentrations between Exp. 357 Type II and III peridotites and Type I serpentinized peridotites, with Types II and III exhibiting greater abundances of all incompatible elements (Fig. 8b). In particular, the peridotites from the western site have PM-normalized incompatible element abundances that are most similar to fluid-dominated peridotites, whereas central sites peridotites exhibit concentrations most similar to melt-dominated peridotites; eastern site peridotites have incompatible abundances more enriched than melt-rock dominated peridotites (Fig. 8b). Apart from U and Sr, the Exp. 357 peridotites show a clear enrichment in all other incompatible elements from the western to central to eastern sites (Fig. 8b).

# *6.4.2. HFSE vs. LREE*

On the basis of selected HFSE vs. LREE and HFSE vs. MREE/HREE variations, Paulick et al. (2006) showed that the global abyssal peridotite dataset of Niu (2004) exhibit relatively steep positive trends, which was interpreted as indicative of dominant melt-rock interaction processes. The reason for this trend is related to differences in the behavior of LREE and HFSE: The LREE are more hydrophilic than the HREE and HFSE and more readily transported in solution. However, melt–rock interaction causes addition of LREE and HFSE to the rock in about equal proportions (Niu, 2004). A trend defined by only minor increase in HFSE concentrations (i.e., a sub-horizontal as opposed to steep positive trend) on the other hand, is indicative of dominantly hydrothermal alteration processes (i.e., fluid-rock interaction), which affect the more immobile HFSE to a lesser extent than the REE (Paulick et al., 2006). In the dataset of ODP Leg 209 peridotites, Paulick et al. (2006) showed that those at Sites 1270 and 1271 exhibit steep trends similar to the dataset of Niu (2004), whereas those of Sites 1268, 1272 and 1274 show less steep, subhorizontal trends, which they interpreted as more consistent with fluid-rock interaction.

Fig. 9 shows Expedition 357 peridotites vs. the trends of global abyssal peridotites, with compositions dominated by (i) melt-rock interaction and (ii) fluid-rock interaction in Nb vs. La and Ti vs. Dy space. These plots produce two distinct linear trends, which mimic the two described above, in agreement with the observations presented in Fig. 8. The peridotites of the central and eastern sites, which show ample evidence of melt-impregnation exhibit steep trends indicative of compositions dominantly controlled by melt-rock interaction similar to those of the global MOR peridotite dataset of Niu (2004) and ODP Leg 209 Sites 1270 and 1271 of Paulick et al. (2006). In contrast, serpentinized peridotites from the western site, which show minimal evidence of melt-impregnation, instead show flatter, subhorizontal trends suggestive of compositions mostly controlled by fluid-rock reactions, similar to trends of peridotites of ODP Leg 209 Sites 1268, 1272 and 1274. We note also that similar relations and trends occur on other plots of HFSE vs. LREE and MREE (e.g., Th vs. Ce, Ti v. Ce, Hf vs. Pr, Nb vs. [Gd/Lu]CN and Ti vs. [Gd/Lu]CN, Supplementary Fig. S2). In the case of Expedition 357 peridotites, in all instances, the slope of the trends of the central and eastern site peridotites are steeper than the slope of the trend of the western site peridotites, consistent with compositions of the former being the result of dominant melt-rock reaction and compositions of the latter being the result of dominantly fluid-rock interaction. When the central location is parsed into discrete sites, compositions of peridotites from central Site M0069 are consistent with being dominated by fluid-rock interaction, whereas those of central Sites M0072 and M0076 are consistent with being dominated by melt-rock interaction.

# *6.5. Petrogenesis: Estimates of degrees of melt extraction*

#  Chondrite-normalized REE and PM-normalized patterns (Fig. 5), are used to explain differences in the relative depletion of peridotites of each site investigated, and provide evidence of fluid-dominated processes and melt-impregnation processes (Sections 6.1.-6.4.), based on the compositional variation of Expedition 357 peridotites. Below, we model estimates of partial melting undergone by the peridotites based on this chemistry (TE and REE).

# Various highly incompatible and immobile trace elements (Yb, Nb, Zr) in peridotites from western Site M0071 and central Sites M0069 and M0076 exhibit extreme depletion relative to DMM, in contrast to the central Site M0072 peridotites that exhibit enriched chondrite-normalized patterns relative to DMM apart from a lone moderately depleted serpentinized dunite. The eastern Site M0068 peridotites exhibit LREE concentrations more enriched than DMM but HREE slightly to moderately more depleted than DMM. Evidence in support of high degrees of melt depletion includes the high depletion in Al2O3 and CaO (Fig. 4), and the aforementioned other incompatible trace elements (Fig. 7, Table 3). Below, we provide estimates of the maximum degrees of melt extraction based on modelling of whole rock REE concentrations and note that REE patterns of many samples are strongly affected by refertilization, which thus needs to be taken into account to derive accurate estimates of melt depletion.

# The REE patterns of the most melt-depleted sample for each of the five sites are shown in Figure 10 and compared with curves predicted by modeling of melt depletion followed by subsequent metasomatism. As LREE are most strongly depleted during partial melting, and therefore sensitive to refertilization, this part of the REE pattern is essentially that of the metasomatizing agent. As a result, different amounts of metasomatism will shift the LREE pattern up or down, but the slope of the LREE pattern (La/Sm) is barely affected. This slope is strongly variable in our dataset, ranging from LREE-depleted ([La/Sm]CN = 0.3-0.9) to strongly enriched ([La/Sm]CN = 2-5). The REE patterns in Figs. 5a-e show at least two distinct melts that have infiltrated the peridotites, an enriched (*E*) and a depleted type (*D*), of which the most REE-rich examples are from eastern Site M0068 (samples 68A-1R1-34-35 and 68A-1R1-1-6). In these samples, the original peridotite REE patterns have been completely overprinted by the infiltrating melts. Therefore, we chose these peridotites to estimate the composition of the two endmember contaminant during modeling (*E* and *D*, respectively). Both types can be observed at each site, although central Sites M0072 and M0076 are dominated by a *D*-type contaminant. Some peridotites show evidence of infiltration by an even more enriched contaminant (*SE*), the composition of which is more difficult to estimate. As this contaminant is strongly LREE-enriched and therefore relatively HREE poor, its exact composition will have little effect on our melt fraction estimates, which are based on the HREE part of the patterns.

# The calculated volume of fractional non-modal melt extraction (see Fig. 10 caption for model parameters) of the most depleted sample from each site ranges from 19 to 21 % (Fig. 10), which indicates little difference in the maximum amount of melt extraction between the sites. The difference in the REE patterns between the sites are primarily due to small but variable amounts of infiltrating melts (<1 % for each of the five most depleted samples, Fig. 10).

# These modeling results show little difference in the maximum amount of melt extraction between the different sites across the footwall. Unfortunately, significant melt infiltration experienced by many of the peridotites makes it difficult to evaluate the average amount of melt extraction experienced by peridotites of the different sites. For example, nearly all whole rock compositions of eastern Site M0068 and central Site M0072 are more enriched than DMM, which could be interpreted as very limited melt extraction, but refertilization of these samples will have obliterated any previous melt extraction history. Our modeling results suggest that differences in REE patterns observed between sites are probably due to differences in refertilization, not partial melting.

# *6.6. Spatial variations in geochemical processes and peridotite composition*

#  It was noted by Früh-Green et al. (2018) that there exists a weakly defined enrichment in peridotites from west to east. This pattern is actually strongly defined in terms of enrichment in LREE, LREE fractionation, ΣREE and HFSE (Figs. 7-9 and Supplementary Fig. S2). For example, Fig. 8 shows a distinct increase in all incompatible elements except U, Pb and Sr in the mean peridotite compositions moving from west to central to east. Specifically, the western peridotites exhibit the lowest concentrations of HFSE of Nb, Zr and Th whereas the eastern peridotites exhibit the highest concentrations of these elements (Figs. 7a-c); the central peridotites have concentrations intermediate to the western and eastern peridotites. However, as we have also noted, there are distinctions in the central location when parsed into individual sites with central Site M0069 being depleted to the same degree as the western peridotites and with the two other central sites (M0072 and M0076) being comparatively more enriched.

# Moreover, this pattern of west to east enrichment is complementary to the relative volume of melt-impregnation and silica metasomatism recorded in sampled peridotite at each site. The eastern site comprises the largest percentage of melt-impregnated and silica-metasomatized peridotites (70%), relative to the central sites (35 %), and the western site (a single sample out of nine, or 11 %, is melt-impregnated, with no silica-metasomatized peridotite). However, the calculation for the central sites is underestimated as we do not include here the four cryptically melt-impregnated peridotites of central Site M0072 from our dataset which show no macroscopic or microscopic evidence of melt-impregnation. If we recalculate with the inclusion of these four M0072 peridotites, the percentage of melt-impregnated and silica-metasomatized peridotites from the central sites increases to 52 %.

# *6.7. Links to OCC processes*

# The observed spatial variations in peridotite composition needs to be interpreted in the context of both the limitations of our observations and taking into account the complex history of detachment fault formation and exhumation. We have shown that the western site peridotites record compositions consistent with dominant fluid-rock interaction processes, whereas the central site peridotites, considered collectively, and those from eastern site record compositions consistent with serpentinization of a peridotite having undergone dominant melt-rock interaction. Furthermore, there is a clear progression in the volume of melt-impregnations from west to central and east and a corresponding increase in incompatible element enrichment, a record of these increasing volumes of melt-enrichment.

# Peridotites from the western sites originated from shallower borehole depths of ~ 0-10 m relative to those of the central sites (a maximum of ~ 16 m in the cases of central Sites M00069A and M0076A, Fig. 1c). The present-day position of these samples cannot be directly related to that of the history of each sample, from lithospheric emplacement, subsequent interaction with melt, alteration, and exhumation. First, the detachment fault zone is likely a complex, anastomosing structure, with a thickness of ~100 m to ~ a few 100s of m (e.g., Karson et al., 2006; Escartín et al., 2017; Parnell-Turner et al., 2018), where fault blocks are transposed in the along-axis direction. In this case, variations in composition vs. borehole depth may not correspond to actual structural depths relative to the fault surface exposed at the seafloor, and now adjacent materials may have originated from different positions (e.g., along the fault). Second, the boreholes also include talus material that is therefore not *in situ*. The present-day location of these samples cannot be directly interpreted as an indicator of spatial and temporal relationships with samples *in situ*, and therefore have an ambiguous structural position. If these debris fields correspond to local mass-wasting deposits, visible at small scales over the detachment fault, the present-day position may be close to the original *in situ* position. Oceanic detachments also display a cover of rubble and sediment that is sourced from the hanging wall, rafted during extension (e.g., Dick et al., 2008; Escartín et al., 2017). Thus, if the talus material corresponds to rubble cover, its source may be the hanging wall rather than the fault zone or footwall instead, and its present-day location does not necessarily reflect its position at the time of formation, emplacement, impregnation, or alteration.

# The consistent grouping of samples with a similar melt-impregnation (or lack thereof) and alteration history at the eastern, central, and western sites may suggest that *in situ* samples have not witnessed significant (km-scale), lateral transposition along the fault zone, or at least at spatial scales that are smaller than any local spatial variation associated with melt-rock interactions. Similarly, the samples that are not *in situ*, with similar melt impregnation and alteration histories, suggest a local source; sampling of hanging wall rubble would likely result in an extremely heterogeneous and variable set of ultramafic samples, as observed from the rubble cover from other oceanic detachments (e.g., Escartín et al., 2007). The homogeneity is therefore consistent with a local origin, with material sourcing from mass-wasted fault zone, eventually mixed with basaltic rubble that is present in the boreholes (e.g., Früh-Green et al., 2018).

# If the samples are either *in situ*, or sourced locally where *ex situ*, and if the lateral transposition of material within an anastomosing fault zone occurs at a smaller scale (< 1 km parallel to extension) than the distance between sites (3-5 km), then spatial patterns observed may be interpreted in the context of the internal structure and evolution of the OCC and its detachment fault. Ildefonse et al. (2007) suggested a temporal variation in melt supply to the ridge axis, with an initial phase of accretion that has limited melt supply, and a late phase of accretion with increased melt supply and the emplacement of gabbros in the footwall, than drilled at U1309D. This would be consistent with early peridotites just showing melt extraction (western sites), and melt-rock reactions in more recent time associated with this recent magmatic phase (eastern sites). Alternatively, the sites may simply record an inherently heterogeneous system, where melt percolation, and hence melt-rock reactions, are inherently inhomogeneous. If this is the case, the east-west patterns may not reflect a temporal evolution but instead indicate that these heterogeneities may occur over distances of a few km, corresponding to the separation among the different sites. We also note that geological observations and drilling document a change in footwall composition along-axis, with peridotites near the transform fault wall, and gabbros ~ 10 km to the north, hence at spatial scales similar to those shown by the western, central, and eastern sites.

**7. Conclusions**

Peridotites sampled during IODP Expedition 357 comprise predominantly Type I serpentinized peridotites, with lesser Type II melt-impregnated and Type III metasomatic peridotites. A principal variation in the nature and composition of Expedition 357 peridotites is an increase in the volume of melt-impregnation products and a concomitant increase in HFSE and LREE enrichments from the western to central to eastern sites. Whole rock chemical compositions of western site Type I serpentinized peridotites are consistent with dominant fluid-rock interaction associated with serpentinization and oxidation whereas compositions of eastern site Type II melt-impregnated and Type III metasomatic peridotites are dominated by melt-rock interaction processes. High to moderate degrees of melt extraction in the peridotites are evident in low concentrations of Al2O3, CaO and incompatible elements. Degrees of melt extraction based on whole rock REE suggest a high range of 19-21 % with no apparent variation between sites. Some peridotite samples are rubble and therefore *ex situ*. Thus, the coherent magmatic history observed at each site may be consistent with a local source originating in the fault zone rather than rafted rubble that would be expected to show more heterogeneity and no spatial pattern. If this is accurate, our sites may provide a time-record of enhanced melt-rock interaction with time, consistent with proposed geological models. Otherwise, the magmatic history may represent heterogeneities in these processes at spatial scales of a few km.

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# Figure captions

Figure 1. (a) Location of the Atlantis Massif at 30°N within the context of the greater MAR spreading system (modified from Kelley et al., 2001). (b) Bathymetric map centered on the southern wall of the Atlantis Massif (modified after Rouméjon et al., 2018a). Inset shows the location of the Atlantis Massif on the western flank of the Mid-Atlantic Ridge axial valley, bordered to the south by the Atlantis Fracture Zone. Circles with numbers in italics and beginning with M00 represent shallow drill hole locations from IODP Exp. 357 (Früh-Green et al., 2017, 2018). White circles indicate drill holes with no recovered peridotite; blue, red and yellow circles represent western (M0071), central (M0069, M0072, M0076) and eastern (M0068) sites, with recovered peridotite samples investigated in this study. White squares represent sites (U1309, U1310, U1311) drilled during Exp. 304/305 (Blackman et al., 2006); white star shows the location of the Lost City Hydrothermal Field (LCHF) (Kelley et al., 2001). (c) Simplified downhole plots showing dominant rock types recovered in the seven drill holes hosting serpentinized peridotites (modified from Roumejon et al., 2018a; see Fruh-Green et al., 2018 for complete expedition drill hole vertical sections). The sections are arranged from right to left according to longitude (see Fig. 1b), and from hole top to bottom. The central holes embody *in situ* segments of the detachment footwall, whereas the western and eastern site holes which yield rubbly intervals and sedimentary structures are interpreted as artefacts of mass wasting and local faulting. Symbols: circles, harzburgite; squares, dunite; triangles, Ca-rich harzburgite; triangles with slash, Ca-rich dunite; crosses, melt-impregnated harzburgite; x’s, plagioclase-impregnated harzburgite; diamonds, talc-amphibole altered harzburgite; diamonds with slash; talc-amphibole-chlorite schist. Blue, red and yellow symbols represent samples of western, central and eastern serpentinized harzburgites and dunites, respectively, analyzed for whole rock chemical analysis. Note ‘metamafic’ includes metabasalt, metadolerite and metagabbro composition samples.

Figure 2. Representative thin section images of Expedition 357 Type I serpentinized peridotite (a-d), Type II (mafic) melt-impregnated (mm-i) peridotite (e, f) and metasomatic peridotite (msp) (g, h). ‘Typical’ completely serpentinized peridotite samples from (a, b) 71A-1R2-85-89, harzburgite and (c) 71C-5R1-6-8, harzburgite. (d) Ca-rich serpentinized harzburgite 69A-9R2-8-12 showing extensive network of carbonate veinlets. (e, f) Mafic melt-impregnated (mm-i) harzburgites 76B-7R1-81-83 and 68B-4R1-23-29 with (e) the presence of rare plagioclase feldspar (f) and secondary (replacive) olivine mantling partially dissolved orthopyroxene porphyroclast. (e) Talc-amphibole altered (t-aa) harzburgite 68B-1R1-10-13, showing replacement of orthopyroxene by talc (Tlc) and tremolite (Tr), and (f) talc-schist 68B-1R1-1-6. Image (a) is under plane polarized light; images in (b-h) are under cross-nicols.

Figure 3. Plot of MgO/SiO2 vs. Al2O3/SiO2 for all studied peridotites (top panel, serpentinized peridotite, bottom panel, melt-impregnated and metasomatic peridotite). The lighter shaded samples (light yellow, light blue and pink) of the same shape here and in all other figures are Expedition 357 Atlantis Massif peridotite from Früh-Green et al. (2016); light orange circles and squares harzburgites and dunites, respectively, from IODP Site U1309 Atlantis Massif peridotites (Godard et al., 2009). Global abyssal peridotite data from Niu (2004), Paulick et al. (2006) and Godard et al. (2008), unless stated otherwise. Fields of serpentinized peridotite and talc-altered peridotite are from Paulick et al. (2006) and melt-impregnated peridotites (MIP) are from Paulick et al. (2006), Godard et al. (2008) and as referenced in Whattam et al. (2011). DMM (depleted MORB mantle) and PM (primitive mantle) from Workman and Hart (2005) and Palme and O’Neill (1983) respectively. The terrestrial array is from Jagoutz (1979).

Figure 4. Variation diagrams of MgO vs. (a) SiO2, (b) Fe2O3, (c) Al2O3, (d) CaO and (e) LOI of Atlantic Massif peridotites from this study, and Godard et al. (2009) and Früh-Green et al. (2018) compared with global MOR peridotite and bulk compositions of serpentine and talc (Blanco-Quintero et al. 2011, mean of ten and eight serpentine and talc analyzes). Symbols as in Fig. 3.

Figure 5. (a-e) Chondrite-normalized REE and (f-j) primitive mantle-normalized incompatible element plots of Atlantis Massif peridotites from this study and the study of Früh-Green et al. (2018). Chondrite and primitive mantle values are from McDonough and Sun (1995). Shown for comparison is mean abyssal peridotite composition determined on the compilations of Niu (2004) and Bodinier and Godard (2003) by Godard et al. (2008), and depleted MORB mantle (DMM) (Workman and Hart, 2005).

Figure 6. IODP Expedition 357 peridotite samples from this study, and the study of Früh-Green et al. (2018) on plots of (a) U and (b) Sr vs. site. Note that three of the four high-CaO peridotites (with 5.59-10.50 wt.% CaO) also exhibit the highest concentrations of Sr ( > 1000 µg/g). Symbols as in Fig. 3.

Figure 7. Expedition 357 Atlantis Massif peridotites from this study and the study of Früh-Green et al. (2018) in plots of (a) Th, (b) Hf, (c) Zr, (d) Ce/Yb and (e) total REE vs. site. Plotted for comparison are the ranges of fluid-rock dominated and melt-rock dominated global abyssal peridotite (GAP, references as in the caption for Fig. 5). Depleted mantle (DM) and primitive mantle (PM) compositions are from Workman and Hart (2005) and Lyubetskaya and Korenaga (2007), respectively. Symbols as in Fig. 3.

Figure 8. Primitive mantle-normalized plots of the mean compositions of (a) global abyssal peridotites interpreted as being dominated by fluid-rock and melt-rock reactions, (b) Atlantis Massif peridotites from this study and (c) central peridotites parsed into site. The fluid-rock dominated peridotite is from Paulick et al. (2006) and represent peridotites collected during ODP Leg 209, Sites 1268, 1772, 1274. The melt-rock dominated peridotite is from Niu (2004) and Paulick et al. (2006) and in the case of Paulick et al. (2006), represent peridotites collected from ODP Leg 209, Sites, 1270, 1271. Symbols as in Fig. 3

Figure 9. Expedition 357 Atlantis Massif peridotites from this study and the studies of Godard et al. (2009) and Früh-Green et al. (2018) in plots of (a, b) Nb vs. La, and (c, d) Ti vs. Dy. Element abundances listed as ‘0’ were assumed to be below detection limit and not used in calculation of the regression. Colors of the regressed lines and text for the Expedition 357 peridotites include: blue, western; red, central; and black, eastern. In (b) and (d), the light blue, pink and light grey regressed lines represent mean of the western, central and eastern sites (i.e., the blue, red and black lines in (a) and (c)). R2 values shown for Exp. 357 peridotites represent ones which include the samples of Früh-Green et al. (2018) in addition to the ones from this study and the numbers in italics in brackets beside R2 values represent number of samples used in regression calculation. The orange line represents the dataset of Atlantis Massif peridotites from Site U1309 (Godard et al., 2009). Linearly regressed vectors (grey) labelled *A*, *B*, and *C* in (a) and (c) represent data from global abyssal peridotite (GAP) and for visual clarity, samples are omitted from the plot. The *A* trend represents the dataset of Niu (2004) which was interpreted by Paulick et al. (2006) as being representative of dominant melt-rock interaction (i.e., melt-impregnation); *B* and *C* are from Paulick et al. (2006) and represent peridotites interpreted as having compositions dominantly associated with melt-rock reaction (*B*, ODP Leg 209, MAR, Sites, 1270, 1271) and fluid-rock reaction (*C*, Sites 1268, 1772, 1274). Depleted mantle (DM) and primitive mantle (PM) compositions from Workman and Hart (2005) and Lyubetskaya and Korenaga (2007), respectively. Symbols as in Fig. 3.

Figure 10. (a) REE compositions of the most melt-depleted sample from each site compared with model estimates of 10, 15, and 20 % partial melting of DMM as well as three ‘best fit’ models of melting and subsequent refertilization to estimate the extent of melting experienced by these samples. Modeling is of non-modal fractional melting (dashed curves encompassing light green shade) of partial melting in % (10, 15, 20) of a four phase DMM spinel lherzolite source comprising ol: opx: cpx: sp in modal proportions of 0.53: 0.27: 0.17: 0.03 and a melt mode of ‑0.06: 0.28: 0.67: 0.11 (Hellebrand et al. 2002). Initial source composition, DMM from Workman and Hart (2005). Partition coefficients from Suhr et al.,1998; missing REE interpolated. Also indicated are compositions of rocks after 20 % non-modal fractional melting and subsequent 1 % or 10 % addition of a mafic melt (mm, uppermost grey shaded area) with a REE composition of the most enriched peridotite (eastern site M0068A-1R1-34-35 talc-schist, Früh-Green et al., 2018, see Fig. 4e) as a proxy for a slightly LREE-enriched melt (darker green shade). Symbols as in Fig. 3.

**Table captions**

Table 1 Evidence and means for classification Expedition 357 peridotites subjected to melt-impregnation and (silica) metasomatism.

Table 2 Mineralogy and modalogy of Epedition 357 peridotites.

Table 3 Whole rock ICP-AES and ICP-MS analyses of Expedition 357 Atlantis Massif serpentinized peridotite from this study.

**Supplementary material**

See Supplementary Document

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