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Length-scales of chemical and isotopic heterogeneity in the mantle section of the Shetland Ophiolite Complex, Scotland

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ABSTRACT

Kilometre to sub-metre scale heterogeneities have been inferred in the oceanic mantle based on sampling of both ophiolites and abyssal peridotites. The ~492 Ma Shetland Ophiolite Complex (SOC) contains a well-preserved mantle section that is dominated by harzburgite (~70 vol.%) previously reported to have variable major and trace element compositions, yet dominantly chondritic initial $^{187}Os/^{188}Os$ compositions. To assess the preservation of compositional heterogeneities at sub-metre length-scales in the oceanic mantle, a ~45 m^2 area of the SOC mantle section was mapped and sampled in detail. Harzburgites, dunites and a pyroxenite from this area were analysed for lithophile and highly-siderophile element (HSE) abundances, as well as for $^{187}Os/^{188}Os$ ratios. Lithophile element data for most rocks are characteristic of supra-subduction zone (SSZ) metasomatic processes. Two dunites have moderately fractionated HSE patterns and suprachondritic $\gamma Os_{(492\ \mathrm{Ma})}$ values (+5.1 and +7.5) that are also typical of ophiolitic dunites generated by SSZ melt–rock interactions. By contrast, six harzburgites and four dunites have approximately chondritic-relative abundances of Os, Ir and Ru, and $\gamma Os_{(492\ \mathrm{Ma})}$ values ranging only from −0.6 to +2.7; characteristics that imply no significant influence during SSZ processes. Two harzburgites are also characterised by significantly less radiogenic $\gamma Os_{(492\ \mathrm{Ma})}$ values (−3.5 and −4), and yield Mesoproterozoic time of Re depletion (T_{RD}) model ages. The range of Os isotope compositions in the studied area is comparable to the range reported for a suite of samples representative of the entire SOC mantle section, and approaches the total isotopic variation of the oceanic mantle, as observed in abyssal peridotites. Mechanisms by which this heterogeneity can be formed and preserved involve inefficient and temporally distinct melt extraction events and strong localised channelling of these melts.

1. Introduction

Earth's mantle is structurally and compositionally heterogeneous at length-scales ranging from ocean basins to hand specimens of mantle peridotite. Understanding the timing and causes of these heterogeneities is important, given that mantle peridotites are key samples for defining the composition of the primitive mantle (PM) and for examining the timing and nature of planetary accretion and primary differentiation, as well as the evolution of plate tectonics (cf., Morgan, 1986; Morgan et al., 2001; Becker et al., 2006; Stracke et al., 2011; Rampone and Hofmann, 2012). Although studies have shown that some mantle domains may have survived the period of early-Earth differentiation to the present (Mukhopadhyay, 2012; Mundl et al., 2017), an array of processes have worked to destroy early-formed heterogeneities in upper mantle materials, such as convective mixing. New heterogeneities have also been created during partial melting and melt extraction, and lithospheric recycling and mantle metasomatism. These latter processes have led to the development of cm-to-km scale heterogeneities in the upper oceanic mantle (also termed depleted MORB mantle, or DMM; Dick et al., 1984; Snow et al., 1994; Workman and Hart, 2005; Liu et al., 2009; Warren et al., 2009). Compositional and isotopic heterogeneities reported from studies of oceanic mantle materials include refractory domains that are older than the presumed age of the mantle they are found in, and fertile components that may sample recycled crustal materials or 'frozen' upper mantle melt channels

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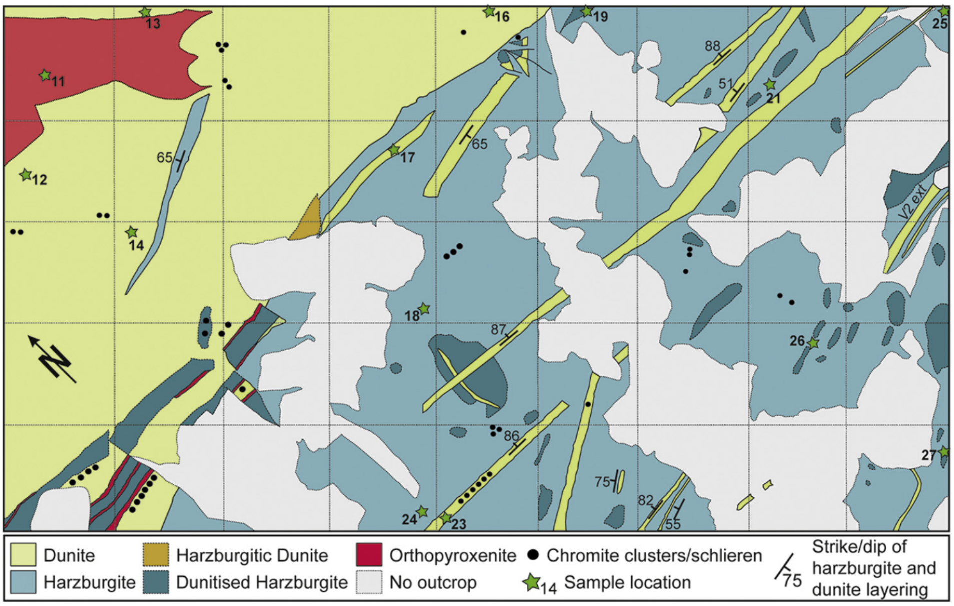

Fig. 1. Sketch map of the lithological relationships in The Viels study area. The horizontal border of this sketch map is oriented 333° and the grid squares are 1 m in length. The thin dunite channel labelled 'V2ext' is the same channel that Sample V2 of O'Driscoll et al. (2012) was sampled from (see text for details).

(e.g., Kelemen, 1990; Büchl et al., 2002, 2004; Alard et al., 2005; Harvey et al., 2006; Bizimis et al., 2007; Warren et al., 2009; Stracke et al., 2011; Burton et al., 2012; Rampone and Hofmann, 2012).

A paucity of accessible exposures of fresh modern-day oceanic peridotites is a major obstacle to a detailed direct assessment of its chemical and isotopic heterogeneity. Abyssal peridotites, commonly presumed to be the residua after partial melting to produce mid-ocean ridge basalts (MORB; Dick et al., 1984; Warren et al., 2009; Lassiter et al., 2014; Warren, 2016; Day et al., 2017a), provide one option for the direct study of mantle peridotites. Abyssal peridotites, however, are most frequently collected by ocean dredging, and so field relations amongst different samples are normally poorly constrained, with a few exceptions (e.g., Harvey et al., 2006; Mallick et al., 2015).

Ophiolite peridotites are also useful for studying upper mantle processes. Ophiolites represent slivers of oceanic lithosphere thrust (obducted) onto continental crust at convergent plate margins. Ideally, they preserve both mantle and crustal sections. Ophiolite peridotites provide snapshots of the long-term evolution of the oceanic lithospheric mantle, as known ophiolites range in age from Archaean to as young as ~6 Ma (Büchl et al., 2002; Schulte et al., 2009; Dilek and Furnes, 2011; O'Driscoll et al., 2012, 2015). Ophiolites also have the advantage that they may provide excellent constraints on field relations, including providing spatial and structural context for lithologically diverse mantle rocks. As with most abyssal peridotites, however, ophiolite peridotites are commonly highly serpentinised, and may also have been modified by supra-subduction zone (SSZ) processes (Dilek and Furnes, 2011). Consequently, study of ophiolite peridotites requires either the application of elements that are minimally affected by secondary processes, or elements for which the secondary effects can somehow be circumvented. The absolute and relative abundances of the highly siderophile elements (HSE; Os, Ir, Ru, Pt, Pd, Re), combined with the Re–Os isotope system, have proven useful in this context because mantle peridotites tend to be characterised by much higher concentrations of these elements than both crustal rocks and fluids whose recycling can strongly modify the compositions of lithophile trace elements and Sr–Nd–Hf–Pb isotope systematics (cf., Becker and Dale, 2016).

Application of the HSE and Os isotopes to ophiolitic mantle samples has potential to provide insights into the distribution and the range of length-scales over which compositional heterogeneities occur in the oceanic mantle. The mantle section of the ~492 Ma Shetland Ophiolite Complex (SOC; Fig. S1) is a valuable locality to examine in detail due to excellent exposure of the mantle section and the context provided by previous work on Os isotopes and HSE abundances (e.g., O'Driscoll et al., 2012; Prichard et al., 2017).

The aim of this study is to advance understanding of mantle chemical and isotopic heterogeneities over length-scales of several metres, i.e., at the outcrop scale, and tie these phenomena to lithological variations observed in the field. We link our metre-decametre scale observations to grain-scale controls by considering the distribution and HSE compositions of base-metal sulphides, platinum-group element (PGE) phases, and Cr-spinel in relevant lithologies.

2. Geological setting and sample selection

The ~492 Ma SOC represents Iapetus Ocean lithosphere, and is one of numerous tectonic ophiolite fragments now dispersed along the length of the Caledonian orogen from NW Norway, through the UK and Ireland, Newfoundland, and as far south as the Appalachians in the eastern USA (Spray and Dunning, 1991; Chew et al., 2010). The SOC is considered to have been obducted onto Laurentia at ~470 Ma (Flinn, 2001). Although overlying components of the ophiolite are missing or poorly exposed (e.g., the sheeted dyke complex), the mantle section is extensive and well-preserved (Derbyshire et al., 2013). The mantle section comprises serpentinised harzburgite (~70 vol.%), with numerous dunite layers and lenses, and less abundant chromitites and pyroxenites (Fig. S1; Flinn, 2001). Chromitite seams occur encased in dunite sheets and pods, a relationship that has previously been explained due to formation of chromitite during high degrees of melt–rock reaction in channels of focused melt flow (O'Driscoll et al., 2012; Derbyshire et al., 2013). In the case of the SOC, melt extraction likely occurred in a forearc supra-subduction zone (SSZ) setting (Crowley and Strachan, 2015).

A ~45 m^2 area situated 200 m below the petrological Moho at "The Viels" (Fig. S1), was selected for study due to the good expo-