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Review Article

Signatures of Refertilisation: Perspective from Peridotites in Ophiolite Sequences

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Majority of the ophiolites is conceded in the geologic record, been formed either in mid ocean ridge (MOR) or in supra subduction zone (SSZ) setting. However, many of their origins are controversial. The peridotites from the mantle section of the ophiolites serve as a window to look deep into the mantle evolution and provide snapshot details on the origin of ophiolite. In this review, we have discussed four different kinds of peridotites from Josephine, Oman, Andaman ophiolites belong to various tectonic settings and abyssal peridotites from Mid ocean ridges.

In general, Cr#, Mg#, trace elements in clinopyroxenes of the peridotites are important indicators of different mantle processes. Variations in peridotite chemistry, their major and trace element concentrations depend on various degrees of partial melting. Refertilisation-a post melting modification event might change the trace element composition of residual peridotites based on the composition of the percolating melt. Effect of refertilisation can be well diagnosed by trace element patterns of clinopyroxenes within the peridotites because Cpx trace element pattern can be easily affected by late stage melt percolation. Comparatively dry partial melting occurs at MOR than SSZ setting during the generation of abyssal peridotites and the effect of refertilisation in these rocks is little. In each stage of dry melting (MOR setting) and/or wet flux melting (SSZ setting)event during the process of ophiolitic peridotite or abyssal peridotite formation, Cpx plays an important role as melting events leave imprints within the Cpx trace element concentrations.

Keywords: Ophiolite; Peridotite; Clinopyroxene; Andaman; Oman; Josephine; SSZ; MOR

Introduction

Ophiolites are fossilised oceanic lithosphere, primarily formed in Supra Subduction Zone (SSZ) or Mid Ocean Ridge (MOR) and/or in transitional environment (Metcalf and Shervais, 2009). They are preserved along the present-day suture zones and provide the 'snapshot' details of origin and evolution of oceanic lithosphere that otherwise been consumed by subduction and/or continental collision. Ophiolites are mainly comprised of mantle section (peridotite), mantle transition zone (i.e. MTZ composed of peridotite, pyroxenite, gabbro, troctolite etc.) and crustal section (basalt and often acid volcanics). However, these occurrences of rock types vary depending on their mode of formation. For example, in a typical SSZ setting, a series of volcanic rocks from basalt-rhyolite to boninite may present whereas, a MOR setting will lack these acidic volcanic rocks (Whattman and Stern, 2011). Nevertheless, there is no unique way to constrain between these major geodynamic environments of ophiolite formation undoubtedly. Thus, inferring the paleo-tectnoic environment from many ophiolites around the world remains debatable. However, in general, melting processes in MOR and SSZ settings are quite different. Any peridotite forms in either of these settings. Relatively dry melting of peridotite (~5 to 15 %) takes place in MOR setting (Jean *et al*., 2010). On the other hand, in SSZ, during initiation of the subduction and fore arc spreading MORB like magmas generate due to decompression melting of mantle. As the subduction proceeds, continued melting of mantle results in depleted mantle

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residue (harzburgite) that has been progressively metasomatised due to continuous input of fluid (>20%) from subducting slab and sediments (e.g., Parkinson *et al*., 1992; Ishii *et al*., 1992; Arai 1994a; Parkinson and Pearce 1998; Pearce *et al*., 2000; Widom*et al*., 2003). Melting of metasomatised mantle residue gives rise to Island Arc Basalt (IAB) and boninite like lavas, consequently. Therefore, we can use peridotite from mantle section of ophiolites to understand the contrasting melting processes in different tectonic settings in order to characterise the different geodynamic environments of ophiolite formation.

Trace element composition of clinopyroxene (Cpx) in residual mantle peridotite from MOR (Johnson *et al*., 1990; Johnson and Dick, 1992; Hellebrand *et al*., 2002) and ophiolites (Rampone *et al*., 1996; Batanova *et al*., 1998; Suhr *et al*., 1998) provides valuable information on melting processes. Clinopyroxene is a common and abundant mineral throughout the ophiolite sequence and a good reservoir of many trace elements including REE. The trace elements and REE in clinopyroxene preserve the signature of chromatographic reaction of melt-rock interaction at each stage of melting. Post melting modification such as refertilisation is common especially in SSZ setting, occurring due to percolating or inefficiently extracted melt that crystallises in interstices and on grain boundaries. Abyssal peridotite typically forms in MOR setting and hence, this study attempts to review how clinopyroxene behaves in anhydrous vs. hydrous melting of mantle residual peridotites in MOR and ophiolites respectively in order to unfold the melting process and ophiolite formation in different tectonic settings.

The mantle residual peridotite from Josephine (Calidonian) and Oman (Tethyan) ophiolites are compared with the abyssal peridotites from MOR. The Josephine and Oman ophiolites have supra subduction zone and transitional origin, respectively. In light of this, we have also discussed the possible mode of formation of residual peridotite from Andaman ophiolite (possibly part of Tethyan orogeny) that shares a common age of formation of 95 Ma (Pedersen *et al*., 2010;Sarma *et al*., 2010) with Oman ophiolite (Lippard *et al*., 1986; Nicolas, 1989).

Geological Background

Josephine Ophiolite

Josephine ophiolite is partly dismembered Caledonian ophiolite sequence emplaced at 157 Ma (Saleeby *et al*., 1982; Dick, 1976) and located in the Kalamath Mountains in southern Oregon and northwestern California (USA). Josephine ophiolite resides in a paleo-position between two segments of rifted Jurassic arc systems. Josephine ophiolite is considered to form in an extensional back arc setting where supra-subduction zone magmas are overlain by MORB magmas. The ophiolite preserves the complete sequence of crustal and mantle section consisting of basalt, sheeted dyke, gabbro and gabbro interlayered with wehrlite, and dunite, in fault contact with peridotite tectonites. The Josephine peridotite is the base of the ophiolite followed by MTZ (Mantle Transition Zone) and crustal sections. Ophiolite sequence is conformably overlain by thin siliceous pelagic sediments followed by thick sequence of turbidites known as “Galice formation” (Harper 1984).

The Josephine peridotite presents large massif body (640 km^2) comprised of variably depleted spinel harzburgite and lherzolite. Plagioclase is largely absent. Peridotites are partially or completely altered to serpentinites (Roux Le *et al*., 2014). In addition to massif peridotites, variations of pyroxene rich and pyroxene poor layers of peridotite are also present at centimetre scale. Dunite occurs as dikes, tabular bodies and large irregular podiform bodies.

Oman Ophiolite

Oman ophiolite is a part of Tethyan oceanic lithosphere that was emplaced at (95 Ma) the Arabian continent (e.g., Lippard *et al*., 1986; Nicolas, 1989). There are controversies regarding the origin of Oman ophiolite whether it was formed in a mid ocean ridge (Boudier *et al*., 1988; Nicolas, 1989) or in a back-arc basin (Alabaster *et al*., 1982; Lippard *et al*., 1986). However, presently a combined origin is concluded where at the first stage MOR magmatism is overlain by second stage arc type magmatism at subduction zone during obduction (Arai *et al*., 2006).

Mantle section of Oman ophiolite is comprised of lherzolite near the base of the lower section (Lippard *et al*., 1986 and Takazawa *et al*, 2003).

Harzburgite with both high and low Cr# spinel is present (e.g., LeMe´e *et al*., 2004; Arai *et al*., 2006; Monnier *et al*., 2006; Tamura and Arai, 2006). Dunite, wehrlite and gabbro are closely associated with harzburgite. The thickness of MTZ varies from m-scale to over 500 m where dunite is the major phase and wehrlite is subordinate (Koga *et al*., 2001; Boudier and Nicolas, 1995). Gabbro sills are frequently present in MTZ. Dunite and wehrlite are found as later intrusive into the crustal section (Benn *et al*., 1988).

Andaman Ophiolite

Andaman Ophiolite occurs on the Andaman accretionary prism of the Indian-Eurasian convergent plate boundary. The age of the Andaman ophiolite complex is 95±2 Ma based on U-Pb geochronology of zircon from plagiogranites (Pedersen *et al*., 2010; Sarma *et al*., 2010). The origin of Andaman Ophiolite remains controversial. Several authors suggested that ophiolite was formed in a transitional geodynamic setting from Mid Oceanic Ridge (MOR) to arc environment (SSZ), where MORB mantle accreted to mantle wedge under subduction zone influence (Pal *et al*., 2011; Ghosh *et al*., 2013, 2014). Other studies suggested a shallow magma chamber origin, possibly beneath a slow spreading ridge (Ray *et al*., 1988; Srivastava *et al*., 2004).

In Andaman Islands, preserved ophiolite sequences show marked mineralogical and geochemical differences from north to south, especially in terms of their mantle sequence (Ghosh *et al*., 2013). The mantle peridotites in middle/ north Andaman Island mostly show lherzolitic affinity and rarely grade into clinopyroxene-bearing harzburgite (Ghosh *et al*., 2013). In contrasts, peridotites in the Rutland Island show harzburgitic nature (Ghosh *et al*., 2014). In Rutland Island the lithological assemblage represents Mantle Transition Zone (MTZ) sequence (Ghosh *et al*., 2014) composed of wehrlite, olivine rich troctolite, pyroxenite and gabbroic rocks.

Abyssal Residual Peridotite

Abyssal (i.e. seafloor) peridotite represents the lithospheric mantle composition (Salters and Stracke, 2004; Workman and Hart, 2005) exposed by thrusting on the seafloor at mid ocean ridges or transform faults. They have wide variation in composition which reflects mantle heterogeneity. They are mainly grouped into residual peridotite and veined peridotite. Peridotites without any interstitial plagioclase or cross cutting vein are classified as residual peridotite. Because, both the plagioclase and cross cutting veins are considered as evidence of melt addition (Warren, 2016). Due to least effect of melt-rock interaction, residual peridotite is widely studied as upper mantle representative following melt extraction.

Here, we compare the global residual peridotite from different MOR setting reported in Warren, (2016) with the peridotites from aforesaid ophiolites.

Petrographic Characteristics

As discussed in section 2, the mantle section of most of the ophiolites contains wehrlite, harzburgite, lherzolite and dunite as primary rocks. Dunite and harzburgite are in general more depleted compared to lherzolite in terms of elemental concentration. Harzburgiteis residual phase formed by melting of lherzolite and dunite is replacive in origin. Thin section studies of these rocks from the mantle section of the ophiolites reveal the melting and melt-percolation history. Though, in most of the scenarios, the rocks are variably altered, only partially preserved primary phases give an idea of the initial composition. In general, the peridotites from Josephine, Oman and Andaman have olivine, spinel, orthopyroxene (Opx), clinopyroxene (Cpx) and sometimes plagioclase as primary phases. At places, Cpx has given way to amphibole (tremolite) as an alteration product. Before going into the petrographic details of peridotites, it is noteworthy to mention that the rocks experiencing higher degree of partial melting have less primary Cpx compared to the rocks with lower degree of melting; because during fractional metilng, Cpx is one of a few first phases that goes into the melt. On the other hand, the occurrence of spinel and Cpx in interstices and on grain boundaries are believed to be a product of late stage melt percolation or metasomatism.

Josephine Ophiolite

In the lower peridotite section of Josephine ophiolite, lherzolites and harzburgites are the abundant ones. Occasionally, dunite is present in various forms e.g. podiform, lenses etc. According to Roux Le *et al.* (2014) the mantle section is devoid of plagioclase and contains less than 5% Cpx. The degree of serpentinisation is predominantly less than 40% for majority of the samples but it is higher at the base of the ophiolite. Lherzolite and harzburgite both show different kind of textures- mylonitic texture formed due to high temperature deformation and proto-granular texture developed as a result of solid peridotite residue which has experienced partial melting. On average, the Cpx content of the peridotites are around 5%, but lherzolites have around 13% of Cpx in it. Irregular shape of the grains and undulose extinction present in Opx, Cpx, and olivine minerals of harzburgite indicate that the rocks have undergone deformation at high temperature. The Cpx grains are mostly smaller in size than Opx. Spinels in lherzolites are present in the interstitial spaces around the pyroxenes and might indicate incongruent melting of pyroxene. The olivine and Opx are altered to serpentine at few places, but degree of alteration is more prominent in Opx compared to olivine which indicates the alteration temperature to be more than 300ºC because at this temperature Opx is more susceptible to transformation compared to olivine.

Oman Ophiolite

The petrography of mantle rocks from north, central and southern part of Oman ophiolite partially varies. The presence of basal lherzolites is reported from the northern and central part whereas, Cpx bearing harzburgites are found from southern Oman ophiolite (Takazawa *et al*, 2003; Khedr *et al*., 2014). The mantle section of central Oman ophiolite is mainly composed of lherzolite at the base and harzburgite with sporadic presence of dunite (Boudier & Nicolas, 1995). Two types of basal lherzolites were observed in the central part of Oman- one is massive with mylonitic structure (Type I) and the other (Type II) is foliated (Khedr *et al*., 2014). The effect of serpentinisation is more on type II lherzolites compared to type I. The mantle section is occasionally intruded by cross-cutting pyroxenite dykes (Takazawa *et al*., 2003). In general, these peridotites contain 0.5-14 vol% Cpx. Presence of Cpx in northern ophiolite is infrequent and they occur as narrow bands within harzburgites. The lherzolites from northern Oman don’t contain any plagioclase and spinel exist as interstitial grains similar to Josephine ophiolite. The Cpx is altered to hornblende at places in the lherzolites of central Oman ophiolite but within harzburgites, alteration has no effect on Cpx (Khedr *et al*., 2014). Sometimes, lamellae of Opx can be found within large Cpx grains and patchy appearance of Cpx is noticed within lherzolites. The harzburgites from central Oman preserve the primary texture of the grains having equigranular olivine surrounded by pyroxenes instead of week serpentinisation. On the other hand, harzburgites from northern Oman has experienced higher degree of serpentinisation and contain Cpx occasionally (Takazawa *et al*, 2003).

Andaman Ophiolite

The Andaman ophiolite consists of a deformed, residual mantle section with a thickness of more than 700 meter in north Andaman (Ghosh *et al*., 2014). This section contains highly serpentinized peridotites (Pal, 2011) and large chromite pods. The mantle section consists mainly of lherzolite, dunite and Cpx-bearing harzburgite. The composition of south Andaman ophiolite consists of mainly depleted harzburgites and Cpx bearing harzburgites, but the middle and north Andaman with: ophiolite comprise of lherzolite (Ghosh *et al*., 2013). Wehrlites can be found in the transition zone of the south Andaman ophiolite. Majority of the mantle rocks have experienced different degrees of serpentinisation ranging from 50-80 vol% in the Andaman Ophiolite (Pal, 2011). A considerable part of the rocks is coarse grained, showing interlocking texture. The grains present in these mantle rocks are often brecciated and the presence of serpentinite veins form a mesh texture (Pal, 2011). In middle and north Andaman, the spinels within mantle section and residual peridotites, are found in two forms- massive pods of chromite within mantle section and as accessory grain in the residual peridotites (Ghosh *et al*., 2013), and also show signs of mantle deformation. The residual spinel grains are embedded within serpentine matrix (Ghosh *et al*., 2013) and show resorbed margins with occasional euhedral grains (Pal, 2011). Within less depleted lherzolites at middle and north Andaman, olivine forms dunite pods and at places, olivine is replacing Opx forming embayed boundary of the relict pyroxene grain (Ghosh *et al*., 2013). But the occurrence of podiform dunite is much less compared to Oman ophiolite. Symplectite texture (intergrowth formed due to recrystallization of unstable phases) of spinel and Cpx can be seen within Opx of lherzolites and are believed to be formed from garnet. Although, this symplectite texture is more developed in north Andaman, it can be observed at other parts of the Andaman ophiolite too. Presence of exsolved lamellae of Cpx within Opx has been also observed. Wherlites in the south Andaman ophiolite transition zones contain less than 40% modal Cpx (Ghosh *et al*., 2014).

Abyssal Peridotite

The residual abyssal peridotite has experienced various degrees of alteration and depending on that, they have preserved mineral phases. Among the mineral phases, spinel is the most preserved one and olivine is the most altered one. While considering the rock types, dunites seem to be affected by alteration to a greater extent compared to others and only 3% of dunites contain Cpx (Warren, 2016). The harzburgites are the most abundant rock type within the abyssal peridotites globally and they contain less than 5 vol% Cpx. Garnet is normally not being found in the abyssal peridotites and the high temperature amphiboles are rare too (Warren, 2016). Low temperature amphiboles can be found as an alteration product.

Major Element Characteristics

Before going into the details of the major element chemistry of mantle rocks, it is noteworthy to mention some important parameters for better understanding of the major element chemistry. The Cr# ((Cr/(Cr+Al)) atomic ratio) of spinel is an important indicator of degree of partial melting in the mantle (Dick & Bullen, 1984). Cr being the compatible element in spinel structure, partial melting results in enrichment of Cr in the residual peridotite by raising the Cr#. On the other hand, Ti is very incompatible during mantle melting and goes into the melt. Thus, progressive partial melting of the mantle removes Ti from the solid and the residue becomes depleted with respect to Ti. Fo (forsterite) content or Mg# (Mg/(Mg+Fe) atomic ratio) of olivine is another useful parameter to constrain the degree of partial melting. Higher degree of partial melting generally increases the Fo content or Mg# of the rock.

Josephine Ophiolite

The Fo content of olivine of the peridotites varies from 90-91.9 comparable with the abyssal peridotite values estimated from spinel peridotites from slow spreading ridges. According to Roux Le *et al*. (2014) the Cr# of spinels shows a range from 16-69.5 and that exceeds the Cr# range of abyssal peridotite. The TiO_2 content of the spinels are low and ranges from 0.01-0.13. The pyroxenes present in the rocks are mainly diopside and enstatite. The Al_2O_3 content of these pyroxenes show a broad range from 1.1-5.3wt% and the Mg# varied from 90.2-93.9 which is quite high. The TiO_2 content of Cpx rich harzburgites and lherzolites are higher than the residual harzburgite. In the OSMA (olivine-spinel mantle array) plot (Fig. 1), most of the Josephine samples (Harzburgite) lie in the forearc peridotite field. There are a few lherzolites plot in the abyssal peridotite field (Fig. 1), showing less amount of partial melting. While the data from

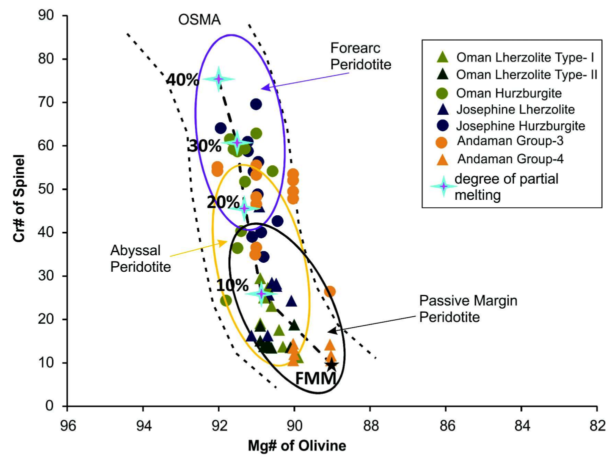

Fig. 1: Compositional relationship between Fo content of olivine and Cr# of coexisting spinel of peridotites from the Josephine, Oman, Andaman Ophiolite on olivine-spinel mantlearray (OSMA) plot of Arai, 1994b. Data sources are from Roux Le (2014), Khedr *et al.* (2014), Takazawa *et al.* (2003) and Ghosh *et al.* (2013)

this rock are plotted on the TiO_2 wt% in Cpx vs. TiO_2 whole rock, they show a nice correlation. There is a considerable amount of TiO_2 in Cpx but the whole rock TiO_2 concentration is low.

Oman Ophiolite

The Fo content of olivines from lherzolites in the northern Oman ophiolite varies from 90-92 indicating higher degree of partial melting whereas, the Cr# of spinel lies between 0.1-0.6, having the lower value of Cr# at the base (Takazawa *et al.*, 2003). These values overlap with the abyssal peridotites. Although, for most of the elements in lherzolites (northern Oman), the ranges are comparable to those of the abyssal peridotites. The Na content of Cpx in some of the lherzolites is higher than the abyssal peridotites and is present at the areas being affected by hydrothermal alteration or melt-rock interaction (Takazawa *et al.*, 2003). The TiO_2 content of the Cpx doesn't change much from sample to sample. The Mg# of olivine from the lherzolites of central Oman ophiolite ranges (90-92) and they show an enrichment in Al_2O_3 (1.9-3.12 wt%). The harzburgites in this area are more depleted in Ti, Na, Ca content compared to the lherzolites (Khedr *et al*., 2014). Major element trend of the peridotites from central Oman matches with the abyssal peridotite trend from the Indian and Pacific mid ocean ridges (Tazakawa *et al*., 2003; Niu, 2004). In the OSMAplot (Fig. 1) for Cr# of spinel vs. Mg# of olivine, Oman harzburgites mainly occupy the forearc peridotite field whereas, the lherzolites fall in the abyssal peridotite field. The spread of Mg# of olivine is tight for the Oman samples in Fig. 1. Further, the Oman harzburgite and lherzolite form two different clusters in the TiO_2wt% in Cpx vs. TiO_2 whole rock. The Oman lherzolite shows wider spread in the TiO_2 content and are enriched in TiO_2 compared to Oman harzburgite.

Andaman Ophiolite

The chromites from mantle peridotite and dunites have high Al content of 32-49.6 wt% (Pal, 2011). Two types of podiform chromites were identified based on their Cr_2O_3 content: one with high Cr_2O_3 content of 54-60% and the other with low Cr_2O_3 content of 39-42% (Ghosh *et al*., 2013). Additionally, the chromian spinels were characterized into four distinct groups on the basis of their Cr#. The group 1 consists of podiform spinels from Rutland (south Andaman) with high Cr# (0.7) whereas the group 2 is from north Andaman podiform chromites containing a range of Cr# from 0.48 to 0.79. Group 3 has the residual spinels from Rutland with medium Cr# from 0.37 to 0.55 and group 4 consists of residual spinel grain from middle and north Andaman having a lower Cr# (0.09-0.23). All these four groups of spinels have different chrome Mg# as well, ranging from 0.41 to 0.81 (Ghosh *et al*., 2013). The TiO_2 content of group 1 and group 2 spinels (0-0.5 wt%) are higher than group 3 and 4 (0-0.25 wt%). The Mg# of olivines from middle and north Andaman varies from 0.71 to 0.81. The wherlites form south Andaman contain olivines with high Fo mole% of 90 and low NiO ($\leq$0.2 wt%) and CaO ($\leq$ 0.05wt%) content (Ghosh *et al*., 2014). Cr# vs.Mg# for all the samples from group-1 to Group-4 are shown in Ghosh *et al*. (2014). Herein Fig. 1, we have only considered plotting peridotite samples from Rutland (group-3) and North Andaman (group-4). The datashows large variation in Cr#. The data plots into two separate regions, one within the area of passive margin peridotite and the other shows a mixed signature of abyssal and some influence of forearc peridotite.

Abyssal Peridotites

A range of Cr# exists for the abyssal peridotites but they don't exceed 60 and varies form 10-60 in residual peridotites (Fig. 1 and Fig. 5 in Warren, 2016). Generally, the Cr# in lherzolite is quite low and has a limit of 30 whereas the harzburgite covers the whole Cr# range mentioned above. The TiO_2 concentration normally do not cross 5wt%.

Characteristics of REE and Trace Elements Composition of Clinopyroxene

Josephine Ophiolite

Clinopyroxenes are generally enriched in HREE (Heavy Rare Earth Element) and depleted in LREE (Light Rare Earth Element) in Josephine peridotites. HREE concentrations of clinopyroxene in Cpx rich Harzburgite/Lherzolite is 6-7 times higher than chondritic values whereas harzburgites are <2 times lower than the chondritic values (Fig. 2A). Harzburgite have variable LREE concentrations however, Cpx rich Harzburgite/Lherzolite and harzburgite have similarly low LREE concentrations. This study observed that the lherzolites are LILE (Large Ion Lithophile Element) enriched and some of the HFSE element like Zr is depleted and a sharp Nb peak is observed (Fig. 2B). The Cpxs in harzburgites are overall depleted in trace element concentrations showing LILE enriched and depleted HFSE patterns (Fig. 2B).

Oman Ophiolite

REE and trace element patterns of Cpx are plotted from Type I and Type II lherzolite, harzburgite from central Oman (Wadi Sarami, Khedr *et al*., 2014) and northern Oman (Fizh block, Takazawa *et al*., 2003) ophiolite (Fig. 2).

REE content of Cpx in Oman lherzolite varies

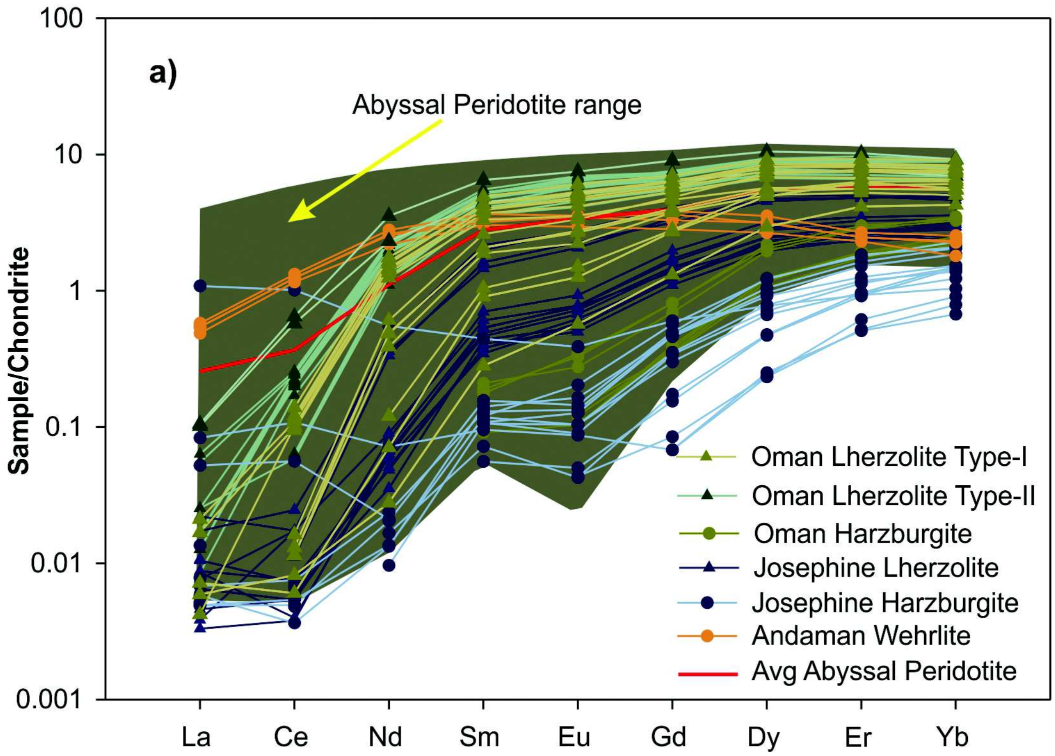

Fig. 2A: Rare Earth Element patterns of clinopyroxene normalised to chondrite (Sun and Mc Donough, 1989) from Josephine, Oman, Andaman and abyssal peridotites

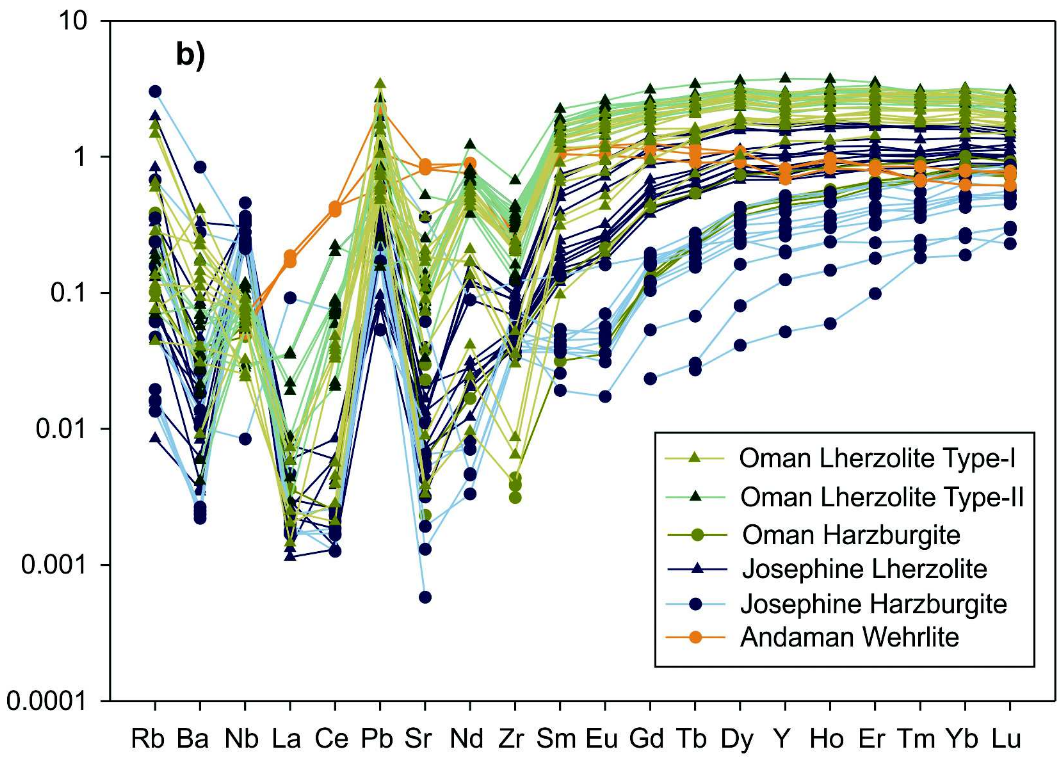

Fig. 2B: Multi Element patterns of clinopyroxene from peridotitic rocks normalised to primitive mantle (Mc Donough *et al*., 1992) from Josephine, Oman, Andaman ophiolite. Data sources of figure 2 are from Roux Le (2014), Khedr *et al*. (2014), Takazawa *et al*. (2003), Ghosh *et al*. (2014) and Warren (2016 and references therein)

from ~5 to 10 times above chondrite. Both Type I and Type II lherzolite from central Oman ophiolite show similar LREE/HREE ratio [$(Ce/Yb)_n$ = 0.007 to 0.028] in Cpx where LREE is strongly depleted and HREE is enriched (Fig. 2A). Only MREE is slightly higher in Cpx of Type I lherzolite than HREE. Type I lherzolite from northern Oman ophiolite shows flat to spoon shaped REE patterns with slight inflection in La and Ce (Fig. 2A of this study and also see Takazawa *et al*, 2003, Fig. 13). This is a typical indication of depleted melt percolation (e.g. Verniéres *et al*., 1997). REE concentrations and patterns of Type II lherzolites from northern Oman ophiolite are very similar to Type II lherzolites of central Oman ophiolite and abyssal peridotites from normal ridge segment (Fig. 2A).

REE contents of Cpx harzburgites from both Central Oman and northern Oman ophiolite have lower concentrations compare to lherzolites. However, their REE patterns are similar to lherzolites with strong depletion in LREE (La, Ce undetectable) and enrichment in HREE.

Trace element patterns of Cpx in both Type-I and II lherzolite and harzburgite from central and northern Oman ophiolites show similar trend (Fig. 2B). They are enriched in fluid mobile elements (e.g. Rb, BaPb) and depleted in HFSE (Zr, Hf, Nb). However, this study observes that the Type I lherzolite from central Oman ophiolite is relatively more enriched than rest of the lherzolites of other study areas. Trace element abundances of Type-II lherzolites from both central and northern Oman are very similar. Harzburgites show lower abundance of trace elements.

Andaman Ophiolite

REE patterns of Cpx from olivine rich troctolite, wehrlite, gabbro and clinopyroxenite are so far only reported by Ghosh *et al*. (2014). But here we mainly focus on peridotite, i.e. wehrlite (Fig. 2A). Clinopyroxene has low REE abundance with slightly LREE depleted and relatively flat to depleted HREE pattern. The HREE depletion may suggest that the melting took place in presence of garnet. CPxs in wehrlite are LILE enriched (Fig. 2B) and they have Eu negative and Sr positive anomalies. That signifies early crystallisation of Cpx than plagioclase from a trapped melt and in addition possibly the first crystallising mineral from melt (Ghosh *et al*., 2014).

Abyssal Peridotite

Globally, REE concentrations of residual peridotites show a wide range from quite high-close to model DM source to very low (Fig. 2). Trace element data are sparse from abyssal peridotite mostly due to their low concentration. Lherzolite shows consistent pattern and restricted range of REE concentrations. Harzburgites show wider range of composition starting from the similar composition of lherzolites to very low concentrations. Harzburgites mainly from EPR (East Pacific Rise) are refractory. Those are cross cut by gabbro veins and show negative Eu anomalies (Dick and Natland, 1996) implying plagioclase crystallisation.

Are SSZ Peridotites Melting Residues?

However, Oman peridotites formed in transitional/mix environment and Josephine peridotites formed in SSZ but in both cases partial signature of MOR overlap with SSZ. This is because, in case of SSZ environment first expression of magma formation is MORB like due to initial extension before initiation of subduction. The Cr# in spinel increases from lherzolite to harzburgite. In Central Oman Cr# in spinel increases from Type-II to Type-I lherzolite to harzburgite although, there is no significant difference observed in Cr# in spinel in both types of lherzolites. In northern Oman, the Cr# in spinel is similar in Type-I and type II lherzolite but later is somewhat lower in range (Fig. 1). Josephine and Andaman peridotites follow the similar trend. Roux Le *et al*. (2014, in Fig. 4a) shows that Cr# in spinel steadily increases with decreasing abundance of clinopyroxene in case of Josephine peridotite.

Residual peridotites with high Mg# in olivine along with higher Cr# in spinel indicate a significant amount of partial melting. As the Cr# of spinel remains mostly unaffected by percolating melt or fractional melting events, it is a good indicator of melting residues. Partial melting preferentially removes Al and Ti from spinel, but Cr get enriched over time as it remains in the solid during melting. So, higher Cr# suggests that the rock has experienced high degree of partial melting. As discussed in the major element chemistry section (or section number), all of the three ophiolites

(Oman, Josephine, Andaman) have higher Cr#. Different Cr# indicates different degrees of partial melting. On the other hand, Mg# of olivine also increases with increasing partial melting, but this cannot be used alone as a probe. Further, in the OSMA plot (Fig. 1) majority of the Josephine samples and Oman harzburgites fall in the forearc peridotite field which has experienced at least 18% of partial melting. Without the input of water, this high amount of partial melting is not possible. The abyssal peridotites (adiabatic melting) experience partial melting ranging from less than 10% to 20% and the Cr# is less than 6. At the subduction zones, the peridotites experience higher degree of melting because of continuous flux of water. Therefore, the peridotites from three different localities with low Al and Ti with high Cr content in spinel indicate melting residues.

Refertilisation and Late Stage Metasomatism

Refertilisation is one of the post melting modifications occurs due to percolating or inefficiently extracted melt that crystallises in interstices and on grain boundaries. Here, we discuss the overall signature and effect of post melting modifications of the aforesaid ophiolites.

Josephine ophiolite has an established supra-subduction zone origin. Therefore, Josephine ophiolite provides direct understanding on the nature of melting and post melting effects that might occur in case of SSZ ophiolites. According to Roux Le *et al*. (2014) field data can reveal a lot about melting condition especially in case of Josephine Ophiolite. Melting of mantle can occur either by increasing temperature or by addition of water. In the former case, variation in degree of melting (~ 15%) could occur due to higher temperature (150°C), in turn gives rise to large scale transitional outcrop between the fertile and depleted peridotite. On the other hand, if water is responsible for the melting of mantle, the solidus temperature of the mantle wedge decreases and facilitates partial melting that in turn leads to small scale lithological variations. However, experimental studies show that little amount of water is also able to produce different degree of melting of peridotite (Kelemen *et al*., 2003, Gaetani and Grove, 1998 etc). Both small and large-scale lithological variations are present in Josephine peridotites. The large-scale variations are attributed to the presence of water. Several authors (e.g. Rampone *et al*., 1997; Muntener *et al*., 2004; Le Roux Le *et al*., 2007) suggested that the refertilisation caused the sharp lithological variations. Roux Le *et al*. (2014) suggested that in addition to refertilisation melt flux is also a probable reason for these sharp metre scale lithological variations in peridotite. Figure 3 shows that clinopyroxenes from Josephine harzburgite plot in the field of supra-subduction zone suggesting a high degree of melting under hydrous condition. However, their quantitative melting models suggest that Josephine peridotite cannot be produced solely by hydrous melting unless otherwise the mantle wedge is replenished by fluids during melting, i.e. flux melting. Therefore, variable degree of flux melting can produce the depleted harzburgite to Cpx rich harzburgite and lherzolite rocks. According to the authors, the harzburgites with depleted REE requires 20-23% flux melting. They have also suggested by using models that a small percentage of boninitic melt (<1%) refertilised the depleted harzburgites leading to the enrichmentof the LREE in Cpx.

Oman ophiolite has combined/transitional origin. Central Oman ophiolite is similar to MORB type representing a fragment of Tethyan oceanic mantle, which was detached along the oceanic fracture zones and exposed along transform or detachment faults (Khedr *et al*., 2014). The study shows convex upward REE patterns of Cpx from central Oman peridotites show depleted LREE (Fig. 2A) very similar to abyssal peridotite. Yb, Dy, Ti and Cr concentrations also confirm their residual origin similar to abyssal peridotites (Johnson *et el*., 1990; Johnson and Dick, 1992; Hellebrand *et al*., 2001, 2002 etc). Enrichment of fluid mobile LILE compare to HFSE and LREE in Cpx (Fig. 2B), absence of textural evidence of melt percolation (presence of interstitial Cpx) suggesting no effect of melt refertilisation. Opx also behaves in similar fashion to Cpx. Melt modelling also confirms no effect of refertilisation in these rocks. Based on the line of evidence, Khedr *et al*. (2014) suggested two melting series and sources for the generation of Type-I and II lherzolite because they have overlapping characters in degree of partial melting, chemistry of pyroxene (Figs. 2 and 3), spinel and olivine (Fig. 1). They have inferred that the Type-I lherzolite which is closely similar to abyssal peridotite in nature were formed at the base of oceanic lithosphere during Neotethyan exapansion. In contrast, Type-II lherzolite are thought to be a remnant asthenospheric material

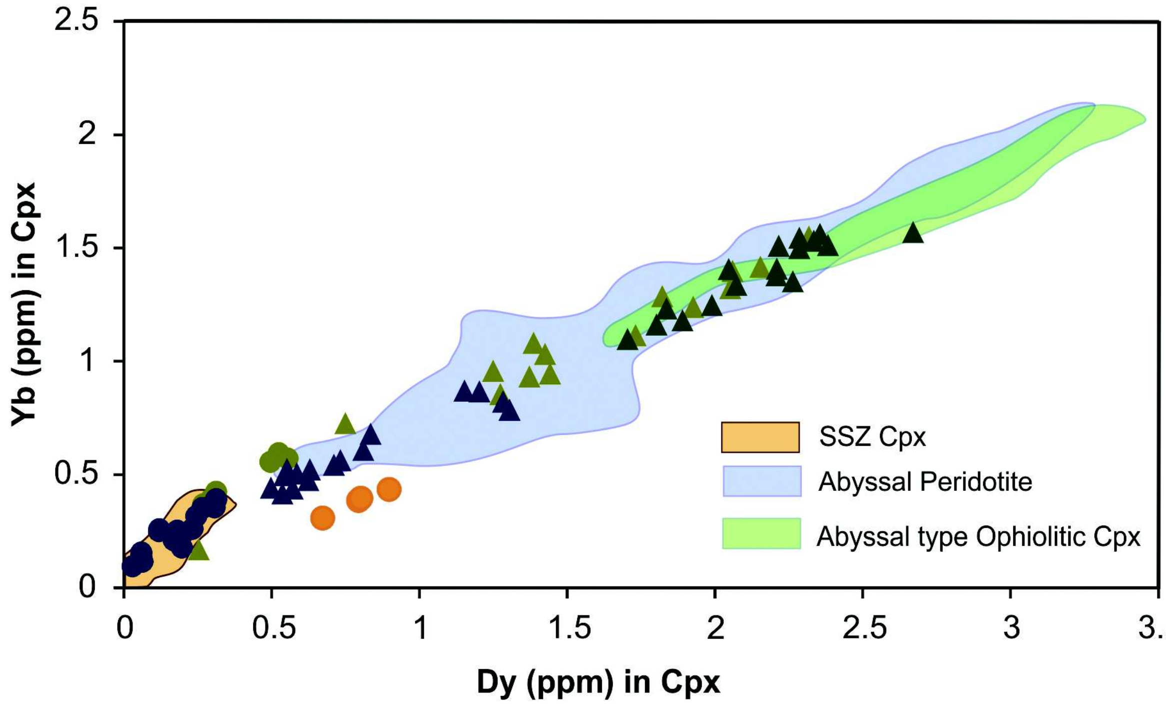

Fig. 3: Dy-Yb (ppm) concentrations in clinopyroxene from Josephine, Oman, Andaman peridotites. The fields are compiled by Jean *et al.* (2010) from their data and from references therein. Data sources are compiled from Roux Le (2014), Khedr *et al.* (2014), Takazawa *et al.* (2003), Ghosh *et al.* (2014)

trapped by the base of oceanic lithosphere during detachment and obduction. HREE in Cpx and spinel composition suggests 3-10% melting of Type-I lherzolite, 1-5% melting of Type-II lherzolite and 15% melting for harzburgites using near fractional melting model and Fig. 1. However, the peridotites are not affected by refertilisation; post melting metasomatic effects are observed resulting in the replacement of Cpx by hornblende and enrichment of LILE.

On the other hand, northern Oman ophiolite (Fizh Block) may have formed under SSZ setting (Arai *et al*., 2006; Tamura and Arai, 2006) during intra-oceanic collapse and closing of a sea floor spreading ridge (Dilek *et al*., 2008). The weakly spoon shaped REE pattern of Cpx (Fig. 2a) and structurally close to a falling ridge system (Nicolas *et al*., 2000) could result refertilisation of lithospheric mantle by MORB melts in northern Oman ophiolite. The clinopyroxenes are highly depleted in incompatible elements and slight enrichment of whole rock REE with a slope from HREE to LREE in Type-I lherzolite resulted due to 12-18% melt extractions from a little garnet bearing source (Takazawa et al, 2003). According to Takazawa et al, (2003) this slight LREE enrichment attributed to the interaction of LREE enriched melt/fluid with residues at low melt/rock ratio. In contrast, incompatible elements in whole rock (not shown) and in Cpx are higher in abundance in Type-II than Type-I lherzolite. The high Na_2O content of the Cpx and rock, LREE depleted and flat MREE and HREE whole rock patterns suggested that the Type-II lherzolite formed by mixing where residual peridotite (Type-I) was refertilised by LREE depleted melt, generated by 10-12% incremental melting of a fertile source.

Chromianspinels from Andaman peridotites reveal a SSZ (?) history (Ghosh *et al*., 2013). Peridotites from Rutland (Fig. 1) to south Andaman (Ghosh *et al*., 2013) are typically of forearc type representing a SSZ setting. In contrast, peridotites from middle and north Andaman are similar to abyssal peridotites (Fig. 1). The composition of coexisting pyroxenes and spinels represent a nearly continuous depletion trend from north to south suggesting that the peridotite at south Andaman suffered a higher degree of partial melting than peridotites at north Andaman. Wehrlites mentioned above are from a mantle transition zone. In Fig. 3, they are slightly out of the Dy-Yb array, however very close to abyssal

Table 1: Comparing charateristics of three different ophiolites

Characteristics	Josephine	Oman	Andaman
Age	157 Ma	95 Ma	95±2 Ma
Formation	Supra-subduction zone	Supra-subduction and MOR (Transitional)	Supra-subduction zone (?)
Lithology	Harzburgite & lherzolites are abundant, less dunite; No plagioclase; less than 5% cpx in most of the peridotites; interstitial spinel	Lherzolite and Harzburgite with sporadic dunite; 0.5-14 vol% Cpx in peridotites; interstitial spinel; no plagioclase reported	Abundant lherzolite, harzburgite, dunite with occasional presence of wherlite and chromite pods; less than 40% modal Cpx in wherlites
Deformation	Presence of mylonite in lherzolite; undulose extinction in opx, cpx and olivine	Presence of mylonites and foliation within lherzolites	Grains in the rocks are often brecciated
Degree of serpentinization	Less than 40%	serpentinization increases from south to north from being week (MOR) to highly serpentinized (SSZ)	50-80 vol%
Fo content of Olivines	90-91.9	90-92	0.71-0.81
Cr# of spinels	0.16-0.69	0.1-0.6	Four different groups havening Cr# from 0.09-0.79
Ti content	0.01-0.3 in spinels; TiO_2 content of Cpx harzburgites and lherzolites are higher than residual harzburgite; bulk rock TiO_2 content is less than what present within pyroxenes	The lherzolites and harzburgites have very different TiO_2 content	0-0.5 wt%
Mixed signature?	The harzburgites plot in the forearc peridotite region whereas the lherzolites plot in the abyssal perodotite region (Fig. 1)	The harzburgites plot in the forearc peridotite region whereas the lherzo-lites plot in the abyssal perodotite region (Fig. 1)	Majority of the peridotites plot both in the abyssal and forearc field (Fig. 1) But the data are mainly obtained from Wherlite
Trace element of CPx	CPx in lherzolites are LILE, HREE enriched and depleted in HFSE like Zr and LREE whereas,CPx in harz-burgites are overall depleted in trace element concentrations with similar patterns.	CPx in lherzolites are enriched in LILE, HREE and depleted in HFSE, LREE. Type I lherzolite from central Oman ophiolite is relatively more enriched than rest of the lherzolites of other study areas of Oman ophiolite. CPx in Harzburgite shows lower abundance of trace element than Lherzolite. Type I lherzolite from northern Oman ophiolite shows flat to spoon shaped REE patterns typical signature of depleted melt impregnation	CPx in wehrlite has depleted LREE and relatively flat to depleted HREE pattern. CPxs in wehrlite are LILE enriched and they have Eu negative and Sr positive anomalies

peridotite composition, similar to Josephine lherzolites. Ghosh *et al*. (2014) suggested that the clinopyroxenite-wehrlite association was formed due to variable degree of mixing between extremely Cpx saturated melt generated by melt-mantle interaction and fresh magma increments. Wehrlite represents the residue left after the formation of clinopyroxenite. Hydrous melt impregnation and transformation of dunite to olivine rich troctolite was identified (Ghosh *et al*., 2014). Here, we suggested this phenomenon as clear indication of melt refertilisation.

Concluding Remarks

Ophiolitic peridotites are mainly composed of lherzolite, harzburgite and sometime wehrlite. Lherzolite represents fertile mantle whereas, harzburgite represents the mantle residue after melting of fertile mantle and are depleted in nature. Higher the melting degree, the more depleted peridotite will be. Andaman wehrlite represents the mantle transition zone rock and a melting residue. The influence of fluid percolation in fore arc peridotites, especially those formed in SSZ, are quite prominent. Melt percolation might results in refertilisation of peridotites. The REE and trace element patterns of secondary Cpx depend on the nature of percolating melt which can be either depleted or enriched. Oman ophiolite represents a complex polygenetic origin and Andaman ophiolite too have controversial origin (SSZ?) belonging to the same orogenic system, whereas Josephine ophiolite is part of the Caledonian orogeny, representing a clear influence of SSZ. However, Andaman peridotites are comparatively least studied so far and more discoveries are needed to unfold, in future. In this review, we have summarised some of the possible characteristics of refertilised peridotite below which will help in identification of peridotites bearing SSZ influence.

i) The rocks will have high Cr# in spinel and high to moderate Mg# in olivine.

ii) The rocks will have secondary Cpx along grain boundaries of other minerals (mainly along orthopyroxene) or within interstices.

iii) LILE will be enriched whereas REE will be comparatively depleted.

iv) Higher the melting degree the depleted in nature it would be.

v) Majority of depleted peridotite (mostly Cpx poor harzburgite) forms in SSZ setting under the influence of slab derived melt/fluid.

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