CHAPTER 6

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6.1 CHAPTER OVERVIEW

Ophiolite is segment of former oceanic crust and mantle pieces which is tectonically exposed on the Earth surface. It display complex internal structure and preserve wide range of chemical heterogeneity. The mantle part of Nidar Ophiolite Complex (NOC) have the thickest (~7 km) best known exposure of ultramafics. These mantle rocks show unique internal structures and wide range of mineralogy. The aim of the present thesis was to characterize the complete mineralogy from basal part of NOC ultramafic section. The outcome of this thesis demonstrates conclusively that the NOC ultramafics retains signature of mantle transition zone (410 – 660 km). This deep mantle rocks are potential to study the nature of upper mantle convection. Besides, ophiolite also bear signature of steep and deep subduction of oceanic (Tethys) slab beneath Asia which has a great significance in Himalayan geodynamics. The evidences for sudden release of water in deep mantle may also put a significant effect in orogenic processes. This thesis work also recognizes first identification zone of natural CO₂ sequestration in the Himalaya.
6.2 RESEARCH SUMMARY

On the basis of in situ micro inclusion and texture, present research suggests ultra-deep origin for the some portions of peridotites of the Nidar Ophiolite Complex of the Indus Suture Zone (ISZ) in western Indian Himalaya (Fig 2.3). The reported systematic mineral phase transitions are yet-to-be recognized in terrestrial rocks as it may be considered originating from the 410 - 660 km deep mantle transition zone.

Detail mapping of Nidar ophiolite (Indus suture zone, SE Ladakh, India) reveals, it is one of the thickest ophiolite suits across the globe. In Nidar valley it is at least 10 km thick and some places it may increase. The ophiolite is consists of three units from top to bottom – pillow lava with volcanics and chert, gabbroic middle part and lower most ultramafic unit. The ultramafic unit (~ 7 km thick) is composed of various types of peridotites (for detail – see chapter 2: Fig 2.3). Such thick mantle section of the basal part of Nidar ophiolite is unique of its own as compare to the other ophiolite suite.

On the basis of field occurrence, petrography and mineral chemistry data relatively primary rock bodies of the mantle section of Nidar ophiolite have been identified. From field occurrences, the ultramafic rocks of Nidar ophiolites can be divided into three types – (1) the dunite channel which cut the mantle section of Nidar ophiolite, (2) the ultramafics carried by the dunite channel (3) ultramafics cut by the channelized dunite (Fig 2.7). After comparing mineral chemistry data of essential minerals (olivine, pyroxene and spinel) of three types of ultramafic rocks show significant differences with the channelized dunite. It is found that the chemistry of essential minerals of
dunite body is significantly different from the ultramafics carried by the dunite channel and the ultramafics cut by the dunite channel. In the dunite the Mg\# of olivine is ~ 93.5\%, Mg\# and Cr\# of spinel is ~ 62.4 – 68.66\% and 48.38 – 61.34\% respectively (Table 4.1). The lherzolites cut by the channelized dunite show Mg\# of olivine is ~ 90 – 90.3\%, Mg\# & Cr\# of spinel is ~ 5.46 – 8.1\% & ~ 85.95 – 90.28 \% respectively (Table 4.5). The harzburgites cut by the channelized dunite have Mg\# of olivine is ~ 91 – 91.22\%, Mg\# & Cr\# of spinel is ~ 44.66 – 45.02\% & ~ 21.45 – 21.86 \% respectively (Table 4.6). The lherzolites carried by the dunite channel display Mg\# of olivine is 90 – 91\%, Mg\# and Cr\# of spinel is 48.9 – 52.8\% and 54.5 – 70.3 \% respectively (Table 4.2, 4.3, 4.4). In a word it can be said that Mg\# of olivine and spinels of the dunites are much higher than the other ultramafics of the Nidar Ophiolite. This implies the ultramafics may be much more primitive than the dunite (Kelemen 1995). Within the two groups of ultramafics (group 2 – ultramafics carried by the dunite channel and group 3 – ultramafics cut by the dunite channel) further classification is made on the basis of petrographic studies. Some rock bodies from both groups of ultramafics bear unusual micro textures and inclusions which could be indicative of primitive signatures.

In an enstatite of group 2 (xenolith – carried by the dunite channel) lherzolite (sample no – 1M1) the primary relict is discovered which show unique co-existence of square shaped coesite + C2/c clinoenstatite + disordered Fe$_2$O$_3$ + disordered carbon and Fe$_2$O$_3$ glass (Fig. 4.8). All the phases are characterised by Laser Raman spectroscopy and Electron Probe Micro analyser. In another lherzolite body (1NU27; adjacent to the 1M1 lherzolite) lamellar C2/c
clinoenstatite inclusions in orthoenstatite (Fig 5.10). Cr – spinel exsolution needles in olivine (Fig 5.8) and high pressure Mg$_2$SiO$_4$ (retrogressed wadsleyite) in Cr – spinel (Fig 4.8 E. F. 4.18, 4.19) are discovered. Presence of Cr – spinel exsolution needles in olivine of high pressure rocks has been earlier interpreted as result of decompression of β-Mg$_2$SiO$_4$ (Dobrzhinskaya et al., 1996). However this interpretation was questioned very soon (Hacker et al., 1997). In the present work the presence of high pressure Mg$_2$SiO$_4$ and C2/c clinoenstatite confirm the original pressure could be as high as mantle transition depth (410 – 660 km; 14 – 22 GPa). Though high pressure mineralogical evidences have been reported from other ophiolites (Robinson et al., 2004; Yang et al., 2007; Yamamoto et al., 2009; Trumbull et al., 2009) but these evidences suggest a systematic mineral phase transition from mantle transition zone and thus infer a progressive upwelling in a spreading center. The given evidences in this thesis advocate for ultra – deep origin of relict mineral phases in the lower ultramafics of the NOC and their P-T stability relations (Fig. 6.1) allow a tentative exhumation pathway of these mineral phases. For the system MgO – FeO - SiO$_2$, this pathway, the adiabat, terminates beneath the mid-ocean-ridge basalt eruption temperatures of ~1200°C. Data suggest this pathway originates from mantle transition zone depths, passes through the stability fields of wadsleyite, continuing successively through high-pressure clinoenstatite field, the stability field of coesite, and finally terminates in the orthoenstatite field (Fig. 6.1, 6.2).
Fig. 6. The P-T path of the relict grains’ journey from place of origin to final emplacement in the peridotitic host beneath the ophiolitic volcanic crust. Inferred adiabat as functions of pressure (P) and temperature (T) for the system MgO – FeO – SiO₂ starts from mantle transition zone, ending at oceanic spreading center. The representative phase diagrams are adapted from Pacalo and Gasparik 1990, Gasparik 1990 Shim and Duffy 2001 and Presnall and Gasparik 1990. Forsterite (a) – Wadsleyite (β) – Ringwoodite (γ) Mg₂SiO₄ phase boundaries are adapted from Katsura and Ito 1989, Kirby et al., 1991 and Akaogi et al., 1989.
It can be concluded that some of the mantle peridotites below the Nidar ophiolite show evidence of high temperature - pressure recrystallization, plastic deformation and solid state flow began their journey in the mantle transition zone depths of 410 – 660 km before arriving beneath the ophiolitic volcanic crust at oceanic ridges.

This study has obvious implications for the nature of upper mantle flow and sources of ocean-ridge basalts in a spreading center (Fig 6.2). Several studies related to this study previously reported ultra-high-pressure minerals, such as diamonds, coesite, high-pressure form of TiO₂ and other minerals in chromitites of a Tibetan ophiolite (Robinson et al., 2004; Yang et al., 2007; Yamamoto et al., 2009; Dobrzhinetskaya et al., 2009) and more recently the high-pressure polymorph of olivine, ringwoodite, found as inclusions in diamond of a Brazilian kimberlite (Pearson et al., 2014). Another group of micro-mineralogical studies in peridotites from continental collision zones has established exhumation of the host peridotites from 300 - 400 km depths in the mantle (e.g. Dobrzhinetskaya et al., 1996, Liou et al., 2007). The current study, however, can be distinguished from previous work by the discovery of a unique set of ultra-high-pressure mineral assemblages that demonstrate contiguity in their pressure- temperature stability space, linking the mantle transition zone to the ocean ridge-formed basaltic crust (Fig 6.2). Unlike previous studies that reported minerals of high- pressure origin in similar rocks, the report here a set of minerals; some newly discovered that shows a continuous pathway from the mantle transition zone to the uppermost mantle region. These minerals began their journey from the transition zone upwards
by solid-state flow, arriving below the ophiolite’s volcanic crust at ocean ridges (Fig 6.2).

The observed orthoenstatite – C2/c clinoenstatite mineral phase transition has implications on sampling the “X – discontinuity” because the phase transformation of (Mg,Fe)SiO₃ pyroxene from orthorhombic (Oen) to monoclinic (Hcen) structure due to compression (for a typical composition with Fe# ~ 10%; Woodland 1998) takes place at a depth of 240 Km (P > 8 GPa, T ~ 900°C; Gasparik 1990).

Presence of aliphatic hydrocarbon as fluid inclusions and volatiles along with carbons in ultra-deep lherzolites indicate a highly reducing environment in mantle transition zone depth (Fig 5.11, 5.12, 5.13). Textural evidences also infer that Fe₂O₃ and its glass is also present as primitive material in 1M1 lherzolite (Fig 4.15, 4.16). It has been shown by experimental studies that at > 250 km depth mantle is metal enriched (Rohrbach et al., 2007). But there was lack of evidences in nature. Present study shows dominance of iron oxide in mantle rocks which is deeper than X discontinuity depth (220 – 250 km).

Signature of serpentine dehydration is observed in peridotites which are cut by the dunite channel. The reaction textures reveal prograde transition from serpentine to olivine + orthopyroxene assemblage occurs in ultramafic rocks of Nidar Ophiolite. In serpentinite primary phase obtained as relict serpentine included in an orthopyroxene showing diffusing margin with host (Fig 5.16 A). The serpentinized matrix around that orthopyroxene grain indicates later hydration event.
Fig. 6.2. Probably in an ancient intra-oceanic arc the process was initiated by a deep oceanic subduction followed by dehydration of serpentines released a huge amount of free water. The water was responsible for melting in mantle wedge. This process created a vacuum in mantle which attracted the regular mantle flow towards the open ‘window’ in the pre-Himalayan intra-oceanic arc where the deep Earth phases are emplaced on to the surface. The flow began its journey from the transition zone upwards by solid – state flow, arrived below the ophiolite’s volcanic crust at spreading center in an intra-oceanic arc.
In the fresh (~20% serpentinized) peridotites, bladed mat serpentines rimmed by quenched melt (?) are characterized as primary serpentine occurring within olivines and pyroxenes (Fig 5.15). The secondary serpentines occur along veins and exhibit mesh texture. The chronological sequence (primary serpentine olivine + orthopyroxene assemblage secondary serpentine) infer serpentine break down to produce olivine + orthopyroxene and release water at mantle depths during subduction of serpentinized oceanic lithosphere. These fluids ascend into the overlying mantle wedge which may be responsible for the hydration and melting. In peridotites two stages of hydration before melting is obtained and it is characterized by crosscutting relationship of veins and their different morphology (Fig 5.14). Different stages of olivine and orthopyroxene are obtained which are characterized on the basis of relict polyphase olivine inclusions in orthopyroxene and vise versa (Fig 5.14 D). These melting and metasomatism events advocate for fluid release from a subducting slab into the overlying mantle wedge and serpentines are possibly the principle source of fluids and volatiles. Within the peridotites which are cut by the dunite channel a garnet bearing serpentinite is noticed (Fig 5.16 B). Some places the garnets bear includes serpentines. This suggests for deep subduction of serpentinites to release water at higher mantle depth (~ 6 GPa). The mineralogical evidences advocate for probably a steep and deep oceanic subduction in early stages of Himalayan orogeny. Geochemical signatures from ophiolite earlier suggested an intra-oceanic arc origin for Indus suture zone ophiolites (Maheo et al., 2004) at around 140 Ma (Ahmed et al., 2008). The dehydration reaction produced high volume of water in overlying mantle wedge result in melting and ascent of the buoyant mantle to create the crustal
part and some portions of the mantle part of the Nidar ophiolite in an intra-
oceanic setting.

The dunite body in the NOC is ~ 3 km thick and covers 10s of km² surface
area and the outcrop surface underwent carbonation of serpentine. The outer
surfaces of dunite body have been modified by heavy alteration process. It has
abundant magnesium silicate (olivine), hydrated silicates (serpentine) and
carbonates (magensite). This dunite has been through a series of deformation
and alteration process. The degree of alteration is less dense and penetrative in
the deeper part of the dunite body (Fig 4.2). However, the alteration and vein
formation is seen dramatically increased at the shallow level of dunite (Fig 4.2).
This alteration process controls the conversion reaction of dunite
(forsterite rich olivine) to serpentine (lizardite and amount antigorite). This
conversion is a slow geological process, which is manifest by low temperature
condition: 330 to 440°C (Khalepp and Burd 1985), would suggests the
reaction of hydrothermal fluids with olivine rich dunite at depth. In contrast,
the newly formed carbonate veins in shallow weathering zone of dunite show
young and brecciated massive in character. These 1-10 cm thick young
massive veins are characterized by magnesite, brucite and low temperature
lizardite. Eventually, thin veins of carbonate on the dunite erode continuously
and subsequently renew by alteration. Serpentine to carbonate conversion is
driven by carbonation reaction by near surface CO₂ and dissolved CO₂ in the
rain and snow melt water and this reaction progresses preferably at low
temperature condition (Power et al 2007, Kelemen 2011). At places, a
crystalline carbonate vein has also been recognized as dolomite and
magnesite. The veins eroded less effect and formed at moderately higher
temperature and deeper depth. Oxygen isotopes analyses have been applied on
those crystalline veins to constrain the indirect interpretation on the initial
temperature of carbonation reaction on the altered dunite for CO₂ capture and
storage. The same approach was taken by Kelemen and Matter (2008).
Assuming that, the crystalline veins may establish isotopic exchange
equilibrium with infiltrate fluids. The higher δ¹⁸O 17.3‰ values signify
alteration of magnesite and Ca-Mg dolomite formed from serpentine relatively
at lower temperature (as per Chako and Denies 2008). It is also noticed
elsewhere, the rate of carbonation is much faster when serpentine formed at
low temperature condition. It attributed isotopes fractionation during diffusive
CO₂ uptake from atmosphere condition (Hammer et al 2005). This result
matches with carbonation of Oman peridotite (Kelemen 2008). With above
data set and oxygen isotopes value on altered ultramafic (dunite) of NOC, it
can be inferred that the rate of the carbonation of altered dunite is controlled
by low temperature with the sequestration of atmospheric CO₂.
6.3 MAJOR CONTRIBUTIONS FROM THE PRESENT STUDY

The results obtained from this thesis can be compiled in following points –

➢ Details mapping reveals that NOC is the one of thickest known ophiolite section on Earth surface.

➢ The plan view of Nidar valley is an “eye” shaped which is the main reason for this abnormal high thickness.

➢ The ultramafic part is ~7 km thick in Nidar valley section which is probably the thickest among known ophiolites.

➢ In Nidar valley a deformed dunite channel (3 km long) is observed which crossects the ultramafics of ophiolite. The structure has implications to the melt extraction processes in a spreading center.

➢ Within dunite channel some entrapped lherzolite xenolith bodies are observed. Some of them bear evidences of unusual high pressure origin.

➢ In an orthopyroxene porphyroclast of “xenolith” lherzolite 1M1 coesite + high pressure C2/e clinoenstatite assemblage has been discovered (Fig 4.14). This evidence challenge the conventional idea of “origin of ophiolite peridotites in a spinel lherzolite stability field” (Coleman 1977). The presence of high P clinoenstatite indicate the origin of host rock at >240 km (> 8 GPa; Gasparik 1990) depth.
> In the lherzolite 1M1 some $\alpha - \text{Fe}_2\text{O}_3$ grain is recovered with disordered carbon and glass inclusion in it (Fig 4.15, 4.16). Laser Raman spectroscopy reveals that the glass follow the trend of $\alpha - \text{Fe}_2\text{O}_3$. The glass and carbon in high pressure peridotite infer a high reducing environment in deep mantle.

> In another lherzolite xenolith (sample 1NU27) entrapped within dunite channel, some orthopyroxene porphyroclasts are noticed with lamellar inclusions of clinopyroxenite (C2/e) (Fig 5.10). The olivines bear strongly oriented exsolution needles of Cr – spinel and $\alpha - \text{Fe}_2\text{O}_3$ precipitations (Fig 5.8, 5.9). They indicate a pre-existing deep mantle environment. From that lherzolite high pressure Mg$_3$SiO$_4$ ($\beta - $Mg$_3$SiO$_4$) is discovered as inclusions in Cr – spinel (Fig 4.8, 4.13, 4.17, 4.18, 4.19). It has been concluded that mantle flow in spreading center originates from transition zone (410 – 660 km).

> Many other micro textures are also reported in this thesis from pyroxenite and peridotites cut by the dunite channels. Most of the textures infer late stage temperature fall from a high $T$ conditions. Among them some micro textures are suspected as evidence in favour of high pressure origin especially within a lherzolite which is cut by the dunite channel.

> In the lherzolite 1NU27 where mantle transition zone (410 – 660 km depth) signature is recovered unusual disordered carbon inclusions are noticed within olivine (Fig 5.11). Along with them primary aliphatic fluid inclusion is also present (Fig 5.12). In the other high P lherzolite
xenolith methane has been detected by Laser Raman spectroscopy (Fig 5.13) with the α-FeOs. These evidences strongly infer a high reducing environment in lower part of upper mantle. This is the rare natural evidence of highly reducing environment in transition zone. From only experimental studies we know that deeper part of the upper mantle is reduced, metal rich (Rohrbach et al., 2007) and these metal and carbon is potential to trigger melting (Dasgupta et al., 2013) at depths ≥ 250 km. This study shows rare natural signature which infer that metal, carbon and hydrocarbons are present in mantle transition zone (410 – 660 km) which result in a highly reducing and metal rich base of upper mantle.

- The signatures of serpentine dehydration and formation of garnet bearing serpentinite (Fig 5.14, 5.15, 5.16) infer deep and steep subduction of primary oceanic lithosphere which releases free high volume of water (~13%) in sub arc depth (Ulmer and Trommsdorff, 1995). This phenomena facilitate melting at the overlying mantle wedge and potential of volcanism in intra oceanic arc. Additionally due to dehydration and ascent of magma a sudden vacuum can be formed in mantle wedge which may trigger upwelling from mantle transition depth (410 – 660 km). Thus subduction induced mantle flow may create the ‘geodynamo’ which initiated the Himalaya building process.
The upper skin of the dunite and serpentine are intensely affected by carbonation in many places. The carbonations preserve evidence of natural CO₂ sequestration.

6.4 SCOPE OF THE FUTURE WORK

The origin of Earth from accretion of chondritic bodies and nature of the pristine Earth is still an unfolded mystery. After studying many extraterrestrial bodies it has been found that only reliable way to determine the nature of the early Earth is by sampling the primitive lower mantle. For that first it is required to sample the deep Earth. Present study suggests systematic mineral phase transitions from at least base of the upper mantle. Thus deep Earth relicts could be a great opportunity to study the hints of primitive mantle and from that the evolution of mantle can be attempted.

After sampling the transition zone rocks it can be further studied about the mechanism of formation of different discontinuities which are probably results of mineral phase transition. From these samples the nature of mantle convection, which passes through different discontinuity planes, also can be studied in detail.

It is very little known from the redox state and metal concentration of deep mantle. Only some speculations can be made on the basis of experimental studies. The signatures of reduced and metal rich mantle transition zone provide a unique opportunity to further substantiate the redox state of the deep mantle at least up to mantle transition zone.