Formation of atoll garnets in the UHP eclogites of the Tso Morari Complex, Ladakh, Himalaya

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The eclogites of the Tso Morari Complex, Ladakh, NW Himalayas preserve both garnets with spectacular atoll textures, as well as whole porphyroblastic garnets. Whole garnets are euhedral, idiomorphic and enclose inclusions of amphibole, phengite and zoisite within the cores, and omphacite and quartz/coesite towards the rims. Detailed electron microprobe analyses and back-scattered electron images show well-preserved prograde zoning in the whole garnets with an increase in Mg and decrease in Ca and Mn contents from the core to the rim. The atoll garnets commonly consist of euhedral ring over island/peninsular core containing inclusions of phengite, omphacite and rarely amphibole between the core and ring. Compositional profiles across the studied atoll grains show elemental variations with higher concentrations of Ca and Mn with low Mg at the peninsula/island cores; contrary to this low Ca, Mn and high Mg is observed at the outer rings. Temperature estimates yield higher values at the Mg-rich atoll garnet outer rings compared to the atoll cores. Atoll garnet formation was favoured by infiltration of fluid formed due to breakdown of hydrous phases, and/or the release of structurally bounded OH from nominally anhydrous minerals at the onset of exhumation. Infiltration of fluids along pre-existing fracture pathways and along mineral inclusion boundaries triggered breakdown of the original garnet cores and released elements which were subsequently incorporated into the newly-grown garnet rings. This breakdown of garnet cores and inward re-growth at the outer ring produced the atoll structure. Calibrated geo-thermobarometers and mineral equilibria reflect that the Tso Morari eclogites attain peak pressures prior to peak temperatures representing a clockwise path of evolution.

Keywords. Atoll garnet; eclogite; fluid infiltration; retrograde metamorphism; Ladakh Himalayas; Tso Morari Complex.

1. Introduction

The occurrence of medium-temperature eclogites is a distinctive feature of many continental collision zones (Smith 1988; Carswell 1990). Garnet, one of the key mineral phases of eclogites, is crucial

in deciphering the chemical and metamorphic evolution of these rocks during subduction. Garnet-bearing rocks are most suitable for determining the duration and timing of mineral growth during metamorphism, and hence to understand the evolution of metamorphic belts. This is possible due

to the slow rates of intra-crystalline diffusion and the complex compositional zoning patterns that are produced and retained in the garnet crystal structure over a wide range of metamorphic conditions (e.g., [Spear and Selverstone 1983](#); [Kohn and Spear 2000](#); [Kohn 2003](#)). Chemically zoned garnets can be used to constrain P–T changes during tectono-metamorphic events. Garnet textures are primarily fingerprints of the history of nucleation and growth over a wide range of metamorphic conditions and can record both subduction (prograde metamorphism) and exhumation (retrograde metamorphism) histories. Metamorphic garnets may display several microstructures such as corona, symplectite, fishnet, atoll and patchy growth fabrics, in addition to normal monocrystalline grains. Major-element zoning patterns in garnets, during both prograde and retrograde metamorphism, have proved useful not only in understanding the P–T evolution of metamorphic rocks but also in elucidating the evolution of metamorphic fluids and deformation patterns ([Hollister 1966](#); [Loomis 1975](#); [Lasaga 1983](#); [Spear and Selverstone 1983](#); [Hickmott et al. 1987](#); [Menard and Spear 1993](#); [Perchuk et al. 1999](#); [Faryad and Hoinkes 2004](#)). The distinct growth patterns preserved in garnets are often separated by strong compositional gradients and/or inclusion-enriched zones that indicate episodic garnet growth during prograde metamorphism ([Konrad-Schmolke et al. 2008](#)). Atoll structure is a special type of microstructure consisting of a garnet ring enclosing a mixture of several phases and/or island-shaped garnet cores ([Passchier and Trouw 1998](#)). Several occurrences of atoll-structured garnets have been reported from eclogites in different ultra high pressure (UHP) belts across the world, e.g., Dabie, China ([Cheng et al. 2007](#)), Krušné Hory, Czech ([Faryad et al. 2010](#)), Alpujarride Complex, Spain, ([Ruiz Cruz 2011](#)) and Yukahe, China ([Chen et al. 2011](#)). Garnets displaying atoll textures have been reported previously from the Tso Morari massif ([Singh et al. 2013](#); [Kayleigh et al. 2014](#)) in the Himalayas, but without deciphering the process of their formation. Several mechanisms of formation have been proposed for these structures, such as overgrowth ([Smellie 1974](#)); selective replacement ([Green 1915](#); [Williamson 1935](#); [Rast 1965](#); [Forestier and Lasnier 1969](#)), multiple nucleation and coalescence of grains ([Spiess et al. 2001](#); [Dobbs et al. 2003](#)), etc., but the mechanism of formation of atoll structures in low- to medium-grade metamorphic rocks is still in the realm of speculation. In the present work, detailed

compositional maps along with line profiles and back-scattered electron images of whole garnets and atoll garnets of the Tso Morari UHP eclogites are reported for the first time. Applying conventional geothermobarometry, the P–T path for the studied samples has been constrained. The present contribution therefore attempts to unravel the mechanism and processes leading to their formation in relation to changing P–T conditions and their implications in understanding the tectonic models of UHP metamorphism.

2. Geological setting and samples

Discovery of coesite-bearing rocks in the Tso Morari Complex, India ([Mukherjee and Sachan 2001](#); [Sachan et al. 2001, 2004](#)) and the Kaghan Valley, Pakistan ([O'Brien et al. 2001](#)) have established the presence of a UHP belt in the Himalayas. The eclogites under investigation form a part of the Tso Morari complex (TMC) located in the Ladakh region, NW Himalayas (figure 1a). The complex is an elongated, dome-shaped structure 100 × 50 km across, and strikes NW–SE ([Thakur 1983](#)). The complex occurs as a doubly plunging anticline with a dip of 10° towards the NW and an overall thickness of <7 km ([de Sigoyer et al. 2004](#)). The Tso Morari unit is separated from the surrounding rocks by ductile shear zones. The TMC is tectonically bounded along its entire northern edge by the Indus suture zone. The north-east dipping Zildat shear zone delimits the Tso Morari unit from the low-grade metamorphic rocks of the Indus suture zone. The south dipping Karzog shear zone separates the dome from the less metamorphosed Mata-Karzog unit, and the Karzog and related ophiolites at its southwestern margin ([Berthelsen 1953](#); [Guillot et al. 1997](#); [de Sigoyer et al. 2004](#); [Mahéo et al. 2004](#); [Epard and Steck 2008](#)). The Puga Formation makes up the core of the complex, while the Tanglang La Formation lies towards the periphery. The complex is dominated by gneisses and schists (Puga Formation) along with phyllites, carbonates (Tanglang La Formation) and intrusive granitic bodies (Rupshu and Polokong La).

Traditionally, two existing models explain the metamorphic association of eclogites with its gneissic host. The ‘foreign’ model favours solid-state tectonic introduction of previously metamorphosed high-pressure eclogites into the lower-pressure gneissic host ([Lappin and Smith 1978](#); [Smith 1980, 1981, 1982](#)). The second model favours the

Figure 1. (a) Geological map of the Himalayas (after Ding et al. 2001; Guillot et al. 2003; Di Pietro et al. 2004). The western Himalayas are clearly distinct from the central-east Himalaya. The stars show the locations of the metamorphic rocks related to subduction processes. Inset, the red box shows the location of the study area. BS: Blueschist unit, Amp: amphibolitic unit; HP: high-pressure unit, UHP: ultrahigh-pressure unit (adapted from Guillot et al. 2008). (b) Geological map of the Tso Morari Complex (after Steck et al. 1998). Black dots represent eclogite sampling locations. Red dot shows the location of the atoll garnet eclogite sample.

co-genetic metamorphism of the pre-existing mafic crustal rocks along with the gneissic host at the same P–T conditions and thereby at the same sub-crustal depths (Griffin and Brueckner 1980; Griffin and Carswell 1985; Griffin and Qvakem 1985).

The TMC is believed to represent a distal remnant block of the thinned northern Indian continental margin (Colchen *et al.* 1994; Steck *et al.* 1998). The area has been the focus of many recent investigations (de Sigoyer *et al.* 1997, 2000, 2004; Guillot *et al.* 1997; Jain *et al.* 2003; Leech *et al.* 2003, 2005; Epard and Steck 2008; Mukherjee and Mulchrone 2012; Lanari *et al.* 2013; St-Onge *et al.* 2013; Singh *et al.* 2013; Palin *et al.* 2014, 2017; Chatterjee and Jagoutz 2015; Wilke *et al.* 2015), primarily aimed at understanding the mechanisms of continental plate subduction and its exhumation during the collision of the Indian and Asian plates. These rocks are believed to have been exhumed through a low-viscosity channel along the top surface of the subducting slab (Guillot *et al.* 2001) although details of the exhumation mechanisms are poorly known. The eclogite samples for the present study were collected from the Puga Formation and the sampling locations are marked on figure 1(b). Eclogite bodies occur as boudins or lenses within the meta-sediments of the lower Puga and overlying Tanglang La Formations. The eclogites are marginally sheared, and exhibit a concordant relationship and sharp contacts with the host rocks (figure 2). Studies of these eclogites by de Sigoyer *et al.* (1997), Guillot *et al.* (1997) and Sachan *et al.* (1999) have recognized three metamorphic stages, *viz.*, eclogite-facies assemblages, blueschist-facies assemblages and greenschist-facies assemblages, while Singh *et al.* (2013) have identified five different mineral associations representative of five stages of P–T evolution of these rocks. P–T estimates using mineral thermometers (garnet–clinopyroxene Fe–Mg exchange) and barometers (Si in phengite, Jd in omphacite; de Sigoyer *et al.* 1997) suggest that the eclogitic garnet cores and rims equilibrated at pressures of 2.0 ± 0.3 and 1.1 ± 0.2 GPa, respectively, at a constant temperature of $580 \pm 60^\circ\text{C}$, suggesting isothermal decompression. St-Onge *et al.* (2013) used P–T pseudosection analysis to conclude that the eclogitic garnet cores and rims equilibrated at 2.15 ± 0.15 GPa/ $535 \pm 15^\circ\text{C}$ and ~ 2.7 GPa/ $630 - 645^\circ\text{C}$, respectively, indicating a P–T increase during the growth of the garnet rims. Thermobarometric calculations by St-Onge *et al.* (2013) also suggest that the garnet

Figure 2. Field photographs of the Tso Morari eclogites. Eclogite bodies occurring as black mafic lenses or boudins observed within the Puga gneisses. Note the man circled for scale.

rims equilibrated at conditions of ~ 2.55 GPa/ $602 - 617^\circ\text{C}$. The report of coesite inclusions in the garnets (Mukherjee and Sachan 2001; Sachan *et al.* 2001, 2004) however, redefined the minimum pressure of 2.8 GPa at 650°C for these rocks. Carbonate-bearing assemblages reported from the TMC suggest conditions of ~ 3.9 GPa at $\sim 750^\circ\text{C}$ for the complex (Mukherjee *et al.* 2003). Whole rock and mineral isotopic ages of the Tso Morari eclogites (47–55 Ma, de Sigoyer *et al.* 2000; Leech *et al.* 2005; St-Onge *et al.* 2013; Donaldson *et al.* 2013) are consistent with the U–Pb zircon, allanite, and titanite ages of the Kaghan eclogites (44–50 Ma, Kaneko *et al.* 2003; Parrish *et al.* 2006; Wilke *et al.* 2010).

3. Analytical methods

Back-scattered electron (BSE) images, elemental X-ray maps, and chemical compositions of minerals were obtained on an automated CAMECA SX-100 electron microprobe micro-analyzer fitted with five crystal spectrometers at GEMOC, Macquarie University, Sydney, Australia. The minerals were analyzed by wave-length dispersive spectrometry (WDS) using an accelerating potential of 15 kV and a probe current of 20 nA and counting 40–60 s times per element. The analyses were carried out with an effective beam diameter of ~ 1 micron. Standards used for the analysis were: jadeite for Na, kyanite for Al, olivine for Mg, orthoclase

for K, wollastonite for Ca andradite for Si, apatite for P, Cr = Cr 100%, Mn garnet for Mn, Fe_2O_3 on Fe, Ti on TiO_2 , Ni for Ni-olivine. Representative analyses for whole and atoll garnets are shown in table 1 and all analyses are plotted in figure 3.

4. Petrography and mineral chemistry

Two representative eclogite samples containing whole and atoll garnets respectively from the centre of the dome hosted within the orthogneisses ~5 km from the Sumdo village were subjected to detailed study. Macroscopically, the eclogites are very fresh and exhibit a fine-grained matrix composed of green omphacite and reddish garnet porphyroblasts. Microscopically, the samples contain predominantly garnets and omphacite porphyroblasts (figure 4a) surrounded by amphiboles (Na–Ca and Ca types), phengite, epidote and carbonates. Quartz/coesite are observed as minor constituents along with rutile, zircon, and oxides (Fe and Ti) representing the accessory phases (figure 4c).

4.1 Sample L1

Garnets occur as large, idioblastic, whole porphyroblasts, 0.5–1.5 mm in size and exhibit intense optical zoning from reddish core to pale mantle and rims (figure 4a). Optical zoning is reflected in a wide compositional range, i.e., of almandine, pyrope, grossular and spessartine. Garnet cores are distinctly rich in Ca–Fe ($\text{Gr}_{528-29}\text{Alm}_{55-59}\text{Prp}_{11-14}\text{Sps}_{1.7-1.9}$) surrounded by thick Mg-rich rims ($\text{Gr}_{517-19}\text{Alm}_{60-66}\text{Prp}_{24-26}\text{Sps}_{0.8-0.6}$). The grossular content decreases and the pyrope content increases sharply from the core to the rim. Garnet cores contain numerous inclusions with the rims being relatively free of inclusions. Common inclusions within the garnet cores consist of bluish-green amphiboles, phengite and epidote (zoisite) (figure 4b), while the rim shows the presence of pale-coloured omphacite and rutile.

Inclusions of bluish-green coloured amphiboles within the whole garnet cores are Na–Ca–amphiboles represented by ferro-kataphorite, kataphorite and taramite [$\text{Na}(+\text{K}) = 0.50 - 0.89$, $\text{Na}(\text{B}) = 0.51 - 0.69$, $\text{Na}(\text{A}) = 0.45 - 0.83$, total $\text{Ca} = 1.23 - 1.42$, $\text{Al}^{\text{iv}} = 0.94 - 2.03$ and $\text{Al}^{\text{vi}} = 0.96 - 1.58$]. Amphiboles found within the garnet rims are represented by ferro-pargasite, while matrix amphiboles and those rimming garnets

are represented by winchite. Na-rich amphiboles occurring as inclusions within the garnet as reported by Singh *et al.* (2013) were not found in the present study.

Clinopyroxene inclusions occurring in garnet rims are primarily of omphacite ($\text{Jd}_{35-40}\text{Ae}_{13-15}$) which also occur in the matrix ($\text{Jd}_{34-39}\text{Ae}_{14-18}$). These grains are colourless to pale green and display feeble pleochroism in shades of light green. Omphacites are strongly zoned with Jd and Ae rich ($\text{Jd}_{35-42}\text{Ae}_{13-17}$) cores where the rims are relatively lower in Jd and Ae contents ($\text{Jd}_{35-40}\text{Ae}_{13-14}$) (figure 4f).

Coesite inclusions have also been observed in the garnet rims of the studied samples, consistent with earlier reports by Sachan *et al.* (2004). Most of the grains have a central core of fine-grained polycrystalline quartz with a radial rim of quartz defining the palisade texture. Coesite/quartz inclusions are surrounded by relaxation cracks, reflecting volume increase during the coesite to quartz transformation (figure 5). Trails of fluid inclusions of various shapes, *viz.*, oblong, ovoid, amoeboid, etc., have been identified in the studied samples and occur within garnet, omphacite, phengite and at times in carbonate grains (figure 6). At places, fluid inclusions are also seen within the zircon and quartz grains. Mukherjee and Sachan (2009) have already identified five major types of fluids, *viz.*, high-salinity brine, N_2 , CH_4 , CO_2 and low-salinity aqueous fluids from these eclogites.

Retrograde assemblages consist of a symplectic intergrowth of possibly clinopyroxene + albite after omphacite (figure 4d); such replacement is very common in eclogites with omphacite that are more severely retrograded than garnet. Most symplectites coarsen away from the omphacite core, indicating that the symplectic aggregates in the outer rim might have formed early with longer recrystallization time.

Matrix omphacite grains exhibit exsolution lamellae which are identified to be of feldspar and minor quartz. Other retrograde features related to amphibolites and greenschist facies metamorphism include: (1) matrix rutile rimmed by titanite; (2) fibrous biotite formed at the expense of phengite (figure 4e); (3) chlorite formed after biotite and garnet; (4) quartz pseudomorphs after coesite in garnet; and (5) phengite inside the atoll is low-Si accompanied by quartz. The matrix here is dominated by Ca amphibole, feldspar and biotite.

Table 1. Representative microprobe analyses of the whole and atoll garnets of eclogites of the Tso Moriri complex.

Mineral	L1 - Normal Garnet Traverse														
	Garnet			Amp		Garnet		Cpx		Garnet		Cpx			
	Outer rim	Mid rim	Inner rim	Inner core	Outer core	Incl in Gt	Core	Inclusion in Gt rim	Rim	Incl in Gt rim	Amp	Incl in Gt rim	Garnet Rim		
Domain															
P-T estimates	2.8 GPa/RV 508 KR														
	462 GH 635 (±50) 2.65 GPa/RV 561 KR 579 GH768 (±50)														
SiO ₂	39.17	38.93	38.45	38.91	38.95	42.31	38.24	38.33	56.34	39.12	38.78	56.52	40.98	38.19	38.23
TiO ₂	0.03	0.04	0.06	0.06	0.62	0.44	0.18	0.20	0.05	0.05	0.03	0.07	0.02	0.03	0.03
Al ₂ O ₃	22.54	22.07	22.37	22.28	21.73	16.54	21.51	21.69	9.91	22.22	22.30	10.93	19.24	22.12	22.05
FeO	24.91	30.81	28.65	28.62	26.00	20.30	28.16	27.55	6.54	23.24	27.91	6.32	16.06	30.65	30.96
MnO	0.29	0.35	0.41	0.44	0.92	0.12	0.71	0.78	0.01	0.28	0.41	0.03	0.09	0.30	0.37
MgO	6.42	4.36	5.19	5.24	3.65	6.22	2.61	2.93	7.91	6.94	5.48	7.28	7.75	4.33	3.82
CaO	8.47	6.22	6.74	6.64	10.61	8.36	10.41	10.40	12.72	8.72	6.95	11.78	10.18	6.29	6.41
Na ₂ O	0.01	0.02	0.04	0.03	0.02	4.87	0.05	0.03	7.54	0.01	n.d.	8.29	3.83	0.03	0.01
K ₂ O	n.d.	n.d.	n.d.	n.d.	n.d.	0.11	n.d.	n.d.	0.01	n.d.	n.d.	0.01	0.50	n.d.	n.d.
Cr ₂ O ₃	0.06	0.03	0.02	0.02	0.02	n.d.	0.05	0.04	n.d.	0.01	0.01	0.04	0.02	0.04	0.01
NiO	n.d.	0.01	n.d.	0.02	0.01	n.d.	n.d.	0.03	0.02	n.d.	0.02	n.d.	0.04	n.d.	n.d.
Total	101.9	102.8	101.9	102.2	102.5	99.26	101.9	101.98	101.0	100.6	101.8	101.2	98.70	101.9	101.8
Alm	51.80	65.45	60.24	60.77	55.28		59.23	57.98		49.11	58.86			64.92	66.34
Pyp	24.42	16.68	20.10	20.02	13.83		10.14	11.35		26.42	21.05			16.78	14.89
Grs	22.64	16.90	18.19	18.04	28.37		27.97	27.96		23.63	18.81			17.06	17.58
Spes	0.63	0.76	0.90	0.95	1.98		1.57	1.72		0.61	0.89			0.66	0.82
Aeg									13.41			15.28			
Jad									38.34			40.74			
Diop									48.24			43.98			
Total Na (B)						0.56								0.34	
Total Na (A)						0.83								0.75	
Total Ca						1.32								1.60	

Table 1. (Continued.)

Sample Mineral	L7 - Atoll Garnet Traverse 1									
	Phg	Cpx	Outer ring	Mid ring	Inner ring	Cpx Inside atoll	Phg Inside atoll	Inner ring GH 497	Garnet Mid ring	Cpx Outer ring
Domain	Outside atoll	Outside atoll	ring 734 (±50)	ring	ring	atoll	atoll	ring 675 (±50)		Outside atoll
P-T estimates	2.29 GPa/RV 377 KR 365 GH 734 (±50)						2.33 GPa/RV 483 KR 497 GH 675 (±50)			
SiO ₂	53.59	57.15	39.42	38.63	39.00	56.58	51.78	38.92	38.91	38.96
TiO ₂	0.28	0.08	0.03	0.04	0.04	0.08	0.62	0.12	0.03	0.04
Al ₂ O ₃	23.46	10.55	22.71	21.98	22.49	9.99	26.53	22.00	22.27	22.46
FeO	2.41	4.46	26.31	27.17	28.30	4.76	2.61	25.36	27.57	28.13
MnO	0.00	0.02	0.45	0.41	0.53	0.03	0.02	0.42	0.43	0.41
MgO	4.92	8.86	7.94	3.40	7.15	8.89	3.80	4.21	6.04	6.65
CaO	0.02	13.44	5.26	10.34	4.50	13.55	0.00	10.56	6.40	4.84
Na ₂ O	0.25	7.37	0.02	0.03	0.03	7.00	0.58	0.05	0.03	0.03
K ₂ O	10.72	0.00	0.01	0.00	0.00	0.00	10.10	0.01	0.00	0.01
Cr ₂ O ₃	0.03	0.02	0.01	0.02	0.00	0.05	0.00	0.02	0.00	0.00
NiO	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.01
Total	95.72	101.95	102.19	102.01	102.04	100.96	96.06	101.67	101.72	101.52
Alm			55.21	57.95	59.76			54.18	58.70	60.36
Pyp			29.68	12.93	26.93			16.03	22.92	25.44
Grs			14.14	28.25	12.18			28.90	17.47	13.31
Spes			0.96	0.88	1.13			0.90	0.92	0.89
Aeg		9.50				8.16				12.72
Jad		40.30				40.15				44.07
Diop		50.20				51.69				43.21

Figure 3. Compositions of minerals in the Tso Moriri eclogites. (a) Triangular plots showing chemistry of clinopyroxenes plotted according to Morimoto (1988). (b) Triangular plots showing compositions of garnet. Eclogites belong to Group C based on garnet chemistry (Coleman *et al.* 1965). (c) Plots showing variation in amphibole chemistry. Amphibole plotted according to Leake *et al.* (1997).

4.2 Sample L7

Garnets exhibiting well-developed atoll structure form a key textural feature in this sample (lat. $33^{\circ}13'19.9''$ N, long. $78^{\circ}18'42.1''$ E) and was studied in detail (figure 7). The atoll structure consists of garnet rings enclosing a mixture of several phases with or without island-shaped garnet cores (Passchier and Trouw 1998) (figure 7a).

Atoll structures are more common in the larger grains although these are present in smaller garnet grains. Majority of the garnet grains preserve complete atoll structure with intact cores, but in some garnet grains the cores are disintegrated and thus only atoll structure rings are preserved. The possible stages of atoll structure formation as retrieved from textural study are presented in figure 8. Phengite is the dominant phase within the atoll structures and is occasionally accompanied by omphacite, quartz, feldspar ($X_{Na} = 0.9198$; $X_{Ca} = 0.2139$; $X_K = 0.5875$) and rarely amphibole (figure 7b). Atolls filled by phengite have sharp and regular internal interfaces that correlate with the crystallographic planes of the garnet. Core and ring compositions of the atoll garnets, like those of whole garnets, show different compositions. Atoll rings are characterized by lower Ca, Mn and higher Mg contents ($Grs_{12-29}Alm_{54-60}Prp_{7-29}Sps_{0.6-1.1}$). Pyrope contents at the atoll rings show a wide variation from inner to outer rings. The atoll cores on the contrary show high Ca and Mn and lower Mg ($Grs_{12-27}Alm_{59-62}Prp_{9-17}Sps_{0.6-0.7}$). Phengite inside the atoll is characterized by Si content ranging from 3.37 to 3.43 p.f.u. Matrix phengite has Si content of 3.56 p.f.u. and is higher than phengite inside the atoll. Larger phengite grains in the matrix exhibit alteration rims that are richer in Mg, but lower in Fe. Amphibole in the atoll garnets are primarily Na–Ca rich kataphorite ($Na(+K) = 0.61$, $Na(B) = 0.95$, $Na(A) = 0.52$, total Ca = 0.96, $Al^{iv} = 0.86$ and $Al^{vi} = 1.13$) in composition. Omphacite within the atoll contain Jd (Jd_{40-45}, Ae_{8-12}) higher than the matrix omphacite (Jd_{40-44}, Ae_{10-13}), but overall show a restricted variation.

Back-scattered electron (BSE) images (figure 9a) and compositional maps illustrate strong zoning in whole garnets with cores being rich in Ca ($X_{Ca} = 0.29$) and Mn ($X_{Mn} = 0.28$), the concentrations of which decrease towards the rims ($X_{Ca} = 0.23$, $X_{Mn} = 0.19$). In contrast, the cores are depleted in Mg, which increase steadily towards the rims ($X_{Mg} = 0.10 - 0.24$), characteristic of garnet showing growth zoning. To understand compositional variation better, line profiles for one representative whole garnet grain A–A' (figure 9b) starting from the rim to the core is presented here. Mn concentrations <1 wt% (0.60 mol%) towards the rim are recorded, whereas in the core Mn peaks at 1.7 mol%. Mg content in the core is ~ 10 mol% and rapidly increase to a maximum of 26 mol% at the

Figure 4. Photomicrographs of the Tso Morari eclogites. (a) Faint pink coloured garnet along with omphacite in the matrix. Note the presence of coesite inclusions towards the garnet rims (PPL). (b) Euhedral garnet with numerous inclusions in the core with dark green rim of Na-amphibole along garnet boundaries. Preferentially aligned Na amphibole inclusions defining the first internal foliation within the garnet cores (BCN). (c) Colourless phengite along with omphacite and epidote (zoisite) and garnet occurring as matrix phases with the Tso Morari eclogites (PPL). (d) Retrogressed eclogites exhibiting varying degrees of amphibolite- and greenschist-facies metamorphism. Symplectitic association of Na-poor clinopyroxene + plagioclase after omphacite (BCN). (e) Breakdown of phengite to biotite and aluminous calcic amphiboles (e.g., pargasite) replacing the earlier, high pressure sodic-calcic or sodic amphiboles (PPL). (f) Omphacite cores showing presence of exsolution lamella (BCN). Abbreviations. Gnt: garnet, Cpx: clinopyroxene, Phg: phengite, Coe: coesite, Zo: zoisite, Carb: carbonate, Omp: omphacite, Bio: biotite, Hbl: Hornblende, Na-amp: Na-amphibole, Qtz: quartz.

outer rims with an equally sharp decrease in the Ca content (18 mol% from 28 mol% at the core). X_{Mg} (i.e., $Mg/(Mg + Fe)$) is around 0.10 in the cores, rising to 0.26 towards the rims.

BSE images of atoll garnets also show the presence of high Ca and Mn cores ($X_{Ca} = 0.28$, $X_{Mn} = 0.012$) with Mg increasing towards the rims ($X_{Mg} = 0.08 - 0.27$) (figure 9c). Detailed compositional

profile across atoll garnet grain 1 (not shown here) clearly indicate lower concentrations of Ca at the outer rings (13.3 mol%) with Ca levels increasing steadily inwards (28.9 mol%). Low Mn (0.89 mol%) concentrations are observed in the outer rings with Mn increasing towards the inner rings (1.13 mol%). Mg peaks in the outer rim at 29.6 mol%, dropping to 16 mol% towards the inner ring.

Figure 5. Photomicrographs of quartz pseudomorphs after coesite occurring as inclusions within garnet grains of the Tso Moriri Complex. Note the presence of radial fractures extending into the host garnet and thin rim of feathery quartz defining the palisade texture clearly observed in the above photographs (PPL). Colour coded images of the coesite showing the characteristic Raman peak.

In the atoll garnet grain 2, two profiles were studied: one from outer ring to inner ring (D1–D2) and one from garnet Island core (B1–B2) (figure

9d). In D1–D2 profile, Ca concentrations are observed to increase slightly from the outer ring to inner ring (28–32 mol%). In contrast, the lowest Mg

Figure 6. Photomicrographs of fluid inclusions observed in phengite mineral of the eclogites from the Tso Morari complex.

Figure 7. Photomicrographs of atoll garnets of the eclogites from the Tso Morari complex. (a) Euhedral atoll garnet with intact atoll rings preserving an atoll island core in the centre. Phengite is the dominant mineral within the atoll structure. (b) Atoll structure showing the inward growth of atoll peninsulas to form the cores.

(7.7 mol%) is recorded at the inner ring with higher values observed towards the outer rings (26.9 mol%). Mn increases from the outer ring at D1 (0.64 mol%) to inner ring at D2 (1.13 mol%). Compositional profile across the atoll garnet island core

(B1–B2) shows high Ca concentrations increasing from 16.7 to 27.5 mol%. Mg drops from 25.7 mol% at outer core to 9.32 mol% in the inner core.

5. P–T estimates

P–T conditions of metamorphism of the Tso Morari eclogites have been constrained from recent studies (e.g., de Sigoyer *et al.* 2000, 2004; Konrad-Schmolke *et al.* 2008; St-Onge *et al.* 2013; Singh *et al.* 2013; Chatterjee and Jagoutz 2015; Wilke *et al.* 2015). The P–T path in the present study has been reconstructed from mineral associations stable along the prograde and retrograde paths during the atoll garnet formation of the Tso Morari eclogites and is shown in figure 10. The P–T estimates for the whole and atoll garnets of the Tso Morari eclogites were constrained by using several conventional geothermobarometers (presented in table 2), in particular, the garnet–clinopyroxene (Gnt–Cpx, Krogh 1988; Ravna 2000; uncertainty $\pm 50^\circ\text{C}$) and garnet–phengite (Gnt–Phg, Green and Hellman 1982; uncertainty $\pm 50^\circ\text{C}$) Fe–Mg exchange thermometers in combination with the garnet–clinopyroxene–phengite (Gnt–Cpx–Phg, Waters and Martin 1993; uncertainties given therein: ± 1 kbar and 25°C) geobarometer and the univariant coesite=quartz reaction, Si content in phengite and the Alb = Jd + Qtz reaction.

As discussed in the previous sections, compositional zoning exists for the garnets and omphacite from the Tso Morari eclogites making temperature estimation for such samples complicated. Another factor affecting temperature estimates is high Ca and Mn contents in garnet (Krogh 1988; Pattison and Newton 1989). Because the concentration of these elements vary widely from core to rim, and their effect on the temperature estimate is not well understood, the temperature estimates based on Ellis and Green (1979) lead to significant errors. Hence, this method although attempted, has not been considered here.

P–T conditions obtained for the whole garnet cores in sample L1 range from 462° to 508°C following the models of Krogh (1988) and Ravna (2000). Temperature of 635°C was obtained using the Gnt–Phg thermometer of Green and Hellman (1982). The calculated temperature of 635°C seems unreliable as phengite used for calculations is observed as relicts in the matrix and does not occur in the garnet core. Hence, this temperature estimate has not been considered. Pressure

Figure 8. Photomicrographs and textural sketches of the different stages of atoll garnet formation shown by the eclogites. (a) The initial whole garnet, rimmed by Na-amphibole. (b, c and d) Phengite mica is present between the atoll rings and central core. The garnet ring extends inwards to form a new core, giving rise to a distinct garnet peninsula; (e) euhedral garnet ring encloses the phengite mica; garnet cores are isolated and detached from the garnet ring and thus form the islands; (f) subhedral garnet grain with an atoll ring enclosing phengite and omphacite; the core may have been completely consumed or not formed at all.

estimation of 2.8 GPa was based on the Gnt–Cpx–Phg barometer of Waters and Martin (1993) seems to be an overestimation considering that no convincing Gnt–Cpx–Phg pairs were available for accurate calculation of pressure. Core domains are assumed to yield considerably reliable P–T estimates assuming that they have formed in equilibrium and they are shielded from lower temperature Fe–Mg exchange during the later stages of metamorphism (Chatterjee and Jagoutz 2015). Therefore, the calculated temperatures of 462°–508°C are considered as reliable for the whole garnet cores.

Whole garnet with omphacite as inclusions near garnet rim and with coesite inclusions yielded temperature estimates of 561°–579°C based on models of Krogh (1988) and Ravna (2000). Gnt–Phg thermometer after Green and Hellman (1982) for the whole garnet rims (outer rim with adjacent phengite in matrix) yielded higher temperatures of 768°C which could be attributed to high Mg in the outer rims of garnet and high Si in phengite (3.56 pfu). Pressure for garnet rims with omphacite inclusions (and coesite) and adjacent phengite were calculated to be 2.65 GPa which is consistent with the minimum pressure of 2.7 GPa based on the

equilibrium of coesite=quartz (Mirwald and Massonne 1980; Bohlen and Boettcher 1982). Considering that omphacite inclusions occur at the inner rim of the whole garnet, the calculated temperature indicates that the inner rim equilibrated at 579°C with temperatures increasing to 768°C towards the outer rim (with phengite) and shows an increase in temperature across the core–rim interface. P–T for the atoll garnets in sample L7 were calculated for inner ring of garnets with coexisting omphacite and phengite inside the atoll structure and with garnet outer ring with neighbouring omphacite and phengite outside the atoll structure.

Garnet–omphacite pairs inside the atoll structure yielded temperature estimates of 483°–497°C (Traverse 1; Krogh 1988; Ravna 2000), but Traverse 2 yielded much lower temperature of 257°–282°C at 2.33 GPa (Traverse 2; Krogh 1988; Ravna 2000). Garnet–phengite pairs for Traverse 1 yielded high temperature of 675°C with traverse 2 yielding a temperature of 614°C at 2.33 GPa.

Coexisting garnet–omphacite pairs outside the atoll structure gave P–T estimates of 365°–377°C at 2.29 GPa (Krogh 1988; Ravna 2000). Gnt–Phg thermometer yielded higher temperatures of 734°C. Although T–P estimates for the atoll garnet (both inside and outside) have been determined using Gnt–Cpx models of Krogh (1988) and Ravna (2000), the Gnt–Phg model of Green and Hellman (1982) for the atoll garnet is preferred here considering that phengite is the dominant mineral phase inside the atoll structure and Si compositions in phengite vary proportionately to the Mg contents of garnet (i.e., highest Mg garnet and phengite with the highest Si is observed at outer atoll rings as compared to those from inside the atoll structure).

6. Discussion

Chemical zoning in metamorphic garnets is an established tool in evaluating the P–T evolution of metamorphic rocks. However, zoning and its

modification in itself is a complex process. Fluid access, deformation and diffusion along grain- or sub-grain boundaries as well as along fractures are the other variables apart from change in the P–T conditions (Joesten 1991; Whitney 1991; Hames and Menard 1993; Florence and Spear 1991).

6.1 Formation of monocrystalline (whole) garnets

Mineral chemistry and petrography show that the eclogites do not represent a single equilibrium assemblage. Whole garnets have highest Ca and Mn concentrations and lowest Mg indicating early nucleation and well-defined prograde zonation pattern with an increase in pyrope and decrease in grossular and spessartine contents from core to rim. Inclusions of Na–Ca amphibole, zoisite, rutile + magnetite within the garnet cores represent the pre-UHP stage resulting from metamorphism of a mafic protolith and constitute the first preserved prograde association of minerals. Presence of omphacite and coesite inclusions at the garnet outer rims defines the UHP stage evident by highest Mg towards the garnet rims. With this background, calculated temperatures in the range of 462°–508°C for garnet cores and temperatures of 768°C for garnet rims (with highest Mg and phengite with the highest Si content) are consistent with garnet growth during subduction. Previously determined P–T conditions of metamorphism for the Tso Moriri eclogites are widely variable. This variation could primarily be a result of differing compositions of minerals and their zoning patterns in the samples examined. Using conventional geo-thermobarometry, Mukherjee *et al.* (2003) reported pressures of >3.9 GPa at 750°C, whereas Wilke *et al.* (2015) calculated temperatures in the range of 560°–760°C for pressures at about 4.4–4.8 GPa extending subduction depths of 160 km well within the diamond stability field. Coesite inclusions have been reported from the Tso Moriri eclogites (Sachan *et al.* 2004) and are also confirmed in the present study. However, the presence of microdiamonds remains unconfirmed till date. Hence the pressure estimation of 2.65 GPa calculated for the garnet rims is considered as peak pressure attained during subduction. The above calculated estimate compares well with the P–T estimates provided by Palin *et al.* (2017) of ~2.6–2.8 GPa and 600–620°C representing depths of 90–100 km for the Tso Moriri eclogites.

Figure 9. (a) Back scattered images for the whole garnets showing the location of EDS analyses on the grain. (b) Major element zoning profile of the whole garnets across profiles A–A' along with representative spectra of the garnet core. (c) X-ray maps for the atoll garnets *viz.*, Mn, Mg, Ca and Fe. Brighter areas represent higher concentrations whereas lower concentrations are darker. Note the presence of cracks and fractures in the atoll garnet indicated by arrows. (d) Back scattered images for the atoll garnet with major element zoning profile across profiles B1–B2 and D1–D2.

Figure 10. Schematic illustration showing evolution of the whole and atoll garnets along the proposed P–T path (red dashed lines). Atoll garnet formation sketches adapted after [Cheng et al. \(2007\)](#) and images A–D represent the textural evidence from the Tso Moriri eclogites bearing resemblance to those documented by [Cheng et al. \(2007\)](#). Crucial reactions used for establishing the P–T evolution path of the Tso Moriri Crystalline Complex have also been marked alongside [Glaucophane(Glau) + Clinozoisite(Czo) $\leftrightarrow$ Garnet(Gt) + Omphacite(Omph) ([Evans 1990](#)), Quartz(Qtz) $\leftrightarrow$ Coesite(Coe) (Bohlen and Boettcher 1982), Titanite(Ttn) + Epidote(Epi) $\leftrightarrow$ Garnet(Gt) + Rutile(Rt) + Coesite(coe)/Quartz(Qtz) + H₂O (Manning and Bohlen 1991), Jadeite(Jd) + Quartz(Qtz) $\leftrightarrow$ Albite(Alb), (Newton and Smith 1966; [Holland 1980](#)), Garnet + Clinopyroxene $\leftrightarrow$ Amphibole + Albite(Plg) (Holland and Powell 1990)]. P–T path proposed by [de Sigoyer et al. \(2004\)](#), [Guillot et al. \(2008\)](#) and [Singh et al. \(2013\)](#) have been shown for comparison by dashed blue, green and purple lines, respectively.

6.2 Formation of atoll garnets

Atoll garnets from the studied samples consist of a euhedral ring of garnet that encloses phengite as the dominant mineral phase between the atoll ring and cores. Atoll structures are observed from a single eclogite outcrop in the complex and probably represent a case of accidental preservation of low-strain volumes, as most of the other outcrops are found retrogressed under amphibolite facies. Textural studies indicate that the garnets are more resistant to retrogression and therefore their chemical zonation is still well preserved. This is consistent with theoretical and experimental work ([Lasaga et al. 1977](#); [Lasaga 1983](#)) suggesting chemical sluggishness of elements during compositional re-equilibration of garnets.

BSE images and compositional profiles of the atoll garnets suggest chemical zoning different from that of the whole garnet, suggesting their formation at different P–T conditions. The peninsula/island cores show high Ca and Mn while the outer rings have low Ca, Mn and high Mg. This observation argues against the multiple nucleation and coalescence model ([Spiess et al. 2001](#); [Dobbs et al. 2003](#)). Temperature estimates based on the Gnt–Phg model of [Green and Hellman \(1982\)](#) show that the atoll garnet rings equilibrated at 734°C at slightly lower pressure of 2.29 GPa, thus suggesting atoll formation due to decompression upon exhumation.

Presence of primary inclusions in garnet as one of the main reactive sources for atoll garnet formation has been discussed by [Smellie \(1974\)](#).

Table 2. Thermo-barometric data for the garnets of the Tso Moriri complex.

Metamorphic Stages	Domain	Minerals used for PT calculations	Temperature (°C)			Pressure (GPa)	
			RV	KG	GH	BB	WM
Whole garnet	Core	Gnt - Cpx - Phg (in core of Gnt)					2.8
		Gnt - Cpx (in core of Gnt)	508	462			
		Gnt - Phg (in core of Gnt)			635		
	Rim	Gnt - Cpx - Phg (in rim of Gnt)					2.65
		Gnt - Cpx (in rim of Gnt)	561	579		2.7	
Atoll garnet	Inside atoll (Traverse 1)	Gnt - Phg (Gnt rim and adjPhg)			768		
		Gnt - Cpx - Phg (inner rim of atoll)					2.33
		Gnt + Phg and Cpx inside atoll)					
		Gnt - Cpx (inner rim atoll Gnt + Cpx in atoll Gnt)	483	497			
	Traverse 2	Gnt - Phg (Phg inside atoll + inner rim of Gnt)			675		
		Gnt - Cpx - Phg (Inner rim of atoll)					2.33
		Gnt + Phg and Cpx inside atoll)					
		Gnt - Cpx (inner rim atoll Gnt + Cpx in atoll Gnt)	257	282			
		Gnt - Phg (Phg inside atoll + inner rim of Gnt)			614		
	Outside atoll	Gnt - Cpx - Phg (outer rim of atoll)					2.29
		Gnt + Phg and Cpx outside atoll)					
		Gnt - Cpx (at outer rim of Gnt with adjcpx)	377	365			
		Gnt - Phg (outer Gnt rim with adjPhg)			734		

Formulations used for calculations are RV: [Ravna \(2000\)](#), KG: [Krogh \(1988\)](#), GH: [Green and Hellman \(1982\)](#), WM: Waters and Martin.

Textural and compositional relations in the studied samples show that the atoll garnet rings could be formed by replacement of the inclusion-rich whole garnet core simultaneously with the breakdown of matrix phases. Prograde resorption of garnet resulted in removal of Mn and Ca from garnet core to contribute to the formation of rims and other phases. Elements released due to the breakdown of initial garnet core were incorporated into the newly-grown Mg-rich garnet rings. In the studied samples, the atolls are filled with phengite (with low Si) as the dominant mineral, and the atoll interior show irregular edges that are either embayed or breached. Chemical modification of garnet interiors during metamorphism has been associated with garnet fracturing and is highlighted by many researchers (e.g., [Hames and Menard 1993](#); [Whitney 1996](#); [Hwang et al. 2003](#); [Konrad-Schmolke et al. 2007](#)). Compositional resetting of mineral grains along fractures and sub-grain boundaries rapidly occurs when fluids are available and chemical potential gradients are maximized between the matrix and grain interiors

([Konrad-Schmolke et al. 2007](#)). [Thompson \(1992\)](#) postulated that substantial quantities of H₂O can be transported to depths >100 km in the form of hydrous minerals, including phengite, clinohumite and epidote-zoisite. Experimental studies and thermodynamic calculations have demonstrated that lawsonite and phengite are able to store H₂O below 200 km in cold subduction zones ([Poli and Schmidt 1995](#)). During exhumation, internal retrograde fluids in UHP metamorphic rocks could be derived from the decomposition of hydrous minerals (e.g., [Miller et al. 2002](#); [Zheng et al. 2003](#); [Li et al. 2004](#)). Similarly, the decrepitation of primary fluid inclusions (e.g., [Xiao et al. 2000, 2001](#); [Su et al. 2002](#)) or the release of structurally bonded OH from nominally anhydrous minerals (e.g., [Zheng et al. 1999, 2003](#)) such as pyroxene, garnet, and rutile can also provide considerable amount of H₂O in the form of OH in their crystal lattice ([Smyth et al. 1991](#); [Bell and Rossman 1992](#); [Rossman 1996](#); [Ingrin and Skogby 2000](#); [Bolfan-Casanova 2005](#)). As proven by experiments, hydroxyl solubility

in nominally anhydrous minerals decreases with decreasing pressures (Lu and Keppler 1997; Withers *et al.* 1998; Mosenfelder 2000; Mierdel and Keppler 2004). Thus, significant amounts of aqueous fluids could be released during the early stages of UHP slab exhumation (Zheng *et al.* 2003). In the Tso Morari eclogites, early assemblages include lawsonite, talc and chlorite which were replaced by zoisite, amphiboles, phengite and quartz during prograde heating (Guillot *et al.* 1997; Chatterjee and Jagoutz 2015). Evidence of fluid activity in the eclogites from the studied area has already been established by Mukherjee and Sachan (2009). Phase equilibria modelling of post-peak metamorphic mineral assemblages in UHP eclogite from the Tso Morari massif by Palin *et al.* (2014) show that a number of petrographically distinct hydration episodes have occurred during exhumation ($\sim 640^\circ\text{C}$, 2.7–2.8 GPa). Although fluid inclusion studies have not been carried out during the present study, evidence of fluid can be reflected by the continuous presence of hydrous minerals such as zoisite, phengite and amphiboles in the rock matrix of the studied samples. The atoll garnets from the studied samples are therefore understood to have formed by infiltrating fluids generated due to breakdown of hydrous phases and/or the release of structurally bounded OH from nominally anhydrous minerals such as pyroxene, garnet at the onset of exhumation. The numerous irregular veins and cracks in garnet probably acted as pathways for the transport of fluid resulting in breakdown of garnet cores from inside. Mineral inclusion boundaries inside the original garnets may have also acted as pathways for infiltrating fluids. Re-growth caused by substitution of the garnet from the outer ring towards the inside may perhaps have resulted in the formation of peninsula-shaped atoll structures confirmed by lower temperature of 614°C – 675°C estimates for inside the atoll structure. Isolated island-shaped garnet relicts may have been formed by modification of some of the garnet peninsulas during early amphibolite-facies.

6.3 Tectonic implications

HP and UHP rocks along the Himalayan belt are observed to occur in different tectonic settings, *viz.*, accretionary wedge, oceanic subduction, continental subduction and continental collision. Rocks of the subducted plate are usually metamorphosed such that these rocks attain peak

pressures before peak temperatures defining ‘clockwise’ P–T paths. The metamorphic facies series encountered in subduction tectonic regimes or settings can be characterized by low geothermal gradients: zeolite→pumpellyite-actinolite facies/lawsonite albite facies→blueschist facies→ type C eclogites (Guillot *et al.* 2008). The reconstruction of the tectonic history of the Tso Morari eclogites proposed below is based on our petrologic study and considers the following constraints: (1) Protoliths for the Tso Morari eclogites are of the Panjal Traps (de Sigoyer *et al.* 2004) and areas old as Late Permian (Spencer *et al.* 1995), whereas the metamorphic ages are as young as Early Eocene (Leech *et al.* 2005); (2) the eclogites have been deformed at least two times; one was synchronous with prograde metamorphism during subduction and the other was related to amphibolite facies retrograde metamorphism during exhumation; (3) The eclogites have been subjected to at least three stages of metamorphism where the subducted rocks attain peak pressures prior to peak temperatures represented by a clockwise P–T time path.

The protoliths for the Tso Morari eclogites believed to have originated from mafic dykes (Ahmad *et al.* 2006) traversing through the northern Indian plate, thus representing the leading margin of the Indian plate which subducted beneath the Tethyan oceanic lithosphere. Subduction of the leading edge of the Indian plate with Late Permian continental eclogite protoliths represent an A-type subduction model of the Indian and Asian Plates at 56 ± 3 Ma (Guillot *et al.* 2008 and the references therein). The continental crustal fragment was probably dragged into subduction beneath the Asian plate after the intervening oceanic crust was completely consumed. During subduction, the crust went through various P–T conditions resulting in phase changes from blueschist (represented by inclusions in whole garnet) due to rapid increase in pressure and temperature to the eclogite facies assemblage represented by presence of coesite in the studied samples at depths of more than 100 km (768°C /2.65 GPa). At this depth, the Indian plate became gravitationally unstable because of its low density causing it to rebound isostatically initiating the exhumation process and thus causing uplift of the continental fragment allowing pressure to be released faster than temperature. Preservation of type C eclogites as well as blueschist facies assemblages is important considering that they are characterized by clockwise P–T paths, and may undergo heating and decompression during their

exhumation. High temperatures of 400°–425°C at 2.2–2.3 GPa to 670°–720°C at 1.8–1.9 GPa during the early stages of exhumation have been reported by Chatterjee and Jagoutz (2015) and are consistent with the estimated temperatures of 497°C at 2.3 GPa for outer garnet rings supporting their formation during exhumation. Relict coesite inclusions with well-developed radiating fractures in the garnet rims of the studied samples resulted due to the volume increase during the transformation from coesite to palisade quartz further support decompression during exhumation. Retrograde assemblage after omphacite consists of a symplectic intergrowth of clinopyroxene and albite; such replacement is very common and preserved in the studied eclogites where omphacite is more severely retrograded than garnet. During exhumation up to the depth of 40–30 km, the Tso Moriri rocks underwent cooling under blueschist facies conditions (1.1 ± 0.3 GPa; $580 \pm 50^\circ\text{C}$; Guillot *et al.* 2008). The amphibolite facies (1.1 ± 0.2 GPa and $630 \pm 50^\circ\text{C}$; *ibid.*) metamorphism is established at 47 ± 0.5 Ma by using variety of methods (de Sigoyer *et al.* 2000; Leech *et al.* 2005). Further, retrogression is characterized by the development of chlorite and chloritoid, which surrounds the garnet and along with white mica occur as shear bands (0.5 GPa and 500°C *ibid.*) in the entire Tso Moriri massif, and mark the final deformation which is dated between 34 ± 2 and 45 ± 2 Ma by Schlup *et al.* (2003).

7. Conclusions

The UHP eclogites from the Tso Moriri complex contain whole garnets along with spectacular atoll garnet structures. The atoll structures consist of garnet rings enclosing mixture of mineral phases between the rings and island cores.

(1) The atoll garnets are formed due to breakdown of the cores of earlier whole garnets as a result of infiltrating fluids at the onset of exhumation.

(2) The elements released due to this breakdown were incorporated in the later-forming atoll rings from the outer rings towards the inside, resulting in peninsula-shaped atoll garnet cores.

(3) Compositional heterogeneity between the whole garnet cores and rims, and atoll rings indicate their formation under differing P–T conditions.

(4) Previously determined P–T paths for the Tso Moriri eclogites show that the garnet cores

and rims more or less equilibrated at 2.0–2.15 GPa at temperatures of 535°–580°C (de Sigoyer *et al.* 1997; St-Onge *et al.* 2013) suggesting isothermal decompression.

(5) However, new temperature estimates calculated during the present study show that the whole garnet cores were formed at lower temperatures as compared to the rims suggesting formation under a prograde sequence from blueschist to eclogite facies.

(6) The atoll garnets are characterized by overall lower temperatures than the whole garnets and support their formation during the early stages of exhumation.

Paragenesis and composition of minerals from eclogites suggest that these rocks have experienced at least three stages of metamorphism, i.e., an earlier stage of blueschist facies metamorphism before they were subjected to an ultrahigh-pressure metamorphism of the coesite–eclogite facies followed by the epidote–amphibolite facies and greenschist facies retrograde stages during uplift. The subducted rocks attain peak pressures prior to peak temperatures represented by a clockwise P–T path.

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