Insights into the P–T evolution path of Tso Morari eclogites of the north-western Himalayas: Constraints on the geodynamic evolution of the region

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The present study is on the Ultra High Pressure Metamorphic rocks of the Tso Morari Crystalline Complex of the northwestern Himalayas. Five different mineral associations representative of five stages of P–T (pressure–temperature) evolution of these rocks have been established based on metamorphic textures and mineral chemistry. The pre-UHP metamorphic association 1 of Na–Ca–amphibole + epidote ± paragonite ± rutile ± magnetite with T–P of ~ 500°C and 10 kbar. This is followed by UHP metamorphic regime marked by association 2 and association 3. Association 2 (Fe>Mg>Ca–garnet + omphacite + coesite + phengite + rutile ± ilmenite) marks the peak metamorphic conditions of at least 33 kbar and ~ 750°C. Association 3 (Fe>Mg>Ca–garnet + Na–Ca amphibole + phengite ± paragonite ± calcite ± ilmenite ± titanite) yields a P–T condition of ~28 kbar and 700°C. The post-UHP metamorphic regime is defined by associations 4 and 5. Association 4 (Fe>Ca>Mg–garnet + Ca–amphibole + plagioclase (An₀₅) + biotite + epidote ± phengite yields a P–T estimate of ~14 kbar and 800°C) and association 5 (Chlorite + plagioclase (An₀₅) + quartz + phengite + Ca–amphibole ± epidote ± biotite ± rutile ± titanite ± ilmenite) yields a P–T value of ~7 kbar and 350°C.

1. Introduction

Reported occurrence of coesite, the high pressure polymorph of quartz as inclusions in the garnets of eclogitic rocks from Norway and the Alps region in the early 80's (Chopin 1984; Smith 1984) was instrumental in renewing the interest in the study of eclogite-bearing terrains. The presence of coesite established beyond doubt that the source of origin of eclogite was quite deep, at least 100 km beneath the earth's surface. Thereafter, numerous studies were carried out to understand the mechanism of plate subduction leading to formation of eclogite as a result of ultra high pressure metamorphism

(UHPM) and their subsequent exhumation and preservation at surface conditions (e.g., UHPM rocks from the Kokchetav massif, Kazakhstan; Dabie-Shan, China and western Gneiss Region, Norway, Dora Maria Massif, W. Alps; Franciscan Complex, California). Ultra high pressure metamorphic eclogite rocks in the Himalayan terrain has been reported from the Tso Morari Crystalline Complex (TMC) in India, the Kaghan and the Neelum valleys in Pakistan and the Ama Drime region and the Arun river valley in Nepal (Guillot *et al.* 1997; Sachan *et al.* 1999; Pognante and Spencer 1991; O'Brien *et al.* 2001; Groppo *et al.* 2007).

Keywords. UHPM (Ultra high pressure metamorphism); eclogites; Himalayas; Tso Morari Crystalline Complex (TMC).

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The Tso Morari Crystalline Complex was the first area from where the occurrence of eclogite rocks in the Himalayan terrain was reported in mid 20th century (Berthelsen 1953). This was corroborated nearly half a century later by reporting of coesite inclusions in garnets (Mukherjee and Sachan 2001). The peak UHP assemblage and its subsequent exhumation through amphibolite facies to greenschist facies in the TMC is generally agreed upon by most workers (de Sigoyer *et al.* 2004; Guillot *et al.* 1997) but textural and mineralogical constraints for the prograde path for attainment of UHP are lacking. Recently, Guillot *et al.* (2008) suggested a refined P–T–t path for the rocks where a pre-UHP path through blueschist facies regime was envisaged but not documented in terms of mineral chemistry or textural evidence.

The present work defines a new P–T evolution path for the UHP rocks of the Tso Morari Crystalline Complex. It works out a pre-UHPM blueschist facies mineral association (association 1) based on textural and mineral chemical data. A new transitional mineral association (association 3) gradational between eclogite and amphibolites facies is being reported for the first time for these rocks. We show that the rocks of TMC were not exhumed in a single step. Our work refines the P–T evolution path for the TMC eclogites which is used to comment upon the geodynamic evolution of this region in terms of slab kinematics and available geochronological constraints.

2. Geological setting

The Himalayan terrain is the most tectonically active zone of the Indian plate. It is characterized by four major tectonic elements that can be seen throughout from the Nanga Parbat in the west to Namcha Barwa in the east. The Himalayan rocks between these tectonic elements exhibit distinct geological characteristics. Based on it the Himalayas are classified into four divisions (Gansser 1964) from south to north: the Sub Himalayas, the Lesser Himalayas, the Higher Himalayas and the Tethyan or the Tibetan Himalayas (figure 1a).

2.1 The Tso Morari dome

The Tso Morari area is a NW–SE trending belt lying between the Tethyan Himalayas in the south and the Zildat ophiolite mélange of the Indus Suture zone to the north. Lithostratigraphically, the area consists of three formations, viz., the Puga Formation, the Taglang La Formation and the Rupshu and the Polokong La granites.

The Puga Formation comprises of schists and gneisses and hosts the boudins of eclogites studied

in this work. The Taglang La Formation comprises of metamorphosed calcareous, marly and argillaceous sediments with concordant bands of amphibolites. The Rupshu and Polokong La granites, the third lithostratigraphic unit of the Tso Morari area are intrusive in the Puga Formation and the Taglang La Formation (figure 1b).

Structurally, the area forms a doubly plunging anticline or a dome. The Puga Formation forms the core of this dome followed by the Taglang La Formation on the outer periphery. The Rupshu and Polokong La granites crosscut these formations in the dome. Three generations of structures are revealed in the field (Guillot *et al.* 1997; Jain *et al.* 2003). The first set of structures is vertical rootless folds and the associated lineation and cleavage. The second generation of structures are preserved as comparatively large recumbent folds with near horizontal axial plane. The third generation of deformation formed normal faults and the Tso Morari dome that delineates eclogite facies rocks from the surrounding lower grade rocks.

2.2 Current status of metamorphic studies

Focus so far in the metamorphic studies of the Tso Morari eclogites has been on establishing the UHP mineral assemblage. Based on metamorphic studies the eclogite rocks of the Tso Morari area are inferred to exhibit three mineral assemblages, viz., eclogite facies assemblage, blueschist-amphibolite facies assemblage and greenschist facies assemblage (de Sigoyer *et al.* 1997; Guillot *et al.* 1997; Sachan *et al.* 1999). For the eclogitic assemblage a pressure estimate varying from 14 to 16 kbar and temperature estimate of $550 \pm 50^\circ\text{C}$ to $580 \pm 60^\circ\text{C}$ has been documented; for the retrograde assemblage of amphibolite facies a pressure estimate of $\sim 8 \pm 3$ to 10 ± 3 kbar and temperature of $\sim 570 \pm 70^\circ\text{C}$ to $630 \pm 30^\circ\text{C}$ and for the third retrograde assemblage of greenschist facies the P–T estimates of ~ 5 to 8 ± 3 kbar and $\sim 500^\circ\text{C}$ to $590 \pm 90^\circ\text{C}$. As is evident the variability of the reported data lies well outside the error ranges of the data.

However, with the report of coesite inclusion in garnet of the eclogites from Tso Morari area (Mukherjee and Sachan 2001; Sachan *et al.* 2004) the minimum pressure attained by these rocks were redefined to be at least 28 kbar at 650°C . Following this report a lot of revisions went into P–T estimates for rocks of this area. For the eclogite facies assemblage, the temperature estimates vary between ~ 600 and 800°C (Jain *et al.* 2003; de Sigoyer *et al.* 2004). A carbonate bearing assemblage has also been reported from the TMC indicating P–T as ~ 39 kbar and $\sim 750^\circ\text{C}$ (Mukherjee *et al.* 2003). Geodynamic evolution models have been proposed by de Sigoyer *et al.* (2000, 2004),

Figure 1. (a) Geological map showing the sub-divisions of the Himalayas (modified after Gansser 1964). The three different locations of Ultra High Pressure (UHP) metamorphic rocks reported so far from the Himalayan terrain have been shown marked as stars in the map. (b) Geological map of the Tso Morari Crystalline Complex, modified after Berthelsen (1953) and Thakur (1983). Three different litho units comprising the study area has been shown with the sample collection locations marked as circles. Filled black circles and open circles mark two different field seasons.

Guillot *et al.* (2007, 2008) and Epard and Steck (2008) and mathematical estimations have been carried out to arrive at the rate and angle of subduction of the lithospheric plate (Kaneko *et al.* 2003; Leech *et al.* 2005).

It is quite clear that the peak UHP eclogite facies assemblage was followed by the development of amphibolite facies assemblage with a slight increase in temperature and a sharp decrease in pressure. Finally, the rocks attained greenschist facies assemblage with decrease in pressure and temperature. The prograde path leading to eclogite facies, however, remains unreported.

Figure 2. Field occurrence of eclogite boudins of the Tso Morari region hosted in Puga Gneisses. Boudins have been highlighted using white coloured boundaries. Sample location is on the road section from Sumdo towards Polokong La, GPS reading: 33 degree 183 minutes N; 78 degree 358 minutes E; Altitude: 15265 ft. The largest boudin in this photograph is about a meter in width. However, at different locations boudin sizes vary. We observed a maximum of 5–6 m length and 2–3 m width boudins.

2.3 The sample localities and field characteristics of the sampled rocks

The eclogite samples for the present work were collected from the Puga Formation and their locations are marked in figure 1(b). Eclogite occur as boudins within the metapelites of the Puga Formation. In the large boudins, unfoliated cores were rimmed by foliated margins (figure 2).

The UHP rocks which occur as boudins in the Puga Formations of the Tso Morari dome are mineralogically zoned on both megascopic as well as thin section scale. The core portions of these boudins consist predominantly of garnet with pyroxenes occurring as inclusions within the garnet. Amphibole and phengite occur with garnet as the other mineral constituents of this core portion. The rim portion of the boudin comprises Ca-amphibole/chlorite, biotite ($\pm$ quartz, K-feldspar and epidote).

3. Petrography and mineral chemistry

3.1 Methods and analytical conditions

The present study was carried out with focus on the eclogites of the Tso Morari area. Textural features of these rocks specially the inclusion minerals/assemblages, zoning, garnet in garnet growth and symplectitic intergrowth of minerals have preserved records of prograde and retrograde path.

The textural signatures associated with each metamorphic episode of the eclogites were observed in thin sections. We established five mineral associations (table 1).

Mineral chemistry were determined using a CAMECA SX51 electron microprobe with acceleration voltage of 15 kV and beam current of 12 nA

Table 1. Mineral associations of the eclogites of the Tso Morari Crystalline Complex, NW Himalayas with associated characteristic textures as observed in rock thin sections.

Association 1	Poikilitic garnet with inclusion assemblage of epidote/clinozoisite, pargonite and Na-Ca amphibole; Zoned amphibole with Na rich core and Na-Ca rich rim.	Na-Ca-amphibole + epidote $\pm$ pargonite $\pm$ rutile $\pm$ magnetite.
Association 2	Poikilitic garnet with inclusion assemblage of omphacite, phengite, rutile; coesite pseudomorph in garnet; two phases of growth in garnet; prograde zoning in garnet.	Fe>Mg>Ca-garnet + omphacite + coesite/usually quartz + phengite + rutile $\pm$ ilmenite.
Association 3	Conversion of omphacite into Na-Ca amph; Na-Ca rich rim of the zoned amphibole.	Fe>Mg>Ca-garnet + Na-Ca amphibole + phengite $\pm$ pargonite $\pm$ calcite $\pm$ ilmenite $\pm$ titanite.
Association 4	Atoll garnet; symplectite of Ca-amphibole and plagioclase after garnet and omph; zoned amph with Na-Ca rich core and Ca rich rim.	Fe>Ca>Mg-garnet + Ca-amphibole + plagioclase (An ₀₅) + biotite + epidote $\pm$ phengite.
Association 5	Fractured and skeletal garnets with fractures filled by chlorite and biotite; pseudomorph of secondary minerals after garnet.	Chlorite + plagioclase (An ₀₅) + quartz + phengite + Ca-amphibole $\pm$ epidote $\pm$ biotite $\pm$ rutile $\pm$ titanite $\pm$ ilmenite.

Table 2. Representative mineral analyses of different mineral associations preserved in the eclogites of Tso Morari Crystalline Complex. The oxygen numbers used for mineral formula calculation have been marked alongside the mineral name. End member calculations are also shown for important mineral constituents.

Mineral Sample no.	Association 1=Na-Ca amphib + Epi + Parg + Rt + Mag									
	Na-Ca amphibole (23O)			Epidote (12O)			Paragonite (22O)			
	in gt(8) 40/47	in gt(5) 65/107	in gt(2) 67/119	in mtx(C) 40/47	in gt(1) 67/119	in gt(3) 37/122	in gt(5) 40/126	in gt(3) 67/119	in gt(1) 40/47	in gt(1) 40/131
SiO ₂	45.76	42.15	40.65	54.73	37.06	38.022	38.751	45.52	46.54	46.57
TiO ₂	0.5	0.79	0.53	0.11	0.21	0.178	0.085	0.08	0.16	0.19
Al ₂ O ₃	14.95	16.26	16.36	12.28	26.58	26.051	30.027	38.96	38.16	38.39
Cr ₂ O ₃	0.09	0	0	0.01	0	0	0	0.08	0.11	0.24
FeO	14.87	16.45	17.12	9.84	8.8	10.081	5.037	1	0.88	1.31
MnO	0.18	0.04	0.33	0	0.09	0.041	0.006	0.04	0	0.04
MgO	9.32	7.81	9.15	11.53	0.14	0	0.187	0.12	0.32	0.41
CaO	7.49	7.55	8.63	3.05	23.22	22.892	23.292	0.47	0.2	0.26
Na ₂ O	4.13	4.54	3.28	6.34	0	0	0	7.79	6.97	6.98
K ₂ O	0.39	0.23	0	0.13	0	0	0	0.03	1.37	0.9
P ₂ O ₅	0	0	0	0	0	0	0	0	0	0.03
Sum	97.68	95.82	96.25	98.02	96.12	97.265	97.385	94.09	94.71	95.33
Amph										
Total Na(B)	0.842747	0.79375	0.637078	1.551026						
Total Na(A)	0.311989	0.518851	0.300312	0.137847						
Total Ca	1.157253	1.20625	1.362922	0.448974						

Table 2. (Continued)

Association 2 = Garnet (Mg-Ca) + Pyx + Coe/Qtz + Phe + Rt																		
Point of analyses Sample no.	Garnet (12O)										Clinopyroxene(6O)				Phengite (22O)		Rutile	
	Gt(C) (5)	Gt(Int)(2)	Gt(C)(5)	Gt(R)(1)	Gt(R)(6)	inn Gt(R)(5)	inn Gt(C)(5)	in gt(6)	in gt(2)	in gt(1)	in gt(2)	in gt	in gt(3)	in gt(2)	In gt(2) 40/47/5			
	75/145	37/122	40/47	40/131	40/04	63/101	63/101	40/47	37/122	65/107	75/145	40/47	40/47					
SiO ₂	39.132	38.05	39.11	39.04	37.942	39.01	39.26	57.04	55.45	55.983	56.043	51.18	49.6	0.079				
TiO ₂	0	0	0.03	0.26	0.035	0.04	0.11	0.08	0.08	0	0.053	0.34	0.55	100.461				
Al ₂ O ₃	21.946	21.8	21.85	21.86	21.88	22.44	22.69	13	10.31	10.01	8.593	25.41	28.53	0.051				
Cr ₂ O ₃	0.023	0.16	0	0	0	0.06	0.07	0.1	0.01	0.075	0.108	0.02	0.12	0				
FeO	26.876	28.2	23.57	21.92	27.818	25.69	24.35	3.75	7.61	6.619	7.911	2.06	1.94	0.97				
MnO	0.257	0.24	0.27	0.21	0.591	0.5	0.31	0.03	0	0	0.222	0	0	0.013				
MgO	6.82	6.21	8.42	7.24	5.802	7.72	8.57	7.26	6.97	7.423	7.882	4.17	2.88	0.028				
CaO	5.693	5.84	6.36	8.53	6.065	5.28	6.09	11.65	11.38	12.206	13.888	0	0.02	0				
Na ₂ O	0	0.02	0.1	0.07	0	0	0.08	7.79	7.7	7.76	6.358	0.46	1.05	0				
K ₂ O	0	0	0	0.02	0	0	0.02	0	0.01	0.007	0	9.58	8.51	0				
P ₂ O ₅	0	0	0.04	0.02	0	0	0	0	0	0.071	0	0	0	0				
Sum	100.747	100.53	99.75	99.16	100.133	100.74	101.79	100.7	99.62	100.154	101.058	93.23	93.19	101.602				
Gt																		
Alm	57.6869	58.61357	49.64618	47.68388	58.7902	54.94584229	49.81765661	36.30159	39.11293	36.31064	28.25783							
Pyx	26.09869	24.37715	32.25701	28.07963	22.77972	29.48026538	32.77297399	30.00045	31.94372	31.56161	34.1092							
Grs	15.6557	16.47408	17.5092	23.77381	17.11191	14.48922152	16.73591129	26.01605	27.2257	26.70965	26.93837							
								7.537274	1.559996	5.418096	10.60321							

Association 3 = Gt (Mg-Ca) + Na-Ca amph + Phe + Cal + Parg																								
Sample no.		Garnet (120)				Na-Ca-amphibole (230)						Phengite (220)				Paragonite (220)								
		Gt(R)(2) 40/47	Gt in amph(4) 67/119	Gt(R)(2) 40/126	Gt(R)(2) 63/104	Gt(R)(2) 37/122	adj Gt(3) 40/48	adj Gt(6) 40/47	adj Gt(11) 67/119	adj Gt(13) 71/134	adj Gt(1) 37/122	in mtx (rim) 40/47	adj Gt(7) 40/126	adj Gt(1) 40/131	adj Gt(1) 40/47	mtx(1) 37/122	mtx(2) 40/126	mtx 40/131	mtx(1) 40/127					
Amph																								
Total Na(B) 0.526277 0.787294 0.955 0.531071 0.61141 1.215716 0.807315																								
Total Na(A) 0.056147 0.378731 0 0.136873 0.510499 2 0.322914																								
Total Ca 1.473723 1.212706 0.989 1.468929 0.911263 0.784284 1.192685																								
Sample no.		Garnet (120)				Ca-amphibole (230)						Plagioclase (80)				Biotite (220)				Epidote (12)				
		Gt(C) 71/134(5)	Gt 40/48(3)	Gt 76/149(5)	adj Gt 40/48(2)	mtx 76/149(8)	symp 67/119(2)	mtx 71/134(2)	symp 40/126(4)	symp 40/126(5)	symp 67/119(2)	mtx 40/48(3)	mtx 63/101(2)	mtx 37/122(2)	mtx 71/134	mtx(2) 76/149								
Association 4 = Gt (Ca-Mg) + Ca-amph + Plag + Bt + Epi + Phe																								
Gt																								
Sum																								
Alm																								
Pyr																								
Grs																								
Gt																								
Sum																								
Alm																								
Pyr																								
Grs																								

Table 2. (Continued)

Association 5 = Chl + Phe + Qtz + Plag + Ca-amph ± Epi ± Bt ± Rt ± Sph ± Ilm																			
Sample no.		Chlorite (28O)				Phengite (22O)				Feldspar (6O)				Ca-Amphibole (23O)				Biotite (22O)	
		adj	Gt(2)	mtx(2)	mtx(6)	mtx(3)	mtx(2)	mtx(1)	mtx(4)	mtx(2)	mtx(1)	mtx(4)	mtx(9)	mtx(1)	mtx(2)	mtx(2)	mtx(2)		
		40/48	23/30	40/127	38/124	38/124	38/124	75/146		75/146	38/124	23/30	23/30	38/124	75/146	75/146	23/30		
SiO ₂	26.211	26.531	25.028	26.322	37.129	51.36				66.667	64.213		49.719	45.851	37.17	37.444			
TiO ₂	0.022	0.008	0.115	0.072	1.623	0.39				0	0		0.167	0.424	0.96	1.546			
Al ₂ O ₃	21.222	21.269	21.628	21.235	15.688	26.68				20.34	20.561	23.045	7.083	13.935	16.59	16.854			
Cr ₂ O ₃	0	0	0	0.092	0.222	0				0.09	0	0	0.083	0.075	0	0			
FeO	20.584	20.784	23.981	19.632	17.221	3.18				0.07	0	0.24	11.474	14.115	17.05	15.497			
MnO	0.158	0.216	0	0.183	0.165	0.09				0	0	0	0.136	0.019	0.23	0.176			
MgO	18.347	18.381	14.576	18.622	12.893	3.28				0	0	0.046	13.895	10.758	11.82	12.28			
CaO	0	0	0.028	0.118	0.027	0				1.01	1.539	3.86	12.56	8.664	0	0.173			
Na ₂ O	0	0	0.057	0.019	0.07	0.42				11.73	10.533	9.825	0.581	2.704	0.12	0.108			
K ₂ O	0.052	0.027	0.043	0	9.405	9.23				0.13	0.051	0.035	0.112	0.423	8.64	9.017			
P ₂ O ₅	0	0	0	0.044	0.066	0				0	0	0	0	0.053	0	0			
Sum	98.123	98.828	96.614	86.339	94.509	95.02				100.32	99.351	101.264	95.81	97.021	92.57	93.095			
										Fsp					Amph				
										X _{Na}	0.94862	0.922571	0.819704	Total Na(B)	0.027364	0.6634245			
										X _{Ca}	0.044719	0.07449	0.178325	Total Na(A)	0.137764	0.0914386			
										X _K	0.00666	0.002939	0.00197	Total Ca	1.972636	1.3365755			

Abbreviations: in gt = inclusion in the garnet, in mtx(c) = constituent of the matrix minerals, Gt(C) = Garnet core, Gt(R) = Garnet rim, Gt(5) = Garnet data of average 5 analyses for that point, symp = data point from symplectitic growth of association 4.

at the Electron Microprobe Analyzer Laboratory, Geological Survey of India, Faridabad. The analyses were carried out with the effective beam diameter $\sim 1\ \mu$. Standards used for calibrations include synthetic MnTiO_3 for Mn and Ti, albite for Si and Na, corundum for Al, magnetite for Fe, andradite for Ca, orthoclase for K, apatite for P, chromite for Cr and olivine for Mg. The raw data was corrected using inbuilt PAP (Pouchou and Pichoir 1987) correction.

Table 2 lists the mineral data for the five mineral associations containing all the phases representative of that metamorphic stage in the P–T path. The amphiboles in eclogites are classified after Leake *et al.* (1997) and Schumacher (2007) (figure 3a and b); Pyroxene classification is after Morimoto (1988) (figure 4a and b); Mica classification is after Deer *et al.* (1992) and Tischendorf (1997); Tischendorf *et al.* (2004) (figure 5). Additional data for each association is supplied in supplementary data – table 1.

Figure 3. Plots showing variation in amphibole chemistry for different mineral associations of eclogites as reported in this study. (a) Si versus X_{Na} ; (b) Al^{IV} versus Al^{VI} (amphibole has been abbreviated as amph).

Figure 4. Plots showing chemistry of clinopyroxenes from the eclogites of the Tso Moriri Crystalline Complex. (a) Classification of pyroxenes after Morimoto (1988). All the pyroxenes of the eclogites are omphacite. (b) A triangular plot showing variation in pyroxene chemistry when present as inclusion in garnet and while occurring in matrix as relict in amphibole ($\text{Q}\% = \text{Ca} + \text{Mg} + \text{Fe}^{2+}$, $\text{Aeg}\% = \text{aegerine}\%$, $\text{Jd}\% = \text{Jadeite}\%$, $\text{Cpx} = \text{clinopyroxene}$, $\text{Aug} = \text{Augite}$).

3.2 Petrographic, mineral chemical attributes and associated metamorphic reactions

Garnet, clinopyroxene, amphibole (Na-, Na-Ca and Ca-rich), phengite, quartz/coesite, paragonite, biotite, epidote, clinozoisite, rutile, ilmenite, calcite, plagioclase, chlorite, titanite, apatite and

Figure 5. Composition of different types of mica minerals present in the eclogites of the Tso Morari Crystalline Complex (after Tischendorf *et al.* 2004).

magnetite are the minerals identified in the five associations present in eclogites from the Tso Morari area.

Garnet is the most dominant mineral in the eclogites. It contains a variety of inclusions in the core and in the rim which are representative of different stages of metamorphism. Generally, garnet is a solid solution of almandine, pyrope, grossular and spessartine with $X_{\text{Fe}} = 0.36\text{--}0.75$, $X_{\text{Mg}} = 0.04\text{--}0.46$, $X_{\text{Ca}} = 0.13\text{--}0.38$ and $X_{\text{Mn}} = 0.00\text{--}0.13$. Following garnet composition, these eclogites belong to group 'C' (Coleman *et al.* 1965) (figure 6a). All the garnets are almandine rich but the ratio of the Mg and Ca content of garnet grains varies according to different textural settings (figure 6b). So we refer $\text{Fe} > \text{Mg} > \text{Ca}$ to relatively Mg-rich garnet and $\text{Fe} > \text{Ca} > \text{Mg}$ refers to Ca-rich garnets. Other dominant minerals are the amphiboles with varying proportions of Na and Ca content and the Na pyroxenes.

The five different associations identified can be classified into three different metamorphic regimes namely pre-UHP, UHP and post-UHP stages. Association 1 has been established to be of pre-UHP regime, associations 2 and 3 lie in UHP regime and associations 4 and 5 are representative of post-UHP regime.

3.2.1 Pre-UHP metamorphic regime: (Association 1 – Na-Ca-amphibole + epidote $\pm$ paragonite $\pm$ rutile $\pm$ magnetite)

The inclusion minerals namely sodic-calcic amphibole, paragonite, epidote, rutile and magnetite in the garnet (figure 7a and b) constitute the first preserved prograde association of minerals in the eclogites.

The Na-Ca amphibole (mainly barroisite) of the assemblage contains total $\text{Na}(\text{+K}) = 0.94\text{--}1.71$

Figure 6. Triangular plots showing composition of garnet from eclogites of the Tso Morari Crystalline Complex. (a) The eclogites belong to Group C eclogites based on garnet chemistry (Coleman *et al.* 1965). (b) A triangular plot showing variation in composition of garnets found in association with pyroxenes (association 2) and Ca-amphiboles (association 4) (Gt: garnet, Pyr: pyrope, Cpx: clinopyroxene, Ca-amph: calcic amphibole).

with $\text{Na}(\text{B}) = 0.64\text{--}1.55$; $\text{Na}(\text{A}) = 0.14\text{--}0.52$ and total $\text{Ca} = 0.45\text{--}1.36$; $\text{Al}^{\text{vi}} = 0.83\text{--}1.51$ and $\text{Al}^{\text{iv}} = 0.48\text{--}2.01$ (figure 3). The epidote contains $X_{\text{ps}} = 0.11\text{--}0.22$ where, $X_{\text{ps}} = \text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Al}^{2+})$ (Deer *et al.* 1992) and the Na content of paragonite grains vary from 1.74 to 1.96 a.p.f.u. on the basis of 22 oxygens (O) (table 2). Na-amphibole (glauco-phane) has also been observed from core portions of zoned amphiboles which are present in the matrix. Comparison of the Al^{iv} and Al^{vi} content of these two types of amphiboles (Na-amphibole and Na-Ca amphibole) show that they represent a similar

Figure 7. (a) A back scattered electron (BSE) image of a garnet grain from the eclogite (sample no. TD 38/125) with an inclusion assemblage of Na-Ca-amphibole, clinozoisite and paragonite representative of the association 1. (b) A BSE image of a garnet grain in an eclogite (sample no. TD 67/119) containing inclusions of paragonite, epidote, Na-Ca-amphibole, rutile and magnetite characteristic of association 1 (Gt: garnet, Czo: clinozoisite, Parg: paragonite, Na-Ca-amph: sodic calcic amphibole, Mag: magnetite, Rt: rutile, Epi: epidote).

pressure stability field and can be considered to belong to the same metamorphic stage.

In the investigated rocks association 1 has resulted from metamorphism of a mafic protolith. The preserved association is indicative of blueschist facies.

3.2.2 UHP metamorphic regime: (Association 2 – $Fe > Mg > Ca$ -garnet + omphacite + coesite/usually quartz + phengite + rutile $\pm$ ilmenite)

The textural feature leading to the establishment of association 2 is the garnet in garnet growth with

omphacite as inclusion within garnets. Here the inner garnet contains inclusion of omphacite along with amphibole and rutile. We have also observed quartz pseudomorphs after coesite associated with radiating fractures in the host garnet in different sections of the same samples. Our identification is texture based and no Raman spectroscopy data is available with us. However, presence of coesite from these rocks is well established (Mukherjee and Sachan 2001) and hence considering coesite in our assemblage is justified (figure 8).

The inner garnets associated with omphacites are Mg rich with $X_{Py} = 0.24$ – 0.35 and $X_{Gr} =$

(a)

(b)

(c)

0.14–0.21 (figure 6b). There is a well defined prograde zoning in the inner garnet where X_{Mg} and X_{Ca} increase and X_{Fe} decreases from core to rim. The omphacite is Na rich with X_{Jd} of omphacite =

38.16–44.21 (figure 4b). The Si content of phengite varies from 6.70 to 6.94 with Al content ranging from 4.1 to 4.5 a.p.f.u. (22O) (see table 2).

Association 2, which is the ultra high pressure assemblage, has resulted from association 1. The following reactions were possibly responsible for the formation of association 2.

From the textural evidence of two stages of garnet growth it is likely that fluids present in the system reacted with the core garnet to form amphibole and phengite first. As the temperature rose garnet recrystallization took place (second phase of garnet) from amphibole and phengite.

Fluid source in such a setting can be many. Engvik *et al.* (2000, 2001) pointed out that it could be the water coming off from the dehydrating subducting slab which migrate up the subduction zone and hydrates the system all over again. In many terrains progressive dehydration and decarbonation reactions during prograde HP (high pressure) and UHP metamorphism leads to transformation of hydrous protolith to an anhydrous assemblage, but we do find hydrous minerals like phengite, amphibole, zoisite, etc., in HP and UHP rocks (Mottana *et al.* 1990; Peacock 1993; Poli and Schmidt 1995, 1997). Such minerals serve as important phase to deliver H_2O in the subduction zone (Schmidt and Poli 1998; Fumagalli and Poli 2005). Conversion of glaucophane + clinozoisite = garnet + omphacite + H_2O has been considered to demarcate the transition of blueschist to eclogite facies in many UHP metamorphic terrains (e.g., Ridley 1984; Evans 1990). It has been experimentally shown that a large amount of water can be released by this transition which can get stored as grain boundary fluid or as fluid inclusion (Liu *et al.* 1996). The fluid inclusion data in Tso Morari

Figure 8. (a) A BSE image of the garnet grain with inclusions of omphacite and quartz pseudomorph after coesite. Radial cracks developed around the coesite inclusions as can be seen in the image. (b) A BSE image of garnet in garnet growth texture in eclogite with two distinct rings of garnets. The core garnet with inclusion of omphacite is part of the association 2 (sample no. TD 63/101). (c) A BSE image of the eclogite (sample no. TD 40/47) showing garnet grain with inclusions of rutile, omphacite, phengite and Na-Ca-amphibole representative of association 2 (Gt: garnet, coe: coesite, omph: omphacite, Phe: phengite, Rt: rutile, Na-Ca-amph: sodic calcic amphibole).

eclogite supports this idea (Mukherjee and Sachan 2009).

Experimental studies show that amphibole can be stable up to 22 to 30 kbar pressure depending on the bulk chemistry of the rock (Schmidt and Poli 1998). Infrared spectroscopy (IR) and transmission electron microscopic (TEM) study has shown that garnet and clino-pyroxene can host a lot of water as molecular water under these conditions (Su *et al.* 2002; Katayama and Nakashima 2003). Thus, anhydrous minerals too can be a transporter of water to the earth's deeper level.

Another important factor regarding the source of fluid in UHP environment is that the top and base of the subducting slab may follow different thermal path during subduction, which leads to redistribution of fluid rather than its loss (Liu *et al.* 1996). The base of the crust being cooler than the top of the crust will not undergo much devolatilization reactions.

3.2.3 Association 3 – $Fe > Mg > Ca$ -garnet + Na-Ca amphibole + phengite $\pm$ paragonite $\pm$ calcite $\pm$ ilmenite $\pm$ titanite

The outer garnet is separated from the inner garnet by a rim of Na-Ca amphibole. At places the amphiboles are zoned with a Na-rich core and Na-Ca rich rim. In the matrix also an association of Na-Ca amphiboles along with garnet, phengite, paragonite, calcite and rutile is present.

The outer garnet contains relatively less Mg and more Ca than the inner garnet ($X_{Mg} = 0.17$ – 0.31 and $X_{Ca} = 0.16$ – 0.25). The associated Na-Ca rich amphiboles with total Na = 0.63 – 1.58 ; Na(B) = 0.53 – 1.45 ; Na + K(A) = 0.01 – 0.51 ; Ca = 0.55 – 1.48 ; $Al^{iv} = 0.42$ – 2.25 and $Al^{vi} = 0.5$ – 1.42 mol fraction a.p.f.u (23O) and phengites have an Al content of 4.1 – 4.5 a.p.f.u (22O) (table 2).

The most conspicuous changes in assemblage of association 3 are related to the type of amphibole present (see figure 3). The Na-Ca amphibole which is a part of this association is present in the matrix of eclogites (figure 9). These amphibole grains have formed from clinopyroxene as is evidenced by the

replacement texture. The compositional difference between the pyroxene away from amphibole and those which are replaced by Na-Ca amphibole is distinct. Probably initially all the pyroxenes were omphacite as indicated by the preserved inclusions

(a)

(b)

(c)

Figure 9. (a) A BSE image of a zoned grain of amphibole with Na-rich core and Na-Ca rich rim (sample no. TD 40/47). The Na-rich amphibole present in the core is an amphibole of earlier generation. (b) A BSE image of an eclogite sample showing relict Ca-pyroxene within a grain of Na-Ca amphibole in the matrix (sample no. TD 71/134). (c) A BSE image of a garnet grain in an eclogite with inclusion of relict clinopyroxene rimmed by Na-Ca amphibole (sample no. TD 40/47) (Na-Ca amph: sodic calcic amphibole, Cpx: clinopyroxene, Gt: garnet).

in the garnet (i.e., pyroxene of association 2). While the pyroxene inclusions in the garnet retained the original composition, those in the matrix got converted to Na-Ca amphibole. In the later case, most of the Na composition in the pyroxene migrated to form amphibole (figure 4b).

This is well illustrated in sample no. TD 40/47 where pyroxenes are preserved as both inclusion and as relict in amphibole grain. The inclusion pyroxene has composition $(\text{Na}_{0.58}\text{Ca}_{0.43})(\text{Mg}_{0.35}\text{Fe}_{0.15}\text{Al}_{0.50})(\text{Si}_{1.99})\text{O}_6$ representative of the original pyroxene while the matrix pyroxene which is present as relict within the amphibole grain has lower Na and Fe $(\text{Na}_{0.53}\text{Ca}_{0.44})(\text{Mg}_{0.38}\text{Fe}_{0.11}\text{Al}_{0.53})(\text{Si}_{1.99})\text{O}_6$. The surrounding amphibole has a composition $\text{Na}_{0.51}(\text{Na}_{0.62}\text{Ca}_{1.38})(\text{Mg}_{1.82}\text{Fe}_{1.73}^{2+}\text{Fe}_{0.36}^{3+}\text{Al}_{1.08})(\text{Si}_{6.55}\text{Al}_{1.45})\text{O}_{22}(\text{OH})$ showing transfer of the Na and Ca component (see table 2 and supplementary data table 1).

3.2.4 Post-UHP metamorphic regime (Association 4 – Fe > Ca > Mg-garnet + Ca-amphibole + plagioclase (An_{05}) + biotite + epidote $\pm$ phengite)

A characteristic texture observed in the eclogites is the atoll garnets (figure 10a). Here the core is entirely occupied by Ca-amphibole, phengite, $\pm$ epidote, $\pm$ biotite, $\pm$ albite (An_5) while the rim is made up of garnet. These minerals are also present in symplectitic association around garnet grains. Assemblage 4 is essentially a replacement or symplectitic breakdown texture of UHP stage. There are zoned matrix amphiboles where the core part is Na-Ca amphibole and the rim is Ca-amphibole. The symplectitic growth of Ca-amphibole and plagioclase adjacent to garnet is also documented. At places Ca-amphibole and plagioclase symplectite replaces pyroxene grain. Biotite growth along the cleavage plane of phengite is seen in many samples as well (figure 10b and c).

Amphiboles of this association has a Ca content varying between 1.52 and 1.73 and Na content of 0.34–1.1 (see figure 3); garnet is also Ca-rich with $X_{\text{Gr}} = 0.16$ –0.31 (see figure 6b); plagioclase is albitic in composition with $X_{\text{Ab}} = 0.90$ –0.98;

biotite is Mg rich ($X_{\text{Mg}} = 0.51$ –0.74, $X_{\text{Fe}} = 0.30$ –0.50) and epidote has $X_{\text{Ps}} = 0.05$ –0.18 (table 2). The following reactions have resulted in association 4

(a)

(b)

(c)

Figure 10. (a) A BSE image of a garnet grain, showing atoll texture characteristic of the association 4 in eclogite (sample no. TD 40/47). (b) A BSE image showing clinopyroxene breakdown to Ca-amphibole and plagioclase which occurs as symplectitic intergrowth in eclogite (sample no. TD 40/126). (c) A BSE image showing symplectitic intergrowth of Ca-amphibole and plagioclase occurring adjacent to garnet in eclogite (sample no. TD 67/119) (Cpx: clinopyroxene, Phe: phengite, Na-Ca amph: sodic-calcic amphibole, Plag: plagioclase, Gt: garnet).

(a)

(b)

(c)

from association 3 which is also a part of the high pressure assemblage.

3.2.5 Association 5 – Chlorite + plagioclase (An_{05}) + quartz + phengite + Ca-amphibole ± epidote ± biotite ± rutile ± titanite ± ilmenite

The last stage of metamorphism preserved in the eclogites is documented by the presence of textures like skeletal garnets where garnet was replaced by chlorite, phengite and Ca-amphiboles; many of the samples show chlorite pseudomorphs after garnet with association of biotite, quartz and plagioclase. Locally highly fractured garnets with fracture filling of chlorite and biotite are also present (figure 11).

Chlorites of this association are Mg rich ($Mg = 4.67\text{--}5.85$ and $Fe = 3.25\text{--}4.31$). Phengite contains $Si = 5.65\text{--}6.86$ and $K = 1.55\text{--}1.82$ p.f.u. (22O); Feldspar is albitic in composition with $X_{Na} = 0.92\text{--}0.98$; biotite is Mg rich with ($X_{Mg} = 0.50\text{--}0.60$ and $X_{Fe} = 0.41\text{--}0.47$) and amphibole present in some samples are Ca rich with total Ca of $1.34\text{--}1.73$ p.f.u. (23O) (table 2). Breakdown of minerals in association 4 through following reaction is inferred for the association 5.

4. P–T estimates for the eclogites

For temperature estimation, $Fe^{2+}\text{--}Mg^{2+}$ exchange geothermometry between coexisting garnet-clinopyroxene, garnet-phengite and garnet-biotite mineral pairs has been employed. Apart from this, a number of experimental studies such as $\text{Quartz} \leftrightarrow \text{Coésite}$ transition reaction, Si content in phengite, $\text{Albite} = \text{Jadeite} + \text{Quartz}$; $\text{Titanite} + \text{Epidote} = \text{Garnet} + \text{Rutile} + \text{Clinopyroxene}$ + $\text{Coésite/Quartz} + H_2O$ reaction and conversion of clinopyroxene to Na-Ca amphibole have been used to deduce the pressure and temperature limits of the associated minerals. Besides the conventional

Figure 11. (a) A BSE image of pseudomorph of a phengite, chlorite, biotite and quartz after garnet in eclogite (sample no. TD 38/124) representing Association 5. Pseudomorph outline has been highlighted in the image using a boundary line. (b) A BSE image showing relict garnet replaced by chlorite, phengite and quartz in eclogite (sample no. PF-36/04). (c) A BSE image of embayed and fractured garnet grains in the matrix of chlorite, Ca-amphibole, phengite and quartz in eclogites (sample no. TD 76/149) (Phe: phengite, Chl: chlorite, Bt: biotite, Qtz: quartz, Gt: garnet, Ca: amph: calcic amphibole).

thermo-barometers, THERMOCALC has also been used to determine the P–T conditions for various mineral associations established by petrographic and mineral chemistry data (table 3). Henceforth, mineral name and abbreviations will be used in tables and figures: Albite (Ab), Aegerine (Aeg), Augite (Aug), Almandine (Alm), Amphibole (Amph), Biotite (Bt), Calcite (Cal), Chlorite (Chl), Clinopyroxene (Cpx), Clinozoisite (Cz), Coesite (Coe), Epidote (Epi), Garnet (Gt), Glaucophane (Glu), Grossular (Gr), Ilmenite (Ilm), Jadeite (Jd), Magnetite (Mag), Omphacite (Omph), Paragonite (Parg), Phengite (Phe), Plagioclase (Plag), Pyrope (Py), Pyroxene (Pyx), Quartz (Qtz), Rutile (Ru), Titanite (Ttn).

For the association 1 of Na–Ca amphibole + epidote/clinozoisite $\pm$ paragonite pressure of 11 kbar and temperature of 500°C has been established based on the stability limits of the minerals (Evans 1990). Using the garnet-clinopyroxene core assemblage in the garnet in association 2, the average temperature has been estimated to be $\sim$ 580°C at 27 kbar (Ellis and Green 1979). Garnet-phengite thermometry has also been used for the temperature estimate of 637°C at 27 kbar (Green and Hellman 1982). A minimum pressure limit of

27 kbar for this association is indicated from the quartz to coesite transition reaction (Bohlen and Boettcher 1982).

To estimate the peak metamorphic conditions attained by association 2 we have used the reaction Titanite + Epidote $\leftrightarrow$ Garnet + Rutile + Coesite + H₂O (Manning and Bohlen 1991) for the end-member reaction in CASTH system. Application of the garnet-clinopyroxene thermometer of Ellis and Green (1979) and the reaction above yielded a well constrained estimate of $834 \pm 12^\circ\text{C}$ and $\sim$ 33 kbar.

However, the Manning and Bohlen (1991) curve is for end member compositions and it cannot be used without correction for solid solutions. The locus of this reaction in rocks is not univariant but depends critically on grossular content in garnet and clinozoisite content in epidote. Using the term epidote rather than clinozoisite implies Fe³⁺, and the reaction if balanced with epidote would then depend on fO₂, the Fe³⁺ # of epidote and the Fe²⁺ # of garnet (Donohue and Essene 2000). Page et al. (2003, 2007) applied the quartz equivalent of the reaction for eclogites from North Carolina and California. Their calculations for solid solutions in titanite, epidote and garnet with Holland and

Table 3. Thermobarometric data for the eclogites of the Tso Moriri Crystalline Complex.

Metamorphic stages	Minerals used for calculations	T (°C)	P (kbar)	Thermocalc	
				T (°C)	P (kbar)
Pre-UHP	Association 1				
	Glu $\pm$ Epi/czo $\pm$ pg			515	8.5
UHP	Association 2				
	Gt-pyx (in core of Gt)	555($\pm$ 45) _(EG)	27 _(BB) 20 $\pm$ 3 _(WM) 33 _(MB)	760	39.5
	Gt-Pyx (in rim of Gt)	837($\pm$ 11) _(EG)	27 _(BB)		
	Gt-Phe (in core of Gt)	637($\pm$ 24) _(GH)			
	Association 3				
	Gt-Phe	689($\pm$ 17) _(GH)	28 _(FH)	810	25
	(Gt rim and adj Phe)	700 _(FH)	28 _(FH)		
Post-UHP	Association 4				
	Gt-Bt (Gt rim and adj Bt)	796($\pm$ 50) _(FS)	14 _(H)	840	14.4
	Association 5				
	Gt-Phe (gt-rim and adj Phe)	473($\pm$ 13) _(GH)	8 _(MS)	425	6.5
	Gt-Bt (Gt rim and adj Bt)	370($\pm$ 25) _(FS)	8 _(MS)		

T (°C) – temperature in degree celcius; P (kbar) – pressure in kilobars. Formulations used for calculations are: EG = Ellis and Green (1979); GH = Green and Hellman (1982); FR = Forneris and Holloway (2004); FS = Ferry and Spear (1978); BB = Bohlen and Boettcher (1982); MB = Manning and Bohlen (1991); H = Holland (1980); MS = Massonne and Schreyer (1987); WM = Waters and Martin (1993). Mineral abbreviations used are: Glu: glaucophane, Epi: epidote, Czo: clinozoisite, Parg: paragonite, Gt: garnet, Pyx: pyroxene, Coe: coesite, Qtz: quartz, Phe: phengite, Cal: calcite, Na–Ca amph: sodic calcic amphibole, Rt: rutile, Bt: biotite. Thermocalc window version 3.21, based on internally consistent thermodynamic dataset of Holland and Powell (1998) was used. Mineral activities were calculated by A-X Program of Holland and Powell (1998). All the possible reactions between given end member phases with P–T values were calculated for the Na₂O–CaO–K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O system.

Powell (1998) data set show a strongly back-bending reaction that does not cross into the coesite field for those compositions.

Manon *et al.* (2008) recalculated this reaction and placed it above 45 kbar for temperatures estimated by us for association 2. They measured C_p (heat capacity) of titanite and found that the $V(P,T)$ data for titanite in Holland and Powell (1998) fit experimental data much better than the data of Berman (1988). Manon *et al.* (2008) recommended using Holland and Powell (1998) dataset for titanite-bearing equilibria and showed that the locus of the reaction is shifted upward by 1 kbar relative to Page *et al.* (2003, 2007). Tropper and Manning (2008), pointed out that Al can also substitute Ti in titanite which needs to be considered for geobarometric calculations involving reaction discussed above. In our study, in the presence of rutile and epidote, we can at least use end-member clinozoisite and titanite to get a lower P limit for our association 2.

Pressure calculation using Thermocalc based on Holland and Powell (1998), data set for the association 2 (Garnet + omphacite + phengite + rutile + coesite/quartz) has yielded a pressure of 39.5 kbar. Thus, conservatively we estimate pressures exceeding 33 kbar for association 2.

For the association 3 an average P–T $\sim$ 28 kbar and 740°C has been obtained on the basis of conversion of omphacite to Na–Ca amphibole based on the experimental study of Forneris and Holloway (2004). The average temperature estimation for association 4 is calculated on the basis of garnet-biotite K_D thermometry as $\sim$ 800°C (Ferry and Spear 1978). Average pressure calculation is done by using Jd (jadeite) barometry given by Holland (1980) as $\sim$ 14 kbar. The P–T estimate for the association 5 have been determined using garnet-biotite and garnet-phengite thermometry and phengite barometry as $\sim$ 370°C and $\sim$ 7 kbar (Ferry and Spear 1978 and Green and Hellman 1982).

5. Evolution of the P–T path

In discussing the P–T path for the Tso Morari eclogites the time markers are based on the work of de Sigoyer *et al.* (2000, 2004), Kaneko *et al.* (2003), Leech *et al.* (2003, 2005) and Schlup *et al.* (2003). The reconstruction of P–T path implies explaining the development of above-described five mineral associations in the Tso Morari eclogites.

The mineral association 1 has a P–T estimate of about 11 kbar and 500°C. In the context of the tectonic setting of the Tso Morari area we believe that initiation of metamorphism of this UHP terrain is coincident or began soon after the collision of the Indian plate with the Asian plate at $\sim$ 57 Ma.

This event is well constrained by geologic, paleontological and paleomagnetic records (Klootjwijk *et al.* 1992; Garzanti *et al.* 1996; Rowley 1996; Leech *et al.* 2005). With the initiation of subduction of the Indian plate, the mafic protolith underwent a burial to a depth of about 30 km. This resulted in sudden rise in pressure with relatively less rise in temperature and the protolith experienced a blueschist facies regime of metamorphism resulting in mineral association 1 (figure 12).

Further burial to a depth of up to $\sim$ 130 km raised the temperature and pressure regime to about 750°C and 33 kbar leading to the transformation of blueschist facies assemblage to eclogitic assemblage of association 2. This ultra high pressure rocks possibly formed at about 53 Ma on the basis of U–Pb SHRIMP dating of zircon (Leech *et al.* 2005), and 53 ± 0.2 Ma $^{39}\text{Ar}/^{40}\text{Ar}$ age of phengite (Schlup *et al.* 2003).

The mineral association 3 of Fe>Mg>Ca–garnet–Na–Ca amphibole – phengite $\pm$ paragonite $\pm$ carbonate $\pm$ ilmenite is reported for the first time in the P–T evolution path of the Tso Morari eclogites. The P–T range for this transition is $\sim$ 28 kbar and 780°C. Hence, association 3 is also in the UHP regime that represents decreasing pressure suggesting a phase of uplift.

There is evidence of fluid activity in the eclogites from this region as is reflected in the continuous presence of phengite, amphiboles and calcite in equilibrium with association 3. Association 3 was followed by association 4 consisting of Fe>Ca>Mg–garnet–Ca–amphibole – plagioclase (Ab_{95}) – biotite – clinozoisite/epidote $\pm$ phengite. The average P–T of formation for this particular mineral association is estimated to be 14 kbar and 800°C at a depth of about 45 km. This is the time when slab moved up at $T \sim 47$ Ma, marking the initiation of retrograde phase of metamorphism. During this exhumation, these rocks underwent slight increase in temperature. This could be a result of slab break-off or dumping of granitic material with radioactive elements on top of the rock-pile (formation of the Himalayan nappes) as suggested by some researchers (de Sigoyer *et al.* 2004; Leech *et al.* 2005). The later decompression episode as recorded by the mineral association 5 has pressure–temperature regime of $\sim$ 7 kbar and 400°C corresponding to an uplift to a depth of 30 km at about 29 Ma.

The initial burial rate along the P–T slope changed the confining P from 11 to 33 kbar (ca. 35 to 130 km, transition from association 1 to 2) in 57 to $53 = 4$ Ma (rate = $100 \text{ km}/4 \text{ Ma} = 2.4 \text{ cm yr}^{-1}$). Further, after the formation of assemblage 3, the decompression of the Tso Morari rocks took place from 33 to 14 kbar from a depth of 130 to 45 km (for association 3 to 4 transition) took

53–47 = 6 Ma (rate of 85 km/6 Ma = 1.4 cm yr⁻¹). The exhumation of the eclogitic unit from 45 to 28 km occurred over a time interval of 47–29 = 18 Ma, suggesting a linear rate of 17 km/18 Ma ~ 1 cm/yr⁻¹.

The significance of the present study is that a prograde sequence is indicated through the epidote blueschist facies regime that sheds light on the nature of the burial. Our findings show a higher value of pressure being attained by rocks of the Tso Morari area. The retrograde path is also shown to have attained a higher temperature and is well constrained with respect to mineral assemblages, reactions and the pressure temperature data.

The coesite bearing assemblage from the Kaghan eclogite yielded an age of 46.4 ± 0.1 Ma (Parrish *et al.* 2006). Zircons from the host rock of the same area also yielded almost identical ages of 46.2 ±

0.7 Ma (Kaneko *et al.* 2003; Parrish *et al.* 2006). There is a difference of about 8 to 9 Ma in the age of UHP metamorphic assemblage from the Tso Morari and that of Kaghan Valley samples.

5.1 Implications on the geodynamics of the region

There have been propositions that the protolith for the metaafic rocks of the Tso Morari terrain is the Zildat Ophiolitic Melange as both have consanguineous trace elements and Nd isotopic data (Ahmad *et al.* 1996, 2006 and Unpublished PhD thesis, Preeti Singh 2008). Although the exact timing of the initiation of subduction leading to the formation of this mélangé suit is lacking, paleomagnetic, geochronological and stratigraphic data point to 65–57 Ma as its beginning (Garzanti *et al.* 1987; Klootwijk *et al.* 1992; Rowley 1996). This

Figure 12. The proposed P–T path for the eclogites of the Tso Morari Crystalline Complex. Rectangles with numbers mark each mineral association. Errors in estimation of pressure and temperature conditions for each association have been marked along with the rectangular boxes. The P–T path has been marked in dark coloured solid line passing through each rectangle. The subduction rate calculated for the proposed P–T path has been shown in dotted lines capped with an arrow mark along with the P–T path drawn. P–T paths proposed by previous researchers have been shown alongside for comparison. The age quoted for each association is, viz., for Association 1: Rowley (1996), Garzanti *et al.* (1996), Klootwijk *et al.* (1992); Association 2: Leech *et al.* (2005), Schlup *et al.* (2003); Association 4: Schlup *et al.* (2003); Association 5: de Sigoyer *et al.* (2004). Crucial reactions used for establishing the P–T evolution path of the Tso Morari Crystalline Complex have also been marked alongside [Glaucophane(Glau) + Clinzoisite(Czo) ↔ Garnet(Gt) + Omphacite(Omph) (Evans 1990), Quartz(Qtz) ↔ Coesite(Coe) (Bohlen and Boettcher 1982), Titanite(Ttn) + Epidote(Epi) ↔ Garnet(Gt) + Rutile(Rt) + Coesite(coe)/Quartz(Qtz) + H₂O (Manning and Bohlen 1991), Jadeite(Jd) + Quartz(Qtz) ↔ Albite(Alb), (Newton and Smith 1966; Holland 1980), Garnet + Clinopyroxene ↔ Amphibole + Albite(Plg) (Holland and Powell 1990)]. Reactant mineral phases are being marked on one side of the reaction curve and the other side shows product phases.

suggests that the subduction of Indian plate and the obduction of the mélange may have initiated close in time. It is possible that some of these mafic rocks, now the eclogites were emplaced within the subducting continental Indian plate at the time of formation of the mélange.

The depth to which a subducting slab would travel has bearing on the pressure–temperature–time evolution path of the rocks associated with the slab and is invariably a function of the subduction angle. Many studies on calculation of subduction angle for the Indian plates exist and are based on trigonometric calculations taking into account convergence rate and geochronology data. Our findings have established a prograde path and hence a precise subduction angle can be calculated. If we consider the rate of change of convergence from 18 to 10 cm^{−1}yr at the time of initiation of the subduction (Klootwijk *et al.* 1992; Epard and Steck 2008), the subduction angle would be ~10° [subduction angle = (tan^{−1}(depth/distance)); where total depth is assumed to be the distance from about 35 km to the depth of maximum UHP, i.e., 130 km.

It is quite likely that the subducting Indian plate along with the overlying sediments experienced rigidity up to a depth of about 20 km during subduction (e.g., Bilek and Lay 1999). Experimental structural modeling work by Chemenda *et al.* (2000), has shown that it generates numerous steep dipping faults in such kind of subduction setting. The Indian plate on its downward journey might have developed a number of steep brittle faults at different levels. As a result, the downthrown blocks must have sunk deeper than rest of the downgoing lithospheric slab. As and when the fault-bounded blocks reached the deeper higher temperature ductile environment, the density difference between the dense slab and that of the mantle would have decreased progressively resulting in slowing down of the downward travel of the slab.

During the course of downward movement, mineralogical constituents of the slab also underwent phase changes from lighter to denser structures facilitating the break off of the sinking slab (Van der Voo *et al.* 1999). This could have initiated a halt in subduction after an initial phase of slowing down the downward movement. While the convergence of the Indian and Asian plates was still continuing, parts of the subducting plate may have been squeezed up. Contemporaneously the upper parts of the subducting plate may have failed and were squeezed back up the tapered angle of the interface. The subduction channel now became easier pathway to exhume the buoyant rocks under the action of fluids and associated serpentinisation. The exhumation would continue and the depth at which this would stop depends on the strength of

the lithosphere as well as the depth to which it sank.

The process of subduction and exhumation of the Tso Morari region till the slab came to a halt may have taken ~10 Ma. However, the duration of the pause in the exhumation path of the slab is not certain. It could be as much as 10 Ma because the earliest medium grade metamorphism as documented by presence of kyanite-staurolite in the Central Crystallines of the Himalayas is during the Oligocene, i.e., ~37–29 Ma (Vance and Harris 1999). We suggest that the exhumation of the Central Crystallines and the final exhumation of the Tso Morari Complex (including eclogites of all levels) took place simultaneously, i.e., post Mid-Miocene (Liou *et al.* 2004).

Exhumation of plates may be caused by erosion and isostatic adjustments, extensional collapse (DeCelles *et al.* 2002), or underplating accompanying corner flow (de Sigoyer *et al.* 2004). However, the erosional rates calculated by previous researchers for the Tso Morari region are too high to be accounted for by the isostatic adjustment. The case of underplating would require entire Indian Plate to go down to great depths with consequent widespread UHP metamorphism. We propose that the downgoing segments used the already available shear zones to flow back up to ca 45 km at current plate tectonic (seafloor spreading) velocities presumably as part of one continuous episode during the subduction of the Indian Plate under the Asian Plate (Thompson *et al.* 1997). The proposed mechanism thus accounts for the short duration of the ultra high pressure metamorphism as well as its restrictive outcrop nature and the field settings.

New findings presented in this paper have been able to sharpen our concepts regarding the evolution of UHP rocks. The basic process of generating them through subduction and subsequent exhumation was one single process. In this light it is easier to explain why only restricted areas within the Tso Morari Complex have UHP assemblages. Incorporation of mafic protoliths from the ophiolites occurred at different levels; only those parts which crossed through a depth equivalent to the 27 kbar pressure attained garnet-clinopyroxene-phengite-rutile assemblage and rest show only up to Ca-amphibole-plagioclase-biotite-epidote assemblage attained when these rocks were coupled with rest of the Himalayan crust.

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References

- Ahmad T, Khanna P P and Thakur V C 1996 Geochemistry, petrogenesis and tectonic significance of the basic volcanic units of the Zildat Ophiolitic mélange, ISZ, E Ladakh (India); *Geodin. Acta* **9** 222–233.
- Ahmad T, Tanaka T, Sachan H K and Mukherjee B 2006 Petrogenesis of coesite bearing Tso Morari eclogites: Isotopic and elemental constraints in 21 Himalayan Karakoram–Tibet Workshop, S.I.; Abstract volume, *J. Asian Earth Sci.* **26** 121.
- Berman R G 1988 Internally consistent thermodynamic data for minerals in the system $\text{Na}_2\text{O}-\text{K}_2\text{O}-\text{CaO}-\text{MgO}-\text{FeO}-\text{Fe}_2\text{O}_3-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{TiO}_2-\text{CO}_2$; *J. Petrol.* **29** 445–522.
- Berthelsen A 1953 On the geology of the Rupshu district, Northwest Himalaya; *Medd. Dansk Geol. Foren.* **12** 350–414.
- Bilek S L and Lay T 1999 Rigidity variations with depth along interplate megathrust faults in subduction zones; *Nature* **400** 443–446.
- Bohlen S R and Boettcher A L 1982 The quartz-coesite transformation: A precise determination and effects of other components; *J. Geophys. Res.* **87** 7073–7078.
- Chemenda A I, Burg J and Mattauer M 2000 Evolutionary model of the Himalaya–Tibet system: Geopoe based on new modeling, geological and geophysical data; *Earth Planet. Sci. Lett.* **174** 397–409.
- Chopin C 1984 Coesite and pure pyrope in high grade blueschists of the western Alps: A first record and some consequences; *Contrib. Mineral. Petrol.* **86** 107–118.
- Coleman R G, Lee D E, Beatty L B and Brannock W W 1965 Eclogites and eclogites: Their differences and similarities; *Geol. Soc. Am. Bull.* **76** 483–508.
- Dcelles P G, Robinson D M and Zandt G 2002 Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan plateau; *Tectonics* **21**, doi: [10.1029/2001TC001322](https://doi.org/10.1029/2001TC001322).
- Deer W A, Howie R A and Zussman J 1992 An introduction to the rock forming minerals; ELBS Publ., UK, 696p.
- de Sigoyer J, Guillot S, Lardeaux J M and Mascle G 1997 Glaucophane eclogites in the Tso Morari dome (eastern Ladakh, NW Himalaya); *Eur. J. Mineral.* **9** 1073–1083.
- de Sigoyer, Chavagnac V, Toft J B, Villa I M, Luais B, Guillot S, Cosca M and Mascle G 2000 Dating the Indian continental subduction and collisional thickening on the NW Himalayas–multichronology of the Tso Morari eclogites; *Geology* **28** 487–490.
- de Sigoyer J, Guillot S and Dick P 2004 Exhumation of the ultra-high pressure Tso Morari unit in eastern Ladakh (NW Himalayas): A case study; *Tectonics* **23** 1–18.
- Donohue C L and Essene E J 2000 An oxygen barometer with the assemblage garnet–epidote; *Earth Planet. Sci. Lett.* **181** 459–472.
- Ellis D H and Green D J 1979 An experimental study of the effect of Ca upon garnet and clinopyroxene Fe–Mg exchange equilibria; *Contrib. Mineral. Petrol.* **71** 13–22.
- Engvik A K, Austrheim H and Andersen T B 2000 Structural, mineralogical and petro physical effects on deep crustal rocks of fluid-limited polymetamorphism, WGR, Norway; *J. Geol. Soc. London* **157** 151–134.
- Engvik A K, Austrheim H and Erambert M 2001 Interaction between fluid flow, fracturing and mineral growth during eclogitization, an example from the Sunnfjord area, Western Gneiss Region, Norway; *Lithos* **57** 111–141.
- Epard J L and Steck A 2008 Structural development of the Tso Morari ultra-high pressure nappe of the Ladakh Himalaya; *Tectonophysics* **451** 242–264.
- Evans B W 1990 Phase relations of epidote blueschists; *Lithos* **25** 3–23.
- Ferry J M and Spear F S 1978 Experimental calibration of the partitioning of Fe and Mg between biotite and garnet; *Contrib. Mineral. Petrol.* **66** 113–117.
- Forneris J F and Holloway J R 2004 Evolution of mineral compositions during eclogitization of subducting basaltic crust; *Am. Mineral.* **89** 1516–1524.
- Fumagalli P and Poli S 2005 Experimentally determined phase relations in hydrous peridotites to 6.5 GPa and their consequences on the dynamics of subduction zones; *J. Petrol.* **46**(3) 555–578.
- Gansser A 1964 Geology of the Himalayas, John Wiley, London, 289p.
- Garzanti E, Baud E and Mascle G 1987 Sedimentary record of the northward flight of India and its collision with Eurasia (Ladakh Himalaya, India); *Geodin. Acta* **1** 297–312.
- Garzanti M, Critelli S and Ingersoll R V 1996 Paleogeographic and paleotectonic evolution of the Himalayan range as reflected by detrital modes of Tertiary sandstones and modern sands; *Geol. Soc. Am. Bull.* **108** 631–642.
- Green T H and Hellman P L 1982 Fe–Mg partition between coexisting garnet and phengite at high pressure, and comments on a garnet phengite geothermometer; *Lithos* **15** 253–266.
- Groppo C, Lombardo B, Rolfo F and Pertusati P 2007 Clockwise exhumation path of granulitized eclogites from the AmaDrime range (Eastern Himalaya); *J. Meta. Geol.* **25** 51–75.
- Guillot S, De Sigoyer J, Lardeaux J M and Mascle G 1997 Eclogitic metasediments from the Tso Morari area (Ladakh, Himalayas): Evidence for continental subduction during India–Asia convergence; *Contrib. Mineral. Petrol.* **128** 197–212.
- Guillot S, Replumaz A, Hattori K H and Strzeczynski P 2007 Initial geometry of Western Himalayas and ultra-high pressure metamorphic evolution; *Tectonophysics* **30** 557–564.
- Guillot S, Maheo G, De Sigoyer J, Hattori K H and Pecher A 2008 Tethyan and Indian subduction viewed from the Himalayan high to ultra-high pressure metamorphism; *Tectonophysics* **451** 225–241.
- Holland T J B 1980 The reaction albite = jadeite + quartz determined experimentally in the range 600°–1200°C; *Am. Mineral.* **65** 129–134.
- Holland T J B and Powell R 1990 An enlarged and updated internally consistent thermodynamic data set with uncertainties and correlations: The system $\text{K}_2\text{O}-\text{Na}_2\text{O}-\text{CaO}-\text{MgO}-\text{FeO}-\text{MnO}-\text{Fe}_2\text{O}_3-\text{TiO}_2-\text{SiO}_2-\text{C}-\text{H}_2-\text{O}_2$; *J. Meta. Geol.* **8** 89–124.
- Holland T J B and Powell R 1998 An internally consistent thermodynamic data set for phases of petrological interest; *J. Meta. Geol.* **16** 309–343.
- Jain A K, Singh S, Manickavasagam R M, Joshi M and Verma P K 2003 HIMPROBE Program: Integrated studies on geology, petrology, geochronology, and geophysics of the Trans Himalaya and Karakoram; *Geol. Soc. India Memoir* **53** 1–56.
- Kaneko Y, Katayama I and Yamamoto H 2003 Timing of Himalayan ultrahigh pressure metamorphism: Sinking rate and subduction angle of the Indian continental crust Asia; *J. Meta. Geol.* **21** 589–599.

- Katayama I and Nakashima S 2003 Hydroxyl in clinopyroxene from deep subducted crust: Evidence for H₂O transport into mantle; *Am. Mineral.* **18** 229–234.
- Klootwijk C T, Gee J S, Peirce J W, Smith G M and Mcfadden P L 1992 An early India-Asia contact: Paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121; *Geology* **20** 395–398.
- Leake B E, Woolley A R, Arps C E S, Birch W D, Gilbert M C, Grice J D, Howthorne F C, Kato A, Kisch H J, Krivovichev V G, Linthout K, Laird J and Mandarino J A 1997 Nomenclature of amphiboles. Report of the subcommittee on amphiboles of the International Mineralogical Association: Commission on new mineral names; *Mineral. Mag.* **61** 295–321.
- Leech M L, Singh S, Jain A K and Manickavasagam R M 2003 New U–Pb shrimp ages for the UHP Tso Morari Crystallines, E Ladakh, India; The Geological Society of America (GSA) annual meeting, Seattle, USA, abs No: 61682, paper no 260–64.
- Leech M L, Singh S, Jain A K, Klempner S L and Manickavasagam R M 2005 The onset of India-Asia continental collision: Early, steep subduction required by the timing of UHP metamorphism in W Himalaya; *EPSL* **234** 83–97.
- Liou J G, Tsujimori T, Zhang R Y, Katayama I and Maruyama S 2004 Global UHP metamorphism and continental subduction/collision: The Himalayan Model; *Int. Geol. Rev.* **46** 1–27.
- Liu J, Bohlen S R and Ernst W G 1996 Stability of hydrous phases in subducting oceanic crust; *EPSL* **143** 161–171.
- Manning C E and Bohlen S R 1991 The reaction Titanite + Kyanite = Anorthite + Rutile and Titanite-Rutile barometry in eclogites; *Contrib. Mineral. Petrol.* **109** 1–9.
- Manon M R, Dachs E and Essene E J 2008 Low T heat capacity measurements and new Entropy data for titanite: Implications for thermo barometry of high pressure rocks; *Contrib. Mineral. Petrol.* **156** 709–720.
- Massonne H J and Schreyer W 1987 Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite and quartz; *Contrib. Mineral. Petrol.* **96** 212–224.
- Morimoto N 1988 Nomenclature of Pyroxenes; *Am. Mineral.* **73** 1123–1133.
- Mottana A, Carswell D A, Chopin C and Oberhänsli R 1990 Eclogite facies mineral parageneses; In: *Eclogite facies mineral parageneses* (ed.) Carswell D A, Blackie (Glasgow and London), pp. 14–52.
- Mukherjee B K and Sachan H K 2001 Discovery of coesite from Indian Himalaya: A first record of ultra-high pressure metamorphism in Indian continental crust; *Curr. Sci.* **81** 1358–1361.
- Mukherjee B K, Sachan H K, Ogasawara Y, Muko A and Yoshioka N 2003 Carbonate-bearing UHPM rocks from the Tso-Morari region, Ladakh, India: Petrological implications; *Inter. Geol. Rev.* **45**(1) 49–69.
- Mukherjee B K and Sachan H K 2009 Behavior of fluids in coesite bearing rocks of Tso-Morari region, NW Himalaya: Implication for exhumation process; *Geol. Mag.* **146** 876–889.
- Newton R C and Smith J V 1966 Investigations concerning the breakdown of albite at depth in the earth; *J. Geol.* **75** 268–286.
- O'Brien P J, Zotov N, Law R, Khan M A and Jan M Q 2001 Coesite in Himalayan eclogites and implications for models of India-Asia collision; *Geology* **29** 435–438.
- Page F Z, Essene E J and Mukasa S B 2003 Prograde and retrograde history of eclogites from E Blue Ridge, North Carolina, USA; *J. Meta. Geol.* **21** 685–698.
- Page F Z, Armstrong L S, Essene E J and Mukasa S B 2007 Prograde and retrograde history of the Junction School eclogite, and an evaluation of garnet-phengite-clinopyroxene thermobarometry; *Contrib. Mineral. Petrol.* **153** 533–555.
- Parrish R R, Gough S J, Searle M P and Waters D J 2006 Plate velocity exhumation of UHP eclogites in the Pakistan Himalayas; *Geology* **34** 989–992.
- Peacock S M 1993 The importance of blueschist-eclogite dehydration reactions in subducting oceanic crust; *Geol. Soc. Am. Bull.* **105** 684–694.
- Pognante U and Spencer D A 1991 First report of eclogites from the Himalayan belt, Kaghan Valley (Pakistan); *Eur. J. Mineral.* **3** 613–618.
- Poli S and Schmidt M 1995 H₂O transport and release in subduction zones: Experimental constraints on basaltic and andesitic systems; *J. Geophys. Res.* **100** 22,299–22,314.
- Poli S and Schmidt M W 1997 The high-pressure stability of hydrous phases in orogenic belts: An experimental approach to eclogite forming processes; *Tectonophysics* **273** 169–184.
- Pouchou J L and Pichoir F 1987 Basic expression of 'PAP' computations for quantitative EPMA; In: *Proc. Eleventh IXCXOM* (eds) Brown J D and Packwood R H, University of Western Ontario, London Ontario, pp. 249–253.
- Ridley J 1984 Evidence of temperature dependent 'Blueschist to Eclogite' transformation in HP metamorphism of metabasic rocks; *J. Petrol.* **25** 852–870.
- Rowley D B 1996 Age of initiation of collision between India and Asia: A review of stratigraphic data; *EPSL* **145** 1–13.
- Sachan H K, Bodnar R J, Islam R and Law R D 1999 Exhumation history of eclogites from the Tso Morari crystalline complex in Eastern Ladakh: Mineralogical and fluid inclusion constraints; *J. Geol. Soc. India* **53** 181–190.
- Sachan H K, Mukherjee B K, Ogasawara Y, Maruyama S, Ishida H, Muko A and Yoshioka N 2004 Discovery of coesite from Indus Suture Zone (ISZ), Ladakh, India. Evidence for deep subduction; *Eur. J. Mineral.* **16** 235–240.
- Schlup M, Carter A, Cosca M and Steck A 2003 Exhumation history of eastern Ladakh revealed by ⁴⁰Ar/³⁹Ar and fission track ages: The Indus river–Tso Morari transect, NW Himalayas; *J. Geol. Soc. London* **160** 385–399.
- Schmidt M and Poli S 1998 Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation; *EPSL* **163** 361–379.
- Schumacher J C 2007 Metamorphic amphiboles: Composition and coexistence; *Rev. Mineral. Geochem.* **67** 359–416.
- Singh P 2008 Petrologic and Geochemical studies of Igneous and Metamorphic rocks from the Tso Morari Crystallines, SE Ladakh; PhD thesis, University of Delhi, Delhi, India (unpublished).
- Smith D A 1984 Coesite in clinopyroxene in the Caledonides and its implications for geodynamics; *Nature* **310** 641–644.
- Su W, You Z, Cong B, Ye K and Zhong Z 2002 Cluster of water molecules in garnet from ultra-high pressure eclogite; *Geology* **30**(7) 611–614.
- Thakur V C 1983 Deformation and metamorphism of the Tso Morari crystalline complex; In: *Geology of the Indus Suture Zone of Ladakh* (eds) Thakur V C and Sharma K K, Wadia Institute of Himalayan Geology, Dehradun, India, pp. 1–8.
- Tischendorf G 1997 On Li bearing micas; estimating Li from EPMA and an improved diagram for graphical representation; *Mineral. Mag.* **61** 809–834.
- Tischendorf G, Rieder M, Forster H J, Gottesmann B and Guidotti Ch V 2004 A new graphical presentation

- and subdivision of potassic micas; *Mineral. Mag.* **684** 649–667.
- Thompson A B, Schulmann K and Jezek J 1997 Extrusion tectonics and elevation of lower crustal metamorphic rocks in convergent orogens; *Geology* **25** 491–494.
- Tropper P and Manning C E 2008 The current status of titanite-rutile thermobarometry in ultra high-pressure metamorphic rocks: The influence of titanite activity models on phase equilibrium calculations; *Chem. Geol.* **254** 123–132.
- Van der Voo R, Spakman W and Bijwaard H 1999 Tethyan subducted slab under India; *EPSL* **171** 7–20.
- Vance D A and Harris N B W 1999 The timing of prograde metamorphism in the Zaskar Himalayas; *Geology* **27** 395–398.
- Waters D J and Martin H N 1993 Geobarometry in phengite bearing eclogites; *Terra Abstract* **5** 410–411.

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