

Occurrence and Stability of Allanite and Monazite in the Greater Himalayan Sequence, Dhauliganga Valley, Garhwal Himalaya

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ABSTRACT

The occurrence and relative stability of metamorphic allanite and monazite in metapelites of the Greater Himalayan Sequence (GHS) in the Dhauliganga valley, Garhwal Himalaya have been studied. The GHS is marked by kyanite grade metamorphism in the lower and middle structural levels and sillimanite grade metamorphism in the upper structural level. The occurrence of allanite is restricted to the lower structural level, while monazite occurs in the middle and upper structural levels. The allanite-out reaction occurred at ~660 °C and 9.5 kbar. Monazite shows widely varying ThO₂ content which can be explained mostly by brabantite substitution. The rocks of the GHS of the Dhauliganga valley display inverted metamorphic sequence and the allanite-out reaction is the result of prograde metamorphism.

INTRODUCTION

Allanite and monazite are the main rare earth element (REE)-bearing accessory minerals in metapelites which are known for their use as petrochronometers. Among these, monazite is a more frequently used petrochronometer, however, allanite has rather limited use because of quick change in its crystalline state. The relative stabilities of allanite and monazite depend on pressure (*P*)–temperature (*T*) conditions, bulk rock composition and fluids (Wing et al., 2003; Rasmussen et al., 2006; Spear, 2010; Budzyn et al., 2017; Engi, 2017). Phase relations between the two minerals can be used to relate precise ages to *P*–*T* conditions of metamorphism, provided these are identified and understood. In the past three decades, considerable progress has been made to understand the occurrence and origin of monazite and allanite, especially the monazite geochemistry (DeWolf, 1993; Zhu et al., 1999a, 1999b; Ayers et al., 1999; Catlos et al., 2002; Wing et al., 2003; Kohn and Malloy, 2004; William et al., 2007; Janots et al., 2008; Spear, 2010; Pandey et al., 2013; Finger et al., 2016; Thakur et al., 2018). Despite various studies, however, the conditions at which allanite and monazite are produced and consumed during prograde metamorphism of pelites still need to be better understood.

Petrological investigations in metapelites show that metamorphic allanite generally forms at the expense of detrital monazite or allanite (± xenotime) close to the biotite-in reaction, while allanite breaks down to monazite at the staurolite isograd (Wing et al., 2003; Yang and Pattison, 2006; Janots et al., 2008; Gasser et al., 2012). Allanite can also occur in the kyanite zone (Janots et al., 2008; Finger et al., 2016; Thakur et al., 2018), where the stabilisation of the mineral is attributed to bulk-rock compositional effect (Spear, 2010; Budzyn et al., 2017). Contrasting views prevail on the influence of whole-rock Al₂O₃ content on the temperature of allanite–monazite transition. Spear (2010)

thermodynamically showed that this transition moves towards higher temperature with decreasing Al₂O₃ and increasing CaO content in the whole-rock. On the other hand, Wing et al. (2003) demonstrated that increasing whole-rock Al₂O₃ content stabilises allanite at higher temperatures.

In the present study, the compositional characteristics of allanite and monazite and their relative stabilities with changing metamorphic temperatures in the GHS metapelites of the Dhauliganga river valley, Garhwal Himalaya are presented.

GEOLOGICAL BACKGROUND

The GHS in the Garhwal Himalaya is a ~15–30 km thick sequence of medium to high-grade metasedimentary rocks (Fig. 1). The GHS is demarcated from the Lesser Himalayan Sequence (LHS) in the south by a north dipping top-to-south shear sense thrust, known as Vaikrita thrust. In the north, the GHS is juxtaposed against the Tethys Himalayan Sequence (THS) by a north dipping normal fault known as the South Tibetan Detachment System (STDS).

The GHS in the region is divided into three formations based on rock types and mineral assemblages, which with increasing structural level from south to north are: (1) Joshimath Formation, (2) Pandukeshwar Formation, and (3) Badrinath Formation (Virdi, 1986; Valdiya et al., 1999). The Joshimath Formation mainly comprises kyanite-bearing pelitic schists with subordinate quartzite, while the Pandukeshwar Formation is dominated by micaceous quartzite with intercalations of garnetiferous mica schists, which are locally kyanite-bearing (Virdi, 1986; Paul, 1998). The Badrinath Formation consists of sillimanite grade pelitic gneisses of migmatitic nature and is intruded by the 19.0 Ma Malari leucogranite (Sachan et al., 2010); aplite and pegmatite veins are common throughout this formation. Depositional age of sediments in the GHS basin is bracketed to be between 0.88 to 0.47 Ga (Mukherjee et al., 2019).

The rocks in the GHS show a prominent schistosity/gneissosity with an average dip of ~30° to 45° towards north to northeast. A 3–4 km thick lithounit of pelitic and psammitic rocks belonging to the LHS and occurring immediately below the Vaikrita thrust is intensively deformed and sheared due to southward thrusting of the GHS over the LHS (Metcalfe, 1993). This zone defines the Main Central Thrust Zone (MCTZ), in which the rocks are locally grouped as the Munsiri Formation. The MCTZ is marked by inverted metamorphism from chlorite- to staurolite grade (Gururajan and Choudhuri, 1999; Spencer et al., 2012; Thakur et al., 2015). The GHS shows kyanite grade rocks at the lower and middle structural levels and sillimanite–K-feldspar grade rocks at the upper structural level (Hodges and Silverberg, 1988; Gururajan and Choudhuri, 1999; Spencer et al., 2012). The LHS

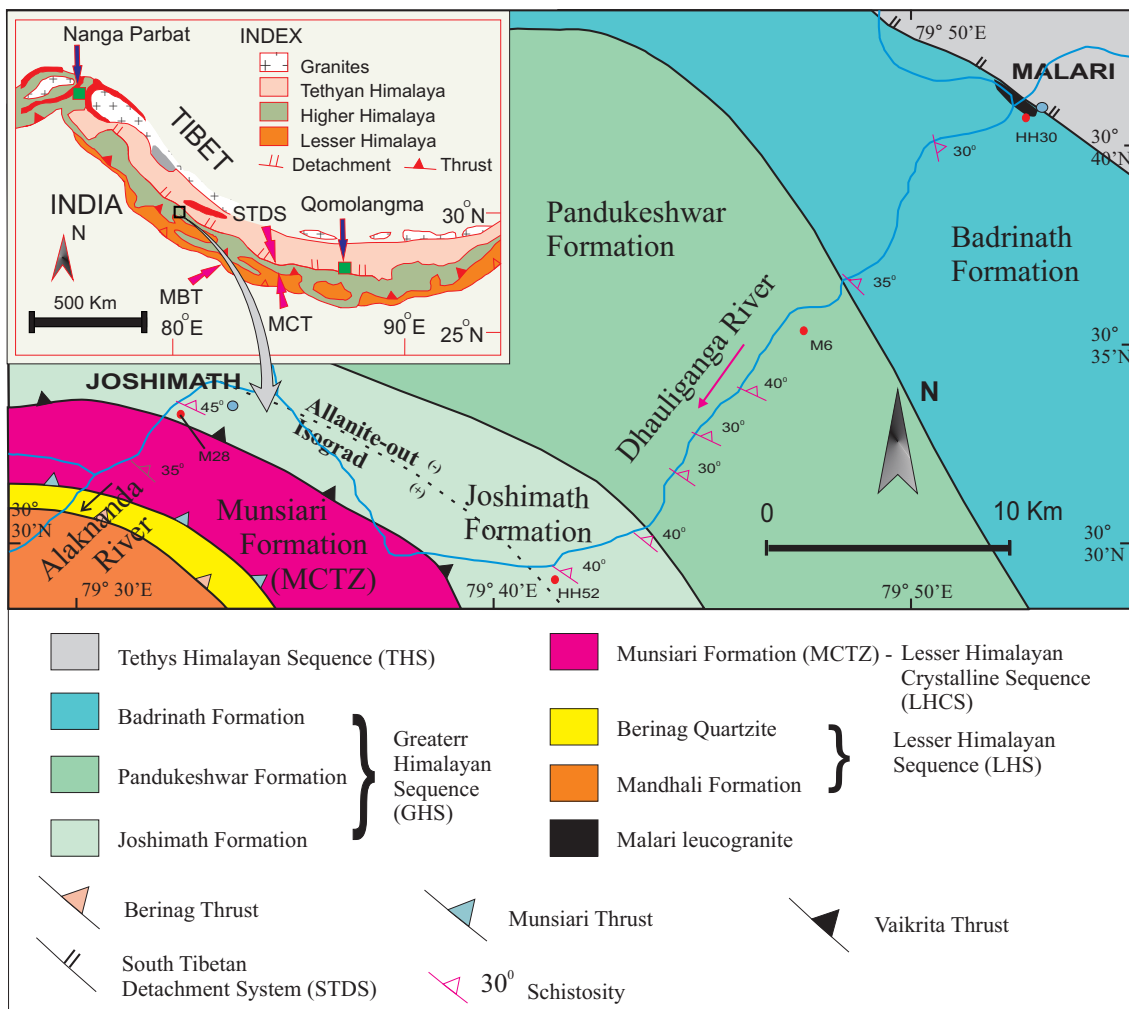


Fig. 1. Geological map of the Dhauliganga valley (modified after Valdiya et al. 1999; Spencer et al., 2012). Sample locations are marked by pink circles. Inset shows map of the Himalayan orogen. (abbreviation: MCTZ = Main Central Thrust Zone).

lithologies south of the MCTZ and the THS lithologies north of the STDS are largely unmetamorphosed.

Samples and Analytical Methods

Four pelitic schist samples (M28, HH52, M6 and HH30) from the GHS in the Dhauliganga valley in which allanite or monazite occurs as accessory mineral have been studied (Fig. 1). The samples are from different structural levels of the GHS. Samples M28 and HH52 are from the lower structural level. Sample M6 is from the middle structural level, while sample HH30 is from the upper structural level. Salient

petrological features of these samples are summarised in the Table 1.

Back scattered electron (BSE) imaging, elemental X-ray imaging and quantitative analysis of allanite and monazite were carried out with a Cameca SX-five electron probe micro-analyser (EPMA) at IIT Bombay. Elemental X-ray maps for Y in monazite were generated at an acceleration voltage of 15 kV and beam current of 100 nA. Major, minor and trace elements in allanite (Si, Ti, Al, Fe, Mn, Mg, Ca, Th, U, Y, La, Ce, Pr, Nd, Sm) and monazite (Si, Al, Ca, P, Th, U, Pb, Y, La, Ce, Pr, Nd, Sm, Gd, Dy) were analysed at an acceleration voltage of 15 kV, beam currents of 100 nA (allanite) and 200 nA (monazite),

Table 1. Mineral assemblages and *P-T* conditions of metamorphism (*T* in °C; *P* in kbar). Mineral abbreviations in the tables and text are from Kretz (1983)

Sample	Mineral assemblage	Metamorphic zone	Occurrence of allanite and monazite	<i>T</i> and <i>P</i> from Av. <i>P-T</i> Method (<i>P</i> in bracket)
M28	ky-grt-bt-ms-pl-qtz-ilm-ap-aln	ky zone	Allanite occurs as inclusion in the garnet as well as in the matrix. Monazite is absent in the sample.	708 ± 30 (11.9 ± 1.4)*
HH52	ky-grt-bt-ms-pl-qtz-ilm-rt-ap-mnz	ky zone	Monazite occurs as a matrix phase. Allanite is absent in the sample.	659 ± 25 (9.5 ± 1.3)*
M6	grt-bt-ms-kfs-pl-qtz-ap-mnz	ky zone	Monazite occurs as a matrix phase. Allanite is absent in the sample.	723 ± 61 (8.7 ± 2.8)**
HH30	sil-grt-bt-kfs-pl-qtz-ilm-ap-mnz	sil-kfs zone	Monazite occurs as a matrix phase. Allanite is absent in the sample.	800 ± 45 (10.4 ± 2.0)**

*From Thakur et al., (2015); **From this study

and a nominal beam diameter of 1 micron. Calibration settings for allanite and monazite analyses are given in Thakur et al. (2018). Raw element data were ZAF-corrected using the X-PHI algorithm of Merlet (1994). Major element analyses of garnet, biotite, muscovite and plagioclase for samples M6 and HH30 were carried out by a Cameca SX100 EPMA at the Wadia Institute of Himalayan Geology, Dehradun at an acceleration voltage of 15 kV, beam current of 20 nA and a nominal beam diameter of 1 micron. Matrix correction was done using the PAP program of Pouchon and Pichior (1984). Representative analyses of allanite and monazite are presented in Tables 2 and 3, respectively, and those of garnet, biotite, muscovite and plagioclase in Table 4.

PETROGRAPHY

Mineral assemblages are listed in Table 1. Sample M28 contains the assemblage *ky-grt-bt-ms-pl-qtz-ilrn-ap-aln*. The sample is rich in plagioclase with modal abundance of ~12%. HH52 has the assemblage *ky-grt-bt-ms-pl-qtz-ilrn-rf-ap-mnz*. The sample has plagioclase modal abundance of ~4%. Kyanite is absent in M6, in which the assemblage is *grt-bt-mu-kfs-pl-qtz-ap-mnz*. HH30 contains the assemblage *sil-grt-bt-kfs-pl-qtz-ilrn-ap-mnz*. Kyanite is present in HH30, but has corroded margins and is considered as a relict phase (Fig. 2a). The quartz–muscovite boundary is often corroded in the *sil-kfs* zone (Fig. 2b). A few of the muscovite grains are also deformed. Samples at higher structural level exhibit lobate undeformed quartz occurring in association with K-feldspar (Fig. 2c), intergrown quartz and plagioclase in quartz–plagioclase pods (Fig. 2d), relatively large feldspar grains (plagioclase and K-feldspar) and thin film of K-feldspar in low dihedral angles against residual solids are indicative of partial melting in the rocks.

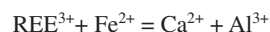
Allanite occurs as inclusions in garnet porphyroblasts (Fig. 3a) or biotite grains (Fig. 3b) and also as discrete grains in the matrix. Allanite

grains are equant to elongate in shape with ~20–25 micron length for inclusions and ~50–100 micron length for those in the matrix. Other inclusion phases in garnet porphyroblasts are quartz, plagioclase, biotite and ilmenite, among which quartz is the most abundant.

Samples HH52, M6 and HH30 lack in allanite but contain monazite. Monazite grains in the samples are equant to elongate in shape and 50–250 micron long (Figs. 3c–d, 4a–c). Most of the elongate grains are aligned parallel to the foliation in the rocks. Monazite shows considerable zoning in Y (Figs. 4a–c) and Th. Y-poor core and Y-rich rim can be clearly identified in some of the grains (Fig. 4b).

Mineral Chemistry

The total LREE₂O₃ content of allanite falls in the range of 9.7–12.9 wt% with 4.4–5.9 wt% Ce₂O₃, 2.3–3.1 wt% La₂O₃ and 2.0–2.7 wt% Nd₂O₃ (Table 2). ThO₂ and UO₂ contents are in the ranges of 0.43–1.10 wt% and 0.08–0.23 wt%, respectively. Y₂O₃ content varies from 0.77 wt% to below the detection limit of 0.02 wt%. Total iron expressed as FeO is between 7.7 and 9.8 wt%, while MgO content is considerably low (< 0.60 wt%). In a Ce–La–Nd triangular plot the allanite compositions show a tight cluster (Fig. 5a). The plot of Σ REE vs Al shows the increase of epidote end member with sharp decrease in REE in allanite (Fig. 5b). The plot of Σ REE + Fe vs Ca + Al shows a perfect negative correlation (Fig. 5c), which can be explained by the following atomic substitution (Giere and Sorensen, 2004):



Monazite has total LREE₂O₃ content in the range of 54.4–61.1 wt% (Table 3). The mineral is rich in Ce₂O₃ (24.9–28.2 wt%), La₂O₃ (12.8–15.2 wt%) and Nd₂O₃ (10.0–13.1 wt%). ThO₂ varies widely between 4.9 and 11.6 wt%, and UO₂ is in the range 0.57–1.32 wt%. Y₂O₃ content of monazite is variable from 0.05 to 1.98 wt%. The formation of Y-poor core (Fig. 4b) indicates monazite growth during

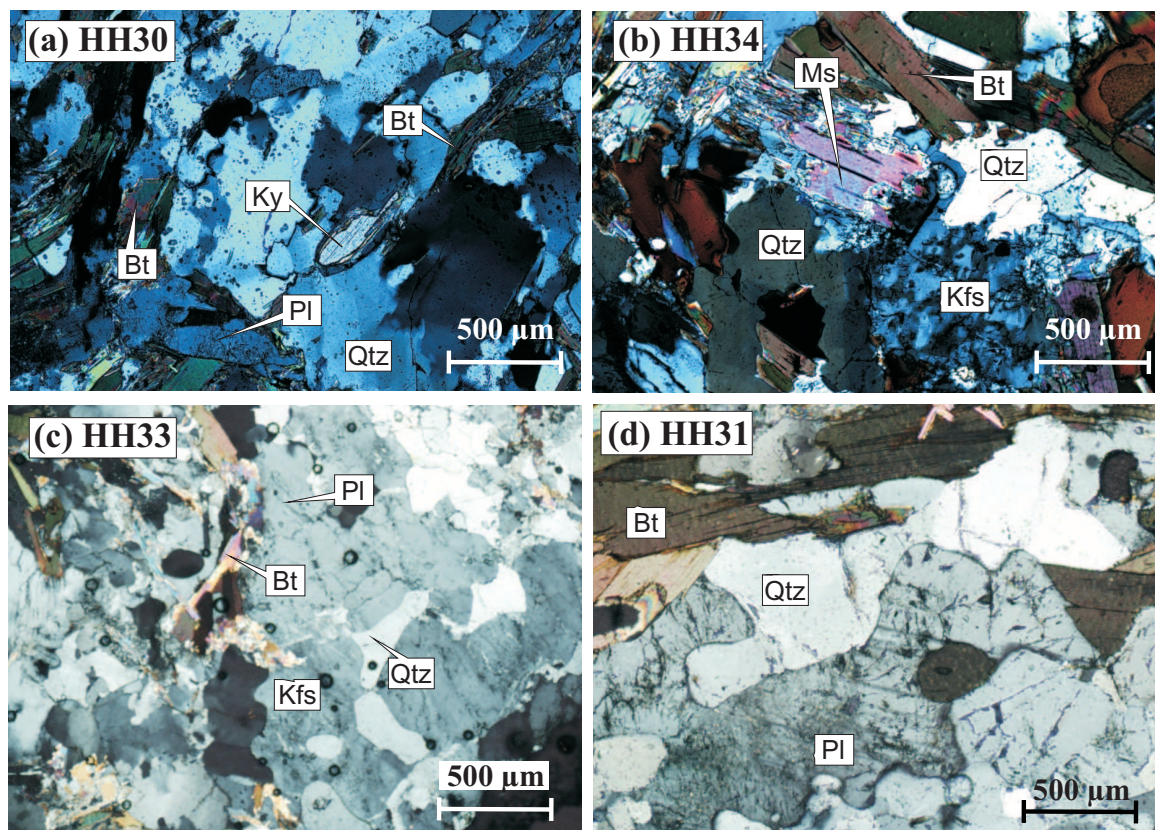


Fig. 2. Photomicrographs of GHS pelitic gneisses of higher structural level (under crossed polar condition). (a) relict kyanite in a sillimanite grade rock; (b) unstable muscovite–quartz boundary; (c) lobate undeformed quartz occurs in association with K-feldspar; and (d) intergrown quartz and plagioclase.

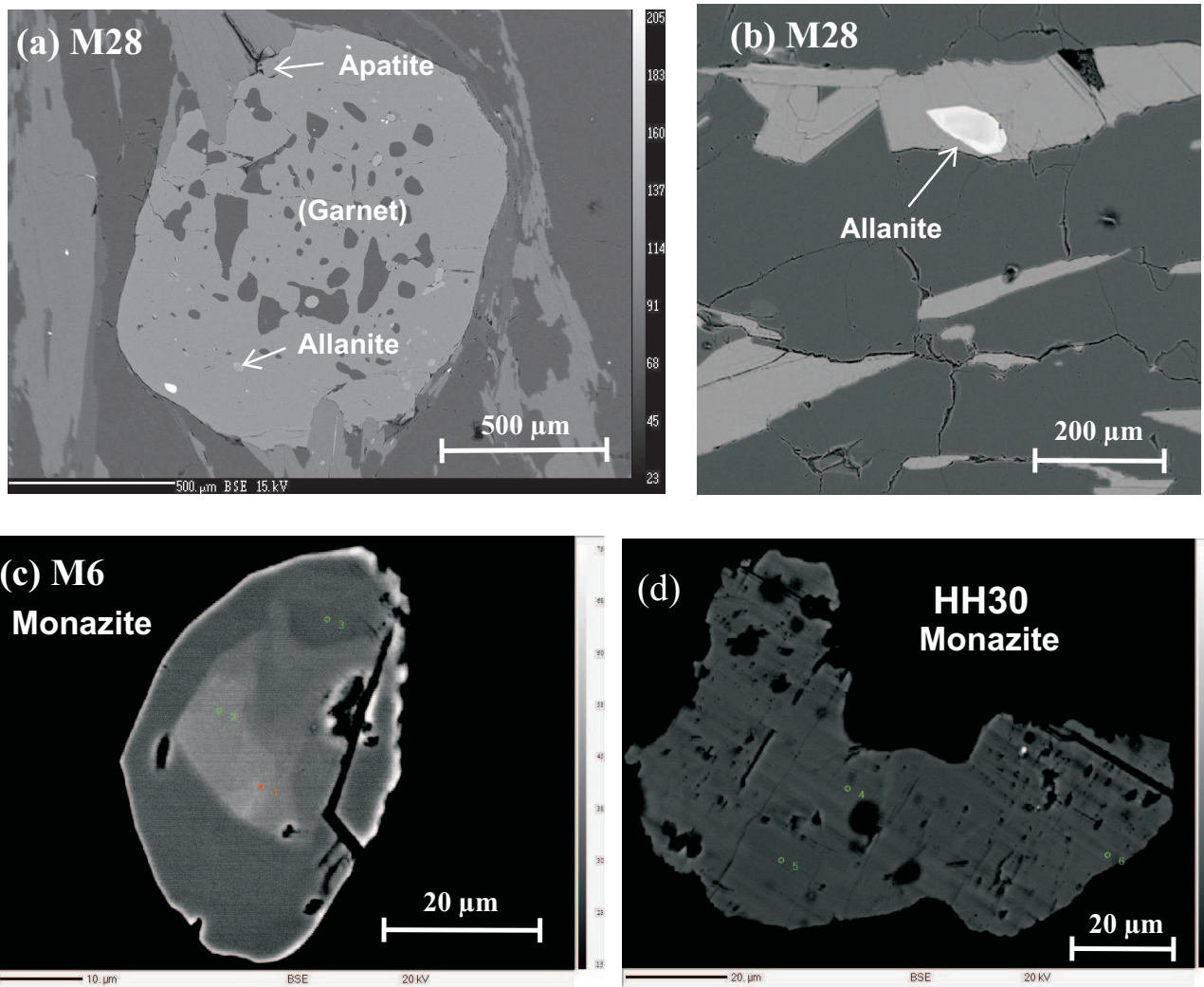


Fig.3. BSE images of (a) Allanite inclusion in garnet porphyroblast. An apatite grain is partially enclosed in the garnet; (b) Zoned allanite grain included in biotite in the matrix; (c) Equant monazite grain showing zoning; (d) Elongate monazite grain.

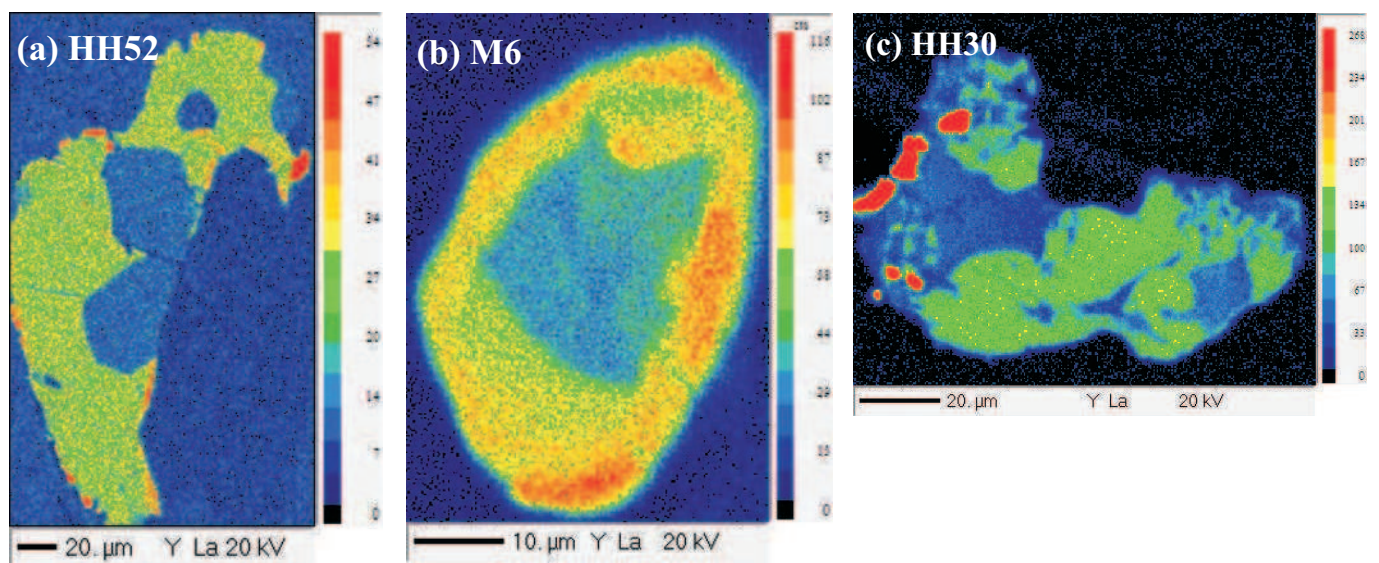


Fig.4. False colour X-ray elemental images of yttrium in monazite.

Table 2. Representative electron microprobe analyses of allanite in sample M28. Cations are based on 12.5 oxygens.

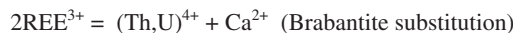
	Inclusion in garnet	Matrix grain			
		Grain 1	Grain 2	Grain 3	Grain 4
SiO ₂	35.52	35.48	34.57	35.94	
TiO ₂	0.12	0.14	0.14	0.09	
ThO ₂	0.43	1.10	0.86	0.50	
UO ₂	0.08	0.23	0.18	0.22	
Al ₂ O ₃	23.16	22.92	22.61	23.75	
Y ₂ O ₃	0.31	b.d.	b.d.	0.77	
La ₂ O ₃	2.27	3.03	3.10	2.35	
Ce ₂ O ₃	4.42	5.90	5.82	4.67	
Pr ₂ O ₃	0.59	0.72	0.73	0.62	
Nd ₂ O ₃	2.04	2.72	2.46	2.28	
Sm ₂ O ₃	0.39	0.55	0.42	0.60	
FeO	9.78	7.91	7.69	7.96	
MnO	0.03	0.04	0.03	0.02	
MgO	0.57	0.59	0.53	0.46	
CaO	16.70	15.56	16.06	16.70	
Total	96.38	96.89	95.21	96.93	
ΣLREE ¹	9.69	12.92	12.53	10.51	
Si	3.065	3.090	3.062	3.080	
Ti	0.008	0.009	0.009	0.006	
Th	0.008	0.022	0.017	0.010	
U	0.002	0.004	0.004	0.004	
Al	2.355	2.352	2.361	2.399	
Y	0.013	b.d.	b.d.	0.031	
La	0.072	0.097	0.101	0.074	
Ce	0.140	0.188	0.189	0.147	
Pr	0.018	0.023	0.024	0.019	
Nd	0.063	0.085	0.078	0.070	
Sm	0.011	0.017	0.013	0.018	
Fe	0.706	0.576	0.570	0.570	
Mn	0.002	0.003	0.002	0.002	
Mg	0.073	0.076	0.070	0.059	
Ca	1.544	1.452	1.525	1.533	
Total	8.080	7.994	8.025	8.022	
X _{Mg}	0.09	0.12	0.11	0.09	

ΣLREE¹ = La₂O₃ + Ce₂O₃ + Pr₂O₃ + Nd₂O₃ + Sm₂O₃

Detection limit (in ppm): Si = 178, Ti = 130, Th = 237, U = 99, Al = 176, Y = 138, La = 265, Ce = 283, Pr = 829, Nd = 873, Sm = 642, Fe = 514, Mn = 180, Mg = 119, Ca = 228.

garnet formation so that Y was partitioned into garnet (e.g. Yang and Pattison, 2006). In the Ce–La–Nd triangular plot, the monazites show a tight cluster (Fig. 6a). Positive correlations are observed in the plots of Si + Ca vs Th + U (Fig. 6b), Ca vs Th + U (Fig. 6c), and Si vs Th + U (Fig. 6d), whereas negative correlation is witnessed in the plots of

Th + U + Si vs ΣREE + P (Fig. 6e) and Th + U + Ca vs ΣREE (Fig. 6f). The plots indicate the following atomic substitutions (Spear and Pyle, 2002):



Chondrite-normalised LREE plot for allanite and monazite are given in Fig. 7. The plot shows negatively sloping patterns for both the minerals. The pattern for allanite is gently sloping, while monazite is more LREE-enriched than allanite and has a steeply sloping pattern.

Garnets from samples M6 and HH30 are mostly homogeneous in composition and almandine-rich. M6 garnet has 82 mol% almandine, 7 mol% pyrope, 7 mol% spessartine and 5 mol% grossular, while HH30 garnet contains 70 mol% almandine, 17 mol% pyrope, 6 % spessartine and 6 mol% grossular (Table 4). Plagioclase is of andesine variety with X_{Ca} [= Ca/(Ca+Na+K)] of 0.15 in M6 and 0.26 in HH30. Biotite has an X_{Mg} [= Mg/(Mg+Fe)] value of 0.21 in M6 and 0.45 in HH30. Muscovite has significant content of FeO (1.0–2.3 wt%) and minor amount of Na₂O (0.47–0.53 wt%).

P–T Conditions of Metamorphism

Thermobarometric calculations were done for two samples (M6 and HH30) following the “average P–T method” of Powell and Holland (1994) and using the garnet, plagioclase and mica compositions listed in Table 4. Activity of H₂O was taken as 1. The calculated P–T values are 8.7 ± 2.8 kbar and 723 ± 61 °C for M6 and 10.4 ± 2.0 kbar and 800 ± 45 °C for HH30. The P–T conditions for samples M28 and HH52 were calculated earlier by Thakur et al. (2018) which are listed in Table 3 for comparison. The results show increasing temperature and pressure of metamorphism with increasing structural level in the GHS. The upper structural level represented by the sample HH30 shows textural evidence of the following muscovite breakdown reaction:



Although sample M6, which is from the middle structural level of the GHS, contains K-feldspar, it has not undergone the muscovite breakdown reaction because muscovite and quartz stably coexist in the rock.

Allanite-out Isograd

The occurrence of allanite in sample M28 from the lowest structural level and its absence in the samples up-section lead us to draw an allanite-out isograd in the Dhauliganga valley at ~ 4–5 km northward of the Vaikrita thrust (Fig. 1). Sample HH52 occurs structurally above

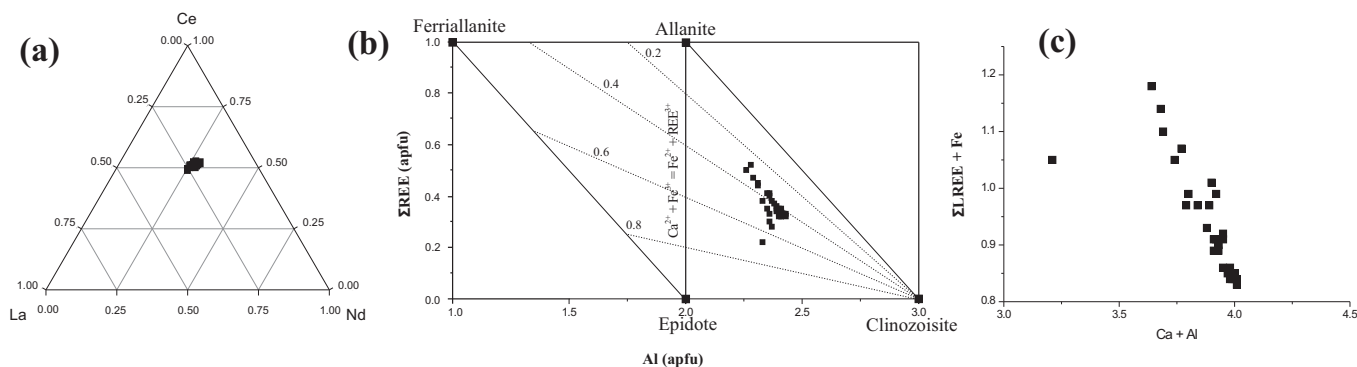


Fig. 5. Compositional plots for allanite. (a) Ce–La–Nd triangular plot; (b) ΣREE vs Al plot; (c) (ΣLREE + Fe) vs (Ca + Al) plot. Lines radiating from clinozoisite end-member in (b) are values of Fe³⁺/(Fe³⁺ + Fe²⁺).

Table 3. Representative electron microprobe analyses of monazite. Cations are based on 16 oxygens

	HH52			M6			HH30		
	grain 1	grain 2	grain 3	core	mantle	rim	core	mantle	rim
SiO ₂	0.53	0.46	0.46	1.33	1.04	0.32	0.49	0.30	0.43
ThO ₂	6.54	5.55	4.94	11.63	9.67	6.28	5.13	5.14	4.97
UO ₂	1.32	1.08	1.15	1.01	1.06	0.94	1.05	0.57	0.95
PbO	0.08	0.07	0.06	0.13	0.11	0.07	0.06	0.04	0.06
Y ₂ O ₃	0.06	0.05	0.35	0.31	0.26	1.98	0.38	3.13	0.80
La ₂ O ₃	14.32	14.54	13.10	12.85	13.50	13.81	15.22	13.89	14.75
Ce ₂ O ₃	27.63	28.05	27.08	24.89	26.04	27.20	28.19	25.99	27.63
Pr ₂ O ₃	2.95	2.97	3.16	2.60	2.62	2.65	2.91	2.83	2.97
Nd ₂ O ₃	11.11	11.51	13.10	10.24	10.55	10.05	11.30	10.71	11.45
Sm ₂ O ₃	2.29	2.29	2.91	2.24	2.33	2.05	2.18	2.23	2.35
Gd ₂ O ₃	1.02	1.05	1.57	1.36	1.37	1.21	1.15	1.61	1.37
Dy ₂ O ₃	0.06	0.05	0.16	0.21	0.18	0.55	0.20	0.77	0.33
CaO	1.37	1.22	1.06	1.67	1.53	1.40	1.09	1.18	1.16
P ₂ O ₅	30.43	29.82	30.04	28.51	29.17	30.24	29.83	30.63	30.35
Total	99.71	98.71	99.12	98.97	99.42	98.75	99.19	99.03	99.56
ΣLREE	59.38	60.46	61.08	54.38	56.58	57.54	61.15	58.03	60.84
Si	0.082	0.072	0.072	0.212	0.164	0.049	0.077	0.047	0.067
Th	0.231	0.199	0.176	0.422	0.347	0.223	0.183	0.181	0.176
U	0.046	0.038	0.040	0.036	0.037	0.033	0.037	0.020	0.033
Pb	0.003	0.003	0.003	0.006	0.005	0.003	0.003	0.002	0.003
Y	0.005	0.004	0.029	0.027	0.022	0.165	0.032	0.258	0.066
La	0.821	0.846	0.758	0.755	0.786	0.796	0.882	0.793	0.847
Ce	1.572	1.621	1.557	1.452	1.505	1.557	1.622	1.473	1.574
Pr	0.167	0.171	0.181	0.151	0.151	0.151	0.167	0.160	0.168
Nd	0.617	0.649	0.735	0.583	0.595	0.561	0.634	0.592	0.636
Sm	0.123	0.124	0.158	0.123	0.127	0.111	0.118	0.119	0.126
Gd	0.053	0.055	0.081	0.072	0.072	0.063	0.060	0.082	0.071
Dy	0.003	0.003	0.008	0.011	0.009	0.028	0.010	0.038	0.016
Ca	0.228	0.207	0.178	0.285	0.259	0.234	0.183	0.196	0.193
P	4.004	3.985	3.993	3.845	3.897	4.002	3.971	4.014	3.999
Total	7.955	7.977	7.969	7.977	7.974	7.976	7.982	7.974	7.974

Detection limit (in ppm): Si = 129, Th = 114, U = 128, Pb = 118, Y = 253, La = 308, Ce = 326, Pr = 646, Nd = 684, Sm = 514, Gd = 835, Dy = 500, Ca = 157, P = 319.

M28 and is devoid of allanite. The allanite-out reaction line passes through from north of the sample location of M28 to south of the sample location of HH52 broadly parallel to the Vaikrita thrust (Fig. 1). The P - T conditions of HH52 are 9.5 kbar and ~660 °C. It is inferred that allanite reacted out and gave rise to monazite at temperatures above ~660 °C. The P - T estimates of the three samples (HH52, M6 and HH30) from the Dhauliganga Valley (Table 1) further show that the temperature gradually increases with increasing structural level which is indicative of an inverted Barrovian sequence and suggests that the allanite-out reaction is the result of prograde metamorphism.

Although sample M28 occurs below the allanite-out isograd, it records a relatively high P - T conditions of ~12 kbar and 710°C and contains allanite. This anomaly can be explained by the stabilisation of allanite by higher Al₂O₃ content of the whole-rock (Thakur et al., 2018) relative to average pelite, which is consistent with the observation of Wing et al. (2003) that increasing whole-rock Al₂O₃ content stabilises allanite to higher temperatures. Sample HH52, which records lower temperature has a bulk-rock Al₂O₃ content of 17.74 wt.%. Sample M28 has a higher Al₂O₃ content (18.66 wt.%), which is believed to have stabilised allanite at higher temperature. Although the two rocks are mineralogically similar, the modal abundances of minerals are different. Plagioclase modal abundance in M28 is higher (~12%) compared to HH52 (~4%) and this is one of the reasons for the higher bulk-rock Al₂O₃ content of M28.

The elevated LREE-enriched pattern of monazite compared to allanite (Fig. 7) indicates that monazite sourced its LREE from other minerals in addition to allanite. Alternatively, simultaneous formation of garnet and monazite can cause preferential sequestration of HREE in garnet and lead to LREE-enrichment in monazite. A possible

Table 4. Representative electron microprobe analyses of garnet, muscovite, biotite and plagioclase

	M6				HH30			
	grt	ms	bt	pl	grt	ms	bt	pl
SiO ₂	36.72	47.59	34.00	64.84	37.7	47.38	36.61	62.05
TiO ₂	0.02	0.21	2.27	b.d.	0.01	0.03	2.73	0.04
Al ₂ O ₃	20.41	34.00	17.31	21.36	20.68	34.61	18.16	22.21
FeO	36.42	2.34	27.14	0.27	31.6	1.04	18.18	0.08
MnO	3.17	0.04	0.34	b.d.	2.88	0.06	0.14	0.03
MgO	1.64	0.67	4.13	0.01	4.31	0.59	8.37	b.d.
CaO	1.60	0.03	0.01	3.11	2.24	0.05	b.d.	5.28
Na ₂ O	0.06	0.53	0.08	9.96	0.02	0.47	0.11	8.35
K ₂ O	0.01	10.74	9.27	0.17	0.02	11.01	9.87	0.12
Total	100.05	96.15	94.55	99.72	99.46	95.24	94.17	98.16
Oxygen basis	12	22	22	8	12	22	22	8
Si	2.999	6.308	5.454	2.869	3.022	6.305	5.608	2.799
Ti	0.001	0.021	0.274	b.d.	0.001	0.003	0.314	0.001
Al	1.965	5.311	3.272	1.114	1.954	5.428	3.278	1.181
Fe	2.488	0.259	3.641	0.010	2.118	0.116	2.329	0.003
Mn	0.219	0.004	0.046	b.d.	0.196	0.007	0.018	0.001
Mg	0.200	0.132	0.987	0.001	0.515	0.117	1.911	b.d.
Ca	0.140	0.004	0.002	0.147	0.192	0.007	b.d.	0.255
Na	0.010	0.136	0.025	0.855	0.003	0.121	0.033	0.730
K	0.001	1.816	1.897	0.010	0.002	1.869	1.929	0.007
Total	8.022	13.992	15.597	5.006	8.003	13.973	15.419	4.978
X _{Mg}	0.07	0.34	0.21		0.20	0.50	0.45	
X _{alm}	0.82				0.70			
X _{prp}	0.07				0.17			
X _{sps}	0.07				0.06			
X _{grs}	0.05				0.06			
X _{an}				0.15				0.26

Detection limit for elemental oxides is <0.01 wt% (except FeO = <0.02 wt%)

X_{Mg} = Mg/(Mg+Fe); X_{alm} = Fe/(Mg+Fe+Mn+Ca);

X_{prp} = Mg/(Mg+Fe+Mn+Ca); X_{sps} = Mn/(Mg+Fe+Mn+Ca);

X_{grs} = Ca/(Mg+Fe+Mn+Ca); X_{an} = Ca/(Ca+Na+K)

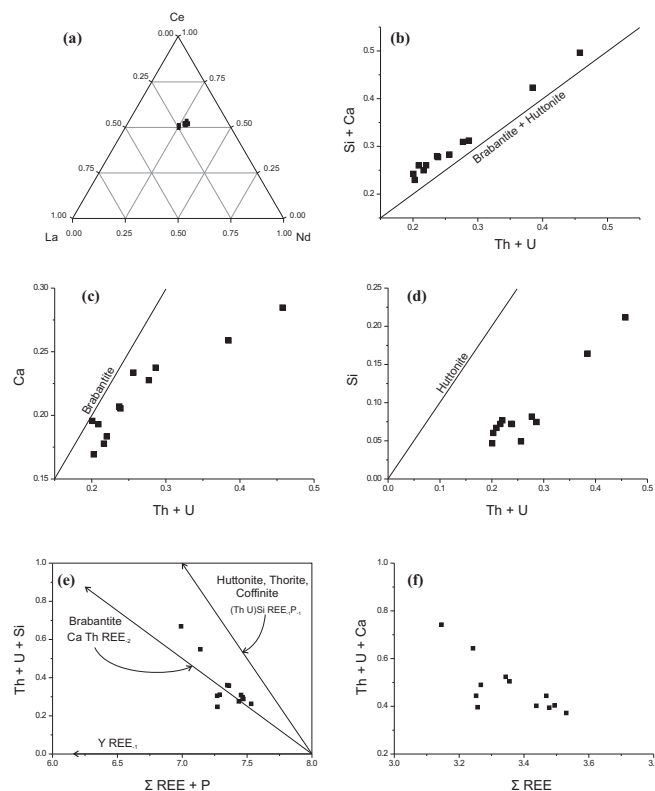


Fig. 6. Compositional plots for monazite. (a) Ce–La–Nd triangular plot; (b) (Si + Ca) vs (Th + U) plot; (c) Ca vs (Th + U) plot; (d) Si vs (Th + U) plot; (e) (Th + U + Si) vs (ΣREE + P) plot; (f) (Th + U + Ca) vs ΣREE plot.

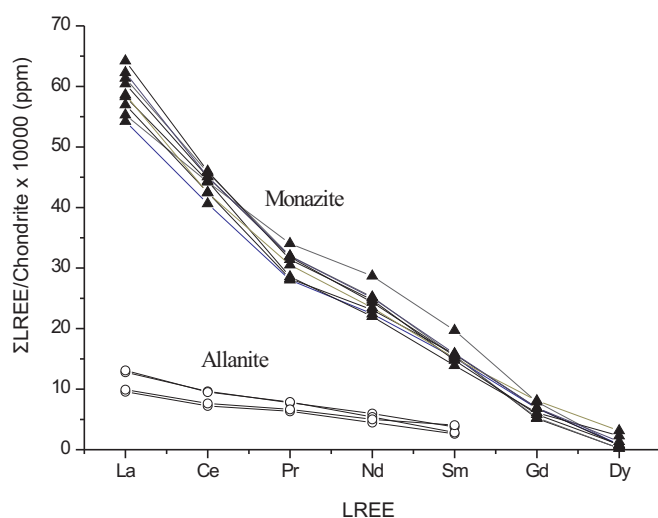
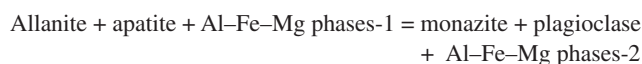


Fig.7. Chondrite normalized REE plot for allanite and monazite. Normalising values are from McDonough and Sun (1995).

generalised reaction for the breakdown of allanite is (Janots et al., 2008; Corrie and Kohn, 2008):



DISCUSSION

In a study of the GHS in the Dhauliganga valley, Spencer et al. (2012) reported peak metamorphic *P-T* conditions of ~14 kbar and 850°C in the middle structural level and then a decrease in pressure to 8–10 kbar up-section with the temperature remaining almost uniform. However, the present data indicates increase in both pressure and temperature from the lower to the upper structural levels of the GHS.

An inverted metamorphic sequence within the GHS has been suggested by some workers in different sectors of the Himalayan orogen (Yakymchuk and Godin, 2012 and references therein). Other workers have proposed that the inverted metamorphism is likely to be apparent rather than real (Metcalfe, 1993; Hodges and Silverberg, 1988). In the Dhauliganga valley, occurrence of kyanite grade metamorphism at lower to middle structural level and sillimanite grade metamorphism at higher structural level of the GHS suggest the occurrence of inverted Barrovian metamorphism. Although an early Palaeozoic regional metamorphism of the GHS has been widely recognized (Cawood et al., 2007 and references therein), it is difficult to distinguish its imprints because of intense reworking and overprinting of the rocks during the Cenozoic Himalayan orogeny. In such a scenario, some of the allanite grains in GHS rocks in different sectors of the Himalaya may record a pre-Cenozoic age which needs to be explored through detailed petrological and geochronological studies.

CONCLUSIONS

1. The lower and middle structural levels of the GHS in the Dhauliganga valley show kyanite grade metamorphism, while the upper structural level shows sillimanite grade metamorphism.
2. Allanite occurs in metapelites in the lower structural level, whereas monazite occurs in the middle and upper structural levels.
3. The allanite-out reaction occurred at ~660 °C and 9.5 kbar. Monazite likely formed by breakdown of allanite with increasing temperature.
4. Monazite shows large variations in ThO₂ content which can be explained mostly by brabantite substitution.
5. The apparently inverted metamorphism in the GHS can be

attributed to polymetamorphism in which a prior kyanite-forming episode is superimposed by a later sillimanite-forming episode in the upper structural level.

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