Quartz *C*-axes and metastable phases in the metamorphic rocks of Almora Nappe: Evidence of Pre-Himalayan signatures

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The alternating sequence of metapelites and metapsammites exposed in the central part of the Almora Nappe is part of the Saryu Formation of the Almora Group[1]. These metamorphic rocks have escaped pervasive mylonitization that characterizes the Higher Himalayan Metamorphic Belt[2–4], considered to be root zone of the Almora Nappe. These metamorphics do not show field or petrographic evidence of mylonitization. Lattice preferred orientation of quartz in these rocks suggests that they remained unaffected by shearing during the southward tectonic transport of the nappe from Higher Himalaya to Lesser Himalaya during the Himalayan orogeny. These unmylonitized rocks of Almora Nappe preserve Pre-Himalayan metamorphic signatures.

ALMORA Nappe[1,5–7], one of the largest nappes in Himalaya, is a consequence of tectonic transport of rocks of the Himalayan Metamorphic Belt (HMB) from the Higher Himalaya to the Lesser Himalaya during Eocene–Oligocene[8]. It is flanked by the North Almora Shear Zone (NASZ) and the South Almora Shear Zone (SASZ), which represent the northern and southern exposures of the Basal Shear Zone separating its constituent metamorphic rocks from the underlying sedimentaries[7].

The Almora Nappe comprises two distinct lithostratigraphic units, viz. the Ramgarh and Almora groups. The Ramgarh Thrust separates the mylonitized rocks of the Ramgarh Group from the underlying sedimentaries and is designated as North Ramgarh Thrust in the northern flank and South Ramgarh Thrust in the southern flank of the nappe[7]. The Ramgarh Group is tectonically separated from the overlying Almora Group by the North Almora Thrust (NAT) and the South Almora Thrust (SAT) in the northern and southern parts of the nappe respectively (Figure 1). The Ramgarh Group comprises mylonites after granite/gneisses, schists and phyllites which are exposed in kilometre scale all along the northern and southern margins of the nappe. The Almora Group, comprising the central part of the nappe, consists of mica schists, garnet-mica schists, gneisses and micaceous quartzites of the Saryu Formation. Thus the Almora Group largely comprises metasediments and paragneisses but for its basal part, which is now seen as mylonites after the metasediments, whereas the Ramgarh Group granitic/gneissic rocks now occur as mylonites and phyllonites (Figure 2).

The whole of the Ramgarh Group and the basal part of the Almora Group of rocks exposed near the thrust margin are strongly mylonitized. Various asymmetric shear sense indicators (Figure 3 *a*) are common in these mylonites. The intensity of mylonitization gradually decreases towards the central part of the nappe and the mylonites eventually grade into unmylonitized rocks of the Saryu Formation of the Almora Group. It is in central parts of the nappe that the rocks between Chaunsali and Hawalbagh have escaped the effects of mylonitization, as evidenced by the absence of shear sense indicators both on mesoscopic as well as microscopic scales and by the occurrence of idioblastic garnet that escaped shearing (Figure 3 *c*). Thus, the unmylonitized rocks of the Saryu Formation of the Almora Group preserve the structures which developed prior to the shearing associated with the southward tectonic transport of the nappe. The pre-shear structures include the lithological banding (S_0) and the F_1 and F_2 tight to isoclinal folds. The strike of S_0 varies from E-W to WNW-ESE and the dips are generally southerly in the northern half and northerly in the southern half of the central part of the nappe owing to the 'synclinal' structure of the nappe (Figure 2). The F_1 and F_2 are tight to isoclinal folds and are developed in the quartzites of the Saryu Formation and plunge from sub-horizontal to about 25° in approximately NNE direction. The axial planes of these folds dip NNE at angles around 30°.

Megascopic structural analyses along with microscopic (petrofabric) analyses of the shear sense indicators, viz. shear bands, asymmetric porphyroclast systems (σ_a-, σ_b- and δ-type)[9], mica fish[10], pressure shadows and the Lattice Preferred Orientation (LPO) studies of quartz have been carried out to understand the evolution of basal shear zone of the Almora Nappe. Two thin sections (viz. *XZ* and *XY* sections) were prepared for each oriented sample of quartz-rich rock to understand the nature and behaviour of LPO of quartz during shearing associated with tectonic transport of the nappe. For each thin section at least 300 grains of quartz were measured on Leitz UT-5, five-axes universal stage. All the measured data for the

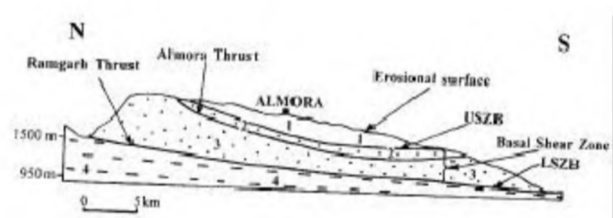

Figure 1. Schematic diagram showing geological setting across the Chhara–Someshwar section of the Almora Nappe. 1, Almora Group; 2, Almora Group mylonites; 3, Ramgarh Group mylonites; 4, Autochthonous sedimentaries of the Damtha and Jaunsar groups; USZB, Upper Shear Zone Boundary; LSZB, Lower Shear Zone Boundary.

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two thin sections were fused in the *XZ* plane, by rotating the measured data from the *XY* plane by 90° to the *XZ* plane.

The penultimate stages of ductile shearing for all the rocks of the Ramgarh Group and the basal parts of the Almora Group, i.e. in the vicinity of NAT and SAT, have been deduced from the geometry of type-I crossed girdles[11–13] of quartz *C*-axes. This penultimate shearing was directed from top-to-north for the mylonites of NASZ and from top-to-south for the mylonites of SASZ (Figure 2). The possible mechanism for the reversal in the shear sense has been discussed by Joshi[7]. The last stage of shearing was characterized by brittle-ductile and finally

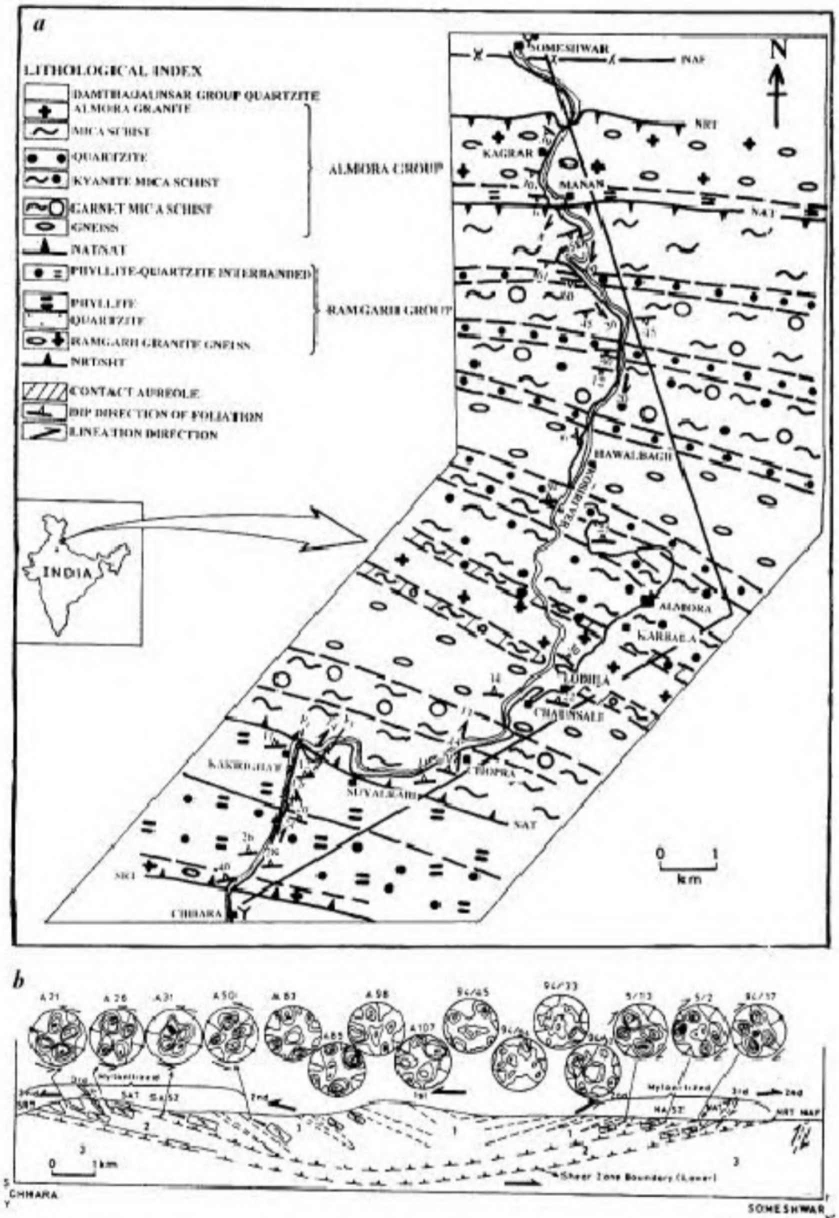

Figure 2. ***a***, Geological map of the area in Almora Nappe along Chhara–Someshwar transect. ***b***, Kinematic section of Chhara–Someshwar transect along *Y–Y′* line (see Figure 1 *a*) showing quartz *C*-axes orientations on equal area projections within the circles. The line drawn along the diameter shows the orientation of foliation in the *XZ* section and the bold dots at the two ends of the line represent the stretching lineation in mylonites. NASZ, North Almora Shear Zone; SASZ, South Almora Shear Zone; NAT, North Almora Thrust; SAT, South Almora Thrust; NRT, North Ramgarh Thrust; SRT, South Ramgarh Thrust; NAF, North Almora Fault. Contours at 2, 4, 6, 8, 10, and 12% interval.

by brittle shearing. However, it is important to note that the quartz *C*-axes orientation diagrams for the schists and gneisses of the Almora Group exposed in the central parts of the Almora Nappe (sample nos A83, A85, A98, A107, 94/45, 94/32, 94/33 and 94/34, Figure 2) have recorded plain strain to flattening strain conditions[14] during their last ductile deformation. It is clear that these rocks are totally unaffected by shearing and preserve the imprints of only pre-shear deformation.

Almora Nappe is a Lesser Himalayan representative of the HMB that was tectonically transported from Higher Himalaya. The Main Central Thrust is a consequence of this tectonic transport. As stated, the rocks exposed in the northern and southern extremes of the Almora Nappe are strongly mylonitized. However, in the central part of the nappe extending from Chaunsali to Hawalbagh, the unmylonitized schists and gneisses of the Almora Group are exposed. Comparing the LPO patterns of quartz *C*-axes with the flinn diagram of Lister and Hobbs[14], it is inferred that the rocks exposed in the central part of the nappe were subjected to plain strain to flattening strain conditions (Figure 2) during their last deformation. The strain conditions deduced for the central part of the nappe suggest that these rocks have completely escaped the intense shear deformation which strongly affected the basal parts of the Almora Nappe during Eocene–Oligocene orogeny. Interestingly, the Almora Group of rocks document two metamorphic events, one related to the Himalayan orogeny (M_2) and the other to the Pre-Himalayan event (M_1). These two events have also been identified by many workers[15–20] in different parts of the Himalaya. These include development of two generations of garnet; the garnet within garnet shows a clear hiatus in crystallization (Figure 3 *b*). Garnet within garnet was earlier reported by Das and Pandey[21] in Chaukhutia area. Such an occurrence of two garnets with different internal schistosity (S_i) has been designated as tectonometamorphic angular unconformity by Rosenfeld[22]. An undisputed evidence of Pre-Himalayan metamorphism is reported from Sutlej valley, Himachal Pradesh, where kyanite–sillimanite-bearing paragneisses are seen within the Lower Paleozoic Kinnaur Kailas granite[23]. Also, Pre-Himalayan metamorphism is

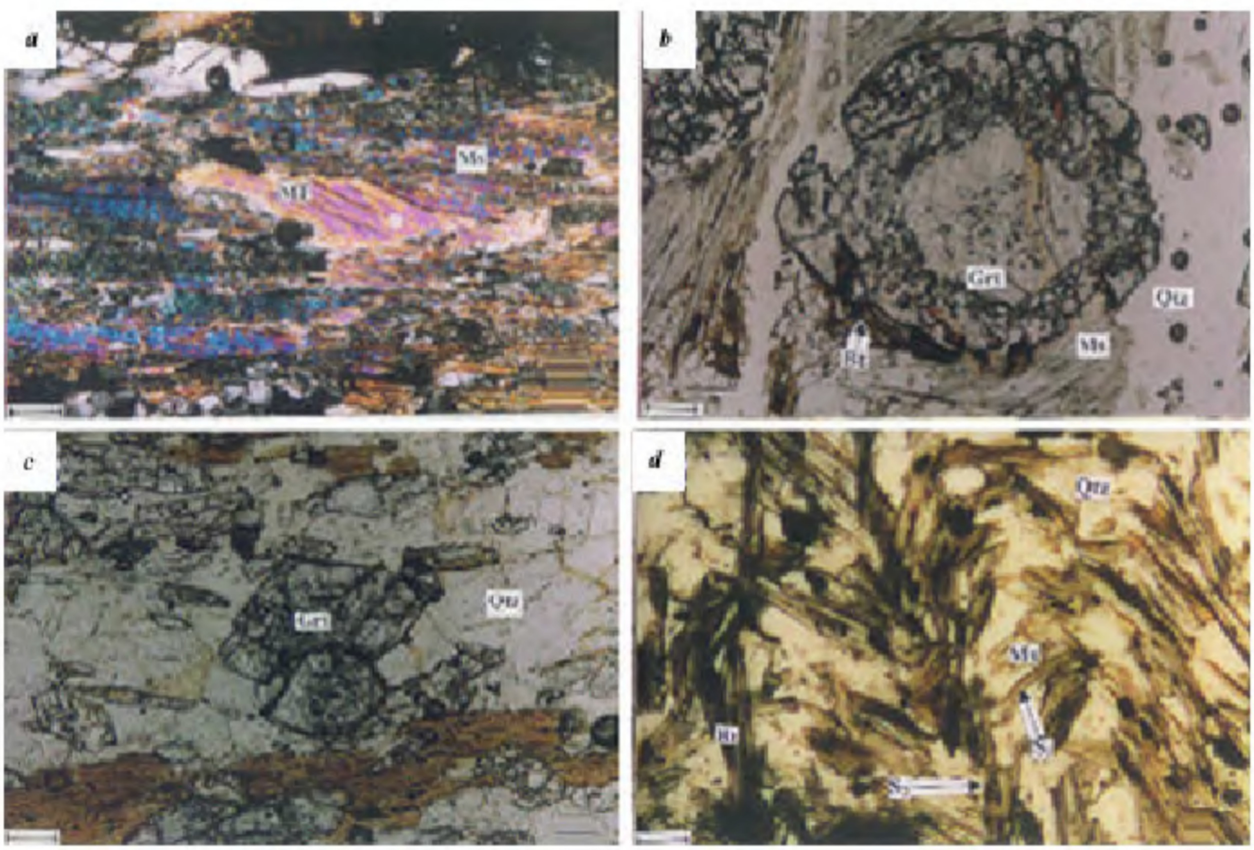

Figure 3. Photomicrographs. ***a***, 'Mica-fish' in mylonites after garnet mica schists of Saryu Formation of Almora Group. Loc: Chopra. MF, Mica fish; MS, Muscovite (bar denotes 0.08 mm). ***b***, Two generations of garnet, i.e. garnet within garnet in garnet mica schist of Saryu Formation of Almora Group. Grt, Garnet; Qtz, Quartz; Bt, Biotite (bar denotes 0.2 mm). ***c***, Pre-Himalayan post-kinematic idioblastic garnet in unmylonitized garnet kyanite schists of Saryu Formation of the Almora Group. Loc: Hawalbagh (bar denotes 0.08 mm). ***d***, Tight microfolding of S_1 plane in mica schist defined by muscovite, biotite and inequant quartz, while the S_2 plane is a crenulation cleavage developed by the biotite and muscovite flakes (bar denotes 0.12 mm).

reported from Mount Everest by Ferrara *et al.*[24], where garnet-bearing paragneisses yielded 449 ± 56 Ma (whole rock age by Rb–Sr). A critical evaluation of such occurrences has not been done for these Himalayan metamorphics, all of which have been assumed 'monometamorphic' and the inversion of metamorphic grade in Higher and Lesser Himalayan rocks have been variously interpreted. Evidence of multiple deformation in the central parts of the Almora Nappe that have escaped Tertiary shearing is quite common, e.g. in Dhunaghat region located east of the present area, mica schists of the Saryu Formation showing evidence of multiple deformation (D_1 and D_2) are observed. The older S_1 schistosity planes, developed during D_1 deformation defined by muscovite and biotite flakes along with inequant quartz, have been affected by tight to isoclinal folds (F_2). The S_2 schistosity planes parallel to the crenulation cleavages developed during D_2 deformation are defined by the mica flakes (Figure 3 *d*; B. N. Singh, unpublished Ph D thesis, 1990). The metapsammites of the Saryu Formation in Khatyari region near Almora town document well-developed F_1 and F_2 folds. The F_1 are gently plunging (≤ 30°) reclined to recumbent-type folds, while the F_2 folds are coaxial with the F_1 folds, but are generally tight. These folds are characteristically unaffected by mylonitization and are unrecognizable in the mylonites of basal shear zone of the Almora Nappe due to a thorough reworking during the Eocene–Oligocene tectonic transport[8] of the nappe. Therefore, the F_1 and F_2 folds can be regarded as representatives of Pre-Himalayan deformational structures.

The metamorphic rocks of Almora Group comprising schists and gneisses (1860 ± 50 Ma)[25] have undergone greenschist to upper amphibolite facies metamorphism[26], and the estimated peak P–T conditions are ≥ 700°C at 7.4 ± 0.5 kbar. Four metamorphic zones, viz. chlorite–biotite, garnet–biotite, kyanite–biotite and sillimanite–K-feldspar, recognized[27] (A. N. Tiwari, unpublished Ph D thesis, BHU, 2000) on the basis of specific reaction isograds are exposed across the Chhara–Someshwar transect in the Almora Nappe. The sillimanite–K-feldspar-bearing gneisses dated[25] at 1860 ± 50 Ma are the end-products of culmination of prograde regional metamorphism[26]. Although mineral dates from Almora Nappe are not available, many Pre-Himalayan $^{232}Th/^{208}Pb$ ages of monazite inclusions within garnet grains from kyanite–garnet–biotite schists are known from the crystalline thrust sheets and the Greater Himalaya in Nepal[28]. The whole rock ages of the Almora gneisses are Precambrian[25] and it is highly likely that the mineral paragenesis remained unaffected either by their spatial position or by the prevalence of similar P–T conditions also during the Himalayan orogeny, including thrusting. It is inferred in conjunction with the LPO analyses and mineralogical studies, that the present regional metamorphic assemblage in the Almora Nappe is Precambrian. The reaction isograds show repetition across the nappe due to post-metamorphic F_2 folding. Again, well preserved contact metamorphic aureoles with randomly oriented contact metamorphic assemblages, viz. fresh chlorites, chloritoids and andalusites occur around the Early Palaeozoic granitoids (560 ± 20 Ma)[25], overprinting the regional schistosity ($S_1 \parallel S_2$)[29] of Saryu Formation of the Almora Group, which further substantiates the find that the unmylonitized rocks of the Almora Nappe are Pre-Himalayan metamorphics, which have escaped shearing due to strain path partitioning during emplacement of the Almora Nappe.

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Origin of oceanic plagiogranite in the Nidar ophiolitic sequence of eastern Ladakh, India

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Occurrence of high-SiO_2, low K_2O leucocratic rocks, the 'oceanic plagiogranite' of Coleman and Peterman, within the basic and ultrabasic rocks of the ophiolites and modern oceanic settings, is of particular interest because of their extreme composition and controversial origin. Ophiolitic sequences are considered incomplete without these rocks. However, these rocks are not present in all the known ophiolite sequences in the world. The present study reports the occurrence of plagiogranite to the north of Kyun Tso, within the Nidar ophiolitic sequence of eastern Ladakh. Plagiogranites occur as intrusives within the gabbro, in the northern part of the ophiolitic sequence. Chemically, they are classified into tonalite and trondhjemite. They show nearly flat REE pattern and fractionation relation that are comparable with the host gabbro. The origin of these rocks is explained by fractional crystallization aided by filter-pressing processes of sub-alkaline tholeiitic magmas.

THE plagioclase-rich leucocratic rocks globally occur in the Precambrian as well as in the Phanerozoic terrains of the earth's crust. These rocks are variously termed as plagiogranite, oceanic plagiogranite, trondhjemite, continental trondhjemite and keratophyre. Coleman and Donato[1] have emphasized the need to distinguish the oceanic plagiogranite from continental trondhjemite. The plagiogranites, which form the most distinctive rock type of relatively small dimensions in most ophiolite complexes, provide an important contrast to continental trondhjemite and tonalite. Their origin is distinct from those of continental trondhjemites, formed at the margins or in the interior of the continents. Despite numerous studies, there is no general consensus about the nature of the genetic link between gabbroic rocks and plagiogranite[1–7].

The Indus Suture Zone is characterized by ophiolite and ophiolitic mélange sequences with frequent breaks throughout its length, which extend for about 2500 km, between Nanga Parbat in the west and Namcha Barwa in the east. The shape, size and composition of these bodies vary from place to place. In the Dras–Kargil area, volcanic rocks, with occasional ultrabasic and basic intrusions, dominate the suture zone. In the central zone, flyschoidal rocks dominate, while in eastern Ladakh, basic and ultrabasic rocks dominate. Nidar is one such area, where ophiolite complex is well developed between Nidar village and Kyun Tso. The Nidar Ophiolite Complex is constituted by serpentinite and ultrabasic rocks along with gabbro, lava flows and dykes of basic composition. The ophiolitic complex is sandwiched between the metamorphics of Tso Morari Complex in the south and sedimentaries of the Indus Formation to the north, with north and south hading thrusts. The Liyan Molasse was deposited within this complex. To the north, the ophiolitic complex is covered by flyschoidal sequence with radiolarian chert of Lower Cretaceous age. Cherts gradually pass upward into flyschoidal sediments, which range up to Eocene. These sediments comprise lava flows and entrapped chert blocks.

The geology of the Nidar Ophiolite Complex has been described by some earlier workers[8–13], but it is to be noted that plagiogranites are not reported from this zone. How-

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