Geology, structure and metamorphism of the Mai khola area, southwestern part of Ilam Bazaar, eastern Nepal

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Abstract

The study area consists of three tectonic zones from south to north, they are the Siwalik, Lesser Himalayan Sequence and Higher Himalaya Crystalline thrust sheet. The Lesser Himalayan Sequence is composed of chlorite, biotite and garnet grade metasediments and augen gneiss. The Higher Himalayan Crystalline thrust sheet is composed of kyanite to sillimanite grade paragneiss, orthogneiss and quartzite. The area is affected mainly by two deformational episodes (i) Syn-MCT metamorphic ductile deformation and (ii) Post-MCT metamorphic deformation. Syn-MCT metamorphic ductile deformation is characterized by (a) development of bedding-parallel foliation and syn-metamorphic stretching lineations trending NNE- SSW and (b) development of S-C structure. Three sub phases of the post-MCT metamorphic deformation are observed in the study area *viz.* (a) development of folds, (b) new generation of foliation and extensional shearing features and (c) small-scale brittle fault, shear bands and cross-cut veins.

The Lesser Himalayan Sequence has been metamorphosed to greenschist-amphibolite facies whereas the Higher Himalayan Crystalline thrust sheet has been metamorphosed to amphibolite to granulite facies. At least two metamorphic events could be recorded in the Lesser Himalayan Sequence. During Pre Himalayan metamorphic phase, the Lesser Himalayan Sequence might be metamorphosed up to anchizone grade prograde metamorphism(?). But Eo-Himalayan metamorphic phase could not affect the Lesser Himalayan Sequence. The Neo-Himalayan (Syn-MCT) metamorphic phase has been recorded on S-C fabric and is revealed by inverted metamorphic zonation in the Lesser Himalayan Sequence. The final phase in the Lesser Himalayan Sequence was retrograde phase shown by chloritization of garnet and biotite. At least three metamorphic events are recognized in the Higher Himalayan Crystalline thrust sheet of the study area. In the Eo-Himalayan (pre-MCT) metamorphic event kyanite grade prograde metamorphism has been occurred. This is followed by sillimanite grade retrograde metamorphism (lower P/high T) on the hanging wall of MCT and is assigned as Neo-Himalayan (Syn-MCT) metamorphic event. Finally the replacement of garnet and biotite by chlorite is the third (retrogressive metamorphic event) occurred during

post MCT movement.

INTRODUCTION

The Himalaya is a part of the great arcuate orogenic belt in central Asia extending from east to west, about 2500 km length with width of 230 to 350 km. The Himalaya was evolved as a result of repeated deformation of the sedimentary successions that accumulated in the Tethys sea lying between the Indian continent in the south and the Eurasian continent in the north. It lies in a unique geological position i.e. the Indian subcontinent with normal thickness (35 km) to the south and the Tibetan plateau the highest plateau in the world, with a double crustal thickness (70 km), to the north (Thakur 2001). The origin of the Himalaya was attributed to the continent-continent collision of the Indian and the Eurasian plate around 55 million years ago. Due to the continued movement of the Indian plate, the northern margin of the Indian continent was sliced into slivers along the three principal intracrustal thrusts: the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Himlayan Frontal Thrust (HFT) from north to south respectively (Gansser 1964; Schelling and Arita 1991). The Higher Himalayan Crystalline (HHC) thrust sheet consists of amphibolite to granulite facies metamorphic rocks and is separated by a normal fault, the South Tibetan Detachment Fault (STDF) from the overlying Cambro-Ordovician to Eocene Tethys Sedimentary Series (TSS) (Burg et al. 1984; Pêcher 1991). Further south the HHC over thrust to the low grade (greenschist to lower amphibolite facies) metasedimentary rocks of the Lesser Himalayan Sequence (LHS). Similarly the MBT carries the LHS on to the Mio-Pleistocene Siwalik rocks. The Himalayan Frontal Thrust (HFT) is the youngest thrust and forms the boundary between the Siwaliks and Quaternary sediments of the Indo-Gangetic plain.

Auden (1935), Lombard (1952, 1958), Bordet and Latreille (1955) Bordet (1961), Hagen (1969), Kyastha (1969), Hashimoto et al. (1973), Schelling (1989), Schelling (1992), Upreti et al. (2000) Chamlagain (2000) and Rai et al. (2001) studied the geology of the eastern Nepal. The extensive thrust sheet covering the most of eastern Nepal represents the HHC zone in the eastern Nepal. The area has been well mapped by Schelling and Arita (1991). The deep erosion of this thrust sheet has produced large window e.g. Taplejung and Arun window in the eastern Nepal. The LHS is characterized by low-grade metamorphic rocks of greenschist to lower amphibolite facies metamorphic rocks (Rai, 2001).

The aim of this paper is to present the geology, structure and metamorphism on the basis of field observation and petrographic study in the southwestern part of Ilam bazaar, eastern Nepal. The study area covers the latitudes 26° 48' 30" N and 26° 57' 00" N, and longitudes 87° 52' 30" E and 87° 57' 30" E (Fig. 1).

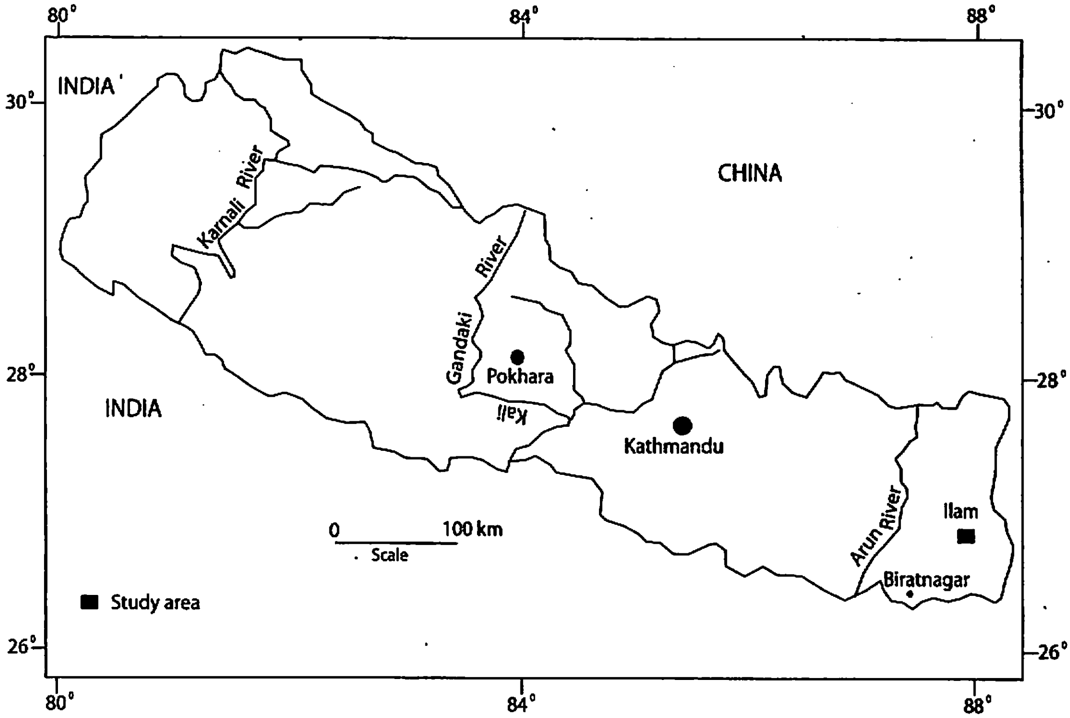

Fig. 1. Location map of the study area.

GEOLOGICAL SETTING

Three tectonic zones could be recognized in the area. From south to north, they are Siwalik, Lesser Himalayan Sequence and Higher Himalayan Crystalline thrust sheet (Fig. 2). The HHC rocks form more or less E-W trending synclinorium (Schelling and Arita, 1991).

Higher Himalayan Crystalline (HHC)

This zone includes the tectono-stratigraphic unit that lies between the MCT to the south and the South Tibetan Detachment Fault (STDF) in the north. In Nepal, different authors have variously named the Higher Himalayan zone. Gansser (1964) used term 'Central Crystallines' and Le Fort (1975) used it as Tibetan slab along the entire Himalayan range. Fuchs and Frank (1970) have described this unit as 'Upper Crystalline Nappes'. Japanese workers (Hashimoto, et al. 1973; Arita 1983) have included the unit into their Himalayan Gneiss zone. Schelling (1992) has described this unit as Higher Himalayan Crystallines (HHC) in the eastern Nepal. The term Higher Himalayan Crystalline is more consistently used in Nepal. The width of HHC in eastern Nepal reaches to tens of kilometers.

The HHC comprises garnet-kyanite-sillimanite gneiss and white to grey coloured quartzite with intercalation of orthogneiss containing garnet and tourmaline. Because of

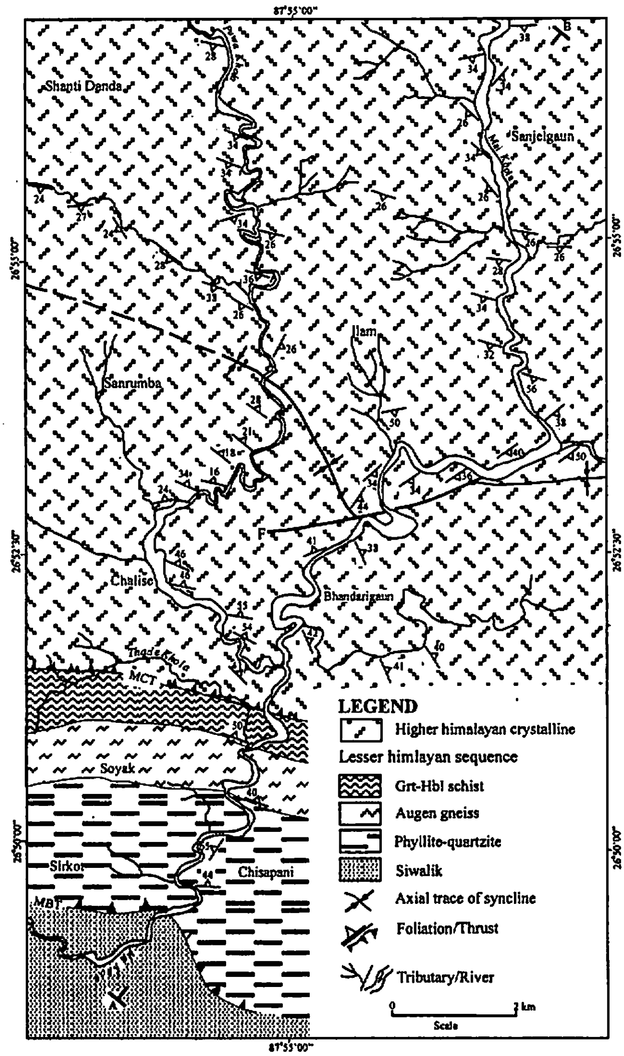

Fig. 2. Geological map of the southwestern part of Ilam bazzar. MBT: Main Boundary Thrust, MCT: Main Central Thrust.

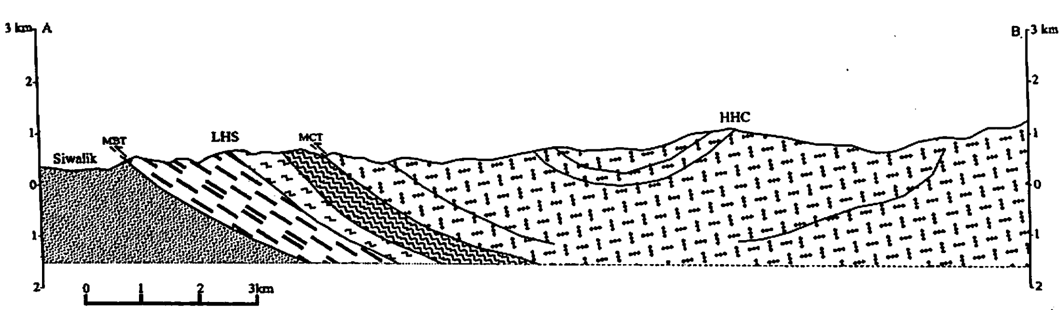

Fig. 3. Geological cross-section along A(SW)-B(NE) in Fig.2, MBT: Main Boundary Thrust, MCT: Main Central Thrust, LHS: Lesser Himalayan Sequence, HHC: Higher Himalayan Crystalline.

folding the rocks are repeatedly exposed in the northern and southern part of the study area (Figs. 2 and 3). In the southern part, it is well exposed along the Mai Khola, Puwa Khola and Karphok Khola. But in the northern part, it could be observed along the Puwa Khola, Mai Khola and Soyan Khola.

The basal part of the sequence comprises mainly kyanite-sillimanite-garnet gneiss with grey quartzite. At the confluence of the Puwa Khola and the Mai Khola, kyanite-sillimanite-garnet gneiss with prominent crenulation cleavage is observed which resembles to schistose gneiss. The main minerals in gneiss are kyanite, sillimanite, garnet, quartz and plagioclase. Sillimanites show fibrous habit and are associated with garnet and kyanite. Garnet crystals are reddish brown, highly fractured and are embedded in the mica, biotite and quartz matrix. The domainal structure is apparent in hand specimen i.e. M-domains (mostly muscovite and biotite) and QF-domains (quartz and feldspar) and are folded. The folded gneissosity contains garnet and quartz in the core whereas garnet, biotite and quartz occur in the outer margin, which in turn reversely faulted indicating polyphase deformation. The quartzite is grey coloured having bed size thin to medium. In the upper reaches of the Puwa Khola and the Mai Khola areas i.e., within Khalte, Tilkeni, Dhankutegaun and Besidanda villages little variation in the lithology could be observed. It mainly consists of white quartzite and orthogneiss, which are lacking in lower part of the HHC. The quartzite is characterized by its white colour, coarseness, thickness, impurity and fracturing, which are frequently observed along the Puwa Khola section. The quartzite beds pinch out towards the Mai Khola. It lies in the core of syncline. This is mainly composed of coarse-grained quartz, plagioclase, biotite and tourmaline as accessory mineral. Orthogneiss is exposed in a narrow zone (about 10 m thick) around Setuwabesi and southwest of the Golakharka Bhanjyang that shows poorly developed gneissosity. It is mainly composed of garnet, plagioclase, quartz, muscovite, biotite, K-feldspar and tourmaline as accessory mineral. Similar rocks are also exposed in the north but lacking orthogneiss. The trend of the mineral lineation varies from 40° to 50° and the plunge varies from 10° to 24° . This unit has an almost east-west strike. It has northerly dip in the order of 30° to 55° in the southern part of the area, but to the north of Ilam, it dips south easterly giving rise to synclinal structure (Figs. 2 and 3).

It is difficult to describe the rock units as different formation in Higher Himalaya due to repeated lithology though the general lithology in the study area resembles to the Formation I (Le Fort, 1975) of Tibetan Slab in central Nepal.

Lesser Himalayan Sequence (LHS)

The LHS is sandwiched between MBT in the south and MCT in the north. It mainly consists of chlorite-sericite phyllites, micaceous-metaquartzites, garnet-hornblende schist and augen gneiss. The rocks of the LHS can be divided into the following litho-units.

Phyllite and quartzite

This unit lies on the hanging wall of the MBT and is well exposed along the Mai Khola section in the southernmost part of the study area. It mainly consists of flysch like alternation of phyllites, phyllitic quartzites and few intercalation of schist. Chlorite is predominantly present in phyllite. The overall colour is light green. The phyllites are argillaceous and silty. In particular, this unit comprises frequent intercalations of *gritty* phyllite consisting of detrital grains of feldspar and rock fragments. Quartz veins are frequently found in phyllite and muscovite schist. Small-scale folds are developed in highly deformed phyllite. Quartz grains are also stretched to ellipsoid giving the shape of augen. At the upper reaches of the Mai Khola, southwest of Malbase, few quartzite beds are interbedded with phyllite. Another noteworthy feature of the unit is a strong mineral lineation, predominantly in a NNE-SSW direction, seen in nearly all outcrops. This unit, on the basis of lithology, structural position and grade of metamorphism, can be compared with the Kuncha Formation (Stocklin and Bhattarai, 1977 and 1980) of the central Nepal.

Augen gneiss

The augen gneiss is well exposed just above the phyllite and quartzite unit. It consists of biotite-muscovite-quartz-feldspar showing the granitic composition. Augen shaped porphyroblast of quartz and feldspar are well developed. At the middle part, augen gneiss is interbanded with fine-grained, cross-bedded quartzite and pale green garnet-biotite-muscovite schist. Quartz lenses are frequently observed in schist and are well cleaved. Stretching and mineral lineation in augen gneiss has trend N15° E/45°. This unit is comparable in lithology and tectonic position with the Melung, Salleri, Khandbari and Sisne Khola augen gneiss in eastern Nepal (Schelling 1992) and the Ulleri augen gneiss (Le Fort 1975 and Arita 1983) in central Nepal.

Garnet-hornblende schist

This unit lies just below the MCT. The main rock type is coarse grained, crystalline, greenish grey schist. Biotite present as predominant mineral, is most common but lighter varieties muscovite and chlorites also occur. Red garnet (almandine) is particularly characteristic in this unit and may occur in great abundance. Sometimes size of the garnet reaches up to 8 mm. Quartz lenses are frequently observed in schist. Hornblende also occurs as an important mineral and aligned along the main foliation. The stretching and mineral lineation trend NNE-SSW direction. The garnet-hornblende schist includes subordinate layers of grey quartzite.

STRUCTURE AND DEFORMATION

Two large-scale thrust faults are clearly recognized in the area. They are MBT in the south and MCT in the north. The rocks also have undergone intense deformation forming several secondary structures. A short description of the main structure of the region is given below.

Main Central Thrust (MCT)

MCT is a major post-collisional intracrustal thrust fault traceable throughout the Himalayan range (Gansser 1964; Le Fort 1975; Pêcher 1989). The most controversial topic in the Himalayan geology is, the nature, position, and location of the MCT, though a great deal of research has been carried out around it. There is no identical view about the nature and position of the MCT in Nepal Himalaya.

The Main Central Thrust (MCT) in eastern Nepal is the tectonic discontinuity along which the Higher Himalayan Crystallines, has been thrust to the south-southwest onto the LHS. Throughout the Nepal Himalaya, the MCT is subparallel to foliation of both the Higher Himalayan Crystalline and the Lesser Himalayan metasediments (Frank and Fuchs 1969; Hashimoto et al.1973; Le Fort 1975; Maruo and Kizaki 1983; Stocklin and Bhattarai 1982; Arita 1983; Schelling 1989), which is also true in the eastern Nepal. Therefore, foliations in the Higher Himalaya Crystalline can be used with some confidence to determine the subsurface geometry of the MCT and underlying Lesser Himalayan rocks. Thus the MCT is believed to dip at an average angle of 30° to 50° to the northeast in the eastern Nepal (Schelling and Arita, 1991). In the study area, MCT is placed where the granoblastic kyanite-sillimanite bearing gneiss and schist overlie the highly sheared rocks of the LHS. The southernmost exposure of the MCT throughout the study area is found just a few kilometers north of the Main Boundary Thrust (MBT), which proves the HHC thrust sheet at once must have completely covered the presently exposed Lesser Himalayan rocks.

Main Boundary Thrust (MBT)

The Main Boundary Thrust (MBT), which forms the southern boundary of the Lesser Himalayan rocks, is steeply north dipping (60°) thrust fault along which the low-grade Lesser Himalayan rocks have been over thrust the Siwalik. The Middle Siwalik rocks (*salt and peeper* sandstone with mudstone) are exposed in the footwall whereas low-grade (chlorite zone) Lesser Himalayan rocks are observed in the hanging wall of the MBT.

Folds

The syncline, predicted on the basis of foliation is one of the major structures of the area. Its axis passes through the Sadhewa, Bistagaon, Golakharka, and Maibesi along SE (Fig. 2). The core of syncline is made of white quartzite and garnetiferous-kyanite-sillimanite gneiss. The rocks of HHC are intensely deformed giving rise to a numbers of minor folds. S-type fold is observed in white quartzite and garnetiferous-kyanite-sillimanite gneiss whose interlimb angle varies from 22° to 30°. Ptygmatic folds are also observed in deformed pegmatitic vein in gneiss (Fig. 4). Minor fold is observed in the white quartzite which has the asymmetrical profile with axial surface dipping 48° due NW (Fig. 5). The wavelength varies from a meter to tens of meter. Minor scale recumbent fold is observed in the intercalation of the quartzite and gneiss at Chureghanti (Fig. 6).

Deformation History

Detailed geological mapping at 1:25000 scale and structural analysis were carried out covering the lower part of HHC and LHS (Fig. 2). The structure of the HHC and LHS display polyphase deformation. The area is affected mainly by two deformational episodes (i) Syn-MCT metamorphic ductile deformation and (ii) Post-MCT metamorphic deformation.

Fig. 4. S-type fold formed by deformation of bedding plane (S_o) and foliation (S_m) where S_o parallel to S_m and ptygmatic fold at the left corner of the photograph observed in the HHC.

Fig. 5. Assymmetrical fold observed in quartzite in HHC.

Fig. 6. Recumbent fold observed in intercalation of quartzite and gneiss at Chureghati HHC.

Syn-MCT metamorphic ductile deformations

At least two major deformations are observed in both HHC and Lesser Himalayan Sequence.

(i) Foliation and syn-metamorphic stretching lineation

The sedimentary structures and stratifications (S_o) are still well preserved in the LHS and occasionally in less metamorphosed rocks of HHC which are well distinguished from the metamorphic foliation (S_m). The platy minerals (mica and biotite) in the rocks of HHC and LHS show their orientation along NNE- SSW i.e. along the direction of MCT movement.

(ii) S-C structure

The S-C structures are poorly developed in HHC and phyllite, schist and augen gneiss of the LHS and are associated with the shearing caused by the movement of MCT, indicating top to south movement.

Post MCT metamorphic deformations

The post MCT metamorphic deformation episodes can be considered as a single-phase continuous phase of deformation (Paudel and Arita 2000). At least four principal types of deformations are recorded in the study area. However, their chronology of development is difficult to distinguish.

(i) Development of fold

In HHC, this event corresponds to the deformation of the S_o and S_m producing S-type, ptygmatic and small scale fold with NNE-SSW trending axes (Figs. 4, 5 and 6). Such structures are also conspicuous in the LHS.

In the HHC, on the northern part of the syncline (Fig. 2), the best plane for S_m is 148/48 (Fig.7a). On the southern part of the syncline S_m of the HHC dip mostly to the north. The best plane for S_m is 44/24 (Fig. 7b). The combined S_m data show a fold axis (82/19) of the metamorphic deformation (Fig. 7c).

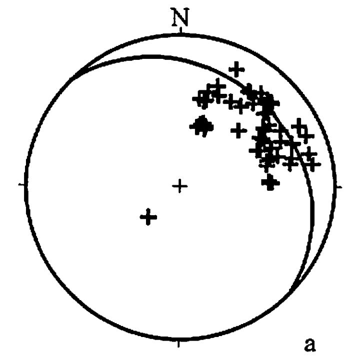

Fig. 7 (a). Fabric diagram showing the dip lines of the foliation (Sm) in the northern flank of syncline. Equal area projection in the lower hemisphere. Best plane Sm: 148/48, n=104.

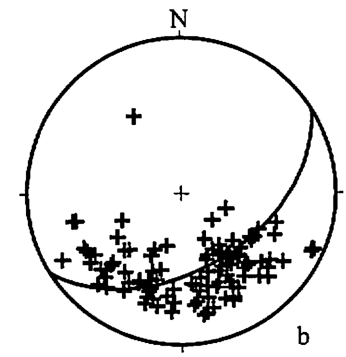

Fig. 7 (b). Fabric diagram showing the dip lines of the foliation (Sm) in the southern flank of syncline. Equal area projection in the lower hemisphere. Best plane Sm: 44/24, n=53.

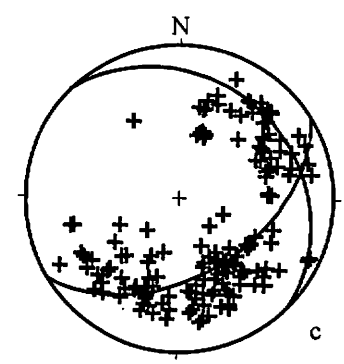

Fig. 7 (c). Fabric diagram showing combined dip lines of the foliation (Sm) syncline. Equal area projection in the lower hemisphere. Fold axis 82/19.

(ii) New generation of foliation and extensional features

During this deformation new generation of foliation planes were developed in both HHC and LHS, which are mostly defined by phyllosilicate minerals giving rise to, crossed foliation (Fig. 8). It is very difficult to say whether they were formed simultaneously or one was superposed over the other indicating that the two deformations took place at different times. Kizaki (1995) explained that such crossed foliation result from a conjugate shear failure, which may possibly be verified by studying the slip direction. The extensional shearing structures are well developed within the augen crystals of quartz and feldspar in the Ulleri-type, augen gneiss of LHS (Fig. 9).

(iii) Small scale brittle fault, shear bands and cross cut veins

During this phase of deformation small-scale brittle fault shears bands and cross cut veins were formed. The folded gneissosity were reversely faulted recording two phases of deformation in the HHC and cross cutting all of the previous structures. Similarly, shear bands were developed in the phyllite and quartzite unit (equivalent to Kuncha Formation of Stocklin, 1980) of the LHS (Fig. 10). Similar shear bands also observed in Garnet-hornblende schist (Fig. 11). Cross cut veins were reported in the HHC and augen gneiss of the LHS.

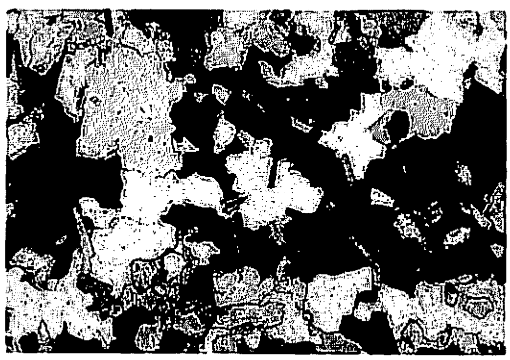

Fig. 8. Cross foliation developed in quartzite of HHC (Under cross nicol x 40).

Fig. 9. Extensional shearing structure developed in augen gneiss in LHS (Under cross nicol x 40).

Fig. 10. Shear band observed in phyllite of the LHS (Under cross nicol x 40).

Fig. 11. Shear band observed in Garnet-hornblende schist of the LHS (Under cross nicol x 40).

PETROGRAPHY

Samples were collected from the HHC and the LHS. Seven samples from the HHC thrust sheet and six samples from the LHS were selected for the detailed petrographic studies. The following petrographic description (Table 1) pertains to these samples. Mineral abbreviations are after Kretz (1983).

Lesser Himalayan Sequence

The LHS comprises phyllite and quartize unit, augen gneiss and garnet- hornblende-schist from bottom to top. The Lesser Himalayan rocks are characterized by the mineral assemblage of Qtz+Pl+Bt+Ms+Grt±Chl with accessory minerals (Fe-Ti oxides).

Phyllite and quartzite

In this unit, phyllite shows the assemblage of Qtz+Pl+Ms+Chl accessory (Fe-Ti oxides) minerals and detrital grains. Quartz is the main constituent mineral. It is mostly in anhedral shape and fine grained. Some of the grains are stretched along the main foliation.

Table. 1. Mineralogy of the studied samples (quartz in excess), xxx - abundant, xx- less abundant, x- rare, HHC: Higher Himalayan Crystalline LHS: Lesser Himalayan Sequence. For mineral name abbreviations, see appendix

Unit	Sample	Rocktype	Grt	Bt	Chl	Pl	Ms	Kfs	Ky	Sill	Tr	Ru	Hbl	Fe-Ti Oxides	Detrital Grain
LHS	TP 149	Phyllite			xxx	x	xx							x	xxx
	TP 148	Phyllite			xxx	x	xxx							x	xx
	TP 147	Phyllite			xxx	x	xxx							x	
	TP 146	Phyllite		xx	xxx	x	xxx							x	
	TP 145	Augen Gneiss		xx	x	xxx		xxx						x	
	TP 144	Schist	xxx	xxx	xx	xx	xxx						xx	xx	
HHC	O_3	Paragneiss		xxx		xxx	xxx	xxx	xx					x	
	D_{11}	Paragneiss		x	xxx	xxx	xxx	xx						x	
	D_{13}	Paragneiss	xxx	xxx	x	xxx	xx		x	x		x		x	
	D_{18}	Quartzite		xxx		x		x						x	
	M_2	Orthogneiss	x	xx		xxx	x	xxx			x			x	
	M_3	Paragneiss	xx	xxx	x	xx	xxx			x				x	
	P_{10}	Quartzite		x	x	x									

Plagioclase grains are mostly subhedral and are mostly parallel to the main foliation. A few strained crystals show the undulose extinction indicating internal ductile deformation. Biotite together with muscovite defines the main foliation. They are anhedral to subhedral and are fine grained. Progressive increase in grain size could be observed towards top of the unit. Detrital grains of quartz and rock fragments occupy the significant proportion. In this unit augen shaped detrital grains have been embedded in phyllosilicate layer ranging in size from 0.04 to 0.17 mm in elongation diameter. Quartz aggregates are recrystallized on either sides of detrital grain producing pressure shadows and are aligned parallel to foliation plane (Fig. 12). The samples contain 5% to 7% detrital grains. Shear bands are another notable micro-structures observed in all samples of this unit. These shear bands are slightly curved and persistent which indicate sinistral shear of bulk rock. The sense of shear along these late shear bands is the same as that of the main shear zone and can be used to deduce the overall sense of shear. Because of lack of orientation of sample, it is impossible to give conclusive statement about the shear sense.

Augen gneiss

Usually rock has an equilibrium assemblage of Q+Kfs+Pl+Bt+Ms with a variable grain sizes. Quartz grains are mostly anhedral and are often polygonized. Quartz, plagioclase and K-feldspar are aligned parallel to the foliation plane. The size of the quartz grains reach up to 0.2 mm. K-feldspar crystals are anhedral in shape, slightly sericitized, and deformed. The size of K-feldspar grain reaches up to 0.65 mm. Plagioclase crystals are

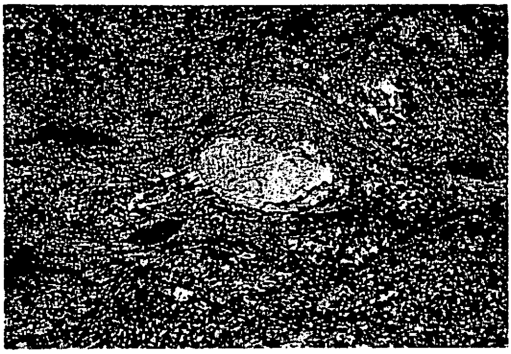

Fig. 12. Quartz aggregates developed in opposed sides of the detrital grain in phyllite of LHS (Under cross nicol x 40).

euhedral to subhedral and range between 0.5 to 0.9 mm. Few strained crystals show the undulose extinction indicating deformation. Biotite and muscovite define the major foliation plane of gneiss. Biotite is occasionally altered to chlorite.

Garnet-hornblende schist

This unit is characterized by the assemblage of Grt+Hbl+Pl+Qtz+Bt+Ms+Chl with accessory minerals (Fe-Ti oxides). Syntectonic garnet porphyroblasts are subhedral to euhedral reaching in diameter up to 8 mm. They contain helicitic inclusion of Qtz, Bt, Ms Chl and Fe-Ti oxides giving rise to sigmodial texture and are also aligned parallel to foliation plane. Hornblende crystals are subhedral to euhedral and are aligned to foliation plane with biotite and muscovite. The size of grain ranges from 0.4 mm to 0.11 mm. Polygonal anhedral quartz grains having undulose extinction indicate ductile deformation. Strained plagioclase grains are also present and are sericitized in their outer margin. The phyllosilicate minerals (biotite and muscovite) constituting M-domains, define the main foliation in which quartz and feldspar grains are embedded. Secondary chlorite is developed in the expense of garnet and biotite along the fracture of garnet and periphery of garnet and biotite.

Higher Himalayan Crystalline

The HHC mainly comprises gneiss and quartzite. The paragneiss mainly contains the assemblage of Qtz+Grt+Bt+Pl+Ms$\pm$Ky$\pm$Sill (accessory: Tr and Fe-Ti oxides). This assemblage is analogous to Formation I of the HHC between the Manaslu and the Dhaulagiri massif (Le Fort et al., 1986; Vannay and Hodges, 1996). The main penetrative fabrics (foliation, stretching lineation and S-C fabric) are defined by the preferred orientation of biotite, muscovite and kyanite. During this retrogression, garnet is replaced by chlorite (Fig. 13). The HHC rocks just above the MCT recrystallized under amphibolite facies condition with mineral assemblage Ky+Sill+Grt+Bt+Ms$\pm$Chl (accessories Tr and Fe-Ti oxides). Paudel and Arita (2000) have described the similar assemblage in central Nepal.

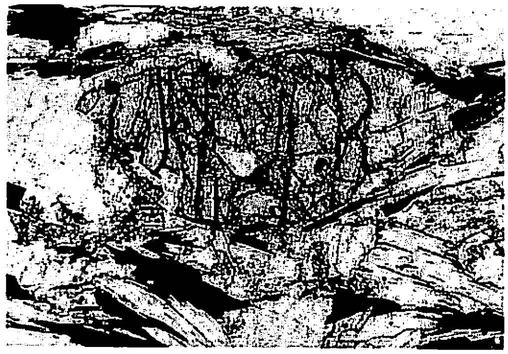

Fig. 13. Photograph showing the replacement of garnet (central part) by chlorite (Under cross nicol x 40).

Garnet

Garnets are syn-kinematic, poikiloblastic, anhedral to subhedral ranging in size from 0.04 mm to 4 mm in diameter. They have inclusion rich core and inclusions free rims. Quartz, Fe-Ti oxides, and chlorite are present as an inclusion in garnet. At least two generations of garnets could be recognized in the Grt-Ky-Sill gneiss. Pressure shadows are occasionally conspicuous around garnet grains.

Biotite

Biotite crystals are euhedral to subhedral defining the main foliation. The size of grain varies from 0.02 mm to 0.42 mm. Some samples show the inclusion of Fe-Ti oxides and quartz in biotite. In the middle part of the HHC, biotite flakes in quartzite show the cross-foliation indicating late stage deformation.

Muscovite

Muscovite flakes are the pre-dominant matrix phases defining the major foliation. They are mostly subhedral to euhedral and range in size 0.017 mm to 0.3 mm in length. They contain inclusions such as biotite, plagioclase, and Fe-Ti oxides.

Plagioclase

Plagioclase crystals are euhedral to subhedral and ranges between 0.06 mm to 0.34 mm in length. Most of the plagioclase are inclusion free but altered to sericite. A few porphyblasts of strained plagioclase show undulose extinction, indicating ductile deformation. The process of sericitisation in their margins is very common. In some samples plagioclase crystals are highly fractured.

K-Feldspar

K-Feldspar crystals are conspicuous in orthogneiss and are less frequent to other samples. They mostly occur in assemblage of Bi+Ms+Qtz+Pl and tourmaline as a accessory mineral. The diameter of grains varies from 0.3 mm to 0.9 mm. They are slightly strained and are altered to sericite.

Quartz

Quartz is the predominant mineral in all studied samples. The size of the grains varies from 0.12 mm to 0.22 mm in diameter. Crystals are mostly anhedral and show undulose extinction indicating deformation. Commonly quartz grains define ribbons with long axis-oriented parallel to the main foliation indicating syn-kinematic recrystallization at high temperature.

Kyanite

Kyanite is widespread in the area and is elongated parallel to foliation and the stretching lineation. Kyanite crystals are, euhedral to subhedral and range from 0.03 mm to 0.30 mm in length. They occasionally contain inclusion of biotite and quartz. They also show the strong sericitization in their margin. They are associated with Bi-Ms-Sill-Grt and define the major foliation planes. Occasionally, kyanites are replaced by fibrolite.

Sillimanite

Sillimanite is developed in the expense of garnet and biotite (Fig. 14). It occurs in the assembelage of Grt-Ky-Bi$\pm$Ms.

Fig. 14. Photograph showing sillimanite gneiss of the HHC (Under cross nicol x 40).

Chlorite

Chlorite is secondary mineral developed by the alteration of garnet (Fig. 13) and biotite. They are anhedral to subhedral shape and are the indicator of retrograde metamorphism. They are mostly developed in the fracture of garnet and vicinity of biotite crystal.

METAMORPHISM

The LHS contains low to medium grade metasediments (greenschist to amphibolite facies) whereas HHC have been metamorphosed to amphibolite to granulite facies and are suffered by polyphase metamorphism.

Polyphase metamorphic history of the LHS is complicated. At least two events could be recorded in the study area (Table 2). During Pre Himalayan metamorphic phase LHS might be metamorphosed upto anchizone grade prograde metamorphism(?). Paudel and Arita (2000) have described the anchizone grade prograde metamorphism in the LHS of central Nepal on the basis of Illite Crystallinity (IC). But during Eohimalayan metamorphic phases the LHS were possibly unaffected (Upreti, 1999). The Neohimalayan (Syn-MCT) metamorphic phase has been recorded the inverted metamorphic zonation with well-characterized Barrovian type isograd in the LHS. Barrovian type isograd could be traced in the study area. The final phase in the LHS was retrograde phase, shown by chloritization of garnet and biotite.

Table. 2. Metamorphic events in the Higher and Lesser Himalaya of eastern Nepal

Metamorphic Events	Higher Himalaya	Lesser Himalaya
Pre-Himalayan	?	anchizone (?)
Eohimalayan	Kyanite grade Prograde Metamorphism	?
Neohimalayan	Inverted Metamorphism	Chlorite to garnet prograde inverted metamorphism
Post MCT	Late Stage of retrogression	Late Stage of retrogression

Polymetamorphism of the HHC has been described by Le Fort (1975), Arita (1983) and Pêcher (1989). Most of them are reported an earlier high P/high T kyanite grade Barrovian type metamorphism (Eohimalayan) followed by a lower P/high T sillimanite grade metamorphism (Neohimalayan). At least three metamorphic events are recognized in the HHC of the study area. Table 2 shows very tentative metamorphic events in the study area based on Poudel and Arita (2000). During the Eohimalayan (pre MCT) metamorphic event kyanite grade prograde metamorphism has occurred. This was followed by sillimanite grade retrograde metamorphism (lower P/high T) on the hanging wall of MCT and is assigned as Neohimalayan (Syn MCT) metamorphic event. Finally the replacement of garnet and biotite by chlorite (Fig. 13) is the third retrogressive metamorphic event occurred during post MCT movements.

CONCLUSION

Three tectonic zones could be recognized in the present study area. From north to south, they are the Siwalik, Lesser Himalayan Sequence and Higher Himalaya Crystalline thrust sheets. The Lesser Himalayan Sequence is composed of chlorite, biotite and garnet zone metasediments, and augen gneiss. The Higher Himalayan Crystalline thrust sheet is composed of kyanite to sillimanite grade paragneiss, orthogneiss and quartzite. The area is affected mainly by two deformational episodes (i) Syn-MCT metamorphic ductile deformation and (ii) Post-MCT metamorphic deformation. Two phases are recorded in the syn-MCT metamorphic ductile deformation i.e. the development of bedding parallel foliation and syn-metamorphic stretching and mineral lineations trending NNE- SSW and the development of S-C structure. Three sub phases of the post-MCT metamorphic deformation are observed in the study area. They are the development of fold, new generation of foliation and extensional features and small-scale brittle fault, shear bands and cross cut veins.

The Lesser Himalayan Sequence has been metamorphosed to greenschist - amphibolite facies whereas Higher Himalayan Crystalline have been metamorphosed to amphibolite to granulite facies and are suffered by polyphase metamorphism. At least two events could be recorded in the Lesser Himalayan Sequence. First, during pre Himalayan metamorphic phase, Lesser Himalayan Sequence might be metamorphosed up to anchizone grade prograde metamorphism (?). The Neohimalayan (Syn-MCT) metamorphic phase has been recorded as the inverted metamorphic zonation in the Lesser Himalayan Sequence. The final phase in the Lesser Himalayan Sequence was retrograde phase shown by chloritization of garnet and biotite. At least three metamorphic events are recognized in the Higher Himalayan Crystalline of the study area. In the Eohimalayan (pre-MCT) metamorphic event kyanite grade prograde metamorphism has been occurred. This is followed by sillimanite grade retrograde metamorphism (lower P/high T) on the hanging wall of MCT and is assigned as Neohimalayan (Syn MCT) metamorphic event. Finally the replacement of garnet and biotite by chlorite is the third retrogressive metamorphic event occurred during post MCT movements.

REFERENCES

Arita, K., 1983. Origin of the inverted metamorphism of the lower Himalayas, central Nepal. *Tectonophysics* **95**, 43-60.

Auden, J. B., 1935. Traverse in the Himalaya. Records of the Geological Survey of India 69, pp.123-167.

Bordet, P. 1961. Recherches gèologiques dans l'Himalaya du Nepal, region du Makalu. *Edit.cent.Nat. Rech.Sci. Paris*, 275p.

Bordet, P. and Latreille, M. 1955. Prècisions sur 1 tectonique de l'Arun. *C. R. Acad. Sci. Paris*, **241**, 1594-1597.

Burg, J. P., Leyreloup, A., Girardeau, J., and Chen, G. M., 1984. Himalayan metamorphism and deformation in the North Himalayan belt (Southern Tibet, China). *Earth Planet. Sci. Lett.* **69**, 391-400.

Chamlagain, D. (2000). Engineering geological and geotechnical study in and around the Ilam Hydropower Project, far eastern Nepal, Higher Himalaya. Master thesis, *Tribhuvan University, Nepal.* 109+p

Frank, W., Fuchs, G., 1969. Geological investigations in west Nepal and their significance for the geology of the Himalayas. *Geol. Rundsch.*, **59**, 552-580.

Fuchs, G., Frank, W., 1970. The geology of west Nepal between the rivers Kali Gandaki and thulo Bheri. Jahrbuch der Geologischen Bundesanstalt-A 18, 1-103.

Gansser, A., 1964. Geology of the Himalaya. *Wiley-Interscience, London*, 289p.

Hagen, T., 1969. Report on the Geological Survey of Nepal. 1 Priliminary reconnaissance, 86, p.185.

Hashimoto, S., Ohta, Y., Akiba, C., 1973. Geology of the Nepal Himalaya. *Saikon, Tokyo* 286p.

Kizaki, K., 1995. Himalayan metamorphic rocks in thin section. *Japan International Cooperation Agency (JICA)* 101p.

Kretz, R., 1983. Symbols for rock forming minerals. *American Mineralogist* **68**, 277-279.

Kyastha, N. B., 1969. The geology of Ilam district in south eastern Nepal. (Unpublished report) *DMG, Kathmandu, Nepal*, 25p.

Le Fort, P., 1975. Himalaya: the collided range: Present knowledge of the continental arc. *Amer. Jour. Sci.* **275A**, 1-44.

Le Fort, P., Pêcher, A. and Upreti B. N. 1986. A section through the Tibetan Slab in central Nepal (Kali Gandaki valley): mineral chemistry and thermobarometry. In evolution des domains orogéniques d'Asie méridionale (de la Turquie à l Indonésie. (Edited by Le Fort, P., Cilchen, M., and Montenant, C.) *Mémoires des Science de la Terre. Nancy* **47**, 211-228.

Lombard, A., 1952. Latectonique du massif de l'Everest, partie occidentale. Note Prèliminarie. *Arch.sci., Genève*, **5**, 403-405

Lombard, A., 1958. Un itinèraise gèologique dans l'Est du Nepal (Massif du Mont Everest). *Mèm. Soc. Helv. Sci. Nat.*, **82**, 107p.

Maruo, Y., and Kizaki, K., 1981. Structure and metamorphism in the eastern Nepal. *in Metamorphic Tectonite of the Himalaya*, edited by P. S. Saklani, 175-230.

Pêcher, A., 1989. The metamorphism in the central Himalaya. *J. Metam.Geol.*, 7, 31-41.

Pêcher, A., 1991. The contact between the Higher Himalayan Crystallines and the Tibetan Sedimentary Series: Miocene large scale dextral shearing. *Tectonics*, **10**, 587-598.

Paudel, L. P. and Arita, K., 2000. Tectonic and polymetamorphic history of the Lesser Himalaya in central Nepal. *Jour. Asian Earth Sci.* **18** 561-584

Rai, S. M., 2001. Geology, geochemistry, and radiochronology of the Kathmandu and Gosaikund Crystalline nappes, central Nepal Himalaya. *Jour. Nepal Geol. Soc. Spec. Issue*, **25**, 135-155.

Rai, S. M., Upreti, B. N. and Sakai, H. 2001. Geology, structure, and metamorphism of the

Taplejung Window and frontal belt, Eastern Nepal. *Jour. Nepal Geol. Soc. special issue* **24** 26-27.

Schelling, D. 1989. The geology of the Rolwaling and the eastern Nepal Himalya. Ph. D. thesis, *University of Colorado*, 512p.

Schelling, D. 1992. The tectonostratigraphy and structure of the eastern Nepal Himalaya. Tectonics vol. 11, No. 5, 925-943.

Schelling, D. and Arita, K., 1991. Thrust tectonics, crustal shortening and the structure of the far-eastern Nepal Himalaya. *Tectonics* **10**, No. 5, 851-862.

Stocklin, J. and Bhattarai, K. D., 1977. Geology of Kathmandu area central Mahabharat range Nepal. In: Himalaya Report *Department of Mines and Geology, Kathmandu, Nepal* 12p

Stocklin, J. and Bhattarai, K. D.,1982. Photogeological map of part of central Nepal, scale 1:100,000. *Department of Mines and Geology, Kathmandu, Nepal.*

Stocklin, J., 1980. Geology of the Nepal and its regional frame. *Jour. Geol. Soc. London* **137** 1-34.

Thakur, V.C., 2001. Regional Geology and Geological Evolution of the Himalaya. Landslide Hazard Mitigation in the Hindu-Kush Himalayas. *ICIMOD Nepal* 3-15.

Upreti, B. N., 1999. An overview of the stratigraphy and tectonics of the Nepal Himalaya. *Jour. Asian Earth Sci.* **17** 577-606.

Upreti, B. N., Arita, K., Rai, S. M. 2000. Geology of the Taplejung window and frontal belt, far eastern Nepal Himalaya. Abs *Earth Science Frontier*, **7**, 39-40.

Vannay, J. C. and Hodges, K. V., 1996. Tectonometamorphic evolution of the Himalayan metamorphic core between the Annapurna and Dhaulgiri, central Nepal. *Jour. Metamorphic Geol.* **14**, 635-656.

Appendix

Abbreviations

Bi: Biotite
Chl: Chlorite
Fe: Iron
Grt: Garnet
Hbl: Hornblende
Kfs: Potash feldspar
Ky: Kyanite
Ms: Muscovite
Pl : Plagioclase
Qtz: Quartz
Ru: Rutile
Sill: Sillimanite
Ti: Titanium
Tr: Tourmaline