CHAPTER 7

TECTONOSTRATIGRAPHY AND METAMORPHISM

7.1 TECTONOSTRATIGRAPHY

In this chapter, the stratigraphy and structural manifestation of the lithosequences of West Kameng and Tawang district of Arunachal Pradesh is dealt with. The most spectacular geotransect of these two districts joining Bhalukpong at the lowest structural level and Zimithang at the highest structural level bears the identity of an important tectonostratigraphic sequence and stands as a unique multideformed terrain showing lithosequences from Sub Himalayan zone, Lesser Himalayan Zone and Higher Himalayan Zone. Unfortunately, nowhere Tethyan sequence is observed along this geotransect and therefore, Indo – Tibetan detachment fault system is not exposed anywhere in the Indian plate northern boundary.

Most of the findings presented here is based on our extensive field work in connection with our DST sponsored project and different traverse mapping on different scales were prepared accordingly. Although some parts of the area are still inaccessible due to thick forestation, snow cover and lack of road communication, yet as far as possible a few traverses were taken along nalas. These efforts help to fulfill one of the objectives to establish a most rational tectonostratigraphic sequence of the area.

Precise geochronological data from rocks of different stratigraphic zones are not available very much but sporadically a few age data are available in literatures of a few authors. Therefore, an attempt has been made here to decipher tectonostratigraphy set up of western part
of Arunachal Himalaya with some amount of correlation with the eastern and western parts of
Himalayan belt elsewhere.

The lithostratigraphic units from lower to higher reaches of the Himalayan belt of Indian
plate within Indian territory encountered in the western part of Arunachal is more or less can be
equated and correlated with Subansiri sector. The same is also correlatable with the Siang sector
of Mishmi block. But it is surprising to note that the lithosequences of Tawang sector are not
identical and hence not correlatable with the Dibang and Lohit sectors of Mishmi block. The
notable differences between Western Arunachal Himalaya (Tawang sector) and Lohit and
Dibang sectors of Eastern Arunachal Himalaya are as follows:

Ophiolites are present in the Lohit and Dibang sectors while they are missing in the
Tawang sector. In Tawang sector both Siwalik and Gondwana rocks are well exposed while in
Lohit and Dibang, Siwalik and Gondwana are missing. In Tawang sector sillimanite is present in
metapelitic rocks while metapelites of Dibang and Lohit sectors are devoid of sillimanite.
Permian acid magmatic rocks (Zimithang granite) are found in Tawang and such acid magmatic
influx is absent in Lohit and Dibang sectors. Conglomerate horizons are found in Lesser
Himalayan sequences of Tawanag sector while in Lohit and Dibang sectors no conglomerate is
found. High grade migmatitic rocks of SeLa Group are found in Tawang sector while they are
missing in Dibang and Lohit sectors. Tertiary granite – granodiorite complex is significantly
observed in Lohit and Dibang sectors but not in Tawang sector.

Gondwana and Siwaliks are present in Tawang Subansiri and Siang sectors. Therefore, it
would be more logical to draw attention of the geoscientific communities that western Arunachal
Himalaya has a litholinkage with the Subansiri and Siang sectors of Arunachal Himalaya.
Dibang and Lohit sectors probably have maintained their own status in Indian context delinking with rest parts of the Himalayan belt and might have tectonically transported from Burmese plate (Mogok belt of Myanmar) and rest over the Himalayan flank to the SW as tectonic linkage (Sarma et al., 2009).

Since Himalaya is a stack of thrust bound orogenic belt resulted due to continent – continent collision between Tibetan plate to the north and Indian plate to the south, therefore, normal stratigraphic sequences are either obliterated or readjusted. Hence, tectonostartigraphic analyses are advisable as per general consensus of geoscientists. Watkinson et al. (1977) have suggested that the tectonostratigraphy deals with distinguishing megasequences and their interpretations in terms of tectonic setting at the time of their accumulation. In other way, tectonostratigraphy refers to either rock sequence in which large scale layering is caused by the stacking of thrusts or nappes in areas of thrust tectonics or the effects of tectonics on lithostratigraphy.

However, as regards Tawang sector or western Arunachal Himalayan belt it can be pointed out that it is a lateral extension from western Himalaya through Nepal, Sikkim and Bhutan Himalaya upto either Bame fault or At best Siang domain of eastern part of Arunachal Himalaya. The aim of this chapter is to determine the tectonostratigraphy of western part of Arunachal Himalaya along Bhalukpong – Tawang – Zimithang geotransect. The traditional Sub Himalayan, Lesser Himalayan, Higher Himalayan and Trans Himalayan concepts are taken into consideration and a more realistic model is prepared.
7.1.1 Overview of the stratigraphy of the geotransect

Although the present study excludes Siwalik and Gondwana in specific, but to peep into the regional stratigraphy in terms of tectonics, their tectonic settings and order of superposition is partially dealt with in this chapter. Side by side, a broad correlation of the different groups in different parts of Arunachal Himalaya is also discussed. From the above tabular sequences, all together five major thrust bound lithotectonic units are observed and they are classified as follows:

Sub-Himalayan sequences

The Sub Himalayan belt is separated from Brahmaputra alluvium zone by traditional MFT roughly passing through Bhalupong area. The Siwalik sequences of lower Miocene to lower Pleistocene is well exposed along Bhalukpong – Bomdila road section as well as along Kameng river bed. Sandstone, siltstone and shale are the major component of this Siwalik Group. They are tectonically affected by large scale folding (Yin et al., 2206, 2010).

Gondwana Group

Siwalik is overrided by Gondwana, the latter is composed essentially of shale, siltstone, indurated sandstone and mudstone. Gondwana is characterized by continental facies and intercalation of marine plant fossil bearing basal sequence (Bichom formation) is also exposed. It is thus apparent that in Arunachal Pradesh, two facies of Gondwana sequence – continental with typical glossopteris flora and marine with invertebrate fauna are present (Kumar and Singh, 1980). Both the sequences are deformed and weakly metamorphosed. The term Bhareli Formation was introduced by Acharyya et al. (1975) which is exposed in the Bhareli valley between Pinjoli and Sessa nala in Kameng district. The Gondwana Group is correlated with Garu
Formation towards East in Siang and Subansiri district. Goswami et al. (2009) included Gondwana sequence into Lesser Himalayan sequence. In the present study, Gondwana Group is treated as an independent lithotectonic unit thrusted over Siwalik sediments along Tipi Nala hence along Tipi thrust as hinterland (hanging wall of Tipi thrust).

**Lesser Himalayan Sequence**

Gondwana Group of rocks are overlain by Lesser Himalayan Sequence (LHS) and form the hanging wall side of MBT$_1$. The footwall of the MBT$_1$ is dipping roughly NNW to N with varying amount of dip (average being $\sim 60^\circ$). On the regional scale, LHS comprises of metasediments, metavolcanics and crystallines and are grouped into different formations. Conventionally all low grade metasedimentary rocks with intercalation of metavolcanics are classified as Lesser Himalayan Sedimentary Sequence (LHSS) while, the crystallines are categorized under Lesser Himalayan Crystallines (LHC). LHC includes Proterozoic Bomdila gneiss with characteristic porphyroclast of feldspar augen and anastomosing shear foliation. The LHSS includes Tenga Formation, Chilliepam / Dedza Formation and Dirang / Lumla Formation. They are discussed below in short to delineate the order of sequences from lower to higher structural level.

(i) **Tenga / Dedza Formation:** Green phyllites, quartzites, low grade schist exposed in Tenga Valley as well as Tenga – Shergaon section of west Kameng district have been classified as Tenga Formation (Bakliwal and Das, 1971; Das et al., 1975). Typical lithoassemblies are quartzite, phyllites, quartz – sericite schist, actinolite – hornblende schist and marble / dolomite. The Tenga Formation is correlatable with Miri Group of the eastern Arunachal Himalaya and Buxa formation of Bhutan.
Himalaya to the west. A notable conglomeratic horizon is also seem to occur between Bomdila Gneiss and Dedza Formation near Nagmandir (27°12′27″N: 92°33′23″E) (Mazumdar et al., 2014). In Shergaon area (another conglomerate is traceable and both of them can be correlatable as continuous and belong to same stratigraphic status (cf. Figs. 2.6, 3.26).

(ii) Dirang Formation and Lumla Formation: Low to medium grade highly sheared metapelitic rocks (garnetiferous phyllite, ky- st schist, carbonaceous phyllites), associated quartzites, calc silicate rocks, metabasites are well exposed near Dirang and Lumla. Das et al. (1975), Simgh and Sharma (1990) and Bhusan et al. (1991, 1999) were some of the workers who have studied the Dirang Formation in Diggin Valley, Pachuk River section in Subansiri area further towards east. Lumla Formation (=Dirang Formation) is studied by Tripathi et al. (1979), Singh (1988), Sinha (2013) and this formation occur as tectonic window around Lumla.

(iii) Bomdila gneiss: On the other hand, Bomdila gneiss is a suite of felsic igneous rocks bearing augens of feldspar, highly mylonitised, coarse to medium grained granitic rocks, aplites and pegmatites. They are occasionally intruded by doleritic dykes and sills and leucogranites. They maintain sharp intrusive contact between metasediments of dirang Formation and Dedza Formation. Bomdila Group is another stratigraphic nomenclature used in this study area and even elsewhere further east which comprises of all the formations of LHS (Das et al., 1975, Verma and Tendon, 1976). The use of this stratigraphic term is sometimes confusing because of the presence of Bomdila gneiss as one independent unit under crystalline group and the similar Bomdila Group is being used to embrace metasedimentary and metavolcanics. This Bomdila group is
well exposed in subansiri section to the east of the present area. However, this group is correlatable with Daling Group of Sikkim and Darjeeling Himalaya and even Shumar Formation of Bhutan.

**SeLa Group**

Das et al., 1975 introduced this term after SeLa pass (lat) (coined by Bakliwal and Das, 1971) which is equated with Pari mountain gneiss and Pidi Formation by Singh and Malhotra (1983). The SeLa Group equivalent to Darjeeling group structurally overlie BOmdila Group and the contact is marked by MCT. They are well exposed along Dirang towards Tawang further north. All the different rock units like qtz-bt –ky schist, gt-bt-pl schist, pl-hbl-bt-qtz schist are highly feldspathised rocks and injected by lit per lit injection (Kumar and Singh, 1980). The SeLa Group is correlatable with Darjeeling gneiss of Darjeeling Himalaya, Thimpu – Chekha Group of Bhutan Himalaya (Jangpangi, 1978).

**Leucogranite**

Leucogranite is intruded into SeLa Group of Higher Himalayan Sequence of the western part of Arunachal Himalaya. It forms a series of lensoidal intrusions and exposed near Senge, SeLa Pass, Jaswantgarh, Mago, Pangila and many more places on way to Zimithang. These are essentially two mica granite with muscovite dominating over biotite. It comprises microcline, albite, perthite, quartz, muscovite, biotite, garnet and tourmaline and displays sharp contacts with their country rocks. Bhalla and Bishui (1982) gave an age of 27 + 5 million years. R.K. Singh (2013) has opined that leucogranite is a product of pure crustal melt with contamination of mantle derived materials and probably generated at the middle crust (~ 20 km) and emplaced in the form of sill/dykes.
Zimithang Granite

The Zimithang Granite marks the extreme end of the Bhalukpong – Zimithang geotransect and partly exposed in Indian subcontinent and Bhutan and majority covers the Tibetan plate. It is foliated to partly undeformed gneiss, grey to pink in colour and monzo- to syenogranitic in composition. It acts as a large batholithic body emplaced in an extensional tectonic regime. The southern contact of Zimithang granite with Lumla Formation is very sharp and marked by a thrust plane. It has a contact with Sela migmatitic rocks along Zimithang – Tak Tsang Gompa road. Grey type and leuco type are the two variants of Zimithang granite based on their megascopic and petrographic characters.

7.1.2 Discussion

The Bhalukpong – Zimithang section is one of the best section in eastern Himalaya. This section reveals the MCT to be broadly folded above a large thrust duplex. MCT activated along with footwall thrust system between 15 – 2 Ma as indicated by the 40Ar/39Ar thermochrometry used U/Th dating of monazite inclusion in synkinematic garnet (Yin, 2006). Shortening of Himalaya here is approximately 500 km. Arunachal Himalaya was constructed by thick skinned thrust staking of Indian basement. Yin et al. (2006) have opined that due to poor access and general lack of modern geological research, very little is known about the tectonic evolution of the northeast Himalayan region. Tethyan Himalayan sequence in the MCT hanging wall of Arunachal Himalaya is highly speculative.

The tectonostratigraphy of the various tectonic units from south to north along Bhalukpong – Tawang – Zimithang geotransect is explained by different workers. Bhattacharjee and Nandy (2008) have summarized the tectonostratigraphy of the area in Table 7.1.
Table 7.1

| Higher Himalayan Zone / Tibetan Himalayan Zone | Leucogranite
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>------------------</td>
</tr>
<tr>
<td>SeLa Group</td>
<td>Migmatite, garnetiferous gneiss, lit-par-lit biotite gneiss, calc-gneiss/marble (diopside and scapolite bearing), staurolite schist, quartzite</td>
</tr>
<tr>
<td>Main Central Thrust</td>
<td></td>
</tr>
<tr>
<td>Lesser Himalayan Zone</td>
<td>Dirang Formation / Lumla Formation</td>
</tr>
<tr>
<td></td>
<td>Bomdila gneiss</td>
</tr>
</tbody>
</table>

They again subdivided the SeLa Group into two formations namely Taliha Formation and Galensiniak Formation (Table 5.2).

Table 7.2

<table>
<thead>
<tr>
<th>SeLa Group</th>
<th>Galensiniak Formation</th>
<th>High grade schist and gneiss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Taliha Formation</td>
<td>Graphite bearing schist, calc silicate, marble, amphibolite and quartzite</td>
</tr>
</tbody>
</table>
Goswami et al., 2009 have suggested three tectonic units bounded by a number of thrusts for this region namely Sub Himalaya (Siwaliks), the Lesser Himalaya (Including Gondwana) and the Greater Himalaya (Table 7.3).

Table 7.3

<table>
<thead>
<tr>
<th>Tectonic domains</th>
<th>Stratigraphic units</th>
<th>Rock units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater Himalayan</td>
<td>SeLa Group</td>
<td>Garnet sillimanite gneiss, Bi-Hbl-Pl gneiss / migmatite, often garnetiferous, garnetiferous silicate gneiss, tourmaline – garnet bearing two mica granites</td>
</tr>
<tr>
<td>Sequence</td>
<td></td>
<td>MCT</td>
</tr>
<tr>
<td>Lesser Himalayan</td>
<td>Dirang Formation</td>
<td>Garnetiferous mica schist, often st-and Ky-bearing quartzite, calc schist and marble, amphibolites</td>
</tr>
<tr>
<td>Sequence</td>
<td>Shear zone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bomdila gneiss</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bomdila Group</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tenga Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chilliepam Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dedza Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bomdila gneiss</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shear zone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bomdila Group</td>
<td></td>
</tr>
</tbody>
</table>
From the present study, the tectonostratigraphy of the Bhalukpong – Zimithang geotransect is worked out as follows (Table 7.4).

Table 7.4

<table>
<thead>
<tr>
<th>LITHOUNITS</th>
<th>LITHOLOGY</th>
<th>AGE (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zimithang granite</td>
<td>Grey to pink massive to augened granite, a medium grained leoco phase intrudes to grey phase</td>
<td>286±41 Ma 878±12 Ma (Yin, 2006)</td>
</tr>
<tr>
<td>Lumla Formation MCT₂– Thrust window</td>
<td>Leucogranite</td>
<td>27±5 Ma</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td><strong>Intrusive contact</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Higher Himalayan Sequence</strong></td>
<td>SeLa Group</td>
<td>Migmatitic gneiss, sillimanite bearing gneiss, quartzites, amphibolites</td>
</tr>
<tr>
<td><strong>Main Central Thrust</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lesser Himalayan Sequence</strong></td>
<td>Lesser Himalayan Crystalline (LHC)</td>
<td>Augen gneiss</td>
</tr>
<tr>
<td></td>
<td>Lesser Himalayan Sedimentary Sequence (LHSS)</td>
<td>Metapelite, quartzite, amphibolite, calc–silicate rocks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tenga / Dedza / Chiellipam Formation</td>
</tr>
<tr>
<td><strong>MBT$_2$ (Depositional Contact)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gondwana Supergroup</strong></td>
<td></td>
<td>Sandstone, shale,</td>
</tr>
</tbody>
</table>
The Great Himalayan curvilinear orogenic belt is a classic example of inverted metamorphic sequence where high grade rocks appearing at progressively higher structural levels have been traced all along from Nanga Parbat to the west to Arunachal Himalaya to the east (Goswami et al., 2009). There is a considerable debate whether classical Barrovian type of metamorphism of inverted nature is in existence in the Himalayan belt. Sharma (2005) has opined that such type of inverted metamorphic signatures is nowhere observed in plate tectonic related orogenic belts of the world. Therefore, he has pointed out that the way basement – cover relationships are worked out in Peninsular India, it is not so in case of Himalayan orogenic belt. Hence, such type of complicated deformation cum metamorphic history deserved rethinking why most of the precollisional signatures either disappear and/or readjusted during Synhimalayan orogeny. Saha (2013) has pointed out the southern and eastern margins of Peninsular India are associated with exhumed granulitic terrain (eg. Eastern Ghat and Southern granulitic terrains) and they were interpreted as product of continental collision linked to Rodinia assembly, and/or
Pan African orogeny (Collins et al., 2008). As lesser Himalaya is free from granulite facies, therefore, it is a questionable point whether the earlier deformation in this belt is linked to any Alpine Himalayan type collision orogeny, Andean type orogen, accretionary orogen or an intracratonic mobile belt typical of Precambrian craton (Saha, 2013). On the other hand, the spectacular mountain belt registered some confusion and misconception in terms of geographic, stratigraphic and structural divisions particularly emplacement history of the HHC that occupies the core of the orogen (Yin, 2001).

Jain et al. (2002) have suggested three metamorphic episodes based on the study of mineral assemblages and their textural relationships and they are categorically designated as

1. Early or Prehimalayan metamorphism
2. Synhimalayan or Main Himalayan metamorphism
3. Posthimalayan metamorphism.

These three phases of Himalayan metamorphism are synonymously designated as Protohimalayan, Euhimalayan and Neohimalayan episodes respectively and designated henceforth as M₁, M₂ and M₃ phases. Jain et al. (2002) have also suggested that Himalayan metamorphic belt bears the identity of first phase fold (F₁) as the only remains of Prehimalayan identity of Indian crustal plate, the latter acts as the basement of Himalaya. Moreover, such F₁ fold characterizes only greenschist facies metamorphism. Question arises if the Indian crustal plate displays metamorphism of medium grade (amphibolites facies) with multideformational imprints at least three phases (if not more) why then only one phase and that too of isoclinals F₁ fold (a true representative of earliest deformational history associated with intensive development of axial plane foliation) is preserved as remnants in the highly deformed rocks of
Himalayan orogenic episode of Cenozoic period. No proper explanation on this aspect is put forth and hence, it is probable that thrusting, exhumation, remobilization, mineral transportation due to collision tectonism are all in existence. A lot of models are suggested but yet the proper Himalayan tectonic configuration is still to be solved. Bhattacharyya and Mitra (2009) and Matin and Mukul (2010) also opined that Lesser Himalayan Sequence of the Himalayan orogenic belt whether related to Cenozoic deformation is a point of debate, but this is also a fact that there are enough evidences of Prehimalayan deformational structures (Raina and Srivastava, 1980; Joshi and Tewari, 2004; Joshi, 2008). However, evidence based on some explanations is referred to here to justify Prehimalayan, Synhimalyan and Posthimalayan deformation cum metamorphism.

Himalayan orogenic belt is a complex system. Therefore, large scale tectonic configuration invites many hindrances or complexities, confusions and contradictions. Moreover, physiographical inequalities, multinational political obligations also play a vital role why an International geological platform, leaving aside all political differences, could not be built up where all geological information and allied studies be shared together for a common, more realistic, time framed evolutionary model of the youngest mountain belt. An analytical approach from mesoscopic to microscopic scale may have some potential bearings to explore megascopic set up of the Himalayan belt in terms of large scale tectonics, associated exhumation, metamorphism and thermodynamics.

In the following pages, the metamorphic history of the Himalayan metamorphic belt of the studied area is worked out on the basis of the mineral assemblages of the rocks of the different lithologic association, development of the diagnostic index minerals like garnet, kyanite, staurolite, sillimanite, micas in the metapelites and other allied minerals of associated rocks to access information about the deformation and metamorphic history that the rocks have
experienced. Like trace fossil, in structural and metamorphic geology, the mineral development preserved in and around porphyroblasts that grow subsequently or episodically during orogenesis, is treated as ‘window’ (Johnson, 1999). Thus, porphyroblast – matrix relationships and microstructural behaviour need intensive study to explore metamorphic history cum deformation so that most general concept of facies, grades and zones, facies series could be made use of.

Here, such an attempt has been made considering fine to medium grained, strongly anisotropic, foliated and highly crenulated rocks like metapelites, metabasites, highly sheared augen gneisses and partially sheared quartzites.

Porphyroblast microstructures have attracted the attention and imagination of geologists for more than few decades since the days of Zwart (1960, 1062), Spry (1963), Ferguson and Harte (1975), Vermon (1978), Ferguson (1999), Passchier and Trouw (2005) and many references therein. Garnet, more specifically, plays a vital role indicating relative age of mineral growth to deformation. For regional tectonic interpretation such porphyroblast – matrix relationship in terms of internal and external fabrics is most useful (Karanth, 1985; Gururajan, 1994; Mamtani and Karanth, 1997; Mamtani et al., 1999, 2001; Chattopadhyay and Ghosh, 2007, Kakati and Sarma, 2013 and many references cited therein). Before deducing the picture portrayed from porphyroblast study of the studied area, a few more interpretation related concepts are discussed so that before drawing a possible logical conclusion, such interpretations help the author considerably.

Porphyroblasts with internal trails of inclusion in a polydeformed terrain whether rotate relative to geographical coordinates during ductile deformation. Usually they donot do so unless
they are internally deformed (Fyson, 1980; Bell, 1985; Vernon, 1988; Johnson, 1990) which indicate that such $S_i$ fabrics maintain original orientation and growth history even after subsequent deformation (applicable in case of conventional spiral garnet also as noted by Bell and Johnson, 1989). The following study incorporates all the possible aspects as far as practicable.

7.2.1 Sample collection, thin section preparation and interpretation

The samples collected from the Lesser Himalayan and Higher Himalayan parts of the studied area were oriented properly with respect to geographic coordinates and in terms of X, Y and Z directions of the strain ellipse. Two sections were prepared perpendicular to schistosity plane (XZ and YZ), long direction of the flattened quartz and flattened garnet. The orientations are marked on the thin sections accordingly. In case of comparatively large porphyroblasts, a few sections were attempted from central and rim parts of the porphyroblasts to get the history of growth from earliest to the late stage. Garnets are observed as elongated or flattened parallel to the direction of $x -$ axis of strain ellipsoid and this $x$-direction is considered as the direction of tectonic flow of the matrix foliation (Fig. 7.1). Alternate light (Q-domain) and dark (M-domain) bands are observed in metapelites showing variable thickness in mm scale. In M-domains both muscovite and biotite are interleaved together as Mus$_1$ and Biot$_1$ (ignoring biotite flakes within pretectonic garnet) (Fig. 7.2). Their long direction coincide with the elongate flattened orientation of the quartz grains indicating X-direction of the strain ellipse. They define shear foliation ($CS_2$) or matrix foliation, a true representation of the Synhimalayan M$_2$ metamorphism of D$_2$ deformation (Fig. 7.3). In garnet porphyroblasts, internal fabric ($S_i$) is marked by tiny particles of magnetite$_1$ and relatively small, almost equant and sometimes elongate quartz grains (designated as qtz$_1$) and lie at different angle to external foliation ($S_e$) (Fig. 7.4). This $S_i$ fabric
may be considered as $S_1$ or relict of pre-TECTONIC stage (Prehimalayan stage = $D_1$ deformation) and
CORRELATE with $M_1$ metamorphic phase. Internal foliation ($S_i$) imprinted within the garnet
PORPHYROBLASTS are categorised under straight, sigmoidal, curved, continuous and partial with
respect to core and rim parts of the porphyroblast (Figs. 7.4; 7.7; 7.10; 7.12). The relationships
between such internal foliation ($S_i$) and external foliation ($S_e$) is worked out systematically.
Garnet porphyroblasts as a whole in terms of its shape and size also have some significance
although they may not have internal well defined $S_i$ fabrics (Fig. 7.1). External foliation ($S_e$) is
deflected round such flattened garnets either with asymmetric right or left lateral sense of
rotation (Fig. 7.4; 7.9; 7.10). Occasionally, trail region is observed and such strain region is
occupied by quartz grains of relatively large size (Fig. 7.5). The shape morphology and
asymmetric rotational fabrics are indicative of their two stages growth history – earlier they were
rounded, i.e. pre-TECTONIC ($D_1$) to major matrix foliation growth phase and at later stage, they
become flattened and rotated during syntectonic phase of major recrystallization history ($D_2$)
(Figs. 7.7; 7.8; 7.12). Such rigid bodies with or without different inclusion patterns floating
within the ductile sheared matrix under non-coaxial deformation are considered as best
signatures of metamorphic growth history before, after and during their multideformational
history (Kakati and Sarma, 2013).

The $S_e$ is considered as the product of Synhimalayan deformation ($D_2$) and associated
with intensively sheared ductile foliation ($CS_2$) (Fig. 7.4). Therefore, it may be concluded that
$M_1$ metamorphism might have some significance of Prehimalayan orogeny i.e. developed before
the onset of dominant Synhimalayan ductile shear phase marked as $M_2$ event. In low grade
metamorphic rocks of the Lesser Himalayan sequence i.e. garnetiferousphyllite, sometimes it is
difficult to draw logical conclusion relating to the growth of either inclusion free garnet enclosed
within the relatively fine grained matrix composed of mica flakes, elongate quartz and rarely magnetite and chlorite whether they are the true representation of pre-tectonic stage of Prehimalayan orogeny or developed towards the end of Synhimalayan phase (Fig. 7.1). Passchier and Trouw (2005) have opined that in low grade metamorphic rocks, sometimes garnet porphyroblast bears passive inclusions representing event of earlier fabrics, hence considered as pre-tectonic M₁ metamorphic phase. S₁ fabric whenever present, marked as planar and straight whereas Sₑ fabric is curviplanar, coarser and deflected round the garnet porphyroblasts, hence Sₑ fabric acts as an indicator of Synhimalayan metamorphic phase (M₂) erasing D₁ fabric almost totally during D₂ Himalayan phase. Another point of curiosity is that minute flakes of biotite occasionally lie within the tiny particles of quartz and magnetite as S₁ fabric in a few garnet prophyroblasts (Figs. 7.7; 7.8). Are they represents a pre-tectonic stage (M₁) or small biotite grains are penetrated as mica beard along any weak planes of garnet porphyroblasts during M₂ Synhimalayan phase?

Metapelites of LHSS i.e. Tenga Formation, Dedza Formation / Chilliepam Formation are fine to relatively medium grained strongly anisotropic rocks, well crenulated consisting of biotite, muscovite, garnet, quartz, plagioclase rarely chlorite and k-feldspar as dominant mineral phases. Therefore, metamorphism can be fixed under greenschist facies. There is a slight increase in the grade of metamorphism of the Dirang Formation and Lumla Formation along with increasing coarsening habit of the mineral phases with staurolite and kyanite as index mineral. Question may be raised if Indian plate acts as basement of Himalaya then before collisional tectonism with Tibetan plate, the Indian plate bears the identity of at least three phases of deformation (if not more) with characteristic amphibolite facies. Why then only one phase is considered as in the form of remnant during the Synhimalayan orogenic cycle? What happened
to other phases? Jain et al. (2002) have advocated only one phase of deformation in relict form which represents Prehimalayan orogeny under the greenschist facies metamorphism. Could it be possible to reconstruct the idea that the tectonic imprints of deformational phases of Indian plate are readjusted, restructured and remobilised thoroughly during the process of crustal shortening of the Himalayan tectonism followed by extensional tectonic nappe configuration leaving the original setting as discontinuous layers or lenses, sheets and bodies in different forms, floated within the most ductile shear matrix in a Synhimalayan episode? This aspect is an open question, probably a challenging one, which needs rethinking in reconstructing the Prehimalayan orogenic signatures.

Another aspect as regards garnet₁ (pretectonic to Himalayan orogeny) is referred to for explaining a brittle and ductile phase. Some garnet bears intrafracture parallel and / or oblique to most ductile CS₂ fabric (Figs. 7.6; 7.7; 7.8; 7.9; 7.12). Occasionally, such garnets show rotational movement without imprints of any rotation of S₁ fabric. Such behaviour may probably leads to a conclusion that they are the resistant survivor of deformational history of the Indian crustal plate irrespective of phases under the coverage of Himalayan orogenic movement.

Garnet developed during M₂ stage of Synhimalayam orogeny (D₂) with characteristic sigmoidal and spiral trails of inclusion is observed both in Lesser Himalayan sequence and Higher Himalayan sequence (Fig. 7.10, 7.14). Such syntectonic garnet (garnet₂) is not only observed in metapelites but found in garnetiferous amphibolite also. Two stages of overgrowth is frequently seen in garnet with sigmoidal pattern at the core (garnet₂) and inclusion free post tectonic zone (garnet₃) which is defined as M₂ and M₃ stages of Synhimalayan metamorphic episode (Figs. 7.7; 7.8; 7.12). M₂ garnet show both twinning and zoning and alteration to biotite and/or chlorite parallel to the CS₂ fabric signifying retrograde effect. Skeletal garnet often
associated with mica flakes and elongate quartz lie parallel to the CS$_2$ fabric also signify M$_2$ (garnet$_2$) of metamorphism (Fig. 7.11, 7.15). Such skeletal garnet portrays the progressive stage of transformation during Himalayan orogeny (Syn M$_2$ metamorphism).

Garnet porphyroblast also bears the identity of overgrowth characters incorporating CS$_2$ fabric (S$_e$ fabric) of syntectonic M$_2$ stage and they are designated as garnet$_3$. Thus garnet$_3$ is treated as post tectonic to D$_2$ deformation or intertectonic between D$_2$ and D$_3$ deformation representing M$_3$ stage of metamorphism (Figs. 7.9, 7.12). Similarly the external CS$_2$ fabric also truncates and deflects around garnet porphyroblasts which indicates the growth history of the garnet after the formation of regional schistosity (CS$_2$) during D$_2$ deformation and hence intertectonic between D$_2$ and D$_3$ (garnet$_3$). Thus, incorporation of the external fabric (S$_e$) with or without rotation, truncation and deflection of S$_e$ fabric around garnet porphyroblasts with or without S$_i$ fabric are considered as post tectonic to regional tectonic foliation and marked as garnet$_3$ of M$_3$ stage of metamorphism (Figs. 7.9; 7.12).

Many authors are of the opinion that porphyroblasts grow during penetrative deformation but when porphyroblasts grow during non-penetrative deformation, they either do not rotate or grow without inclusions. Both these two aspects are well preserved in the Lesser Himalayan and Higher Himalayan sequences of the studied area. Metapelites are highly crenulated and crenulations are formed either syngenetically during Himalayan orogeny under D$_3$ phase or at a later stage of D$_2$ deformation of Synhimalayan episode. Question may be raised whether intensive and highly penetrative CS$_2$ fabric is the cause and effect of Synhimalayan D$_2$ phase? If so, regional shear foliation when folded or crenulated under layer parallel compressive tectonism?
Fig. 7.1 Elongate garnet (garnet$_1$) without inclusion (S$_i$) lie within CS$_2$ foliation. Long direction of garnet is parallel to the x-direction of strain ellipse.  
Fig. 7.2 Shear foliation (CS$_2$) is defined by micas (biotite$_2$ + muscovite$_2$). Broad and thick biotite plate (biotite$_3$) truncate CS$_2$ at high angle (= D$_3$ axial phase).  
Fig. 7.3 Similar to 7.2. quartz, feldspar lenses lie parallel to CS$_2$.  
Fig. 7.4 Pre-tectonic garnet1 with straight trails of inclusion (S$_i$) defining S$_1$, a Prehimalayan signature.
Fig. 7.5 Kyanite lie within CS$_2$ and bears the identity of Synhimalayan D$_2$ signature. Garnet porphyroblasts are pre-tectonic. Fig. 7.6 Radiating features shown by sillimanite in migmatitic gneiss of SeLa Group. Fig. 7.7 Two stages growth of garnet (garnet$_2$ and garnet$_3$). Fig. 7.8 Similar to 7.7, Core part represent garnet$_2$ with biotite, magnetite and quartz as inclusion and rim is garnet$_3$. 
**Fig. 7.9** Two stages growth of garnet with randomly oriented shear fractures. **Fig. 7.10** Spiral garnet with rotational $S_i$ fabric show truncation of the shear foliation ($CS_2$). Shear fractures are lying high angle to $CS_2$. **Fig. 7.11** Skeletal garnet with sigmoidal rotation and folded behaviour of the $CS_2$ in the strain shadow zone may indicate intertectonic phase between $D_2$ and $D_3$. **Fig 7.12** Two stages growth of garnet is marked by twin garnet. Characteristic conjugate shear fractures are seen. Acute angle bisectrix of the shear fractures is parallel to the mica flakes define tectonic flowage of the ductile matrix.
Considering these two aspects it is probable that both are the resultant fabrics of Synhimalayan D₂ episode, the former forms at the first stage of Synhimalayan D₂ orogeny and the latter represents second stage of Synhimalayan D₂ phase both belong to the highly tectonised products of Synhimalayan D₂ phase. The timing of porphyroblast growth relative to the development of matrix foliation is a complex approach which invites involvement of study under P-T-D-t path system (Johnson, 1999). Unfortunately the present study delimits this study. Again CS₂ foliation is differentiated into mica rich domain (M-domain) and quartz-feldspar domain (Q-domain), both being parallel to the CS₂ fabric i.e. parallel to the orientation of regional tectonic flow direction. This type of mineral zonation/segregation may be referred to as the product of late D₂ phase i.e. M₃ metamorphic episode.

The regional CS₂ foliation is folded by layer parallel compression or layer oblique (<30°) during D₃ deformation and form folds of varied dimension (Fig. 7.13). The microstructural behaviour of F₃ folds is studied mostly in metapelites bearing the index minerals like garnet, staurolite and sillimanite. The matrix foliation (CS₂) is differentiated in M and Q domains forming discrete, zonal and extensional crenulation cleavage (S₃) and they...
are considered as \( M_4 \) metamorphism. Relatively large, short and broad mica flakes transect \( CS_2 \) foliations at different angles (Fig. 7.2). The orientation of such mica plates often coincides with the orientation of slender mica flakes developed along the zonal cleavage direction. Further, broad and short, thick mica (muscovite) lie at about 60\(^\circ\) to the earlier, similar broad mica set. Both the sets transect \( CS_2 \) foliation and they are considered as conjugate set of \( D_3 \) deformation under \( M_4 \) metamorphic stage.

A few garnet porphyroblasts registered the imprints of \( F_3 \) microfolding (Fig. 7.7). Such garnets are available from metapelites of Dirang and Lumla Formations of Lesser Himalayan sequence. It is a point of interest that the garnet growth may be syngenetic to \( D_3 \) deformation (=\( F_3 \) folding) and may be considered as intertectonic between \( D_3 \) and \( D_4 \) deformation. The development of garnet is therefore placed under \( M_5 \) stage of metamorphism. Kakati and Sarma (2013) have noted that such broad and short muscovite plates may be due to reorientation of the earlier muscovite plates and cannot be correlatable with growth history of \( M_4 \) stage of metamorphism. The inclusion trail orientation data with respect to external matrix foliation and associated folding are still quite few to draw more realistic and logistic conclusion. Similar finding is reported by Johnson (1999) who claims that probably it is possible in case of large scale deformation processes in orogenic belts. In metapelites of higher Himalayan sequences, most of the earlier \( S_1 \) fabrics imprinted in garnet porphyroblasts is either lost or restructured. Most of the garnets are shattered, fractured and
occasionally bears the imprints of $S_1$ fabrics marked by relatively large quartz grains, biotite in disordered form and magnetite. Sillimanite is found in fibrolitic form and are clustered like a mica fish and radiating features in quartzofeldspathic gneiss, migmatite as well as metapelites. Staurolite and kyanite are reported by Bhattacharjee and Nandy (2008), Goswami et al. (2009) from Tawang Sector. Bhattacharjee and Nandy (2008) have reported that the basal units of migmatites of the SeLa Group is characterised by the assemblage kyanite + biotite + garnet + staurolite at the lower structural level while at upper level, sillimanite + garnet + biotite are observed within the SeLa Group above MCT zone. Kyanite, on the other hand, is also observed in Lumla of LHS. In Dirang Formation staurolite is found to occur syntectonically during $D_2$ phase. Both kyanite and staurolite have growth history during $D_2$ deformation itself. Garnet growth history with syntectonic core and posttectonic rim have been illustrated with photographs. Goswami et al. (2009) have studied the Tawang sector and adopted and established 5 metamorphic zones namely garnet zone, kyanite zone, kyanite – migmatite zone, kyanite – sillimanite – migmatite zone and k-feldspar – kyanite – sillimanite – migmatite zone. They have referred to mineral growth dominantly late to post $D_2$ phase. Garnet porphyroblasts were classified as syn $D_1$ and post $D_2$ overgrowing matrix foliation ($S_2$). Growth of sillimanite is obviously related to mica transformation and occasionally garnet takes part in the formation of sillimanite as a prograde product under regional progressive phase. In some cases, it apparently looks like that the growth of sillimanite is related to hydrogen metasomatic origin (Vernon, 1979) and / or deformation induced fibrolitisation along shear planes (Wintsch and Andrews, 1988). In the study area, the second approach is more appropriate. Transformation of mica and garnet by deformation induced mechanism leading to fibrolitisation during intensive shearing history of Himalayan orogeny is suggested from this part of eastern Himalaya.
It has already been stated in chapter 4 (Petrography part) that metapelites (including migmatitic gneiss) of LHSS and HHS of the studied area are constituted by the following mineral assemblages:

Quartz + sericite + muscovite + biotite + accessories

Quartz + muscovite + biotite + garnet ± kyanite + accessories

Biotite + muscovite + garnet + kyanite + sillimanite + quartz + plagioclase + accessories

Garnet + biotite + muscovite + sautrolite, quartz + plagioclase + tourmaline + accessories

Kyanite and staurolite minerals are rarely found in Dirang while they are also found in SeLa Group along with sillimanite. The probable mineral reactions of garnet growth from both studies may be referred to here so that metamorphic zonation could be established. In garnet zone, the growth of garnet is probably related to

Chlorite + plagioclase + biotite + quartz → garnet + muscovite + H2O

Biotite + plagioclase → garnet + muscovite

This zone is purely restricted to LHSS i.e. within lower reaches of the Dirang Formation and partly in Lumla Formation. Both staurolite and kyanite are rarely exposed within upper reaches of the Dirang Formation and even in Lumla Formation while both are found in the leucosome of the SeLa migmatites. The probable reaction may be listed as:

Garnet + muscovite → kyanite + biotite + quartz

Garnet + kyanite + H2O → Staurolite + quartz

Growth of sillimanite is responsible for the following reaction

Muscovite + plagioclase → K-feldspar + kyanite + sillimanite + melt.
From the above discussion and probable growth history delineated from the microstructural studies, it is apparent that the grade of metamorphic history is increasing with structural high and as such from LHSS is typically belong to lower part of amphibolite facies or greenschist – amphibolite transitional facies while HHS (SeLa Group) belongs to middle to upper part of the amphibolite facies. PT field is cited as $550^0 - 700^0C$ with 8 kb pressure (Goswami et al., 2009). For the purpose of fixation of grade and metamorphic facies of the study area, metapelitic rocks with characteristic index minerals like garnet, staurolite, kyanite and sillimanite and associated mineral assemblages of other metabasic rocks, calc-silicate (details in petrography chapter) indicate that the rocks have undergone metamorphism under upper greenschist to middle to upper amphibolite facies (Turner, 1968).

A tentative model for successive stages of deformation and their correlation to metamorphism is tabulated below (Table 7.1).

**Table 7.1**

<table>
<thead>
<tr>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$M_3$</th>
<th>$M_4$</th>
<th>$M_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prehimalayan</td>
<td>Synhimalayan</td>
<td>Synhimalayan</td>
<td>Synhimalayan</td>
<td>Posthimalayan</td>
</tr>
<tr>
<td>Syn D1</td>
<td>Syntectonic to D2</td>
<td>Intertectonic between D2 and D3</td>
<td>Syntectonic to D3</td>
<td>Syntectonic to D4</td>
</tr>
<tr>
<td>Quartz1</td>
<td>Quartz2</td>
<td>Quartz3</td>
<td>Quartz4</td>
<td>Quartz5</td>
</tr>
<tr>
<td>---</td>
<td>Biotite1</td>
<td>Biotite2</td>
<td>Biotite3</td>
<td>---</td>
</tr>
<tr>
<td>---</td>
<td>Muscovite1</td>
<td>Muscovite2</td>
<td>Muscovite3</td>
<td>---</td>
</tr>
<tr>
<td>Garnet1</td>
<td>Garnet2</td>
<td>Garnet3</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>---</td>
<td>Kyanite1</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>---</td>
<td>Staurolite1</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Chlorite1</td>
<td>Chlorite2</td>
<td>---</td>
<td>---</td>
<td>Chlorite3</td>
</tr>
<tr>
<td>Magnetite1</td>
<td>Magnetite2</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>