CHAPTER 2:

GEOLOGICAL SETTING
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The Himalayan orogenic belt is a gigantic feature on Earth that poses toughest challenge to the geoscientific community to unveil geological history of this mountain building process. The mountain chain contains some of the deepest Gorges and highest peaks of the world dividing the Indian subcontinent into a 2400 km arc forming an icy blockade between the tropical India and the Central Asia. For this reason, the Himalaya is also referred to as the 3rd pole on the Earth besides the north and south poles. On both eastern and western ends, there is a marked inward bending of the strike of the orogen, called the NW- and NE- Himalayan Syntaxes. In this chapter, a brief description of the evolutionary history of the Himalayan orogeny, geographical characteristics, regional geology and detailed geology of the suture zone with special emphasis on the geology of the accretionary prisms studied in this investigation is presented.

2.1 EVOLUTION OF THE HIMALAYA

The evolution of Himalaya is a mystery, which remains to be unfolded completely. A working model of evolution of the Himalaya was first introduced by Burrard and Hayden (1907) and Argand (1924). During the early 19th century,
the great mountain chains of the world were viewed as having developed through geosynclinal hypothesis and the Himalaya was considered as a mega geosynclinal entity on Earth’s surface. According to this hypothesis, the Himalaya was formed by huge piles of sedimentary succession, deposited in a huge basin called the Tethys Ocean and was uplifted through multi deformational events. However in the mid 19th century, the plate tectonic theory came into light through the pioneering work of McKenzie and Parker (1967), Isacks et al. (1968), Le Pichon, (1968), Morgan, (1968) and others, which gradually picked up momentum and became widely accepted by the geoscientific community (Figure 1.1). Further, in 1970 the plate tectonic theory was arguably used by Dewey and Bird (1970) and put forward a more realistic evolutionary model of the Himalaya. They suggested that the Indian plate collided with the Asian plate resulting in the most spectacular and gigantic event on the Earth, the birth of the Himalayan Mountain chain.

Therefore, to understand the evolution of the Himalaya is a challenging exercise in itself owing to the present and past geographical positions of the Indian plate. The evolution of the Himalaya can only be explained in a proper way by throwing light on the journey of the Indian plate. It becomes necessary to look into the past history and dynamics of the Indian plate since the Proterozoic time. During the Late Paleozoic, the Indian continent was a part of the Pangaea supercontinent. The breakup of Pangaea supercontinent took place at ~200 Ma in three major phases (viz. Early–Middle Jurassic: ~175 Ma; Early Cretaceous: ~145 Ma; and Cenozoic: 65–55 Ma) as suggested by Merali and Skinner (2009). The first phase
of braking up of Pangaea began ~175 Ma (Early–Middle Jurassic period) that
gave rise to two supercontinents namely, Laurasia (to the north) and Gondwana
(to the south) due to rifting from Tethys Ocean in the east to the Pacific Ocean at
the west. The second phase of breaking of Pangaea took place at ~145 Ma (Early
Cretaceous). In this phase, the Gondwana supercontinent separated into two major
continents (i) West Gondwana (together with Africa and South America) and (ii)
East Gondwana (a group of India, Australia, and Antarctica). Following which,
the Indian plate further broke off from the East Gondwana (Australia and
Antarctica), and began its journey northward direction to collide with the Asian
plate at an estimated rate of 18.5 cm/year (fastest known movement of any
tectonic plate), which is responsible to closing the Tethys ocean (Figure 2.1;
Meng et al., 2012). The third and final phase of brake-up of Pangaea occurred in
Cenozoic period (~60–55 Ma) during which the Laurasia was fragmented into
North America and Greenland, collectively referred to as Laurentia.

In the second phase of break-up of Pangaea, the Indian continental plate move
towards the Asian plate and is considered to be the beginning of the Himalayan
orogeny. In Early Cretaceous period (about 120–100 Ma), the Tethys Ocean
began to subduct beneath the Asian plate and resulting in closer of the Neo-
Tethys, through northward movement of the Indian plate and ensuing intra-
oceanic subduction giving rise to arc magmatism represented now by the Dras arc
(Figure 2.1), which was formed at ~120 Ma facilitating formation of an
accretionary prism (including Shergol and Zildat ophiolitic mélangé) at its forearc
basin (Figure 2.1; Mahéo et al., 2006). The Indian plate continued to move northward and upon closer of the Tethys Ocean, the two continents, Asian and Indian plates, came face to face and collided at about 55–50 Ma and shaped another accretionary prism south of Shergol Ophiolitic mélangé, namely South Ladakh Accretionary Prism (SLAP). In this frame of time, numerous magmatic activities also took place and formed magmatic arcs known as Ladakh, Karakoram and Ladakh–Kohistan, which continued until 13 Ma (Kohistan magmatic arc; Ji et al., 2009). In the development of the Himalayan orogeny, the northward translation of Indian plate was associated with the Tethys oceanic plate subducting beneath the Asian plate in two episodes (see Figure 2.1). Following the completion of subduction of Tethys oceanic plate below the Asian plate, the Indian continental plate began to subduct at about 55 Ma in the second phase (Figure 2.1). The first subduction of Tethys oceanic plate (Neo–Tethys) took place at about 120–100 Ma, whereas the second subduction of Neo Tethys occurred at about 65 Ma (Figure 2.1). Therefore, the subduction of Neo Tethys is also referred to as paleo–subduction, with respect to the second subduction of the Indian continental plate (Gansser et al., 1974; Thakur, 1981; Robertson, 2000; Mahéo, et al., 2006). For this reason, the first accretionary prism which was shaped at ~120–100 Ma is referred to as Paleo Accretionary Prism (PAP), whereas the second accretionary prism (SLAP) developed at about 55–50 Ma. The PAP and SLAP are jointly referred to as the Ladakh Accretionary Prism (LAP), which is well exposed along the Indus Tsangpo Suture Zone (ITSZ).
The geographic as well as the litho-tectonic divisions of the Himalaya is presented below (figure 2.1) and is summarized in Table 2.1.

**Figure 2.1:** Schematic diagram of the Himalayan orogeny and shaping of accretionary prisms, modified after Clift et al (2000); Mahéo et al (2006) and Meng et al (2012).
2.1.1 GEOGRAPHICAL DIVISIONS OF THE HIMALAYA

Geographically, the Himalaya lies between two peaks namely Namche Barwa (at eastern syntaxes) and Nanga Parbat (at western syntaxes). It is bounded in the north by two orogen parallel trans-Himalayan rivers, viz. the east–flowing Yalu Tsangpo ("Tsangpo" meaning “big river” in Tibetan local dialect) and west–flowing Indus River and the southern boundary of the Himalaya is marked by the Main Frontal Thrust (MFT) that delimit the northern limit of the Indo–Gangetic depression. The Hindu Kush Mountains demarcate the boundary of western margin, while the Indo–Burma ranges (Rongklang Range) mark the eastern margin of the Himalayan syntaxes. The Karakorum Mountain chain and the Trans-Himalayan terrain are the northern most margin of the Himalayan orogen (Figure 2.2). The southern political boundary of Tibet (i.e., Xizang in China) follows approximately the crown of the Himalayan range. The difference in political and geographic divisions has led to different naming of the same structures in the Himalayan range (e.g., the north Himalayan normal fault versus south Tibet detachment system; Burg et al., 1984; Burchfiel et al., 1992).

From North to South, the Himalayan orogen is separated into two parts; the North Himalaya and the South Himalaya that are defined by its high crest line (Figure 2.2). The North Himalaya is nearly similar to the Tethyan Himalaya or the Tibetan Himalaya as geographically defined by Heim and Gansser (1939) and LeFort (1975), respectively. The South Himalaya covers rest of the Himalaya,
which is further sub-divided into three main divisions such as, Higher, Lesser, and sub-Himalaya, respectively from north to south (Figure 2.2). The southern boundary of the Higher Himalaya is marked as the base line of the northernmost steepest slope of the southern Himalayan range, whereas the boundary between the Lower Himalaya and sub-Himalaya lies along the axis of the lowest intermontane valley parallel to the range (Yin, 2006).

On the basis of elevation, the Himalayan ranges are divided vertically into three categories (i) the Basal: <1500 m, (ii) Middle: 1500–3500 m, and (iii) Upper Himalaya: >3500 m (Yin, 2006). With this criterion, the Upper Himalaya is mostly absent in northern Pakistan, south of the Indus–Tsangpo suture as reported by DiPietro and Pogue (2004).

From west to east (along the strike direction), the Himalayan orogen is divided into the western (66°–81°), central (81°–89°), and eastern (89°–98°) segments (Yin, 2006). The western Himalayan orogen covers the Salt Range in northern Pakistan, Kashmir (NW India), Zanskar, Spiti, Chamba, Himachal Pradesh, Lahul, Garhwal, and Kumaun. The central Himalayan orogen occupies Nepal, Sikkim, and south-central Tibet, whereas the eastern Himalayan orogen includes Bhutan, Arunachal Pradesh of NE India, and southeastern Tibet.
Figure 2.2: A generalized Litho-Tectonic Map of the Himalaya (modified from Searle et al., 2003 and Law et al., 2004).
2.1.2 LITHO– AND TECTONO– STRATIGRAPHICAL DIVISIONS OF THE HIMALAYA

Litho– and Tectono– stratigraphically, the Himalaya is divided into five major classes from south to north (across the strike direction) and are referred to as Sub, Lesser, Higher, Tethyan and Trans Himalaya (Figure 2.2). The Sub Himalaya consists of fine to coarse grained continental foreland basin sediments of Neogene period (23 to 2 Ma) and also known as Siwalik Group. The Proterozoic–Cambrian, Lesser Himalayan Sequence (LHS) is comprised of unfossiliferous low grade metamorphic, metasedimentary and metavolcanic rocks. On the other hand, younger Higher/Greater Himalayan crystalline complex (HHC/GHC) comprised of high grade metamorphic rocks of Cambrian to Early Ordovician period (800–480 Ma) as reported by Yin, 2006 and others. The Tethyan Himalayan Sequence (THS) is demarcated as the northernmost part of the Indian subcontinent, which consists of Late Precambrian to Eocene (about 650–40 Ma) marine sedimentary rocks intrabedded with volcanics (Yin, 2006). The THS overlies to the Indian continental plate along a normal fault called South Tibet Detachment (STD). The major volcanic and magmatic arcs of the Himalaya were developed in the Trans Himalayan terrain. The major divisions of the Himalaya are structurally and tectonically controlled, in which the thrusts/faults of the Himalayan system are difficult to discriminate because of changes in litho units with the thrust/fault.
The Sub–Himalaya is separated from the Ganga Plain to its southern margin by the Main Frontal Thrust (MFT), whereas the northern margin is demarcated by the Main Boundary Thrust (MBT). In the north of the MBT, Lesser Himalaya is well exposed at its hanging wall. Lesser Himalaya is also referred to as footwall of Main Central Thrust (MCT), which lies at the south of MCT. High grade metamorphic rocks of HHC/GHC are well exposed to the north of MCT on its hanging wall. In turn, the HHC is bounded to the north by the high–angle normal fault, which lies to the south of THS and known as South Tibet Detachment (STD). The STD separates the higher Himalayan crystalline from the Tethyan Himalayan Sequence (THS). Thus, STD is the northern most margin of the Indian tectonic plate, which separates the Asian plate to the north by the Indus–Tsangpo Suture Zone (ITSZ). The ITSZ is actually the zone of collision between Indian and Asian plates where the sediments were accreted from both sides of the tectonic plates. In the north of ITSZ, the trans-Himalaya is well exposed, which is considered in northern margin of the Himalayan orogenic belt.

The divisions of the Himalaya on the geographical/ topographic, litho–, chronostratigraphic and structural basis are tabulated below in table 2.1 (modified after Yin, 2006) for comparison.
**Table 2.1: Geographical, Stratigraphic and Structural divisions of the Himalaya.**

<table>
<thead>
<tr>
<th>Geographical/ Topographic Division</th>
<th>Litho- and tectono-stratigraphy Division</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Across Strike Direction</strong></td>
<td><strong>Trans Himalaya</strong></td>
</tr>
<tr>
<td>Tibetan Plateau</td>
<td>Trans Himalaya</td>
</tr>
<tr>
<td>Indus/ Tsangpo River</td>
<td>Trans Himalaya</td>
</tr>
<tr>
<td>North Himalaya</td>
<td>Trans Himalaya</td>
</tr>
<tr>
<td>Himalayan Crest</td>
<td>Trans Himalaya</td>
</tr>
<tr>
<td>Higher Himalaya</td>
<td>Tethyan Himalayan Sequence (THS)</td>
</tr>
<tr>
<td>Lower Himalaya</td>
<td>Tethyan Himalayan Sequence (THS)</td>
</tr>
<tr>
<td>Sub Himalaya</td>
<td>Tethyan Himalayan Sequence (THS)</td>
</tr>
<tr>
<td><strong>Vertical Section</strong></td>
<td><strong>Lesser Himalayan Sequence (LHS)</strong></td>
</tr>
<tr>
<td>Upper Himalaya (&gt; 3500 m)</td>
<td>Lesser Himalayan Sequence (LHS)</td>
</tr>
<tr>
<td>Middle Himalaya (1500-3500 m)</td>
<td>Lesser Himalayan Sequence (LHS)</td>
</tr>
<tr>
<td>Basal Himalaya (50-1500 m)</td>
<td>Lesser Himalayan Sequence (LHS)</td>
</tr>
<tr>
<td><strong>Along Strike Direction</strong></td>
<td><strong>Sub Himalaya/ Siwalik Group</strong></td>
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<tr>
<td>Western Himalayan orogen</td>
<td>Sub Himalaya/ Siwalik Group</td>
</tr>
<tr>
<td>Central Himalayan orogen</td>
<td>Sub Himalaya/ Siwalik Group</td>
</tr>
<tr>
<td>Eastern Himalayan orogen</td>
<td>Sub Himalaya/ Siwalik Group</td>
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<tr>
<td><strong>Gangatic Plane</strong></td>
<td>Sub Himalaya/ Siwalik Group</td>
</tr>
</tbody>
</table>

### 2.2 REGIONAL GEOLOGY OF THE LADAKH HIMALAYA

A sequence of several magmatic activities is noticed in the Ladakh terrain. These activities are represented by Late Jurassic–Cretaceous intraoceanic arc magmatism (Dras–Nidar volcanics and associated with Ladakh–Kohistan batholith) varying from mafic to intermediate compositions. These magmatic sequences are in turn, invaded by Ladakh–Kohistan granodioritic/granitic intrusives (Ahmad et al., 2008). Numerous ages have been assigned to the
Ladakh–Kohistan batholith starting from 103±3 Ma (U–Pb age: Honegger et al., 1982; Schärer et al., 1984) from Kargil, through 49.8 ± 0.8 Ma (zircon U–Pb: Weinberg and Dunlap, 2000) to cooling ages as younger as 48.7±1.6 Ma (biotite K–Ar: Honegger et al., 1982) and 45.7±0.8 Ma (hornblende Ar–Ar: Weinberg and Dunlap, 2000) for rocks from around Leh, in the central part of Ladakh. This suggests that there are several magmatic phases of Ladakh plutonic complex spanning in time and space from ~100 Ma through ~45 Ma to the youngest phase of 30–13 Ma as reported from Tibet (Kohistan magmatic arc) by Ji et al (2009).

Present study area belongs to Ladakh terrain in the NW Himalaya along the NW–SE trending ITSZ (Figure 2.3). As described above in section 2.1.2 of this chapter that ITSZ is the zone of collision of Indian and Asian plates, which consists of two accretionary prisms (PAP and SLAP). The western and eastern margin of the study area is bounded by the mélange zone and ophiolitic rocks of Shergol and Zildat succession, respectively. From north to south across the strike, the Ladakh range may be divided mainly into four groups (map view; Figure 2.3)-

I. southern margin of Asian plate (Karakoram and SSZ),

II. Ladakh Asian Margin (Ladakh batholiths, Nindam Formation and Dras arc)

III. ITSZ (Shergol ophiolitic mélange, Indus Molasse, Shergol conglomerate, Nidar Ophiolitic Complex and Zildat Ophiolitic Mélange)
IV. Passive margin of the Indian plate (Lamayuru, Taglanga-La, Spontang ophiolites, ophiolitic mélange, Zanskar formation and HHC/GHC).

**Figure 2.3:** Regional Geological Map of the Study area (Ladakh Himalaya) modified from Thakur and Mishra (1984); Mahé et al (2004, 2006). The rectangular box refers to- [A] Shergol area (see Figure 2.4); [B] the Nimu–Chilling (NC) Section (see Figure 2.6 for detail); [C] Lato–Miru–Upshi (LMU) Section (see Figure 2.8 for detail) and [D] the Ziladt Section (see Figure 2.10 for detail).

(I) **The Southern margin of Asian plate** consists of Karakoram plutonic complex and SSZ. The Karakoram and Lhasa block was a single tectonic unit, which was displaced and separated by the Karakoram
thrust/fault. This Karakoram plutonic complex is a part of the Ladakh Magmatic Arc (LMA) resulting from subduction of the Indian oceanic plate beneath the Asian plate (Thakur, 1981). In the forearc of Karakoram plutonic complex a suture zone developed, which is known as Shyok Suture Zone (SSZ) having the trends similar to that of ITSZ. The SSZ can be divided into four tectono–stratigraphic units, viz. Shyok ophiolite, Luzarum Formation, Diong Formation and Kole molasses. Developed during Cretaceous to Eocene, the Shyok Group consists of sandstone, conglomerate, basic and intermediate volcanics along with chert, gabbro, peridotite and serpentinite, which is interbeded with shale, limestone and quartzite (Thakur, 1981; Thakur and Mishra, 1984).

Further, SSZ was displaced from the Karakoram zone by a major fault demarked by the mylonitic gneiss and is referred to as the Karakoram thrust/fault by Thakur and Mishra, (1984), however, recently it has been designated as a strike slip fault (Sen and Collins, 2013).

(II) **Ladakh Asian Margin** is composed of Ladakh batholith, Nindam Formation and Dras arc (see Figure 2.3). The Ladakh plutonic complex is a NW–SE trending belt of batholithic body, which consists of tonalite, granodiorite and granite and developed in multiphases of magmatic activity and having cross–cut relationship with Dras volcanics (Thakur and Mishra, 1984). The different intrusive phases of Ladakh plutonic complex have been dated by radiometric method, which
indicates three major activities viz. 120 Ma, 60–40 Ma and 20 Ma (Brookfield and Reynolds, 1981; Honegger et al., 1982). Yet another youngest age, 13 Ma of Ladakh plutonic complex is reported from the Tibet (Ladakh–Kohistan magmatic arc) by Ji et al (2009). Closely associated with the Ladakh plutonic complex, the Dras arc was inferred to have formed in the Cretaceous time by the arc type of volcanic activity as Tethys oceanic plate began to subduct and closure of Neo Tethys 1 (Figure 2.1) ensued (Mahéo et al., 2006). The volcanic rocks contain mainly andesitic and basaltic lavas, which is associated with occasional pillow lava, rhyolite, agglomerate and other volcanioclastic rocks (Thakur, 1981; Honegger et al., 1982; Thakur and Mishra, 1984). To the east of the Dras arc formation, flysch sedimentary sequences occur consisting of red and olive–green shales and sandstones in addition to chert, jasper and limestone. The petrochemical property of volcanic rocks indicates that these are mainly tholeiites of calc-alkaline affinity with minor shoshonites (Honegger et al., 1982). The Dras formation as a whole represent an island-arc tectonic set-up resulting from subduction related magmatic eruption (Figure 2.1) through melting of upper mantle or the upper part of subducting Tethys oceanic plate (Thakur, 1981; Honegger et al., 1982; Thakur and Mishra, 1984).

(III) **ITSZ** is a group of NW–SE trending litho-units, which are known as Shergol ophiolitic mélange, Indus Molasse, Shergol conglomerate, Nidar
Ophiolitic Complex and Zildat ophiolitic mélange (Figure 2.3). As shown in the map (Figure 2.3) the study area is composed of ophiolite and ophiolitic mélange zone of Zildat and Shergol area at the eastern and western part of ITSZ, respectively whereas the central part is comprised of Indus molasse. The southern margin of ITSZ is demarcated by Shergol conglomerate, which separates the ITSZ from the Lamayuru formation. In the north, the ITSZ separates the Ladakh magmatic arc by the deep seated Indus thrust (Kharya et al., 2014), which is also known as Upshi–Bagso thrust (Brookfield and Andrews–Speed, 1984; Tripathy-Lang, 2013).

(IV) Passive margin of Indian plate is represented by various lithounites of Tethys sediments, viz. Lamayuru, Taglanga-La, Zanskar formations and associated Spontang ophiolites and ophiolitic mélange, along with high grade metamorphic rocks of HHC/GHC to the south within Indian plate (Figure 2.3). The Lamayuru and Zanskar formations are composed of sediments, which lie on the Indian subcontinent side to the south of ITSZ in which the Spontang ophiolites and ophiolitic mélange were intruded within Zanskar formation (Figure 2.3). Higher Himalaya crystalline (HHC) exposed further south of Zanskar formation, which is comprised of High grade metamorphic rocks.
2.3 GEOLOGICAL SETTING OF THE LADAKH ACCRETIONARY PRISM (LAP)

The Ladakh accretionary prism (LAP) is shaped in the fore arc basin of Dras and Ladakh magmatic arc along ITSZ which mainly consists of sediments (derived from the Asian and Indian plates), conglomerates, ophiolites and ophiolitic mélange unites and subduction related metamorphic rocks (Blue Schist, Coesite bearing eclogite, etc.) along with numerous mineralized veins. The eastern and western margin of LAP consists of ophiolite and ophiolitic mélange of Zildat and Shergol, respectively, which was shaped at the same time (Cenozoic). The northern and southern margin of LAP is sandwiched between Ladakh magmatic arc and Lamayuru formation. The LAP is also tectonically bounded by the Indus thrust (at the north) and Zanskar thrust (at the south). It is further subdivided into two accretionary complexes on the basis of their progressive time of formation (Figure 2.1). These are named as paleo-accretionary prism (PAP) and South Ladakh Accretionary Prism (SLAP). The PAP was formed at ~100 Ma (Honegger et al., 1989; Mahéo et al., 2004, 2006) in the forearc basin of Dras arc due to closure of Tethys Ocean (Neo–Tethys 1), by the convergence of Tethys oceanic plate underneath the Asian plate (see Figure 2.1). This closer of Neo–Tethys Ocean took place in two stages at different times (i.e. Neo–Tethys 1 and Neo–Tethys 2) by continued north dipping subduction zone (Figure 2.1). The first subduction of Neo Tethys (Neo Tethys 1) started at ~120 Ma when Tethys oceanic plate was subducting beneath the Asian plate (Thakur, 1981; Pedersen et
al., 2001; Mahéo et al., 2004, 2006), which gave rise to magmatic arcs (Dracon volcanic and Ladakh magmatic arc) around the same time. This paleo subduction was subsequently followed by a second northward subduction of Neo–Tethys 2 that began at ~65 Ma and shaped SLAP (Mahéo et al., 2006).

In addition to the formation of LAP in different time periods and development of pertinent litho units, numerous veins are omnipresent present in most of the formations of LAP. These veins cross–cut almost all the litho units present in the accretionary complexes (paleo and South Ladakh accretionary prisms) including even the Shergol conglomerate, which indicates the strong movement of fluid in the formation of veins took place at very last stage. These veins enhance our curiosity to workout, which is still untouched. This is not clear as to where from, these fluids were derived at the waning stage of the Himalayan orogeny, when the magmatic activity seems to have ceased.

These syntectonic mineralized veins are formed by quartz, calcite and/or co-existing quartz–calcite mineral pair, which varies in size from very thin to thick (2mm to few centimeters) and indicate strong movement of fluids during deformation. These veins are randomly distributed in all the direction. On the basis of occurrence, these are further divided into three categories 1) fault/fracture filling veins, 2) network veins and 3) sigmoidal veins (Figure 2.12 to 2.15). The majority (>98%) of the veins are fault/fracture filling type in the study area of LAP, which developed along the week plane such as fault, fracture, bedding
plane, etc. The occurrence of network and sigmoidal veins are very less (<2%) or negligible. It suggests rapid intrusion in week planes (fault, fracture, beading plane). It also indicates that the fault/fracture filling veins were formed during the collapse process of dilatational run within a system (Sibson, 1986). The origin of fault/fracture filling calcite vein preserve the evidence of its source and fluid composition which migrate through faults/fractures (Dietrich et al., 1983; Avigour et al., 1990; Gao et al., 1992) and the co-existing quartz will help to estimate the crystallizing temperature of these veins. The calcite veins are commonly formed with other geological processes such as tectonic deformation, and remagnetization (Kessen et al., 1981; Clauer et al., 1989 and many more).

2.3.1 GEOLOGY OF PALEO ACCRETIONARY PRISM (PAP)

The paleo accretionary prism was shaped in the fore arc basin of Dras arc during the Craterous time. It is mainly comprised of subduction related metamorphic rocks (i.e. Blue schist, Oceanic Island Basalt and Ultra High Pressure metamorphic rocks). The paleo accretionary prism is mainly comprised of cretaceous cherty shale, jasperoid shale, volcanics, sandstone and conglomerate, along with serpentine, magnesite, peridotite, coesite bearing eclogites, Oceanic Island Basalt (OIB) and blueschist facies metamorphic rocks (Virdi et al., 1977; Thakur, 1981; Thakur and Mishra, 1984; Honegger et al., 1989; Mukherjee and Sachan 2001; De Sigoyer et al., 2004). Rodingaite has been observed for the first time to occur in the association with serpentine.
Figure 2.4: Geological Map of the Shergol ophiolitic mélange (SOM) or western paleo accretionary prism (western PAP), modified from Honegger et al (1989).
Figure 2.5: Photographs of Shergol Ophiolitic mélange (or western PAP). (a) Panoramic view of western PAP, and (b) Contact metamorphism of serpentine and rodingaite.
This is suggesting of contact metamorphism with the Shergol ophiolitic rocks (Figure 2.5). The SOM is also referred to as western paleo accretionary prism (western PAP) in this study. The Shergol sedimentary units got metamorphosed to various degrees from Green Schist facies to Blueshist facies with intermixing of rocks (Honegger et al., 1989). Conglomerate, Ophiolites and Ophiolitic mélange units are also encountered in this accretionary complex (Figure 2.4). This unit is separated from the Lamayuru formation via a south dipping thrust (Thakur and Mishra, 1984) at its southern margin. The Nindam formation is well exposed to the north of SOM (Figure 2.4).

Numerous veins are present in most of the lithounits of paleo accretionary prism. These veins are encountered in the mélange units and Conglomerates, on the other hand the veining is absent in the Blue schist. It therefore suggests that the veining did not take place during the development of PAP, but are later phenomena. Except for the blue schist rocks, all other litho-units of PAP are invaded by veining.

2.3.2 GEOLOGY OF SOUTH LADAKH ACCRETIONARY PRISM (SLAP)

The South Ladakh Accretionary Prism (LAP) is well exposed along the Indus–Tsangpo Suture Zone (ITSZ) in the forearc basin of the Ladakh magmatic arc, which consists of sediments (alluvial and marine sediments) derived from both
sides of tectonic plates (Indian and Asian plates). These forearc sediments are among the few deposits that have been recognized worldwide as of an intra-oceanic origin (Brookfield and Andrews-Speed, 1984; Einsele et al., 1994; Robertson and Degnan, 1994; Sinha and Upadhyay, 1997; Clift et al., 2000). Two sections from the SLAP have been studied in detail in the present work to understand the development process of SLAP, these are, Nimu–Chilling (NC) and Lato–Miru–Upshi (LMU). The geological settings of these sections are discussed in detail in the forthcoming sections below. The NC and LMU transverse sections of SLAP are formed by the terrestrial and marine sediments derived from both side of tectonic plates and are very much comparable in terms of lithologies and sedimentation process (Henderson et al., 2010a, 2010b, 2011), whereas the Zildat section of SLAP is similar to the PAP.

The NC and LMU sections are tectonically bounded by the Indus thrust to the north (Brookfield and Andrews-Speed, 1984; Tripathy-Lang, 2013; Kharya et al., 2014) and Zanskar thrust in the south. Several local/shallow thrusts or faults are also present in these sections (Clift et al., 2000), which may be inter-connected with deep seated Indus/Zanskar thrust. These sections are bounded by the Ladakh magmatic arc in the north and Lamayuru formation in the south (Figure 2.3, 2.6 and 2.8). In the north of these sections, terrestrial sediments derived from the Asian plate found which are named as Indus group (Henderson et al., 2010a), while the marine sediments encountered at the southern margin which were derived from the Indian plate are named as Tar group (Figure 2.6 and 2.8). The
geology of NC and LMU sections is explained in detail in the next sections (2.3.2.1 and 2.3.2.2). The Zildat and Shergol sections are developed during the Cenozoic time and having similar lithology (subduction related metamorphic rocks). It is probably formed by the same (ophiolitic rocks) fluid of Shergol area. Therefore, Zildat ophiolitic mélange could be a part of paleo accretionary prism but geographically it is very far off from Shergol area so that many workers do not consider it as a part of paleo accretionary prism. As mentioned above the Zildat was formed by subduction related metamorphic rocks in the Cenozoic time and having the same fluid of Shergol area in the formation of ophiolitic mélange. For these reasons, Zildat is considered as a part of the paleo accretionary prism in this study (see detail in section 2.3.3).

2.3.2.1 GEOLOGY OF NIMU–CHILLING (NC) SECTION

The NC section is well exposed along the Zanskar Gorge between confluence of the Indus–Zanskar River (near Nimu village) and Chilling village (Figure 2.6, 2.7). The NC section is a transverse section of SLAP, which covers the western part of the SLAP (Figure 2.3). This section is comprised of marine and terrestrial sediments derived from both side of the tectonic plates, Indian and Asian, respectively. Marine sediments are well exposed at the southern side of this section, while the northern part of this section is comprised of alluvial/terrestrial sediments. This section is tectonically bounded by the deep seated Zanskar thrust at the south and Indus thrust at the north. The oldest units of this section mainly
consists of Paleocene–Early Eocene marine sediments along with continent derived sediments in minor quantity, which were deposited prior to the collision in the forearc basin of the Trans Himalaya (Garzanti and Van Haver, 1988; Searle et al., 1990; Steck et al., 1993; Sinclair and Jaffey, 2001). This older sequence is a group of Nummulitic Limestone, Chogdo, Sumdo and Jurutze formations, which are jointly referred to as Tar group (Searle et al., 1990; Sinclair and Jaffey, 2001) and comprised of mudstone, sandstone/siltstone (Figure 2.7) in pre–collision time (Figure 2.6). The Tar group is underlined by the Indus group terrestrial sediments of the Eocene period derived from the Asian plate. These terrestrial sediments were deposited in the forearc basin of LMA after the continental collision i.e. post–collision time and named as Indus Group (Garzanti and Van Haver, 1988; Searle et al., 1990; Sinclair and Jaffey, 2001). The Indus Group is composed of Nurla, Chokstí and Nimu formations, which mainly consist of mudstone, silt/sandstone and conglomerate (Figure 2.6 and 2.7). The Indus and Tar Group are jointly referred to as the western part of SLAP, which overlie the Indian northern margin (Cretaceous Khalsi limestone, volcanoclastic sediments of Nindam formation, Triassic–Jurassic deep water sediments of Lamayuru and Ophiolitic mélange units) and unconformably rest over the Ladakh Batholith/Ladakh–Kohistan island arc (Garzanti and Van Haver, 1988; Searle et al., 1997).

The Tar Group developed at the southern part of NC section (Zanskar Gorge), which is further subdivided into Jurutze, Sumdo, Chogdo and Nummulitic
Limestone litho units (Figure 2.6). It is overlain by the sedimentary rocks of passive Indian margin and underlain by the Indus Group (Indus molasses). The Jurutze formation is mainly comprised of black shale, siltstone/ sandstone (fine to medium grained, gray–green color), gray phyllitic rocks. These fine grain lithologies are commonly associated with silt and laminated mudstone and are profusely invaded by numerous quartz, calcite veining. In this formation shales were metamorphosed to blue–gray phyllites. It is underlain by the Sumdo formation, which consists of Early Eocene sedimentary rocks (mud stone and fine to coarse grain sandstone) along with fossiliferous Nummulitic Limestones (of Ypresian age; Henderson et al., 2010b). The overlying Chogdo formation is composed of fine to medium grained green colored sandstone and maroon shales containing calcareous nodules and conglomerates. The Nummulitic Limestone is the topmost stratigraphic section of the Tar group. The Nummulitic limestone unit of Ypresian age (~48 Ma) consists of interfingering lithologies of clastic and carbonate units. This section contains beds of Nummulitic Limestone along with gritty sandstone, mudstone and conglomerates. The subordinate crystalline nummulites are dominant in the limestone with occasional corals.

**The Indus Group** sediments are derived from the Asian plate and overlie the Tar Group. These are fashioned on the northern side of NC section. The Indus Group is further subdivided into Nurla, Choksti and Nimu formations (Figure 2.6). Nurla formation is alienated from the nummulitic limestone by a conformable contact, which is marked by the disappearance of carbonates and presence of shale (red
Figure 2.6: Geological Map of the Nimu–Chilling Section modified from Searle et al (1990) and Henderson et al (2010b).
Figure 2.7: Panoramic view of Zanskar Gorge and Nimu–Chilling section. (a) confluence of Indus–Zanskar River; (b) Zanskar Gorge at Choksti bridge; (c) Deposition of Mud stone, Sand/Silt stone and the presence of veins.
and black), sandstone (coarse green to fine red color) and green color conglomerates. A similar facies of succession is noticed in Chogdo formation. The Nurla can be distinguished from the Chogdo by coarser grained deposits of sediments. The red shale contains well developed cleavage. The red shale is dominant in the Nurla formation towards its northern margin, where it has faulted contact with Choksti conglomerate. The Choksti formation is composed of alternative layers of conglomerate, Shale and sandstone, in which conglomerate is dominant member. The lower succession of Choksti formation is mainly composed of Basal conglomerate has faulted contact with the red shale of Nurla formation and Choksti formation at its southern and northern side, respectively. The basal conglomerate is intrabedded with green–yellow color, fine to coarse grained sandstone. The basal conglomerate horizon is underlain by red shale of Choksti formation, which has faulted contact with the conglomerate. It consists of sandstone and shale which show abundant ripple lamination affected by slumping (Henderson et al., 2010b). The uppermost part of Choksti formation is mainly comprised of sandstone, which is further subdivided into two categories Middle and Upper Sandstone. The middle sandstone part starts from the Choksti Bridge where thin sandstone beds are intrabeded by shale and phylite and are similar to the Nurla formation. The middle sandstone is gradually transit into upper sandstone facies having similar lithology. The upper sandstone member is comprised of yellow sandstone, black to grey and red shale. Numerous internal/local dextral faulting is reported by Henderson et al. (2010b). The Choksti formation underlines the Nimu formation at the north, which has faulted
contact (Searle et al., 1990; Sinclair and Jaffey, 2001; Clift et al., 2002). The Nimu formation is mainly comprised of sandstone, red–black Shale and orange–brown color Conglomerate. Further the upper Nimu formation has faulted contact with the lower Nimu formation.

2.3.2.2 GEOLOGY OF LATO–MIRU–UPSHI (LMU) SECTION

The Lato–Miru–Upshi (LMU) section is the central part of SLAP and is well exposed on Leh–Manali road along the Lato nala, a tributary of Indus River (Figure 2.9). This traverse section of SLAP lies between the Lato and Upshi village. The litho units of LMU section are very much comparable to the NC section, in terms of formation and sedimentation (Table 2.2). Sequences in this section are also divided into groups, viz. Tar Group and Indus Group. The Tar group was formed by the marine sediments derived from the Indian plate and overlying the rocks of the Lato Formation, while the Indus Group consists of terrestrial sediments derived sediments from Asian plate, which is overlying the Tar Group (Figure 2.8).

The Tar group in LMU section is represented by the marine sediments of Miru formation and forms a NW–SE trending syncline at the southern part of LMU section. The northern and southern limbs of this syncline are well exposed near the Miru and Lato village, respectively (Henderson et al., 2011).
Figure 2.8: Geological Map of the Lato-Miru-Upshi (LMU) section, modified from Henderson et al (2011).
Figure 2.9: Panoramic view of LMU Section.
The Miru formation is mainly comprised of mudstone, sandstone, shale and phyllite (Figure 2.9). Minor occurrence of conglomerate is also noticed in this area.

The **Indus group**, in contrast, was formed by the alluvial sediments derived from the adjacent Asian plate, north of LMU section. It is further subdivided into five formations, viz. Gonmaru La, Arsta, Umlung, Upshi and Rong formation (Figure 2.8). The Gonmaru La consists of red–brown shale, red fine–medium grain sandstone along with red–blue–green color shale at the southern margin. The southern part of this unit has faulted contact with Miru formation. The Gonmaru La formation underlies the Arsta formation consisting mainly of red shale, purple sandstone and conglomerate. It has confirmable contact with the Gonmura La formation at the south and faulted contact with the Umlung formation at the northern margin. The Umlung formation in turn is structurally bounded by the faults at its both margins that separate the Arsta formation in the south and Upshi formation in the north. The Umlung formation consists of red–green color sandstone and shale along with minor conglomerate that occur near the northern side of this formation. The overlying youngest member of the Indus group, the Upshi formation, is comprised of conglomerate, red–green sandstone and red mudstone. It is separated from the Ladakh batholiths at its north by the deep seated Indus thrust, whereas the southern contact with the underlying Umlung is conformable.
Table 2.2: Stratigraphical succession/compression of NC and LMU section.

<table>
<thead>
<tr>
<th>Stratigraphical Age</th>
<th>Group</th>
<th>Formations</th>
<th>NC Section</th>
<th>LMU Section</th>
<th>North</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asian Margin</td>
<td>Early Tertiary</td>
<td>Ladakh Plutonic Complex</td>
<td></td>
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<tr>
<td>South Ladakh accretionary prism</td>
<td>Miocene</td>
<td>Nimu</td>
<td>Upper Nimu</td>
<td>Upshi</td>
<td>Rong</td>
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<td></td>
<td></td>
<td></td>
<td>Lower Nimu</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Upper Sandstone</td>
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<td></td>
<td></td>
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<td>Middle Sandstone</td>
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<td></td>
<td></td>
<td></td>
<td>Red Shale</td>
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<td></td>
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<td></td>
<td>Basal Conglomerate</td>
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<tr>
<td></td>
<td>Indus Group</td>
<td>Choksti</td>
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<td></td>
<td></td>
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<td></td>
<td>Umlung</td>
<td>Mirrorly</td>
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<td></td>
<td></td>
<td></td>
<td>Stratigraphically absent</td>
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<td></td>
<td></td>
<td></td>
<td>Nurla</td>
<td></td>
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<tr>
<td></td>
<td>Early Eocene</td>
<td>Tar Group</td>
<td>Nummulitic Limestone</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Chogdo</td>
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<td></td>
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<td>Sumdo</td>
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<td></td>
<td></td>
<td></td>
<td>Jurutze</td>
<td></td>
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<td></td>
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<tr>
<td>Indian Margin</td>
<td>Mid Cretaceous</td>
<td>Khalsi Limestone</td>
<td></td>
<td>Stratigraphically absent</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Cretaceous</td>
<td>Nindam</td>
<td></td>
<td></td>
<td>Lato</td>
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<tr>
<td></td>
<td>Triassic–Jurassic</td>
<td>Lamayuru</td>
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</table>
2.3.3 GEOLOGY OF ZILDAT SECTION

The Zildat section is eastern margin of the LAP, which is mainly comprised of ophiolites and ophiolitic mélange rocks. Therefore it is known as Zildat Ophiolitic Mélange (ZOM). As described above in section 2.3.2; the ZOM shaped during Craterous time and are quite similar to the Shergol Ophiolitic mélange in terms of their formation event and lithology. The Zildat Ophiolitic mélange may be an extension of Shergol Ophiolitic mélange. Therefore, ZOM can be consider as a part of PAP and also referred to as the eastern PAP. ZOM is bounded by the Tso–Morari Crystalline (TMC) and Nidar Ophiolitic Complex (NOC) in south and north, respectively (Figure 2.10). The ZOM has tectonic contact with Tso Morari Crystallines and this faulted contact is referred to as the Zildat fault.

The ZOM is comprised of varying litho-units and clasts of rocks different ages, collectively known as Sumdo complex (Steck et al., 1998). The Sumdo complex is further subdivided into Drakkarpo and Ribil units (De Sigoyer et al., 2004) on the basis of lithounites present in the area. The Drakkarpo unit consists of thick (~2 Km.) polygenic conglomerate, which is a mishmash of schists, green color sandstones, and calcareous slates along with lenses of tuffs, basalts, quartzite, serpentinite and micaceous schists. These tuffs are highly faulted and are filled by quartzes, carbonates, chlorites and oxides bearing hydrothermal veins originating due to metamorphism. These alkaline volcanic rocks have similar characteristics to an oceanic island (OIB) as reported by Fuchs and Linner (1997);
De Sigoyer (1998). The white color limestone (Figure 2.11) also noticed in this section, which are said to have platform type origin and probably are of Permian in age (Colchen et al., 1987; Corfield et al., 1999; Sen et al., 2013). Whereas the Ribil units was got metamorphosed under greenschist facies and comprised of agglomeratic slates, dolomitic marbles, basalts, and vesicular basalts. The basalt is alkaline in nature and part of the oceanic island basalts (OIB) (De Sigoyer, 1998). Therefore, the ZOM predominantly consists of volcanogenic litho units with chaotic associations of basic volcanics, carbonaceous and argillaceous sedimentary rocks. The volcanogenic rocks are mainly alkaline basaltic with E-MORB-OIB characteristics and a minor NMORB component (Ahmad et al., 1996; De Sigoyer, 1998; De Sigoyer et al., 2004). The mélange has undergone upto blue–schist facies metamorphism (Virdi et al., 1977; De Sigoyer et al., 2004), similar to what is observed in the shergol ophiolitic mélange in western Ladakh (Honegger et al., 1989). The coesite bearing eclogites are also reported from this section by Mukherjee and Sachan (2001) suggesting ultra high pressure metamorphism of the Tso-Morari crystallines (Mukherjee and Sachan, 2001; De Sigoyer et al., 2004). The carbonate exotic block and quartz–calcite veining also occur in this area.
Figure 2.10: Geological Map of the eastern paleo accretionary prism (eastern PAP), modified after De Sigoyer et al (2004).
Figure 2.11: Panoramic view of eastern PAP along with the exotic blocks of limestone.
2.4 SAMPLING STRATEGY AND FIELD RELATION

As describe above in section 2.3, the LAP formed in two stages at different time periods giving rise to two separate accretionary prisms. Numerous mineralized veins are omnipresent in both the accretionary prisms. The veins present in LAP are parallel to sub parallel with respect to bedding plane of the associated host rocks, which are dipping nearly vertical (see Figure 2.7, 2.9, 2.12, 2.13, 2.14 and 2.15). This indicates that the veins were intruded in to the LAP during post deformation/tilting of the accretionary sediments along the fault and fractures. Further deformations were not noticed. These fault filling veins are very common in LAP. This veining energy was so strong that it cut the conglomerate strata, suggesting strong fluid movement at the very last stage and are obviously a matter of curiosity to know their role in the upliftment history of LAP. The earlier researchers did not pay attention on these veins. It was generally assumed, though not established, that the veins are locally derived but their presence in entire LAP and nature of occurrence indicates that these are not as simple as were thought to be. These vein samples are most suitable for fluid inclusion studies and can potentially be used to extract information related to fluid source. This is likely to unveil whether or not these veins are locally derived or having affinity to other external sources. The study of veins from LAP would also be expected to throw light to help in better understanding of accretionary processes at the later part of the developmental history of the Himalaya. Thus the veins are selected as the sampling media to unveil the literal source of veining at the accretionary front in
the Ladakh region of the Himalayan orogeny. To accomplish this study, vein samples were systematically collected from each layer of various rock types in a manner that they are representative of the different types and across the stratigraphic sequence in space and time. In view of the importance and objectives of the study, the sampling strategy was devised and adopted as far as possible uniformly in all the four sections, however, tough terrain conditions often restrict sampling to accessible areas only. Nevertheless, the sampling distributions were well representative and satisfactory for the intended purpose.

As discussed in section 2.3 of this chapter the veins types can be classified into three parts on the basis of mineralogy, i.e. (I) Pure Quartz veins, (II) Pure Carbonate veins and (III) Co-paired Quartz–Calcite veins. Apart from the mineralogical division, these veins can also be classified into three categories based on the mode of occurrence and morphology. These are - (I) Fault/Fracture Filling veins, (II) Network Veins and (III) Sigmoidal veins. The representative photographs of these various types of veins from each studied sections are presented in the Figure 2.12, 2.13, 2.14 and 2.15 of Shergol, NC, LMU and Zildat sections, respectively. Most importantly, the stratigraphy and lithology of the host rock were given due consideration. In summary, following points were kept in mind that formed the part of our sampling strategy:

(I) Sampling has to be done across the accretionary prisms by taking the transverse section, i.e. keeping stratigraphic control of sampling.
(II) Representative pure quartz, pure calcite and co-paired quartz-calcite vein samples were collected with or without the host rock.

(III) Few network and sigmoidal type veins samples were also collected wherever possible.

(IV) Wherever possible, samples from all lithounits in stratigraphic sequence (chronological order) in the proximity were collected.

Description of the lithologies, structural elements and field observations along with photo documentation and GPS locations were recorded and are given in Appendix A. Each sample location, thus collected, was prominently numbered and secured in sample bags before transportation to the institute. An inventory was prepared and maintained for all the samples and their field descriptions. A split of all the samples studied is archived for future use and verification. The coordinates of each sample along with other pertinent information are summarized in the Appendix A.
Figure 2.12: Field photographs of various types of veins present in Shergol area. (a-d) Fault/Fracture Filling veins, and (e-f) Network type veins.
Figure 2.13: Field photographs of veins from NC section. (a-d) Fault/Fracture Filling veins, (e-f) Network type veins, (g) Bounded Neck, and (h) Sigmoidal type veins.
Figure 2.14: Field photographs of veins Intruded in the sediments of LMU section. (a-d) Fault/Fracture Filling veins, (e) Sigmoidal type veins, and (f) Network type veins.