CHAPTER 1:

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1.1 OVERVIEW AND RESEARCH MOTIVATION

The Himalaya is the youngest mountain chain on the planet Earth having an arcuate shaped 2400 Km long mountain front and comprising of numerous highest peaks of the world, including the highest peak on the Earth, the Mount Everest (8,848 meter height). The average elevation of Himalayan mountain chain is about 4,500 meter (in Ladakh), which makes it a cold desert. The Himalaya has a great significance to the people of India which plays an important role as an orographic barrier that influences the Indian monsoon system since the early Miocene period. Besides, the Himalaya is a place from where major rivers originates, including Ganga, Brahmaputra, and Indus etc. that are lifelines to a major population of the north Indian subcontinent plays a vital role in the growth of the Indian economy. In addition to its great geographical and climatic importance, the Himalaya is much more important in Hindu folklore than just a majestic mountain chain that extends in a 2400 Km arc. The Himalaya is not only the place for rare sanative herbs, or winter sports, it has always been an abode of Hindu saints and Gods. Therefore, the Himalaya is also referred to as devbholi or God-souled.
The most holy river for Hindus, the Ganga, also originates from the Himalaya, which supplies water to the people of most densely populated Ganga Basin. The Himalaya is therefore as important scientifically as it is societally, culturally and economically to the people of the Indian subcontinent.

The high topography of the Himalaya is a result of Continent–Continental collision where Indian plate subducted beneath the Asian plate. Such type of tectonic activity taken place at convergent plate boundary where two plates collide against each other. In plate tectonics, a convergent plate boundary is an actively deforming region where two (or more) tectonic plates move toward each other. This movement of plates closes and consumes the intervening oceanic plate through the process of subduction of one plate below the other. This results in drifting of continental plates through geological ages and often ending up with collision of continental plates; thus making great mountain chains such as the Himalaya. The sinking of the cold plate, oceanic or continental, deep into the asthenosphere produce partially melted subducting plate and adjoining lithosphere producing extensive magmatism all along the arcuate shaped forefront of the suture zone, referred to as “Arc Magmatism”, which is common phenomenon in the convergent plate boundary (Figure 1.1). Similarly, when a lithospheric plate is subducting at one end, an extension or rifting takes place at the other end and is referred to as divergent boundary. This divergence also causes extensive magmatism through the upwelling of the anthenospheric mantle, e.g. Mid-oceanic ridge.
In convergent tectonic set up, an accretionary prism is developed at the plate boundary in the forearc basin over the subducting plate through ongoing sedimentation and deposition of sediments as well as volcano–clastics derived from both sides of the tectonic plate and accreted onto the overlying plate (Figure 1.1; Mahéo et al., 2006). At the subduction zones, chemical components are cast–off into the mantle through deep subduction and returned to the surface by the arc volcanism. These processes are responsible for the movement of fluids at various stages and levels within subduction zones, which are associated with large volumes of fluid that are dispersed in pulses through seismic activities of larger magnitude (Lallemand and Funiciello, 2009). The fluid can be intruded in an accretionary prism due to the seismicity. Most of the fluids are trapped either within hydrous minerals or as pore water in the oceanic crust and superjacent sediments. These entrapments of fluids are expelled within top few tens of kilometers of the subduction zone (Moore and Vrolijk, 1992) and percolate into the wedge–shaped upper–plate of the accretionary prism within the subduction zone. Experimental and observational evidence indicates sedimentary accretionary prism rocks experience dehydration reactions throughout the subduction process (Vrolijk, 1987, 1990; Sample et al., 1993; Jarrard, 2003; Rowe and Screaton, 2009). These fluids play significant role in development of faulting through both static and dynamic weakening processes during earthquake events at the crustal level (Hubbert and Rubey, 1959; Sibson, 1973; Mase and Smith, 1987; Sibson et al., 1988; Cox, 1995; Ujiie et al., 2007). These processes are usually dominant along the plate boundary thrust and faults
(Yamaguchi et al., 2012). Most of the accretionary prisms are bounded by the weak planes such as faults or thrusts. Records of various stages of movement of fluid history are preserved as veinlets in the development of the mountain chain. The Himalaya is the best example in the world for such type of study, which was developed initially as Alpine–type convergent zones like oceanic–continental subduction followed by continent–continent collision between Indian and Asian plates (Bally, 1981; Meng et al., 2012). Meng et al (2012) suggested that the age and focus of the initial India–Asia collision are at about 50 Ma and 24°N, respectively. These authors further suggest that Tibet stopped India’s northward push during the first 16 Ma of initial impact (~65 Ma) from the collision allowing only little latitudinal displacement. It was little after 34 Ma that Greater India was consumed and thicker Indian Craton subsequently made contact with Asia, resulting in ~6° northward movement of Asia. In this process, Tethys oceanic plate was consumed through subduction first at about 120–100 Ma (Mahéo et al., 2006) beneath the Asian continental plate and shaped an accretionary prism. Subsequently, upon closing of the Tethyan oceanic plate, the Indian continental plate began to subduct beneath the Asian continental plate at about 65–50 Ma (Mahéo et al., 2006; Meng et al., 2012). Due to this continent–continent collision second accretionary prism was formed in the forearc basin of Ladakh magmatic arc along the Indus–Tsangpo suture zone (ITSZ), which is referred to as South Ladakh accretionary prism (SLAP) due to its geographical position and the accretionary prism shaped prior to the SLAP is referred to as paleo accretionary prism (Figure 2.1, modified after Mahéo et al., 2006; Meng et al., 2012). Further,
the subduction of Indian plate is still continuing. Due to these on-going processes, the Indian plate is currently moving at the rate of ~5cm/yr towards the north making the Himalaya as active tectonic region. Such tectonic activity is responsible for thrusting and faulting in the area which can open up pathway for fluid to be entrapped along these weak planes.

**Figure 1.1:** A generalized sketch of the plate tectonics model showing different tectonic set-ups. Plate boundary and their deformation process (adopted from http://en.wikipedia.org/wiki/Plate_tectonics).

The Himalaya offers an unique opportunity to study subduction related processes where two accretionary prisms developed at two different time frames as the subduction process is continued. Such type of subduction/tectonic setup is also reported from Japan where two Nankai and Shimanto accretionary prisms are well developed (Byrne et al., 1993; Michiguchi and Ogawa, 2011; and Yamaguchi et
al., 2012). As explained above that the Himalaya is tectonically induced and seismically very active, these seismic or tectonic activities in the Himalaya probably facilitated opening-up of weak planes in the form of faults, thrusts and fractures providing easy pathways for upward migration of warm fluids that were entrapped en-route from deeper part of the Earth’s crust. The veining in accretionary prism is common, which took place along the fault and fracture planes. These vein forming fluids may be derived either from deeper sources (magmatic) due to seismic or tectonic activity (discussed above) or locally due to diagenetic and metamorphic processes resulting from continued sedimentation in forearc basin and tectonic processes. Thrusts, and normal and strike-slip faults act as preferred conduits for efficient fluid movement, because they are easier to dilate to make space for emplacement of quartz and calcite veins. Quartz and calcite veins more often occur as mineralized fracture fillings that are ubiquitous in accretionary prism and can serve as valuable monitors of fluid flow. Such type of veining also reported from other accretionary prisms (Michiguchi and Ogawa, 2011; Yamaguchi et al., 2012), such as – Calabrian and Aka Accretionary prism in the Mediterranean Sea; Kodiak accretionary prism in southern Alaska; Nankai and Shimanto accretionary prisms are in Japan; Taiwan accretionary prism located in Taiwan; Barbados accretionary prism of Barbados; and Otago accretionary prism located in New Zealand). Invariable quartz or calcite mineral or both in different proportions constitute a simple mineralogical assemblage of the veins. Till date, very little is known about the role of fluid in the development of the accretionary prism and there was no attempt at all in the past on Ladakh
accretionary prism (LAP) except for the sedimentological, metamorphic and geochemical aspects. This is the first ever attempt in Indian scenario to understand the processes of accretion and subduction through appropriate isotopic fingerprinting and geochemical modeling to aid to our understanding of the formation of accretionary prisms in the Himalayan scenario vis-à-vis the subduction related magmatic activity alongside.

The proposed research work is focused at understanding late stage development of the Himalaya through the detailed study of paleo and South Ladakh accretionary prisms up to the penultimate stage of the mountain building process using Quartz–Calcite veins as the target media. To accomplish this study we select four sections from ITSZ as a case study, covering entire ITSZ from west to east. Out of the four sections, two sections are from paleo accretionary prism, called Shergol and Zildat ophiolitic mélangé and two sections from South Ladakh accretionary prism are namely Nimu–Chilling (NC) and Lato–Miru–Upshi (LMU) were chosen for the present investigation. Such types of accretionary prisms are also exposed in Shimanto, Japan and in Chile, between the Nazca and the South American plate which is also known as paleo accretionary prism.

In the Ladakh accretionary prism quartz and calcite veins are generally vertical and at low angle to the bedding plains of the host rock which are also highly tilted and are nearly vertical. This suggests that these veins were intruded in the later stage of deformation of sediments present in the LAP in response to the on-going
Himalayan orogeny. These quartz and calcite veins are common in LAP and elsewhere these are generally aid to be derived from metamorphic or digenetic fluid (Breeding and Ague, 2002 from Otago accretionary prism, New Zealand), marine carbonates or digenetic process (Vrolijk et al., 1991 from Barbados accretionary prism) from shallow depth. The deeper sources of fluid have not been reported so far. Earlier studies from other accretionary prism suggest that the veins are usually developed in an accretionary complex from shallow marine source or associated host rocks. In the present case, however, this does not seem to be entirely true and there is something beyond this. In this context, it is important to note that the northern margin is entirely composed of granitic and igneous related sediments derived from the Ladakh batholiths. Whereas, the southern margin of LAP is comprised of marine sediments. Some preliminary investigation by the author reveal that potbelly these are not ordinary locally derive veins, but has much deeper origin. If so, that it has important implications in term of continued magmatic activity at the last phase of the Himalayan orogeny. It is normally believed that the quartz and calcite veins under such settings are derived from the marine sediments as in the case of Otago accretionary prism, New Zealand (Breeding and Ague, 2002) and Barbados accretionary prism (Vrolijk et al., 1991), however, the geological setting in the present case strongly argue in favor of an alternative source. Depending upon the nature of the alternative source, a detailed study of these vein networks is likely and most potentially unveil hitherto unknown stories about the processes during the later part of the Himalayan orogeny. Therefore, it is necessary to confirm the
fluid source and to verify if these veins were derived from marine source or not. If not then it becomes important to know the source of fluid in formation of veins. This problem has not been addressed so far and without knowing the exact fluid source in the formation of the veins, the development history of the Himalaya remains incomplete. With this motivation, the present problem was chosen with the prospect that it would add to our current understanding about this gigantic continent-continent collision and subduction related processes.

1.2 LITERATURE REVIEW AND BACKGROUND

The Mesozoic period in the geological history witnessed one of the major mountain building events all over the globe, e.g., Alps in Europe, Andes in south America, Rockies Mountain chain in North America and the Himalaya in Asian continent. The Himalayan orogeny is one of the remarkable events that created most of the highest peaks and deepest gorges of the world spreading over 2500 km across the central Asian continent. Earliest scientific mention and geological reports include those of Hooker (1854), Godwin-Austen (1864), Pilgrim (1906), and Auden (1935) who viewed the Himalaya as a continental fold-thrust mountain chain that came into existence through southward push of the northward drift of the Indian continent. It was still not clear as to where from the enormous force was derived that created such a huge structure on the surface. Contributing to the debate, Wadia (1966) hypothesized that plastic Tethys geosynclines against which Gondwana land juxtaposed and got deformed.
However, the classic reviews by Wadia (1953, 1966), Gansser (1964), and Le Fort (1975) provided a holistic modern view of the Himalayan geology in general and combined with the plate tectonic theory, laid the foundation for the present day concept and research in understanding the complex Himalayan orogeny (Gansser, 1964; McKenzie and Parker, 1967; Isacks et al., 1968; Le Pichon, 1968; Morgan, 1968; Coleman, 1971; Ernst, 1973; and Valdiya, 1981, 1984). Ever since the concept of plate tectonics introduced about 3-4 decades ago, there is a marked improvement in our understanding of the complex tectonic history of the Himalaya. Some of the modern reviews on Himalayan tectonics describing the plate tectonic model, subduction of Tethyan oceanic plate, closing of the Tethyan ocean and ensuing continent-continent collision may be found in Acharyya (1980), Thakur (1981), Singh and Chowdhary (1990), Searle et al (1992), LeFort (1996), Hodges (2000), Yin and Harrison (2000), DeCelles et al. (2002), Johnson (2002), Avouac (2003), Steck (2003), DiPietro and Pogue (2004); and Yin (2006) that includes geological summaries at local as well as in regional scale.

references therein. These studies mostly focused on reconstructing the structural set-up and collision tectonics and geochronology of events and resulting geomorphologic expressions thereon. However, very little is known about the accretionary prisms that were developed due to the subduction process and more specifically the extensive occurrence of veins within the rocks of accretionary prisms. It is generally believed that the veins within the LAP were emplaced at the end of the cessation of the fore arc basin and completion of suturing, i.e. post 23 Ma. It is therefore envisaged that these veins might reveal some of the hitherto, unknown mysteries of the tectonic activity at this crucial stage of the Himalayan orogeny.

Veining in other accretionary prism was also reported, but few workers trace the source of vein forming fluid as well as their exhumation history. Very few studies have been done so far on the role of fluid source in the formation of veins and the upliftment history. The metamorphic fluids as source of quartz veins were reported from the Otago accretionary prism, New Zealand by Breeding and Ague (2002), where as the marine carbonates or Sea water precipitation were identified in case of the Shimanto accretionary prism, Japan by Yamaguchi et al (2012). Vein formation associated with digenetic process of associated host rock has been established in case of Barbados accretionary prism at island of Barbados in the North Atlantic Ocean by Vrolijk et al (1991). The tectonic framework of these veins also carried out by few workers such as Byrne et al (1993); Michiguchi and Ogawa (2011) from Nankai accretionary prism, Japan. In no case, the implication
of the quartz-carbonate veins occurring in different levels within the accretionary prisms with the tectonic history has ever been established. This is primarily because the fluid in these cases probably heralds its source from shallower processes as discussed above. The upliftment history of veins was not reported from any accretionary prism so far.

There are two accretionary prism developed in different time frames in Ladakh collision zone, as discussed in section 1.1 of this chapter. A similar set-up has also been reported from the Japanese island arcs from the western Pacific Ocean (Sugimura, and Uyeda, 1973; Vrolijk et al., 1991; Byrne et al., 1993; Taira, A., 2001; Michiguchi and Ogawa, 2011) where two accretionary prisms, Nanki and Shimanto developed separately but are none juxtaposed each other. These accretionary prisms contain numerous veins, which are formed by the metamorphic fluid and sea water/marine carbonates (Vrolijk et al., 1991; Byrne et al., 1993; Michiguchi and Ogawa, 2011).

1.3 OBJECTIVES

In view of the foregoing discussion and the importance of the quartz calcite veins occurring within the Ladakh accretionary prism of the Himalayan orogeny, an attempt has been made to extract useful inferences from these veins that would likely to throw lights on the subduction processes during the veining stage of the orogen. The objectives of the present study are as follows:
a) To understand the veining mechanism in accretionary complex.

b) To know the source of fluid and formation condition of veins and its implication to their tectonics.

c) To understand the fluid flow on a regional scale in a protracted tectonic event (i.e. formation of accretionary complex) from eastern to western Ladakh in a relation to the Himalayan orogeny.

To achieve these objectives, following research model was adopted.

a) Rigorous fieldwork to look for quartz–calcite veins along with host rock, spread over accretionary prism (paleo and South–Ladakh accretionary prism).

b) Intensive Petrographic studies of selected quartz–calcite veins.

c) Detail Fluid Inclusion Petrography.

d) Micro thermometric study of fluid inclusions.

e) Raman spectroscopy of fluid species.

f) Geochemical study (Trace and REE) of selected quartz–calcite veins.

g) Isotopic studies of selected quartz–calcite veins.

Petrography of veins helps to know the mineral assemblage and their deformation conditions in the formation of veins. The systematic investigation of fluid inclusions petrography study helps in identification of different generations of fluid movement. Trace and REE elemental compositions together with the
isotopic characteristics is very useful for understanding and identifying the source and put constraints on the exhumation history of accretionary complexes. Isotopic studies will also help to know the source of fluid in the formation of veins and trace their pathways and final entrapment. A snap shot of the methodology adopted for the systematic study of the veins is diagrammatically presented in the flow Chart above.

1.4 THE STUDY AREA

To accomplish the objectives of this study, four sections from both accretionary prisms are selected that are well spread along strike in the ITSZ (Figure 1.2). These are marked in Figure 1.2 from west to east as- [A] Shergol section of paleo- accretionary prism, [B] Nimu–Chilling (NC), [C] Lato–Miro–Upshi (LMU) of South Ladakh accretionary prism and [D] Zildat section of paleo-accretionary prism.

The local detail geological maps of these studied sections are shown in chapter 2. A cross sectional view of study area also shown in the figure 1.3 which suggest that the Ladakh accretionary prism developed in the forearc basin of Ladakh magmatic arc between the Ladakh batholiths and the Lamayuru formation of Indian margin.
Figure 1.2: Regional Geological Map of the Study area (Ladakh Himalaya) modified after Thakur and Mishra (1984); Mahéo et al (2004, 2006). The rectangular box refers to the investigation sections of this study- [A] represent 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).

The Shergol section is well exposed at the western margin of the Ladakh accretionary prism (LAP) whereas, the Zildat section shaped at the eastern margin of LAP which is an extension of ophiolitic mélange. Therefore, the Shergol and Zildat ophiolitic mélange are jointly referred to as the paleo accretionary prism.

The NC section lies in the Zanskar Gorge between Nimu and Chilling village at the western margin of the SLAP. While, the LMU section is covered the eastern
part of SLAP and well exposed on Leh–Manali road between Upshi and Lato village.

![Diagram](image)

*Figure 1.3: Cross sectional view of the Ladakh Accretionary Prism (LAP).*

### 1.5 CONTRIBUTION OF PRESENT RESEARCH

Veining in accretionary prism occurs during the post deformation event of LAP. The accretion prism developed at very last stage of any orogeny process. Therefore, these veins present in accretion prism can be considered as a media to unravel the history of penultimate stage of evolution of the Himalaya. This is the first ever attempt in the Himalayan tectonic set-up to understand the process of accretion and subduction using vein fluid(s) as media. This research work will enhance our understanding of the formation of accretionary complexes and the Himalayan orogeny during the last phase, through the eye of vein fluid. This work
is expected to provide us clues if any magmatic activity along with tectonic activity was involved at the penultimate stage of the development of Himalayan Orogeny. In true sense, the knowledge towards the development history of the Himalayan orogeny will be improved through this research work by adding the penultimate history.

This research work rises following questions that need to be addressed and a justifiable answer would immensely benefit the geoscientific fraternity:

a. What is the source of vein forming fluid in the development of the Ladakh accretionary prism?

b. What was the formation temperature of veins?

c. What was the possible path of emplacement of these veins?

d. At what depth the vein forming fluid was intruded?

e. What was the fluid composition?

This thesis report is submitted with the hope that the answers to these questions are quite pertinent to our understanding about the tectono-magmatic regime of the late stage of the subduction and continental collision of the Himalayan orogeny.