Project Title

Study of deformation and Tectono-sedimentation history of the Siwalik Group of rocks, Arunachal Himalaya (F. No.41-1025/2012 (SR) dated 23rd July, 2012)

Project Completion Report

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Forewords

The Sub-Himalayan Siwalik sequence in the Arunachal Himalaya has always been drawing attention of geoscientists for its unique characteristics. Although the lithologic similarity of the Siwalik rocks of this segment of Himalaya with the western Himalayan sequence has been well studied, the absence of mammalian fauna in Arunachal Himalayan sequence has always been an enigma. The Siwalik sequence in Arunachal Himalaya is continuous from western to the eastern part and shows a coarsening upward cycle. The structural complexity of the sequence has not been studied so far. Further, the tectonostratigraphy, the basin fill and provenance of the sediments needed an in-depth study specifically in view of occurrence of a similar foreland basin in the southern part of Brahmaputra River. Keeping these aspects in mind, the authors have proposed to study the Siwalik sequence in Arunachal Himalaya in five different transects from Kameng River section in the west to Siang River section in the east. The inhospitable terrain conditions and dense vegetation has been an impediment during the fieldwork. However, authors have left no stone unturned in collecting and analysing the primary field data which can always be considered as the most valuable part for interpretation and description of geologic phenomena that might have taken place in the area. It would be worth noting that the paucity of fund inhibited us to achieve the objectives of the project as proposed. However, based on the field data and laboratory study, we have summarised the outcome of the project in this report. We are hopeful that in future we can further target the unanswered questions in regard to the geometry and tectonosedimentation history of the basin on the backdrop of the Himalayan collision tectonics.

(Dr. Tapos Kumar Goswami)

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Acknowledgements

Any scientific research depends upon the basic component of data generation and meaningful analysis of the datasets. The formulation of any model or interpretation of the phenomenon strongly depends upon the aforementioned components of data generation and analysis. This has always been a critical part and needs a huge amount of physical and mental strength to comprehend what is visualised or conceptualised. The authors are indebted to University Grants Commission, New Delhi for providing the financial assistance to carry out the work. The grants have become a tremendous mental support for us to embark on this project and to work in an inhospitable terrain. The authors are highly grateful to the authority of the Dibrugarh University for providing the necessary support in regard to infrastructure and laboratory facilities. The authors are thankful to the HOD Department of Applied Geology, Dibrugarh University for providing necessary facilities for successful completion of the work. Further, the authors are indebted to the official and technical staff of the Department of Applied Geology. We are also grateful to the research scholars of the Department who have always been helping us to complete the task successfully.

Finally, TKG and RKS are indebted to their respective family members for supporting them through thick and thin and without their support the successful completion of the project would have never been possible.

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Introduction

In Arunachal Himalaya, Siwalik fold thrust belt is a major tectonic unit, extending from the West Kameng District to parts below south of Lower Siang District (Fig.1). In the south, the Himalayan Frontal Thrust (HFT) has brought the Siwaliks above the Brahmaputra alluvium while in the north it is bounded by Main Boundary Thrust (MBT) which can be considered as a major basin margin fault. Thus, the Siwalik -Sub-Himalayan fold thrust belt of Arunachal Pradesh includes Miocene and younger sedimentary rocks that consists northward dipping thrust sheets structurally below the Main boundary Thrust (MBT) and above the Main Frontal Thrust (MFT) (Kelty et al., 2004) (Fig.2). The structural architecture of the Siwalik belt in the western and Central Himalayan belt has been intensively studied (Valdiya, 2003; Mugnier et al, 1999; Husson and Mugnier, 2003; Najman, 2006; Srivastava and Mitra, 1994, DeCelles et.al 2001, Meigs, et al, 1995; Bagati T N 1991; Virdi, 1994; Mugnier et al, 1999; Singh, 1999; Srivastava and Jhon, 1999). However, there are scarce data as far as geometry of the thrust system in the Siwalik belt of Arunachal Himalaya (Acharyya et al, 1983; Rao, 1983; Verma and Tendon, 1976; Kelty et al,, 2004; Yin et al, 2006, Singh and Chowdhury, 1990a; Srinivasan, 2003). On the other hand there are few information about the basin fill, timing of deformation and sedimentation, exhumation history, lithofacies associations and their genetic interpretation in the Siwaliks of Arunachal Himalaya (Rao, 1983; White et al, 2002; Karunakaran and Rao, 1976, Kelty, 2004; Kumar, 1997). Recent discovery of Lower Tertiary rocks containing rich faunal assemblages of Lower to Middle Eocene age in Dalbuik, Gobuik, Dumro, Pasighat in Siang District and Garu-Gensi area in West Siang District of Arunachal Pradesh warrants fresh interpretation and review of the geologic and tectonic setting of the region. The stratigraphic position, age and nomenclature of Lower Tertiary, Upper Tertiary or Siwaliks are rather confusing and need revision (Kumar, 1997). The Upper Tertiary or Siwaliks of Arunachal Himalaya could be the time equivalent of Siwalik Group of NW Himalaya and these deposits may possibly deposited in two separate basins (Karunakaran and Ranga Rao, 1976; Rao, 1983). The biota in these sediments suggests brackish water environment; in contrast to that of the Siwaliks of NW Himalaya, which are of fluvial in origin (Raiverman, 2003).

Considering above, the proposed objectives of the project was to understand the evolution of the basin and its correlation with evolution of the similar basin in the eastern Himalaya. The structural geometry of the Siwalik basin was also proposed to study considering the similarity in the evolution of the foredeep basin in western and central Himalaya. Further, it was intended to understand whether the mesoscale deformation is penetrative to the grain scale and whether the grain scale deformation mimics the mesoscale deformation pattern. Further, it was also aimed to study how the sedimentary and diagenetic fabrics in the rocks are affected by the deformation in the rocks. The evolution of the basin is thus to be interpreted with the field structural, petrographic and heavy mineral composition of the rocks. It would be worth mentioning that although the fission track and isotope study were proposed, these objectives could not be fulfilled due to the paucity of funds and time constraints.

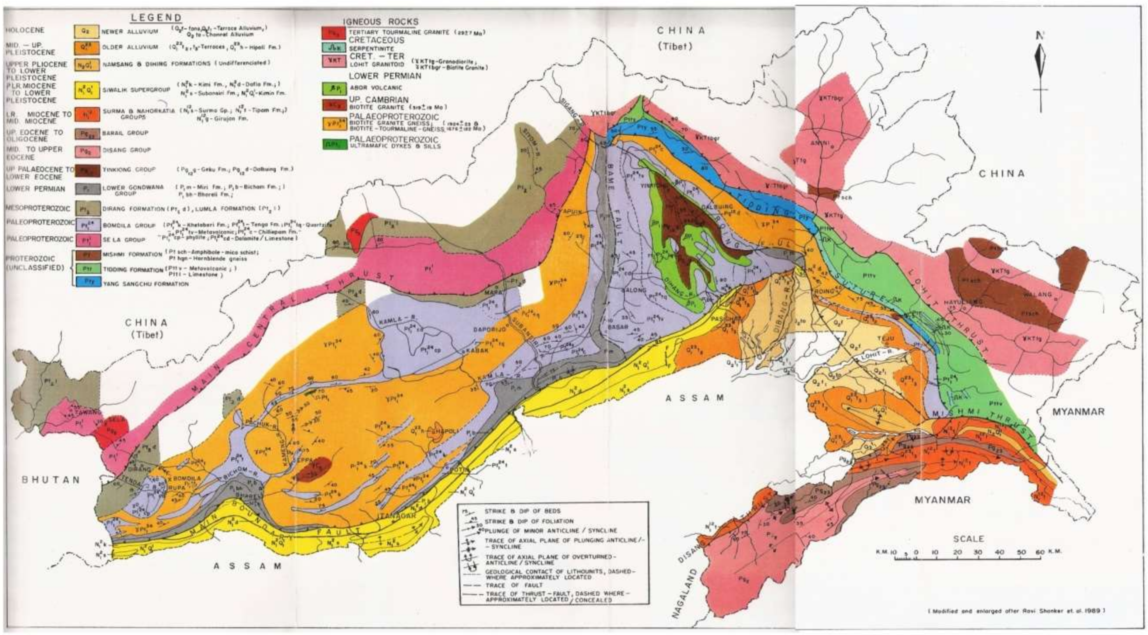

Fig. 1: Regional Geological Map of Arunachal Pradesh (Kumar, 1997). The Sub-Himalayan Siwalik belt is shown as yellow colour. The outcrop of the Siwalik Group of rocks is continuous from Bhutan-Arunachal border in the west, to the east of the Siang River section.

On this backdrop, we have selected five river sections for the studying the Siwalik sequence in Arunachal Himalaya. From the east to the west these sections are are: Kameng, Dikrong, Ranga Nadi, Gai and Siang River sections (Figs.1, 2).

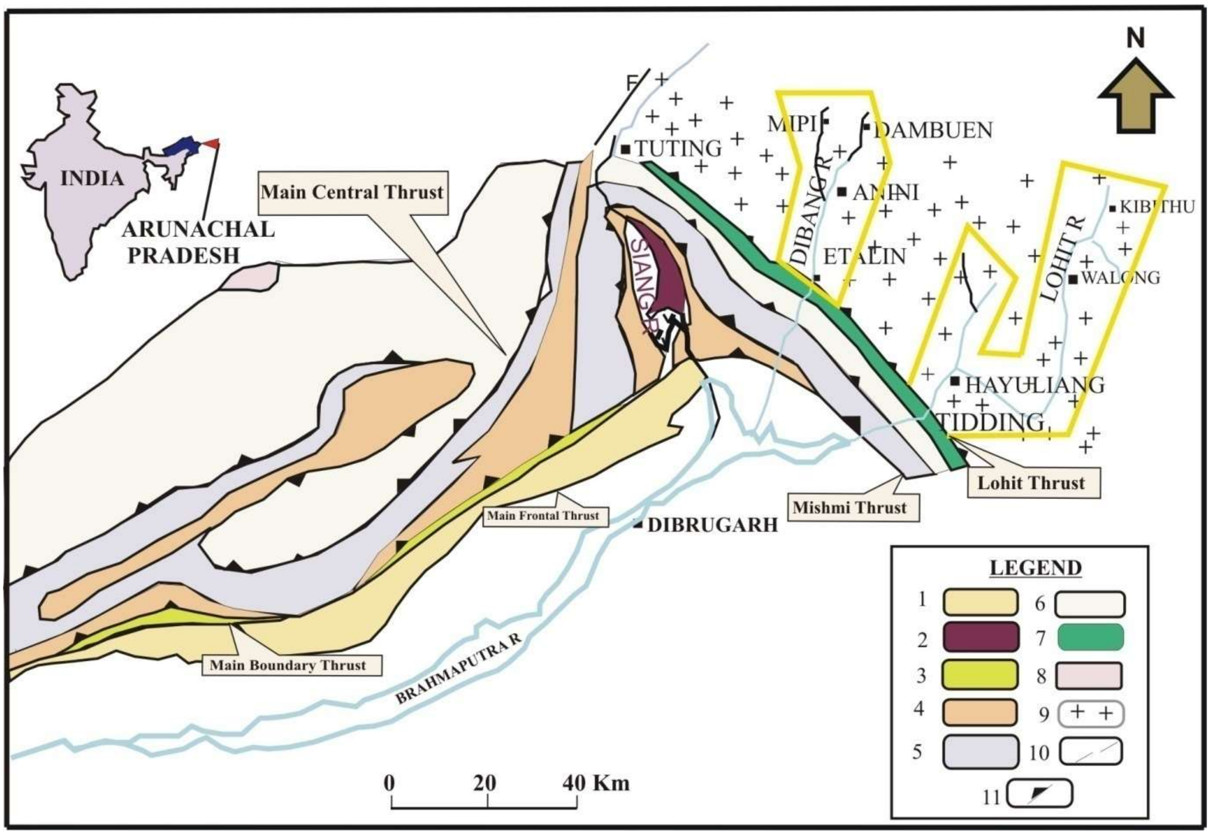

Fig.2: Geological map of Arunachal Himalaya (modified after Kumar, 1997). 1. Siwalik belt. 2. Abor volcanics. 3. Gondwana belt. 4. Dedza Menga belt. 5. Bomdila belt. 6. Sela belt. 7. Tuting –Tidding Belt. 8. Leocogranite . 9. Mishmi belt. 10. Fault. 11. Thrust.

Materials and methods

The intensive field work from the Kameng to Siang River sections were carried out during field sessions of 2012-13, 2013-14 and 2014-15. Survey of India toposheets (83 A/08, 83E/16, 83E/12, 83E/11, 83 E/15, 83 I/ 9 and 831/3) were the base maps for preparation of the geological maps of the area. The mesoscopic field structures in the Siwalik sequence were studied. Representative samples for sedimentological studies were collected from the Dafla, Subansiri and Kimin Formations. A few oriented samples were also collected from the afore-mentioned sections for interpretation of the deformational imprints in the rocks in the microscopic scale. Selected samples were analysed in the laboratory for the thin section studies. Lithological and structural maps were prepared for all the sections and sample locations are also marked. Satellite imageries are also studied for obtaining the regional structural framework of the Sub–Himalayan fold and thrust belt in Arunachal Himalaya. It would be worth mentioning that the objective of the project was to ascertain the differential exhumation of the Siwalik sequence on the backdrop of the structural framework of the frontal fold thrust belt. Further the geochemistry of the selected samples was to be done for interpretation of the provenance. However, the stoppage of sizeable portion of the sanctioned amount inhibited us to complete the much needed work of the project which was originally proposed.

Regional geological setting

The general setup of different lithotectonic units in Arunachal Himalaya is summarised in Table -1 (GSI, 2010). From south to north the major lithotectonic units are Siwalik Himalaya, Lesser Himalaya (including the Gondwana sequence) and the Higher Himalaya and these lithotectonic units are separated by major thrusts from south to north: Himalayan Frontal Thrust (HFT) separates the Siwalik sequence from the Brahmaputra alluvium, Main Boundary Thrust (MBT) separates the Siwalik sequence from the Lesser Himalayan Sequence (LHS) and Main Central Thrust (MCT) separates the LHS from the Higher Himalayan Sequence (HHS). The generalised stratigraphic succession of Siwalik Group (Kumar, 1997) are shown in Table-2.

Wadia (1967) mentioned that the Siwaliks are chiefly the water borne debris. He also equated the Siwaliks of Arunachal Himalaya with the Tipam, Dupitila and Dihing Group of rocks. Karunakaran and Ranga Rao (1976) have dealt with the geology of Eastern Himalaya in great detail. According to them the Siwalik Group comprises of Dafla, the Subansiri and the Kimin Formations. Dutta and Singh (1980) have described these rocks as Siwaliks and correlated them with the Surma, Tipam, Namsang and Dihing Formation of the Brahmaputra Valley. The palynological assemblages show mixed type of Tertiary and Permian floral elements, indicating recycled deposition. The latest compilation of Arunachal Geology by the Geological Survey of India showing both the Gondwana and Siwalik Group of rocks among others is given in Kesari, 2010.

Group	**Formation**	**Age**
Quaternary sediments	Hapoli Formation (Newer Alluvium)	Holocene to Recent
	Older Alluvium	Middle to Upper Pliestocene
-------------------------------------- Main Frontal Fault---		
Siwalik	Kimin (Upper Siwalik)	Mio-Pliocene
	Subansiri (Middle Siwalik)	Mio-Pliocene
	Dafla (Lower Siwalik)	Miocene
	Tourmaline bearing leucogranite	Oligocene
Yinkiong	Dalbuing	Early to Mid Eocene
	Geku	Late Paleocene to Early Eocene
Gondwana	Yamne	Upper Permian
	Abor Volcanics	Permo-Carboniferous
	Bhareli/Khelong	
	Lichi Volcanics	
	Bichom	
	Miri	Lower Palaeozoic
	Rilo/Deed/Hawa pass granite/ Tamen gneiss	500+19 Ma & 480 Ma
	Thingbu	Neo-proterozoic
~~ Unconformity~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~		
	Dirang/Lumla	Meso-proterozoic
~~ Unconformity~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~		
Bomdila	Bomdila/ Ziro/ Biotite Granite Gneiss/ Daporijo Gneiss	Palaeo-proterozoic
	Chilleipam/Dedza/ Menga/ Mukatang	
	Tenga/Potin/ Dublo Kho/ Ragidodoke	
	Khetabari	
~~ Tectonic Contact		

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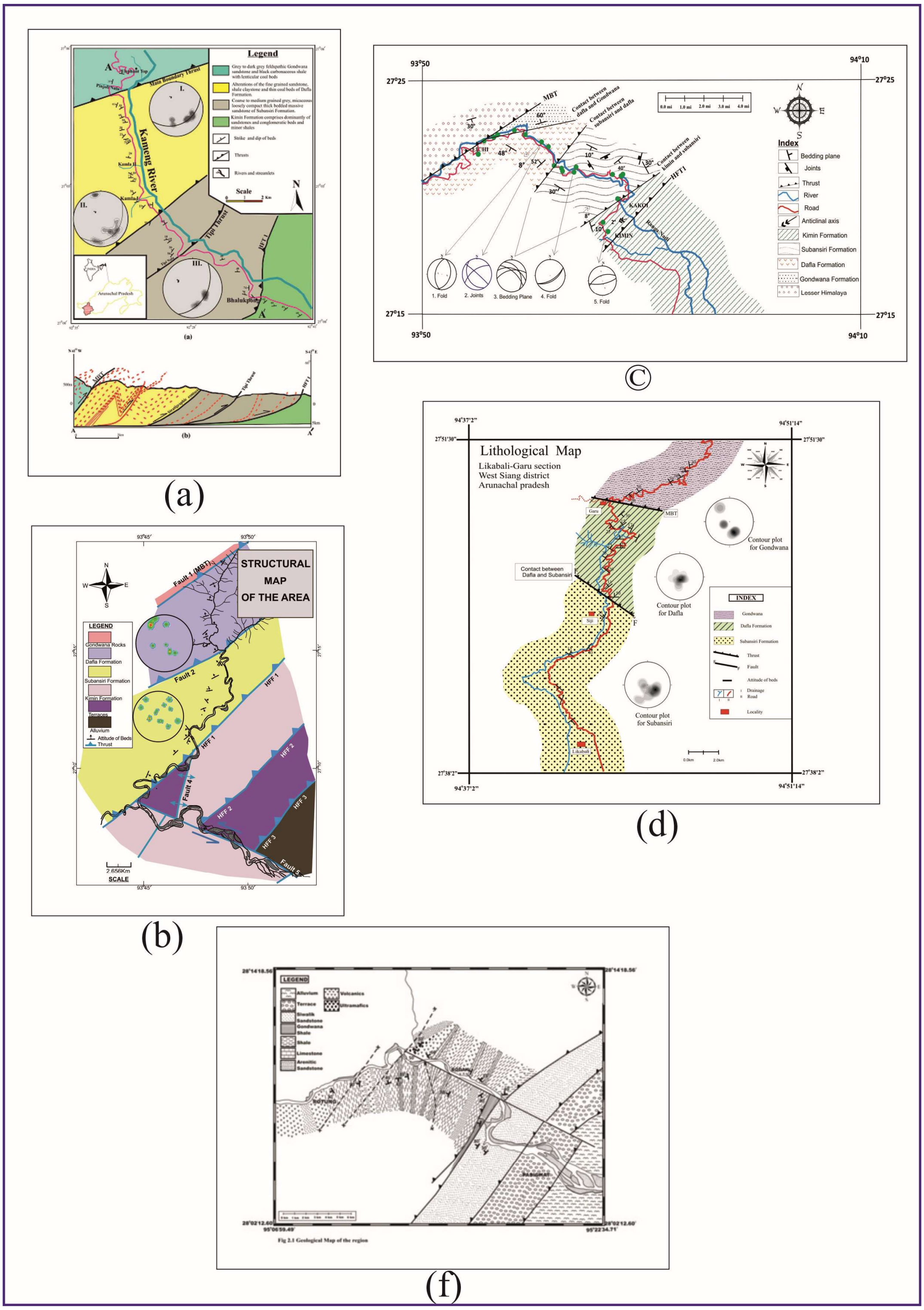
Sela	Galensiniak	
	Taliha/Taksing	Palaeo-proterozoic

Table- 1: Stratigraphy of the Arunachal Himalaya (GSI, 2010)



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(a)

(d)

(b)

(f)

Fig.3. The litho-structural maps of the Siwalik Group of rocks in Arunachal Himalaya. The lithology and structures are shown along: (a) Kameng R. section. (b) Dikrong R. section. (c) Ranganadi R. Section. (d) Gai River section and (e) Siang River section.

Siwaliks of Arunachal Himalaya: general overview

Tectonic setting

The Siwalik belt of Arunachal Pradesh has been studied by a few workers and much need to be explored if compared to the studies made on Siwalik belt of Central and Western Himalaya. Rao 1983 was of the view that the upper tertiary sequence cropping out the foothills of Himalaya in Arunachal Pradesh is about 6500m thick and rests unconformably upon the Gondwana as seen along the Bhalukpong-Bomdilla road. Rao and Babu, 1972 and Karunakaran and Rao 1976, divided the upper tertiary sequence into three mappable rock stratigraphic units viz. Dafla, Subansiri and Kimin formation on the basis of lithology. However the sub Himalayan fold thrust belt between the MBT and HFT are later divided into four lithostratigraphic units, from oldest to youngest it consist of Kimi, Dafla, Subansiri and Kimin Formation(Rao,1983; Kelty,2004) (Fig.3). Kimi and Kimin formations are equivalent to lower and upper Siwalik respectively (Kumar, 1997). The Main Frontal Thrust (Nakata, 1972) demarcates the boundary between the Siwalik front of Himalayan province with the alluvial expense of the Indo Gangetic plains. The age of the Fault as determined in the NW Himalaya is about 1.6 million years(Valdiya, 2003). However there is no age data of Main Frontal Thrust in Arunachal Pradesh as such. Rao, 1983 also observed thatDafala bears lithological similarity with Barail to the extent that contains coal, although coal beds are very thin in Dafla. Bhattacharya 2008, observed that general tectonic setup of the Siwalik belt is the result of the flexural subsidence of the Indian lithospheric plate due to the continued thrust loading. This has resulted in the creation of a foreland basin in front of the Himalayan metamorphic belt and the Siwalik sediments were deposited in this basin. Muiger et al, 1999 suggested that the Siwalik-Ganges basin constitutes a unique present day active foreland system in a geodynamic context of intercontinental collision where synorogenic sediments are continually incorporated into the outer part of the thin skinned thrust belt. The Siwalik of Arunachal Pradesh was studied by a few workers from different perspective (Verma and Tendon, 1976; Rao 1983; Yin et al 2006; Valdiya, 2003; Srivastava and Mishra, 2008). Little attention has been paid to constrain the thrust geometry of the foreland basin (Yin et al, *ibid*; Srivastava and Mishra, 2008) and no detail study has been made so far. For example thrust geometry is not studied from the angle of dip transfer process (Boyer and Elliot, 1982; Mitra and Boyer, 1986).

Lithology

The lithology of the Siwalik foreland basin in Arunachal Himalaya is constituted of sandstones–greywackes and lithic arenites, siltstones, claystones, carbonaceous shales, with boulder beds. The lithounits are divided into Kimi, Dafla-Subansiri, and Kimin formation corresponding to lower, Middle and Upper Siwaliks (Table-1). The lithology in the foreland basin dominantly composed of the sandstones (Greywacke and lithic arenite), siltstone, claystone, carbonaceous shale, boulder beds in the upper part. The Lesser Himalayan sequence in the immediate north of the Siwalik Belt is the Bomdila group of meta-sedimentary and meta-igneous rock corresponding to outer and inner lesser Himalayan sequence (Yin et al., 2006).

The Dafla Formation comprises sandy and fine grained argillaceous lithologic association of thick to medium thick bedded hard and compact, jointed sandstone (Figs.4, 5). The grain size varies from medium to vey fine grained with poor sorting. The colour of the sandstones varies from brown to light grey, sometimes dark grey. The thickness of the sandstone is usually few cms to less than 1m, but at places 1.5 to 4 meters thick sandstone beds are observed.

The Subansiri Formation consists of semiconsolidated to consolidated sandy and argillaceous facies comprising of massive, friable, light grey to yellowish brown sandstone, thick to medium bedded compact sandstone, light grey with salt and pepper character (Fig.5).The argillaceous facies consist mainly of grey shale, fissile to compact in nature, with coaly streak, sticky and non-sticky claystone, sandy clay and with minor siltstone, brown in colour. Numbers of pebbly sandstones alternating with current bedded medium grained sandstone exposed.

The Kimin Formation consists of conglomerate, soft sandstone and clay. At many places terrace deposits occur above the Subansiri exposures. The sandstone is pebbly at places

and is intercalated with claystone and shale which are frequently nodular. The boulders are of quartzites, gneisses, granites, schists and basic rocks. Liquefaction and soft sediment deformation are exhibited by slump folds and convolute laminations (GSI, 2010).

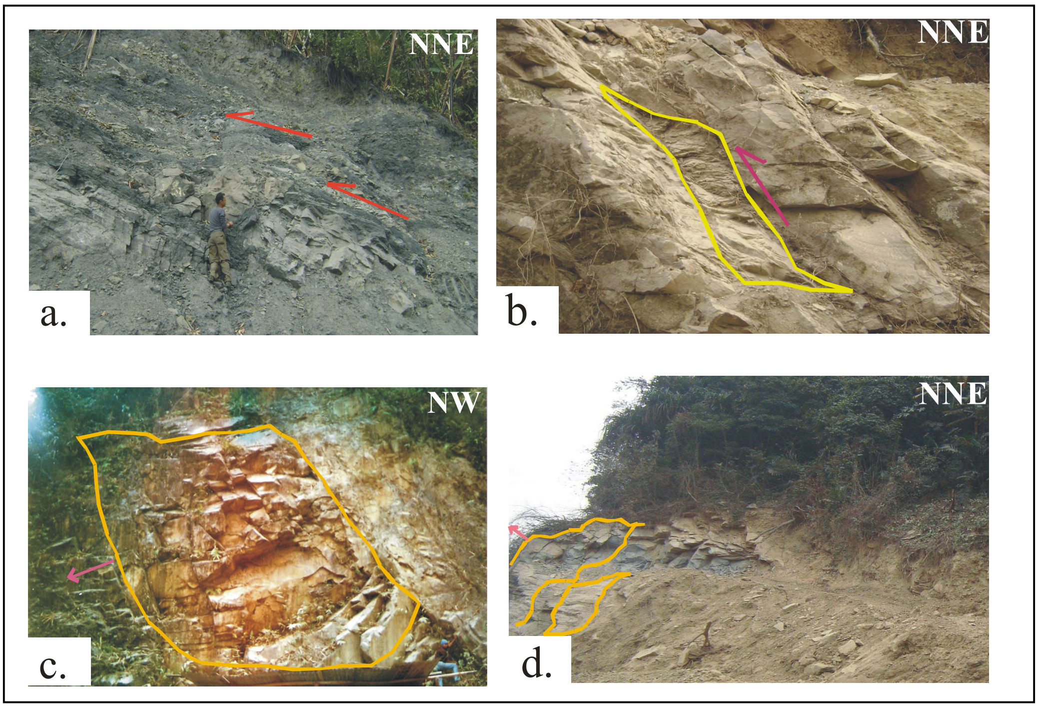

Fig. 4. (a) Carbonaceous shale and sandstone sequence of the Bhareli Formation near Pinjoli Nala showing top to SSW shear sense (b). Hinterland dipping duplex within the Dafla sandstone near Kamla Bridge 1. Top to SSW movement is observed. (c). Large hinterland dipping duplex in the Dafla sandstone near Kamla Bridge 2. The sense of movement is top to SSE (d). Antiformal stack and foreland dipping duplex in the Dafla sandstone at 2 km north of Tipi Nala.

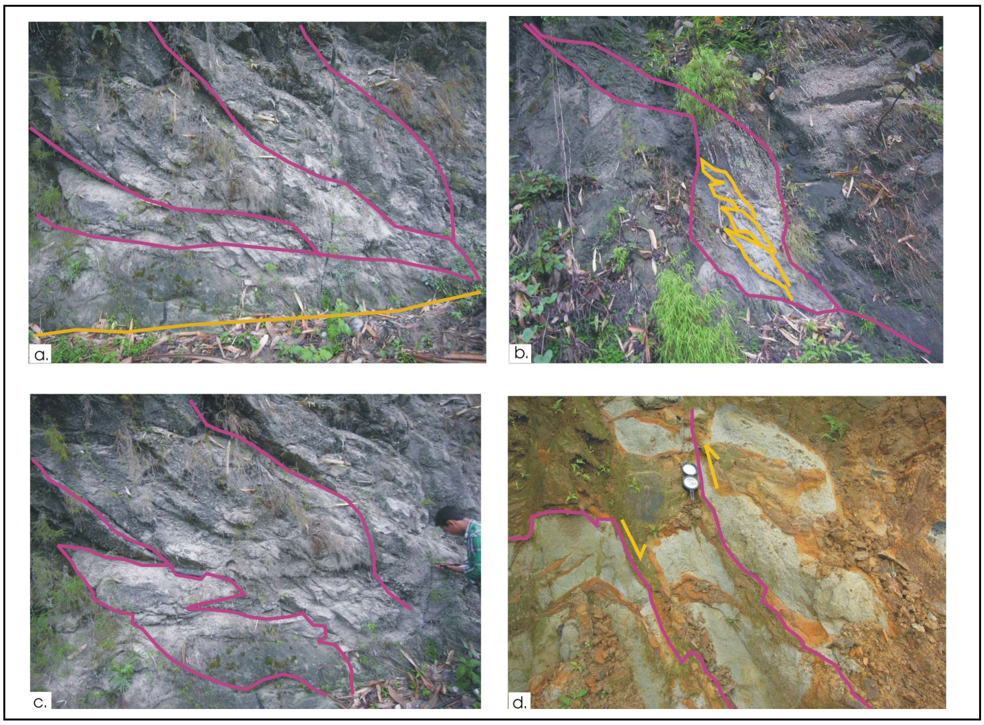

Fig.5. (a) and (b) Imbricate faulted Dafla sequence near Haj -Chidpan area of the dikrong river section; (b) and (c) the Sunbansiri sequence near Midpu and Doimukh showing small scale horses dipping steeply to NW direction.

Stratigraphy

Kelty *et al*. (2004) considered the following broad divisions of Siwalik in Arunachal Pradesh, regions bound between: (i) MFT and Tipi Thrust: N dipping monoclines, fault bent folds, and a series of anticlines and synclines (e.g., Papun syncline and Simna Parbat) in the Subansiri and Kimin Formation that are parts of hanging wall flat of the HFT, and (ii) MBT and Tipi Thrust: at least 6 km shortened 20–60◦ dipping Dafla Formation (Kelty *et al*. 2004).

The generalised stratigraphy of the Siwalik Group is given below in Table-1(Kumar, 1997). In the five traverses along the river sections from Kameng to Siang we have observed that the Kimi Formation is not consistently outcropped along the strike of the Siwalik fold thrust belt.

Table 1: Generalized lithostratigraphy of the Siwalik group, Arunachal Himalaya (Kumar,1997)

Formations	Lithology
Kimin	Alternations of soft, grey sandstone, silt, clay and gravelly boulder beds Carbonised wood and plant fossils.
	-----------------------Gradational contact-----------------------
Subansiri	Sandstone, grey micaceous and salt and pepper texture and calcareous concretions. Clay and claysone in the upper part. Vertibrate fossil *Bos* sp
Dafla	Sandstone, hard, grayish white to greenish grey, khaki grey shale alternations. Plant fossils
Kimi	Hard greyish while to greenish sandstone, calc sandstones and red shales.

Structural development in Sub Himalayan Siwalik belt

The upper tertiary (Mio-Pliocene) molassic sediments of the Siwalik Group occurs as a linear belt along the foothills of Arunachal Pradesh extending from Bhutan-Arunachal border in the west to the east of Pasighat (Fig.1, 2). In the east of Pashighat, the Siwalik Group is tectonically overlain by the Lesser Himalayan rocks along the Roing fault.

Mesoscale deformation

Along the strike of the Siwalik belt in Arunachal Himalaya, the ramp and flat geometry of the thrust sheets and slices are exhibited. The lower most Dafla sequence is asymmetric parallel folded and anticlinally and synclinally folded. The back limbs of the anticlines dip to NNE/NNW (Fig.4, 5) and the forelimb dips to NNW and SSE (Goswami et al., 2018). At places the folds are overturned: both the back limb and the fore limb dips towards NNW. The

Dafla sequence is thrusted over the Sunbansiri Rocks along the Tipi Thrust. The strike of the Tipi thrust is ENE-WSW and the thrust contact is sharp in most cases. As the Tipi Thrust has brought Subansiri over Dafla sequence, therefore it must be younger than the Subansiri Formaion. The depth of the thrust is the combined thickness of the Dafla and Subansiri Formations (Kumar, 1997). The rocks of Kimin Formation are weak and friable, it is easily erodible. Therefore, in the locations where these rocks are exposed, mountain front recede further north which results in low topography where HFT-2 is present. Almost in all the sections we have mapped cross faults in the Siwalik fold belt. Along these cross faulted zones, the advancement of the mountain front is observed leading to higher sinuosity of the mountain front along the strike. Brittle deformation structures are prominent in the Dafla and Subansiri rocks along the fold and thrust belt. The entire zone from MBT (Lower) to HFT is imbricated and numerous zones of cataclasis are observed. Joints sets represent dominantly compressional shear and occasionally extensional joints. Zones of cataclasis exihibit severe grain granulation and grain refinement. Top-to –SE and Top-to-SSW sense of shear is ubiquitous in the brittle deformation zones (Fig.4, 5).

Grain scale deformation

The faulted Dafla and Subansiri sequences exhibit slip transfer processes from one glide horizon to another horizon in a multistoried thrust -duplex array (Boyer and Elliott, 1982; Butler, 1987). At numerous locations formation of horses and duplexes are observed in mesoscale. The mesoscale structural geometry is well displayed in the grain scale. The deformation took place at low temperature and accordingly the deformation is described as diagenetic deformation where pressure solution is the dominant deformation mechanism. Thin sections from Dafla and Subansiri sandstones are studied along all the five sections from Kameng to Siang.

The sandstones of Dafla and Subansiri Formations illustrate some important mechanical and chemical compactional fabrics. The sandstones of Dafla Formation exhibit the effects of compaction and dissolution. The framework grains are rearranged due to mechanical compaction. Prolific development of pressure solution seams is due to dissolution and deformation promotes rapid growth of new minerals caused by removal of elements in solution. At the grain contact between clayey matrix and quartz grains, the increase of pressure results in silica dissolution in the regions of higher pH conditions and the solute migrates to the regions of low pH and precipitates. The segregation of mineral matter is a part of the diagenetic differentiation as evident in the sandstones of both Dafla and Subansiri Formations (Fig.6). The segregated matter is deposited in open spaces (pores and fractures), irregular microcrystalline bodies replacing the matrix. Kinked micas observed in soft clays of Dafla Formation indicate differential slip along the basal cleavage. Some of the quartz grains are fractured and indicate duplex structures (Goswami et al., 2018). Complex twinning in plagioclase grains and authigenic clay minerals are seen in the Subansiri sandstones. The thick twin lamellae make an angle with the common lamaller twin bands (Fig.6). This may be the deformation twins developed over slips (Goswami and Sarmah, 2013).

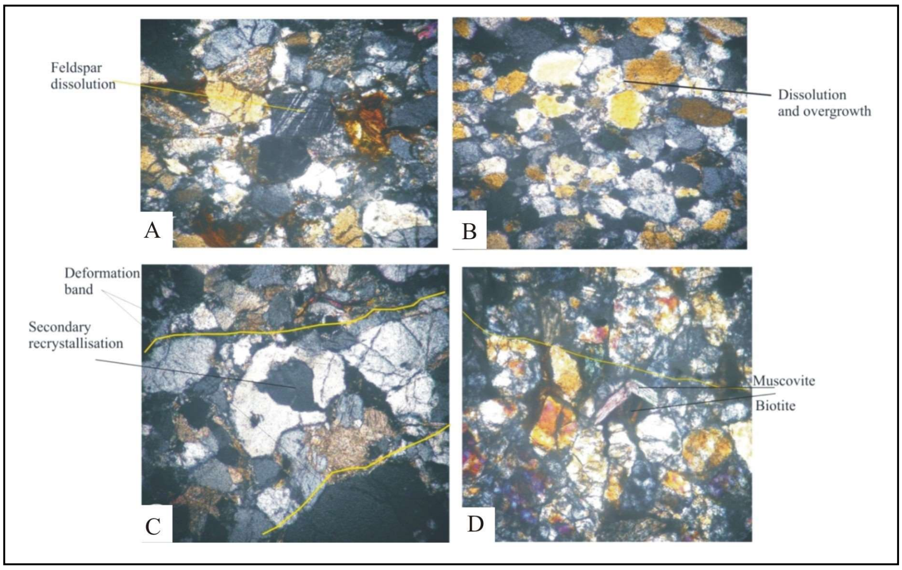

Fig.6. (A) Secondary dissolution of silica along intra-grain fracture changes the grain orientation. Dissolution of the feldspar twin lamellae along the fracture. (B) Dissolution and overgrowth of quartz forming a triple junction (C) Deformation band showing secondary quartz growth within larger grain (D) Clay mineral transforming to biotite and muscovite. Muscovite shows kink banding (all photomicrographs cross polarized.

Sedimentology

Petrography

The pertographic study of Dafla , Subansiri and Kimin rocks from the Kameng, Dikrong, Ranganadi, Gai and Siang sections consists of thin section study of about 70 rock slides.

Modal composition of different rock types are also carried out. These are briefly described below.

Dafla Sandstone

The modal analysis shows that the percentage of quartz varies from 57.32 to 64.88%; feldspar 3.33 to 4.33%; & rock fragment 4.6 to 7.53%. Both monocrystalline and polycrystalline quartz types are present. Quartz grains are generally medium to fine grained. The polycrystalline varieties of quartz include composite quartz and stretched composite quartz. The quartz grains are found to be mainly sub-angular to sub-rounded. In some sandstone the grains are separated by the matrix while in other they are interlocked, packing of the grains is relatively high. The feldspar is generally plagioclase. Plagioclase with twin lamella is also observed which are partially altered. Both detrital and authegenic micas are observed. Sedimentary and metamorphic rock fragments are observed in most of the Dafla sandstones. The sandstone composed of angular quartz grains bonded in argillaceous matrix. From the modal analysis of Dafla Formation, it is observed that the sandstone has higher proportion of quartz, very small percentage of detrital feldspar and mica, but an appreciable amount of diagenetic mica (Fig. 7).

Subansiri Sandstone

The modal analysis shows that the percentage of quartz varies between 62.04%-70.2%., feldspar between 1.66%-4.53%, and rock fragments between 2.85%-3.52%. The Subansiri sandstone is composed of monocrystalline quartz with subordinate polycrystalline quartz. The quartz grains are generally medium to fine grained. The feldspar is generally plagioclase. The proportion of detrital mica varies between 0.5 – 1.2% and the diagenetic mica flakes are observed. . The framework grains are bounded by iron-oxide cements and grains contacts are less. From the modal analysis data of Subansiri sandstone, it is observed that the sandstones has higher concentration of quartz and relatively low proportion of detrital feldspar and mica (Fig.8).

Kimin Formation

The Kimin Formation is dominantly a conglomeratic sequences, consists of alternate beds of pebble conglomerates, coarse-grained sandstone and clays. This Formation is poorly cemented and clasts supported. It is the younger formation of Siwalik Group. The conglomerate beds with fragments of pebble to boulder size are seen. Pebbles are oriented parallel to the bedding. The sandstones are grey to orange brown in color, fine to coarse grained, gritty and pebbly and are generally soft and massive.

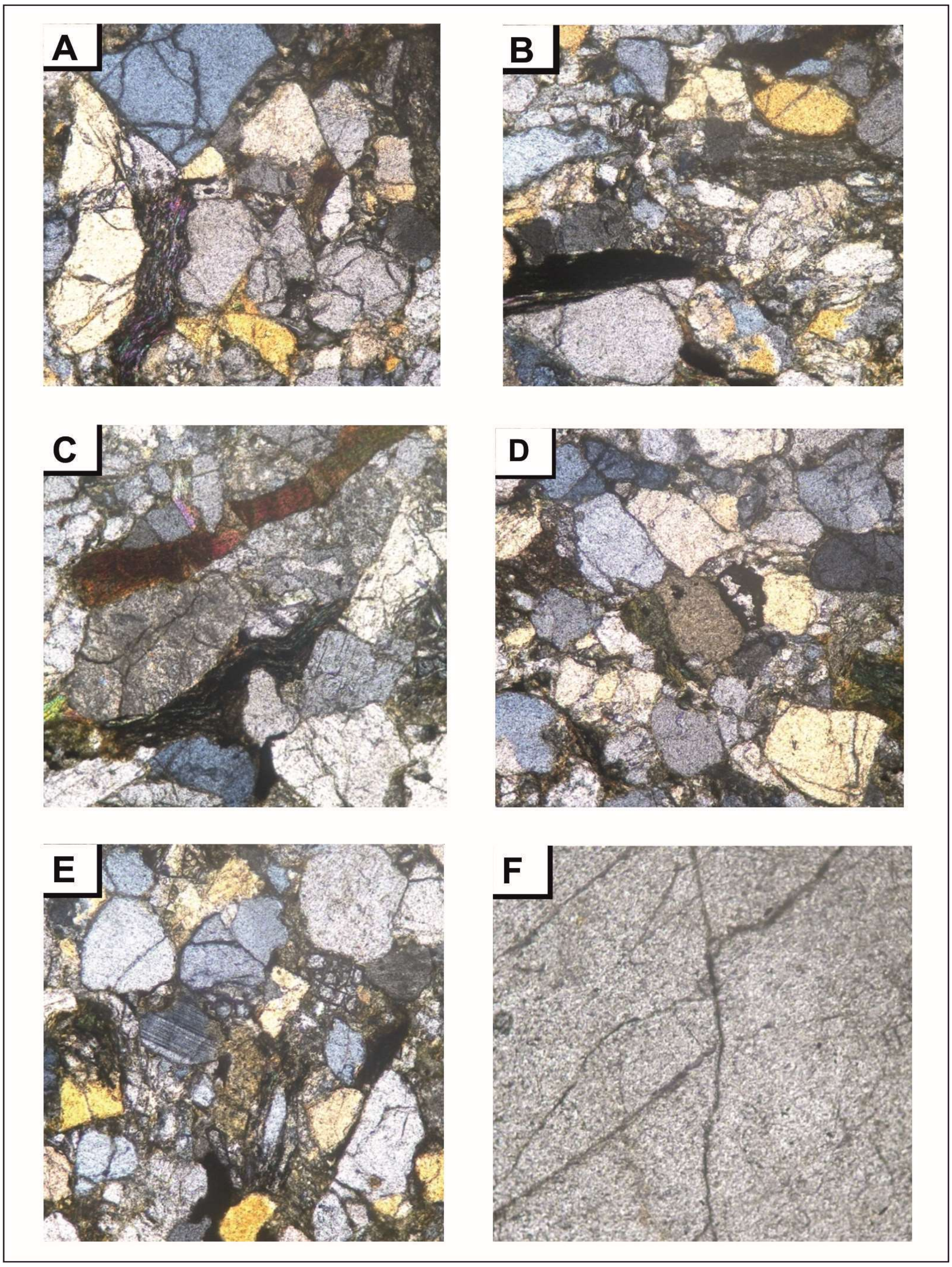

Fig.7. Dafla sandstones : (A) Fractured quartz and diagenetic mica (B) Clay mineral transformation to mica (C) Kink bend in mica and rotation of quartz grains (D) Close packing of quartz grains (E) Plagioclase with twin lamella is seen, partially altered, moncrystalline quartz and polycrystalline quartz, clayey matrix (F) Chert grains with quartz veinlet

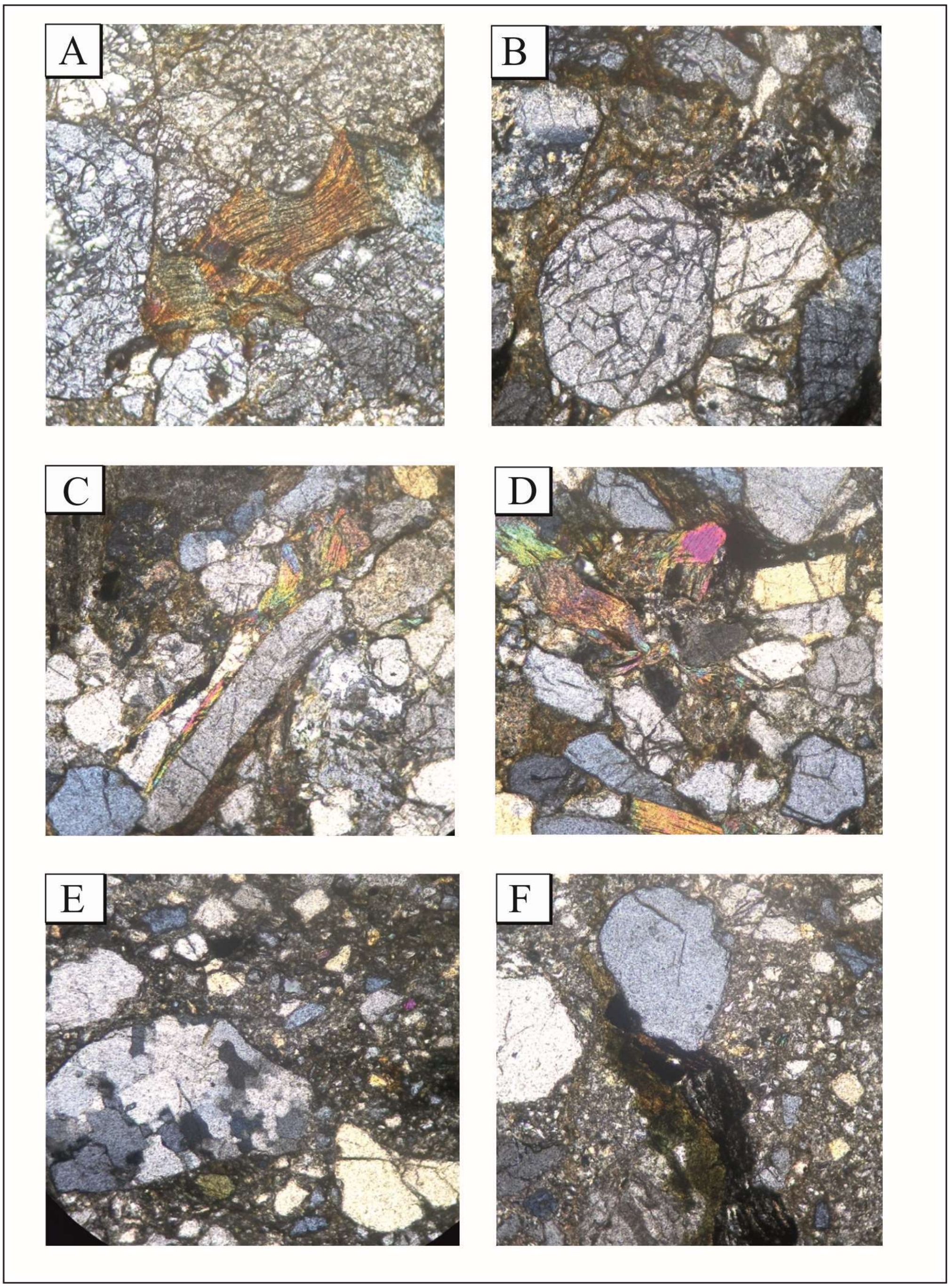

Fig.8. Subansiri sandstones: (a) Fractured quartz, kinking, small pressure solution seam (b) Rounded quartz grain, pressure solution seams, corrosion (c) Mica lamella separating quartz veins (d) Kinking in mica, grain rotation and flowage (e) Grains with suture contact, polycrystalline quartz, enclosed in small sized quartz grains and clayey matrix, degree of compaction is low (f)Clay lamella partially transformed corroding quartz grain, grain packing less, subangular quartz grain

Heavy mineral study

All standard techniques for heavy mineral separation are based on mass separation in a liquid with specific gravities of the minerals or group of minerals to be separated. Ordinarily, the separation is accomplished by gravity settling of the sample in the bromoform.

The heavy minerals found in the rocks are: zircon, tourmaline, rutile, garnet, kyanite, epidote, hornblende, staurolite, sillimanite, chlorite and opaques (Fig.9).

Study of the detrital heavy minerals has enabled the authors to recognize a few terrigenous mineralogic provinces. Each of these provinces is characterized by a distinctive mineral assemblage inferred to have been derived from a well recognized provenance. Rounded garnet, tourmaline, and zircon points towards a pre -existing sedimentary rock from which the sediment were derived and recycled. The heavy minerals like kyanite, sillimanite, Staurolite and garnet (angular) indicate a dominant metamorphic source. Minerals like zircon (angular), garnet, rutile and hornblende indicate an igneous (mainly acid) source rock.

Diagenesis

In Dafla sandstones, it is observed that the degree of compaction of the framework grains is relatively high. This can be evidenced by close packing of sand grains and also due to the presence of concavo-convex and embayed quartz. Compaction seems to be more as evidenced by pressure solution seams .These pressure solution seams are filled up by clayey matrix along with the ferrugenious cement. These seams are associated with deformation features like crenulation and branching pattern of seam. Distortion of shape of the mica grains (banding) due to squeezing between quartz grains during compaction and deformation. In Subansiri sandstones, the framework grains are mostly matrix supported with subordinate amount of ferrugeneous cement. The sandstones are semi-consolidated in nature as seen from the floating nature of grains and point contact per grain. The degree of compaction is low and the grain packing is also less (Fig.6).

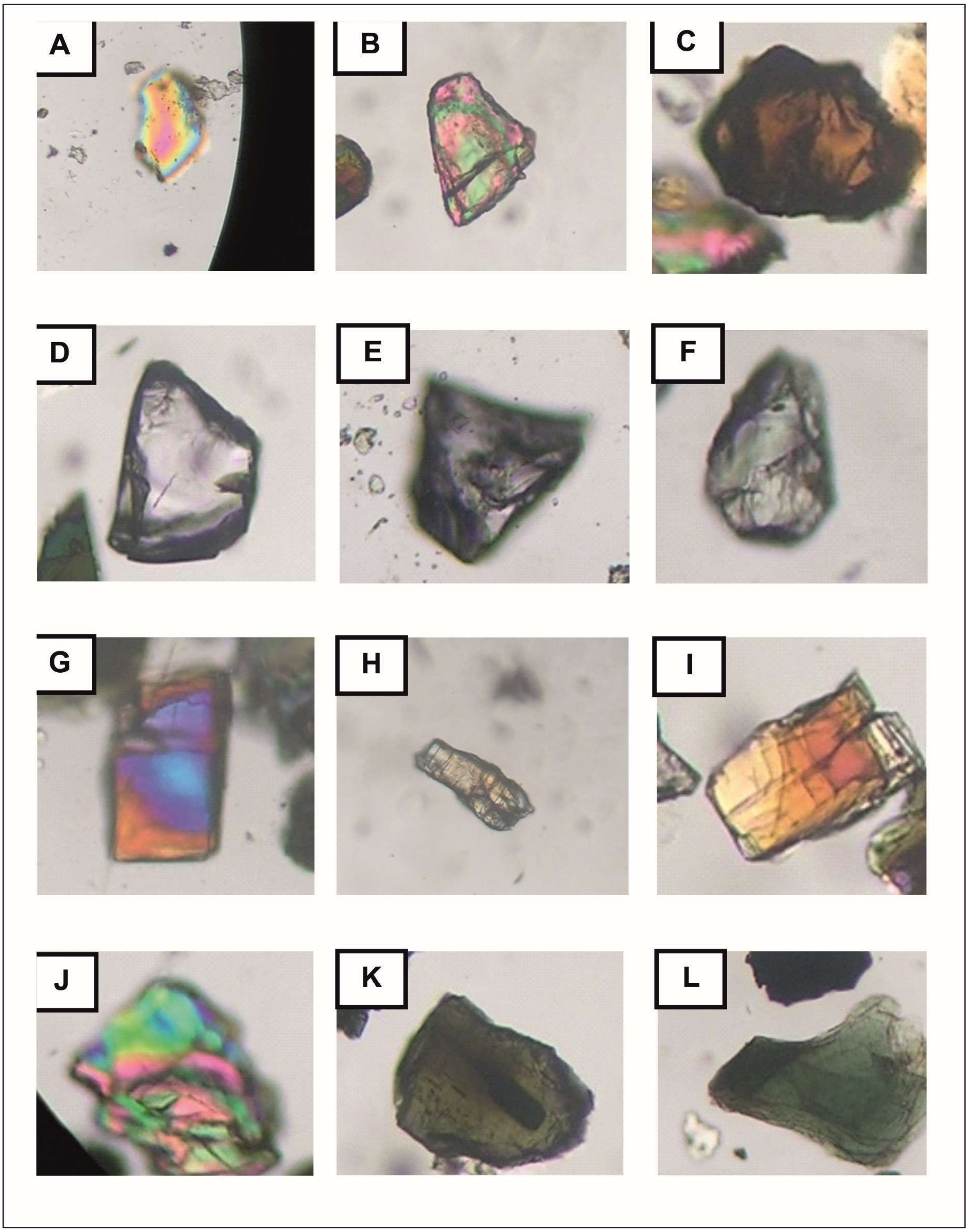

Fig.9. Heavy minerals in Dafla and Sunbansiri sandstones: (A) and (B) Zircon; (C) Staurolite; (D)-(F) Garnet; (G)- (I) Kyanite; (J) Epidote; (K) Chloritoid; (L) Chlorite.

Tectono-sedimentation History

The field characters of the rocks show some distinctive differences which are helpful in recognizing the Siwalik Group of rocks from the sequences in the hanging wall of MBT. The Dafla Formation consists of steeply dipping, highly distorted and fractured beds of sandstone. The sandstone beds are dominantly bluish-grey and brown coloured fine-to medium-grained, well-bedded. The Dafla sandstone as a whole is more compact, hard and deformed considerably in comparison to the rocks of the Subansiri Formation. The dafla sequence is bounded by MBT in the north and Tipi thrust in the south. Subansiri Formation consists of semiconsolidated to consolidated sandy and argillaceous facies comprising of thick bedded, friable, light grey to yellowish brown sandstone with salt and pepper appearance. Subansiri Sandstone shows gritty to pebbly nature in most of the exposures. Very few beds of clay bands present within the sandstone bed. The sandstone beds are grey in colour. It is significant that the emplacement of MBT (~11-9 Ma) led to the formation of a sag basin in the frontal part of the LHS due to the MBT -thrust- loading (Yin, 2006). The initial sedimentation in the molasse basin should be from the HHS. This speculation is based on the fact that in the Kameng River section, the facies transition from Dafla to Subansiri is found to be ~10.5Ma and for Subansiri to Kimin is found to be ~2.6Ma. This indicates that the LHS could be the provenance for the Subansiri rocks as observed along this section (Chirouze et al, 2010). Furthermore, the sedimentation rate and thickness of the Lower and Middle Siwaliks have been affected by the flexural subsidence of the Indian basement craton. This flexural subsidence may be different in eastern Himalaya because of the presence of Shillong plateau in the Himalayan foreland in the south of HFT (Chirouze et al, 2010).

Discussion and conclusions

The general tectonic setup Siwalik basin is the result of the flextural subsidence of the Indian lithospheric plate due to the continued thrust loading. This has resulted in the creation of a foreland basin in front of the Himalayan metamorphic belt, and the Siwalik sediments were deposited in this basin. The lithostructural maps of the Siwalik sequence along all the sections are shown in Figs.10-15. Duplex structures are frequently observed in the Dafla and in the Subansiri sequences mainly in the internal domain. The sub-parallel faults with the floor and roof thrust are occurring as imbricate fashion (Boyer and Elliot, 1982; Mitra and Boyer, 1986). The individual subsidiary faults are known as horses and they are occurring as planar units with straight sides. It is important to note that the beds above and below the duplex are undeformed. These duplex structures are significant manifestation of the processes involved in the internal domain of the Siwalik sequence. The Duplex represent the mechanism of the slip transfer processes from one glide horizon at depth to another horizon at shallower depth (Boyer and Elliot (1982). The forelimb of the antiforrmal stack dips steeply to the foreland. This process of slip transfer and formation of horses are responsible for the formation of structural thickening, duplex growth and mass addition to the moving thrust complex. Duplex also accommodates large amounts of crustal shortening (Mitra et al, 2010). In the present area the Siwalik strata showing duplex structures have undergone structural thickness in their internal domain mainly in Dafla sequence. The differential advancement of the Sunasiri and Kimin rocks are observed in the south of HFT due to the NNW trending Kameng Fault.

Thin section studies of Dafla and Subansiri sandstones reveal that the frame work grains are mostly medium to fine in Dafla sandstone and coarse to fine in Subansiri sandstone. The sandstones are moderate to poorly sorted. Dafla sandstone shows lot of evidences of diagenetic changes. The important diagenetic signature is the recrystallization of clay matrix into mixed layer type of muscovite - sericite and development of new clay minerals. The other diagenetic changes are corrosion of quartz grain boundaries, recrystallization of elongated quartz grains. The formation of diagenetic mica both muscovite and biotitic composition from clay may be considered as indication of the phyllomorphic stage of diagenesis. Compared to Dafla formation, the compaction and grain packing in Subansiri sandstones are less as evidenced by floating nature of the grains and matrix supported framework grains. The clay matrix is recrystallized to muscovite biotite minerals and also to new diagenetic clay minerals.

The original objective of the proposal was to analyse the differential exhumation of the Siwalik fold and thrust belt in Arunachal Himalaya. On the basis of this study, we proposed to understand the uplift and erosional history of the Siwalik belt and also the history of the basin fill through time. However as the fund position has always been an impediment, we have to restrict our study to lithostructural mapping along five traverses along strike in the Arunachal Himalaya. On the basis of intensive field mapping, analysis of the outcrop scale structures and petrographic analysis of the samples we have drawn the following conclusions:

1. The structural geometry of the Siwalik fold and thrust belt in Arunachal Himalaya indicate an imbricate zone between MBT and HFT. The flexural subsidence, formation of ramp and flat structures, thrust duplex and formation of floor and roof thrusts indicate dissipation of slip along different glide horizons due to north south compression. The compression is originated from post India -Asia collision and convergence

2. The mesoscale structures are mimicked in the grain scale through different deformational imprints. The deformation reflects a brittle -ductile regime and grain rotation, grain boundary frictional sliding are the significant structures that reflect low temperature deformation and dominant mechanism is the pressure solution. Numerous pressure solution seams along the grain contact and in the intra- granular spaces are observed.

3. Thin section study indicates that the diagenetic signature is the recrystallization of clay matrix into mixed layer type of muscovite - sericite and development of new clay minerals. The other diagenetic changes are corrosion of quartz grain boundaries, recrystallization of elongated quartz grains. Compared to Dafla formation, the compaction and grain packing in Subansiri sandstones are less as evidenced by floating nature of the grains and matrix supported framework grains.

4. The heavy minerals like kyanite, sillimanite, Staurolite and garnet (angular) indicate a dominant metamorphic source for the Dafla and Subansiri sandstones. Minerals like zircon (angular), garnet, rutile and hornblende indicate an igneous (mainly acid) source rock.

5. Based on the available geochronologic data, we speculate that the initial sedimentation in the Siwalik basin could be from HHS. The supply of sediments in the initial stages and the basin fill may be responsible for the thick sequence of the Dafla sandstone. This episode is followed by next phase of basin fill and the supply of sediments might be from LHS. Subsequently, both HHS and LHS might have contributed to the lithology of the Kimin Formation.

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