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Thrust tectonics and evolution of domes and the syntaxis in eastern Himalaya, India*

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ABSTRACT

The low grade pre-Tertiary metamorphic nappe rocks, underlying widely exposed high grade crystalline rocks in eastern Himalaya, override the narrow frontal belt of Neogene Siwalik molasse sediments along the Main Boundary Thrust (MBT). Marine Eocene or early Miocene sediments are only exposed as narrow thrust slivers over wide lateral extent close to and beneath the MBT, and also within the northern parts of the Neogene sediments. The slivers of pre-Tertiary rocks within the Neogene belt have two modes of occurrence, more frequently they occur as klippen over the Neogene sequence and floored by the MBT, or as basement wedge, which at times preserve unconformable relation with the Neogene cover. Domal window structures in eastern Himalaya, north of frontal belt, expose low grade pre-Tertiary metasediments occurring beneath the crystalline nappe. The largest Siang window located close to eastern syntaxis of the Himalaya, is distinctive and exposes a duplex arch of late Palaeocene-Eocene sediments and the Abor volcanic rocks. The MBT represents the folded roof-thrust of the window. The overlying Himalayan pre-Tertiary nappe rocks are passively folded. The Siang and other windows from eastern Himalaya, located at the external fringes of the Himalayan nappe sheets, have many structural similarities. These are inferred to have evolved in a similar way and during the process of emplacement of the crystalline and low grade pre-Tertiary Himalayan nappes over the Tertiary foreland basin. During the early-mid Eocene period, contemporaneous to terminal collision at the northern margin of the Himalaya, there was continental flood basalt and other volcanic extrusion in the foreland basin located at the marginal parts of the Himalayan fold-thrust belt. The Eocene foreland rocks at present are largely tectonically concealed. Thrust movements involving the pre-Tertiary Himalayan nappes, the subjacent Tertiary sub-thrust rocks and their architecture influenced the structure of the Himalayan nappes at their external fringes and often-formed duplexes and windows.

The Siang window was possibly produced by the interaction between the NE projecting indenture of the Indian continent that acted as an oblique crustal ramp over which the Himalayan and Trans-Himalayan nappes were propagated. Several nappes in the eastern limb of the dome are greatly attenuated in width and are overridden by the frontally advanced Trans-Himalayan granitoid nappe. Convergence of tectonic movements at the eastern syntaxis produced imbricate thrusts and duplex arch in the sub-thrust Palaeogene rocks, which breached the MBT and passively folded overlying Himalayan nappes. The western limb of the complimentary synform, west of the Siang window, is obliquely truncated by a major N-S trending dextral tear-fault, which has also climbed from the floor-thrust of the Siang window and has breached the MBT as well as the Main Central Thrust (MCT). It resembles the imbricate thrusts within the Palaeogene rocks from the Siang window. In other windows, the sub-thrust Tertiary rocks appear to have played more passive role and may not have been tectonically arched up.

INTRODUCTION

The section of the Himalaya east from Nepal is broadly referred to here as eastern Himalaya. The major rock unit consists of the high grade crystalline rocks, the base of which is known as the Main Central Thrust (MCT). It overlies another thrust packet consisting of moderate to low grade Proterozoic and locally present late Palaeozoic metasediments. Over major extent of eastern Himalaya, a nappe within the latter and

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comprising of rocks having Lower Gondwana affinity overrides the Neogene Siwalik foreland sediments of the foothills. The northern tectonic contact of the Tertiary foreland sediments against the overriding pre-Tertiary rocks is generally referred to as the Main Boundary Thrust (MBT), and same nomenclature is followed here.

Because of relative southward advancement of the crystalline nappe, the exposed width of the low grade pre-Tertiary and Siwalik rocks is very narrow in eastern Himalaya. Along this belt, the MCT and MBT generally have steep northerly dips. Such steep dipping thrust sheets are also reported from the frontal and adjoining foothills from other mountain ranges and are inferred to have resulted mainly due to tilting movement along the underlying thrust sheets (Mountjoy, 1992). The relation is also similar for the Himalaya (Acharyya and Ray, 1982).

The Tertiary sequence exposed in the Himalayan foothills consists of both Palaeogene and Neogene sediments, of which the latter occupies the Sub-Himalayan belt almost continuously. The Palaeogene sediments are better exposed in western Himalaya, generally occurring as imbricates within the Lesser Himalayan pre-Tertiary rocks, and also north of the frontal Neogene sediments (Acharyya and Ray, 1982). In the Tansen synclinorium of central Nepal Lesser Himalaya, Palaeogene and early Neogene sediments unconformably overlie the pre-Tertiary nappe rocks (Sakai, 1983). In central Nepal Sub-Himalaya, indurated sediments correlated to the Eocene and associated with basaltic flows are reported to occur juxtaposed with the Lower Siwalik sediments from its northern belt (Gautam et al., 1995). Basement wedges of the Proterozoic carbonate rocks unconformably underlie the northern Lower Siwalik sediments from adjacent section (Shrestha and Sharma, 1996). Indurated sandstones and shale unconformably underlying the Lower Siwaliks, from different tectonic blocks but from nearby section, though correlated to the Proterozoic rocks (Shrestha and Sharma, 1996) lithologically resemble the Eocene rocks. The Palaeogene sediments are even more restricted in occurrence in eastern Himalaya. However, thin thrust slivers of marine Eocene rocks have been recorded over wide lateral extent, mainly occurring close to and beneath the MBT (Fig. 1; Tripathi et al., 1979; Acharyya, 1994). In Darjeeling foothills, early Miocene open sea-type sediments are also recorded from the tectonised northern belt of the early Neogene unit (Fig.1; Acharyya et al., 1987; Sinha and Srivastava, 1992). Marine nature and wide lateral extent of these thrust slivers mainly occurring beneath the MBT and/or within the tectonised northern belt Tertiary sediments imply wide regional extension of these sediments in subsurface.

The regular arcuate trend of the MCT and other major thrust sheets is interrupted at a few locations especially in eastern Himalaya by the presence of domal structures (Fig. 1). Erosion of the upper level nappes at these sites has carved out windows, which mainly expose sub-thrust pre-Tertiary rocks beneath the crystalline nappe. Such domes in the Himalaya and other mountain belts have traditionally been inferred to result from fold interference. In recent years, the sub-thrust rocks exposed at the cores of some major window structures, e.g. Kuru in east Bhutan, Tamor in east Nepal, Rangit in Sikkim and Siang in eastern Arunachal, are inferred to represent hinterland dipping duplex structures (Ray et al., 1989; Schelling and Arita, 1991; Acharyya 1994; Acharyya and Sengupta, 1997). At the core of the Rangit window, late Palaeozoic rocks floored by the Proterozoic rocks reappear from beneath tectonic cover of similar Proterozoic metasediments (Fig. 2). The Siang window located at the eastern syntaxis of the Himalaya is the largest and differs from all the others in the fact that the sub-thrust material here includes the Palaeogene rocks, which have arched up the MBT that represents the roof-thrust of the window (Fig. 3).

The possible northern extension of the foreland Tertiary sediments beneath the Lesser Himalayan thrust sheets and in windows at subsurface have since long been a subject of contention (Acharyya and Ray, 1982; Acharyya, 1994). The role of thrust tectonics, evolution of the Siang window vis-a-vis eastern syntaxis and other windows of eastern Himalaya are discussed in the present discourse.

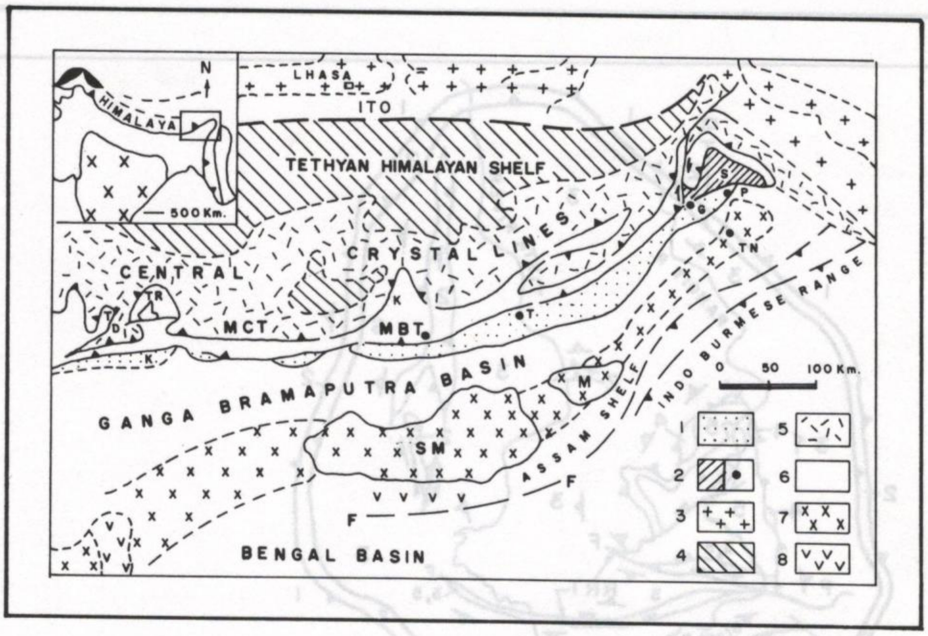

Fig. 1: Tectonic setting of eastern Himalaya showing location of the Siang and other domal structures. Legend: 1- Neogene sediments, 2- Palaeogene sediments/Locations of marine Eocene rocks, 3- Trans-Himalayan granitoids, 4- Tethyan Himalayan sediments, 5- Crystalline rocks of the Himalaya, 6- Lesser Himalayan low grade Proterozoic nappe, 7- Precambrian basement rocks of the Indian shield, 8- Cretaceous basalts. Domes: T- Tamor, T-R- Tista and Rangit, K- Kuru, S- Siang; other locations: ITO- Indus Tsangpo Ophiolites, SM- Shillong massif; M- Mikir massif, D- Darjeeling town, G- Garu, K- Kalijhora, P- Pashighat, T- Tipi, Tn- Tenkaghat.

STRATIGRAPHY OF TERTIARY ROCKS

Frontal Zone Neogene Stratigraphy

Stratigraphy of the frontal belt Neogene sediments is reconstructed from the exposed undisturbed homoclinally dipping coarsening upward sequence from the southern domain of the belt. This comprises a sequence of progressive dominance of sandstone in their frequency, thickness and coarseness within which three lithostratigraphic units have been recognised. The oldest exposed assemblage predominantly consists of claystone, siltstone and fine grained sandstone alternations, whereas, through the primarily sandstones of the middle unit, the youngest unit mainly comprises coarse grained pebbly sandstone and conglomerate. The upper and lower contacts of the sequence are tectonically truncated, as would be described later. The oldest litho-unit is often structurally repeated to the north where it is structurally disturbed. The three Neogene litho-units recognised throughout the eastern Sub-Himalaya have often been given local formational names. But they have been also broadly correlated to the Lower, Middle and Upper Siwalik Subgroups (Acharyya et al., 1979; Biswas et al., 1979; Rao, 1983). The sequence reflects alluvial progradation during southward migration of the Himalayan thrust system, as well as, its elevated topographic front (Acharyya, 1994).

The oldest unit from the northern structural belt of the Darjeeling Sub-Himalaya, christened Chunabati Formation, is somewhat distinct from those exposed in other sections. Based on its calc-argillaceous lithology, which is often variegated in colour, the presence of algal structures within its limestone, marl, parallel bedded character, the depositional environment of this unit appears to be fluvial flood plain to estuary or shallow marine delta. Based on stratigraphic link of these rocks with the succeeding typical Siwalik sequence, as exposed in the homoclinal sequence of the southern domain, the Chunabati Formation appears to be correlatable with

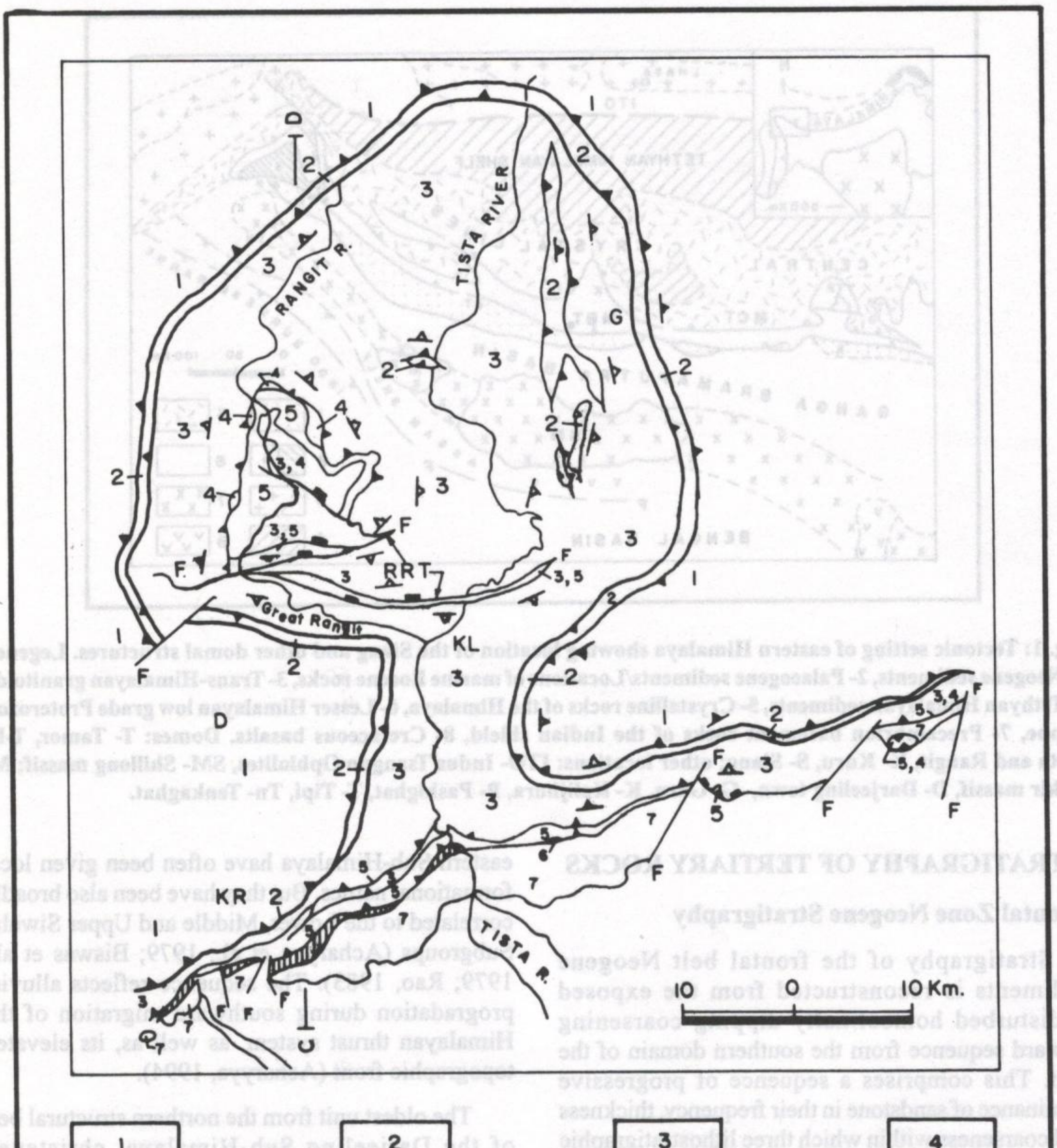

Fig. 2: Geological map of Tista dome, Rangit window and Darjeeling frontal belt. Legend : 1- High grade crystalline rocks, 2- Augen gneiss, granite gneiss, gneiss mylonite, phyllonite, 3- Low-grade Proterozoic meta-argillite (Daling Gp. sensu lato), 4- Proterozoic carbonate - quartzite (Buxa Formation), 5- late Palaeozoic sediments of Gondwana affinity, 6- Tectonised early Neogene sediments with slivers of Late Palaeozoic rocks, 7- Neogene Siwalik sediments of southern belt, 8- Generalised attitude of foliation and layering, 9- Thrust contact, F-F - Fault. CD line of section in Fig. 5b.

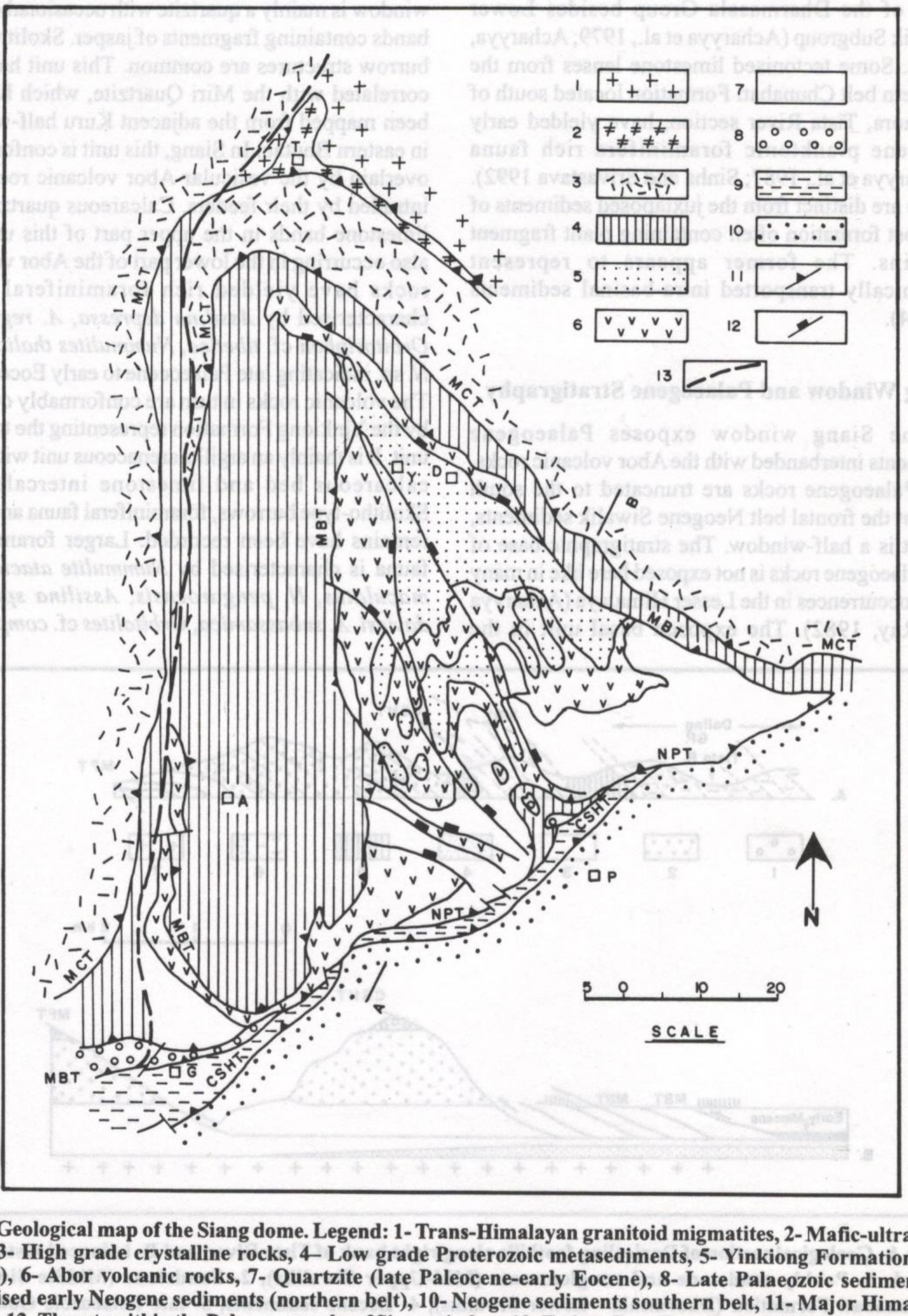

Fig. 3: Geological map of the Siang dome. Legend: 1- Trans-Himalayan granitoid migmatites, 2- Mafic-ultramafic rocks, 3- High grade crystalline rocks, 4- Low grade Proterozoic metasediments, 5- Yinkiong Formation (mid Eocene), 6- Abor volcanic rocks, 7- Quartzite (late Paleocene-early Eocene), 8- Late Palaeozoic sediments, 9- Tectonised early Neogene sediments (northern belt), 10- Neogene sediments southern belt, 11- Major Himalayan thrusts, 12- Thrusts within the Paleogene rocks of Siang window, 13- Tuting-Garu Tear Fault, MBT- Main Boundary Thrust, MCT- Main Central Thrust, NPT- North Pashighat Thrust, CSHT- Central Sub-Himalayan Thrust. Locations: A - Along , D- Dalbuing, G- Garu, P- Pashighat, T- Tuting, Y- Yinkiong. AB line of section in Fig. 5a.

parts of the Dharmasala Group besides Lower Siwalik Subgroup (Acharyya et al., 1979; Acharyya, 1994). Some tectonised limestone lenses from the northern belt Chunabati Formation located south of Kalijhora, Tista River section, have yielded early Miocene planktonic foraminifera rich fauna (Acharyya et al., 1987; Sinha and Srivastava 1992). These are distinct from the juxtaposed sediments of the host formation often containing plant fragment remains. The former appears to represent tectonically transported intra-basinal sediments (Fig. 4).

Siang Window and Palaeogene Stratigraphy

The Siang window exposes Palaeogene sediments interbanded with the Abor volcanic rocks. The Palaeogene rocks are truncated to the south against the frontal belt Neogene Siwalik sediments, thus it is a half-window. The stratigraphic base of the Palaeogene rocks is not exposed here like in many other occurrences in the Lesser Himalaya (Acharyya and Ray, 1982). The exposed basal unit in the window is mainly a quartzite with occasional coarser bands containing fragments of jasper. Skolitho-type burrow structures are common. This unit had been correlated with the Miri Quartzite, which has also been mapped from the adjacent Kuru half-window in eastern Bhutan. In Siang, this unit is conformably overlain by the vesicular Abor volcanic rocks and intruded by their feeders. Calcareous quartzite and limestone bands in the upper part of this unit and also occurring in the lower part of the Abor volcanic rocks have yielded rich foraminiferal fauna characterised by *Assilina depressa*, *A. regularia*, *Orbitosiphon* cf. *tibetica*, *Nummulites thalicus* and *N.* sp. indicating late Palaeocene to early Eocene age. The volcanic rocks in turn are conformably overlain by the Yinkiong Formation representing the topmost unit. It is mainly an argillo-arenaceous unit with marl, calcareous bed and limestone intercalations. Skolitho-type burrows, foraminiferal fauna and floral remains have been recorded. Larger foraminifera fauna is characterised by *Nummulite atacicus*, *N. maculatus*, *N. pengaroensis*, *Assilina spira*, *A. daviesi*, *A. subassamica*, *Orbitolites* cf. *complanata*

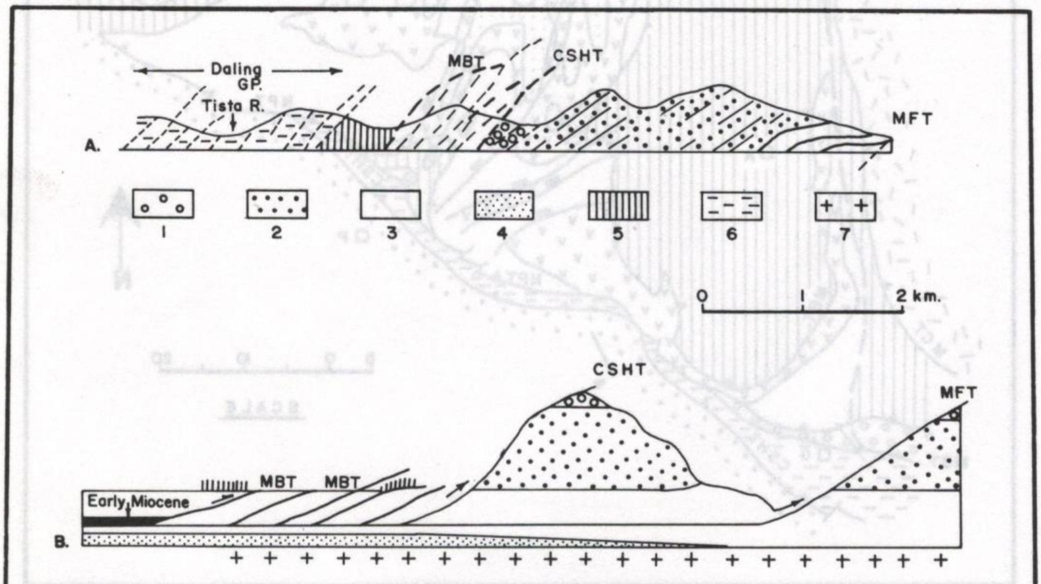

Fig. 4: A- Geological section of Darjeeling foothills along right bank of Tista River, and B- balanced restoration, Legend: 1- Pebbly sandstone and conglomerate (Mid-Upper Siwaliks), 2- Sandstone (Middle Siwaliks), 3- Chunabati Formation (Dharmsala - Lower Siwaliks), 4- Eocene sediments, 5- late Palaeozoic Gondwana sediments, 6- Low grade Proterozoic meta-argillites (Daling Group), 7- Basement rocks of Himalayan foreland basin, MFT- Main Frontal Thrust, other abbreviations as in Fig. 3.

indicating mid Eocene age (Acharyya, 1994; Sengupta et al., 1996).

The Palaeogene sediment packet including the Abor volcanic rocks ranges in age from Upper Palaeocene to mid Eocene. The benthonic foraminiferal fauna, presence of burrow structures, plant fragments and argillo-arenaceous facies suggest shallow marine deposition in a continental shelf. The age of the Abor volcanic rocks so far contentious is thus settled.

STRUCTURE OF TERTIARY ROCKS

Frontal Belt Structure

The exposed narrow span of the frontal belt Tertiary sediments in eastern Sub-Himalaya is truncated to the north along the MBT against the overriding pre-Tertiary nappe rocks. Three structural domains can be recognised. The homoclinally northerly dipping Neogene Siwalik sediments comprise a wider and the main southern structural domain. Broad open synclines with alluviated Dun-type intermontane basin at their core, as those in western Sub-Himalaya are typically absent. The litho-units in the homoclinally dipping sequence at times are structurally repeated. A deformed and discontinuous belt of early Neogene sediment comprise the northern structural domain (Fig. 4 and 5). Thin thrust slivers of marine Eocene rocks are recognised over wide lateral extent occurring close to and beneath the MBT especially from Arunachal Sub-Himalaya (Fig. 1; Acharyya, 1994). These comprise the third structural domain. All these structural domains are bounded by tectonic contacts.

Nature of the MBT

Over a major part of eastern Himalaya, the MBT has followed the incompetent carbonaceous Permian rocks of Gondwana affinity. In surface outcrop, the MBT is generally moderate to steeply dipping to the north and is thus often regarded as a steep dipping reverse or subvertical fault (Karunakaran and Rao, 1979; Biswas et al., 1979; Rao, 1983; Kumar et al., 1989). Acharyya (1976), Acharyya and Ray (1982) on the other hand, emphasised its primary flat-lying sole-thrust character. In a frontal thrust belt distinction between low or high angle dipping thrusts is not justified as these are rotated by movement of the sub-thrust blocks (Mountjoy, 1992).

The flat-lying character of MBT has been demonstrated by the presence of an open synformal klippe and associated imbricated klippen of the Permian and Proterozoic rocks in Darjeeling Sub-Himalaya over the homoclinally dipping Siwalik sequence and occurring far south of location where the MBT has emerged along its regional trend with these pre-Tertiary rocks exposed to its north (Fig. 2; Acharyya, 1976; 1994). Imbricated klippe of Permian rocks also occur more frequently within the northern structural belt of early Neogene sediments from Darjeeling, Bhutan and Kameng foothills (Acharyya, 1994). The flat-lying nature of the MBT is also corroborated by its up-arched nature in the Siang window overlying the Palaeogene rocks, which would be discussed later.

Structure of Frontal Neogene Rocks

The northern structural unit of early Neogene sediments within the frontal belt is regionally persistent and represents a structurally disturbed imbricate zone. The thrust at the base of this unit is designated Central Sub-Himalayan Thrust (CSHT). It is also known by several local names e.g., Churia Thrust in Nepal, Chunabati Thrust in Darjeeling, Tipi/Dafla Thrust in Arunachal Pradesh. At Tipi in Kameng river section, narrow slivers of Eocene sediments and mafic volcanic rocks occur beneath the early Neogene sediments of the northern belt, and these are floored by CSHT and thrust over the uppermost pebbly sandstone unit of the Mid-Upper Siwalik (cf. Karunakaran and Rao, 1979; Acharyya, 1994).

The thrust slivers of pre-Tertiary rocks occur in two modes within this belt of early Neogene imbricate zone. These are inferred to occur more frequently as faulted klippen over the Neogene sediments and floored by the MBT as established in parts of the Darjeeling Sub-Himalaya where these occur in close association with open synformal klippe (Acharyya, 1976, 1994). In Darjeeling foothills, narrow slivers of coal bearing Damuda rocks with Permian plant remains and lamprophyre intrusives of Cretaceous age also occur as

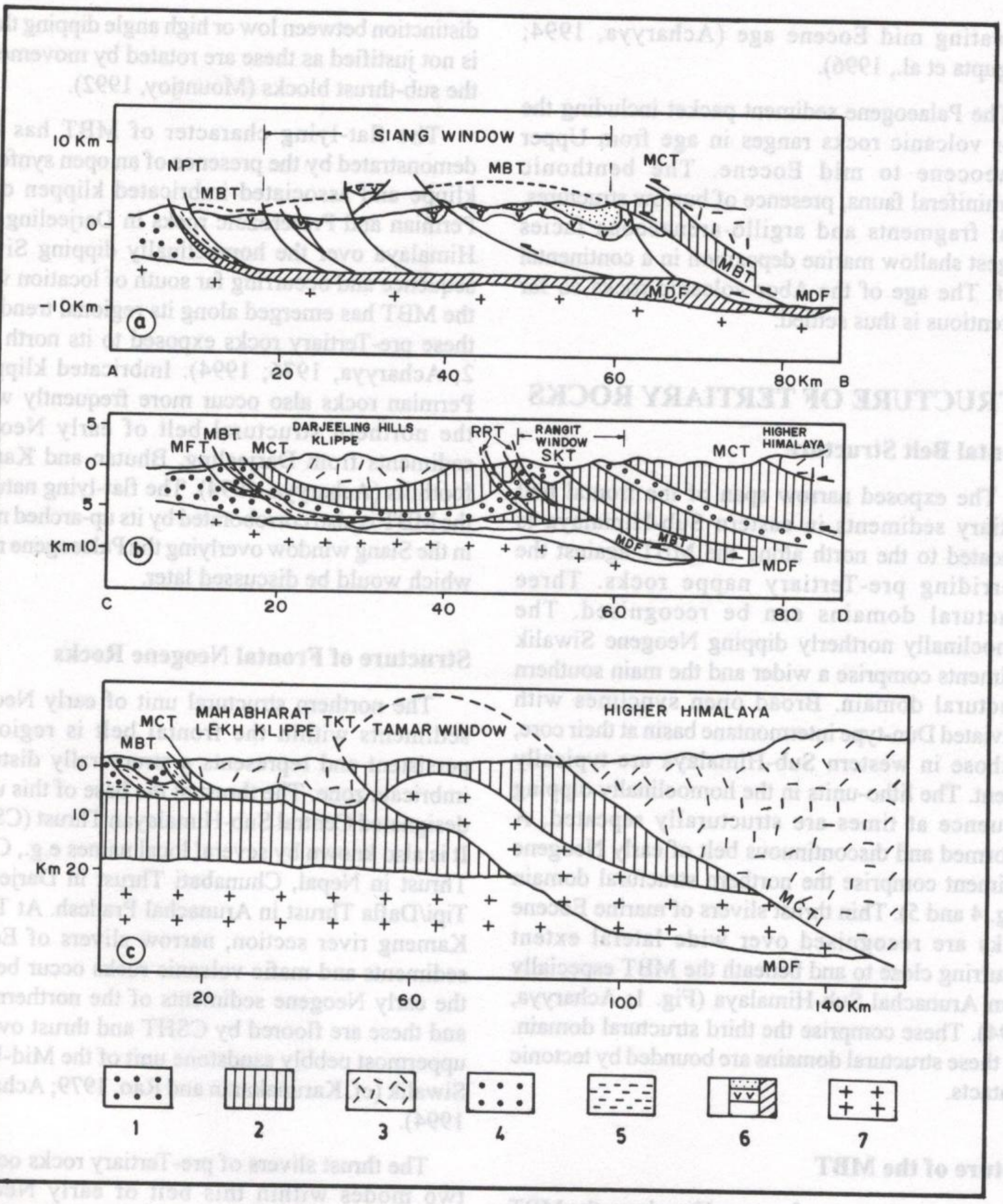

Fig. 5: Structural cross-section of Siang, Rangit and Tamar half-windows. Legend : 1- Late Palaeozoic sediments, 2- low grade Proterozoic metasediments, 3- High grade crystalline nappe of the Himalaya, 4- late Neogene sediments foreland basin, 5- early Neogene sediments foreland basin, 6- Palaeogene sediments undifferentiated in Fig. 5b, differentiated in Siang window (5a) into Yinkiong Formation, Abor volcanics, Lower quartzite, and undifferentiated floor rocks, 7- Crystalline basement and granitoid rocks of the Himalayan foreland basin. Tamor window structural section (5c) after Schelling and Arita (1991). The section has been drawn assuming allochthonous Proterozoic rock of the Lesser Himalaya to directly underlie the autochthonous Neogene, and the Neogene basin to terminate against the steeply dipping MBT. The structural cross-section of Rangit window on the other hand, drawn assuming the northern extension of the foreland Tertiary basin beneath the MBT nearly up to the window zone.

pseudoconformable horses within the Chunabati Formation. The latter often contains angiospermous leaf remains (Acharyya, 1976, 1994). Though individually such thrust sheets are not mappable in 1:31680 scale, the composite tectonised zones of the Permian and early Neogene sediments have been mapped (Fig. 2). These pre-Tertiary rocks, being closely similar to those overriding the Neogene rocks along the MBT, are inferred to represent remnants of klippe of the frontally advanced MBT nappe over the early Neogene sediments. Later thrust movement has breached the MBT and imbricated these pre-Tertiary rocks within the early Neogene sediments (Fig. 4; Acharyya, 1994). Similar mode of occurrence of pre-Tertiary rocks over the Palaeogene rocks is also inferred from the southern parts of the Siang window (Acharyya and Sengupta, 1997) and would be described later. As against these, at places pre-Tertiary slivers in the northern structural belt of early Neogene sediments also occur as basement wedges. Presence of such slivers of Proterozoic carbonates having unconformable relation with the Lower Siwalik sediments has been demonstrated from the Sub-Himalaya of central Nepal (Shrestha and Sharma, 1996).

The homoclinally dipping Neogene sequence of the southern structural unit is also structurally repeated in some sections (Karunakaran and Rao, 1979; Rao, 1983). Abrupt southern termination of the Sub-Himalayan Siwalik Range along a linear zone is possibly caused by the Main Frontal Thrust (MFT). The oldest exposed Neogene litho-unit often occurs at the cores of truncated anticlines resembling "snake head folds" along the frontal termination of the Sub-Himalaya, or at the floors of structurally repeated Neogene sequence. Thus, it appears that these thrusts located within the frontal Neogene sediments invariably sole into the oldest exposed litho-unit at their hanging-walls. The CSHT and imbricate thrusts within the northern structural belt also broadly sole at the same stratigraphic level. The soles of these thrusts possibly represent a stratigraphy controlled detachment level, as would be discussed later. The "snake head folds" are caused due to thrust-related movements affecting the sequence e.g., Sevoke anticline in the Tista section (Fig. 4; Acharyya, 1994).

SIANG WINDOW AND EASTERN HIMALAYAN SYNTAXIS

Two structurally discordant units can be recognised in the Siang half-window (Fig. 3). The crystalline thrust packet and the subjacent thrust sheets of low grade Proterozoic metasediments framing in the Palaeogene sediments of the half-window to the north and above the MBT, preserve identical structural style and constitute one congruous tectonic unit. The shape of the Palaeogene sediments comprising the core of the window is due to the curved disposition of the MBT which forms the roof-thrust of the Paleogene thrust packet and the tectonic base of the pre-Tertiary Himalayan nappe rocks. The MBT, thus, forms the roof-thrust and northerly fold closure of the window. Structurally conformable high grade rocks floored by the MCT also define a conformable northerly fold closure. The Palaeogene thrust packet is truncated to the south by a ENE-WSW trending north dipping North Pashighat Thrust (NPT) representing their floor-thrust against the frontal belt Neogene rocks.

The presence of the Permian rocks just over the MBT is ubiquitous to the west of the Siang window. Along the curve trace of the MBT in the eastern flank of the Siang window, thin slivers of the Permian rocks are exposed near Dalbuing (Fig. 3). The bivalve fossils in them are extremely flattened and deformed (Sinha et al., 1986). Deformed volcanics intercalated with the Permian mioflora are also recorded from this and nearby area (Prasad et al., 1989). Along the same zone the Palaeogene basalts are also more intensely deformed than those at the core of the window. North of Yinkiong (Fig. 3), the amygdules in the basalts are extremely flattened and stretched forming a strong linear fabric plunging NNE. This linear structure is inferred to lie parallel to the movement direction along the MBT.

The disposition of the Palaeogene rocks located at the core of the Siang half-window is controlled by a distinctly different structural style compared to that of the overriding thrust sheets of pre-Tertiary rocks. The former is dissected by a group of interconnected subsidiary faults associated with upright folds. These maintain consistent NNW-SSE orientation of the axial traces parallel to the faults but are oblique in orientation to both the MBT at the roof and the NPT at the floor of the window. These faults usually meet the NPT asymptotically but truncates and dislocates the MBT located at the roof (Fig. 3 and 5). The axial traces of these folds maintain strict parallelism with the traces of faults affecting this packet. Change in orientation of the axial traces of these folds following the change in strike of the fault traces has produced the complex map pattern of the Palaeogene rocks. The orientation of the large-scale major fold axial traces in the overlying pre-Tertiary thrust sheets is nearly parallel to those within the Palaeogene rocks.

The Siang half-window is also located very close to the eastern syntaxis of the Himalaya. To the west of this domal structure, the Himalayan rocks and thrust system have broad ENE-WSW trend which takes a sweep round the dome and trend broadly to NW-SE. Along the eastern fringe of the Siang dome, Trans-Himalayan dioritic migmatites with granodiorite intrusives override the high grade crystalline rocks. The width of crystalline rocks in this limb of the dome is very much attenuated compared to its other limb. A discontinuous narrow belt of mafic-ultramafic rocks of ophiolitic affinity is also exposed around Tuting and also Moutuo (Zheng and Chang, 1979) in the upper reaches of the Siang River along this thrust contact (Fig. 3). These may represent eastern extension of the Indus-Tsangpo Ophiolite. This would also mean that the entire section of the Tethyan Himalayan rocks are truncated out along the eastern limb of the Siang dome by the overriding the Trans-Himalayan rocks.

Immediately to the west of the Siang half-window, a complimentary open synform is located around Along, with low grade metamorphic rocks at its core flanked by the Palaeogene rocks to the south continuing from the Siang window (Fig. 3). The western limb of this Along synform is truncated by a major N-S trending dextral tear fault. At its southern end, it truncates the low grade thrust stack of pre-Tertiary rocks and possibly swerves to join the NPT at its western end, near Garu (Fig. 3). The tear fault offsets the MBT. To its west, the MBT is aligned along the trace of the NPT, whereas to its east, it is shifted north, where from the MBT with a curved outline delineates the northern boundary of the Siang half-window. Thus the tear fault, near its southern end, delineates the western boundary of the half-window.

The Permian rocks occurring north of the MBT around Garu continue further east, being located to the north of NPT and wedged between the Paleogene and Neogene sediments. Slivers of Palaeogene rocks are tectonically imbricated near the base of the Permian and against the top of the Neogene sediments from the MBT/NPT zone, in Garu area (Sinha et al., 1986). Similarly, at the eastern end of the Siang half-window further east, the arched up MBT marking the northern boundary of the Palaeogene rocks asymptotically joins with the eastern end of the NPT, and further east, the MBT has a rectilinear trend located between pre-Tertiary rocks and the Neogene sediments (Fig. 3).

OTHER WINDOWS IN EASTERN HIMALAYA

The Siang window has close geometrical similarities but certain distinctions from other windows from eastern Himalaya (Fig. 1). The common features in all these are their up-arched and folded northern tectonic margin and mainly rectilinear truncated southern margin, i.e. half-window form. All the windows except the Siang are mainly defined by the up-arched and folded northerly dipping MCT, which asymmetrically bound them on three sides. At the cores of these windows, low grade Proterozoic metasediments, wedges of basement granite-gneiss with or without late Palaeozoic sediments are exposed which occur beneath the high grade crystalline rocks. In contrast, the Siang half-window is defined by the up-arched MBT and Palaeogene rocks are exposed at the core occurring beneath the pre-Tertiary metasediments.

The adjacently located Tamor and Rangit half-windows from east Nepal and Darjeeling-Sikkim Himalaya are closely similar. The Tamor Khola Thrust (TKT), delineating the southern margin of the Tamor half-window, appears to join with the Rangit-Raman Thrust (RRT) system further east which delimits the southern boundary of the Rangit half-window (Fig.1 and 2). In the Kuru half-window, in east Bhutan, the southerly-located Shumar thrust although partly folded (Ray et al., 1989) can be compared to the TKT and RRT. In the Siang half-window the comparable structural element is the NPT.

The southern boundary of the Rangit half-window is delimited by the broadly east-west trending and north dipping Rangit-Raman Thrust system (Fig. 2, modified after Acharyya, 1989). The nortern set of these imbricate thrusts truncate the southern boundary of the late Palaeozoic Gondwana sediments of the window and bring them to juxtaposition against the south dipping low grade Proterozoic meta-argillites (Daling and Reang formations) and locally exposed thrust slices of the late Palaeozoic diamictites. These also truncate the roof-thrust of the window. At the core of the window, the low grade Proterozoic metasediments are thrust along a WNW-ESE trending Sikkip thrust over its own cover of late Palaeozoic Gondwana sediments located further south. The Sikkip thrust appears to terminate against the roof-thrust of the window. Further south, and along the southern set of thrusts of the RRT system, highly deformed late Palaeozoic rocks occur within a narrow zone of lithostratigraphically distinct Reang-type Proterozoic rocks, and they are emplaced within the Daling-type low grade Proterozoic meta-argillites (Acharyya, 1989). Still further south in turn, the low grade Daling metasediments tectonically underlie the low dipping crystalline rocks of the Darjeeling Hills (Fig. 5b).

Inspite of remarkable geometrical similarity of the Tamor and Rangit windows, a minor but noteworthy difference exists between them. The Tamor half-window only exposes low grade Proterozoic metasediments and their basement granitoid rocks occurring beneath the high-grade crystallines. The Rangit half-window, instead, exposes late Palaeozoic and Proterozoic rocks, which occur structurally beneath a nappe of similar low grade Proterozoic metamorphic rocks. The latter also contains several wedges of basement granitoid rocks.

STRUCTURAL CROSS-SECTION: FRONTAL BELT AND WINDOWS

Balanced Section Across Darjeeling Frontal Belt

Based on subsurface, structural and seismic evidence, the thrusts in the Himalayan frontal belt from Pakistan and northwest India have been inferred to have been caused by a detachment horizon within the foreland Tertiary sediments and the overlying sediments are forced southward over an unyielding basement surface (Yeats and Lillie, 1991). The detachment model appears to be consistent with available surface data from eastern sector, although subsurface data are lacking. The concept of balanced cross-section has been introduced to understand the geometry of the thrust belt structures (Dahlstrom, 1969). A balanced cross-section of the frontal zone Neogene section from Darjeeling foothills has been reconstructed (Fig. 4; Acharyya, 1994). However, there is lack of subsurface data to constrain the profile. South of Darjeeling foothills, there are only two distantly located deep well sections, the Purnea and Salbonhat wells (Karunakaran and Rao, 1979; Alam et al., 1990). The Neogene sediment column at the frontal edge of the Darjeeling foothills, based on these subsurface data is assumed to have a thickness of about 3000 m for the balanced section (Fig. 4). Subsurface data from the Ganga basin have revealed that the basin axis of older Neogene sediments of the foreland basin progressively shifted northward, i.e. towards the mountain front (Acharyya and Ray, 1982). Stratigraphically, the foreland Tertiary sediments cannot be linked and tied up with the pre-Tertiary Himalayan rocks, which override them along the MBT. However, the presence of Palaeogene sediment cover over the Himalayan nappe rocks as in the Tansen synclinorium (Sakai, 1983), and rare presence of the Proterozoic basement wedge unconformably beneath the early Neogene Sub-Himalayan rocks from central Nepal indicate that the northern limit of the foreland Tertiary basin, which extended over the older Himalayan rocks.

The Palaeogene-early Neogene sediments located at the northern parts of the foreland basin were thrust by the pre-Tertiary rocks over a flat-lying MBT. Further south, the MBT encroached over southern parts of the basin and over younger Neogene sediments. Subsequently, movement appears to be transferred from the MBT to a detachment level within the subjacent early Neogene sediment. In the process of southward advancement of this detachment and the overlying sediments and thrusts ramping up from this level, the early Neogene sediments got imbricated and deformed at the sole of the thrust sheets. Further, these younger thrusts breached the MBT and also tilted and imbricated pre-Tertiary nappe rocks and encased them within the early Neogene sediments (Fig. 4). The presence of early Miocene open-sea type micro fauna imbricated within the early Neogene paralic facies sediments as recorded from the Darjeeling foothills is inferred to represent intrabasinal sediment incorporated tectonically to the frontal zone. The imbricated early Neogene sediments from the northern parts of the frontal belt, thus, represent a parautochthonous zone, rocks from which were ultimately ramped up against the autochthonous column of the Neogene sediment further south. This regional tectonic contact is represented by the Central Sub-Himalayan Thrust (Fig. 4). At places like Tipi in Kameng foothills, a narrow sliver of Eocene rocks, lithologically and faunistically very similar to those exposed at the cores of the Siang window, is exposed at the hanging-wall of the CSHT. Here, the detachment level appears to be located within the Eocene beds wherefrom the Tipi/CSHT has ramped up and surfaced (Acharyya, 1994).

The southern autochthonous Neogene column is affected by more limited scale southward movement broadly along an early Neogene detachment level. Thrust ramping up from this level tilted the Neogene sequence to assume homoclinal dip. The ramped up thrust against the alluvial covered Neogene-Quaternary sediments marks the Main Frontal Thrust (MFT), which may be blind or might have surfaced. In some sections, the Neogene column is structurally repeated by further southward movement and advancement of the detachment level and ramping up from this level.

Cross-Section of Siang Window

In respect of the Siang window, no subsurface data derived from bore holes or seismic studies are available and cross-section balancing could not be done. However, to the south of the Siang half-window in the alluvial covered Brahmaputra basin, Palaeocene to early Eocene marine sediments have been recorded recently at subsurface from the Tenkaghat area (Fig. 1) occurring near the crestal parts of the buried basement high (Baruah et al., 1992). These sediments represent undisturbed counterpart of the Palaeogene foreland basin, the continuity of which is observed in the Siang half-window. They have flat dips and consistent bed thickness, which have been used to constrain the structural cross-section.

A cross-section has been drawn along NNE-SSW parallel to the direction of tectonic transport as revealed from the linear fabric described from north of Yinkiong (Fig. 5a, Acharyya and Sengupta, 1997). The thickness of the Abor volcanic rocks within the Palaeogene packet and parallel geometry of the folds in the packet have been used as constraints for drawing this section.

The pre-Tertiary thrust sheets above the Palaeogene rocks of the Siang window are characterised by parallel beds, with lithological contacts and planar structures parallel to the thrust planes. They are folded into a pair of major N-S trending antiform and synform, which are open folds with rounded hinges (Fig. 3). Apparently, these folds are confined to the upper thrust sheets and terminate at the MBT. The folds affect multiple imbricated thrust sheets consisting of low grade Proterozoic nappe and the crystalline nappe. The character of these folds are comparable to fault-bend folds (Suppe, 1983), and possibly result due to stepping up of the MBT from a lower to higher detachment horizon along a frontal ramp (Fig. 5a). As a result, bedding in the sub-thrust Palaeogene sequence is truncated at high angle at the ramp. The bedding within the Lesser Himalayan pre-Tertiary nappe dips away from the transport direction, indicating that the upper block has moved over a ramp in the footwall. The arching up of the Palaeogene rocks and consequent antiformal fold in the roof nappes are also due to imbricate thrusts and related folds in the sub-thrust block. The folds above the MBT are discordant with the folds in the sub-thrust block.

In contrast the dislocations in the sub-thrust Palaeogene block broadly have NNW-SSE trend and diverge from the floor-thrust, i.e. the NPT and step up through the Palaeogene section. The faults usually begin with a gentle dip when they diverge from the sole thrust and becomes steeper upwards. The faults cut through a series of folds and breach them as well as the roof-thrust MBT. The folds are of uniform shape, asymmetric in nature with steep axial planes dipping near parallel to the faults and always maintain a parallel geometry. The northern back limbs are straight and the southern forelimbs are cutoff against the faults. Displacement along all these faults is generally small compared to the overlying MBT and MCT, and in all of them the hanging wall has been upthrown. One antithetic southerly dipping fault diverges from one of these northerly dipping faults, instead of diverging from the sole thrust (Fig. 5a). The characters of the folds resemble fault-propagation folds (Woodward et al., 1989) and the dislocations are comparable in geometry to an imbricate thrust system developed from a system of fault-propagation fold (Mitra, 1986). The faults in the sub-thrust block are characterised by steeper dips compared to the MBT and the MCT (Fig. 5a).

The Siang window is truncated to the south and is, thus, a half-window, and its imbricate thrust system of the Palaeogene rocks is thrust over the tectonised early Neogene sediments across the NPT. Splays of NPT bound two prominent horses of pre-Tertiary rocks. The Permian rocks occur near its western end, and Proterozoic carbonates and late Palaeozoic metasediments occur near central part of the NPT (Fig. 3). These pre-Tertiary rocks possibly represent down faulted klippe of the MBT nappe overriding the Palaeogene rocks and are juxtaposed against the tectonised early Neogene sediments of the frontal zone (Fig. 5a). Similar occurrences are reported from the Neogene belt from Darjeeling foothills (Acharyya, 1976,1994). The relation is also very similar to the Rocky valley anticline and Rocky valley thrust (Fischer and Woodward, 1992). Thrust slivers of marine Eocene sediments also occur within the imbricated early Neogene sediments of the frontal belt further south. Marine Eocene sediment and volcanic rocks, similar to those of the window, are also exposed further south at the base of the tectonised early Neogene unit and at the hanging-wall of the CSHT at Tipi, as discussed earlier. The tectonised early Neogene sequence rest against the northerly dipping homoclinal autochthonous Neogene sediments along the CSHT further south (Fig. 5a). The structural set-up in the frontal belt is very similar to that of Darjeeling Sub-Himalaya.

Cross-section Across Other Windows of Eastern Himalaya

In the non-balanced structural cross-section through the Tamor half-window, Schelling and Arita (1991) inferred that the window rocks occur as hinterland dipping arched-up duplex (Fig. 5c). The MCT, TKT, MBT, and the thrusts within the Sub-Himalayan Neogene belt and the Main Frontal Thrust (MFT) at its frontal termination are all linked to a single Main Detachment Fault (MDF). The MDF is located at the lower crustal level in northern and internal parts of the Himalaya, wherefrom MCT has branched and ramped up. In the process of advancing towards the frontal zone, the Main Detachment Fault progressively climbed up to upper structural/stratigraphic levels. The Tamor Khola Thrust branched up from the Main Detachment Fault located beneath the Tamor window and within the granitoid basement rocks of the Proterozoic metasediments. It appears to have climbed a north dipping ramp and a thrust-flat, and then surfaced as the steep dipping Tamor Khola Thrust (Fig. 5c). As a result, the hinterland dipping horse comprising the low grade Proterozoic rocks and its granitoid basement rocks are arched up as a fault-bend antiform, which passively folded the overlying MCT. Schelling and Arita (1991) based their structural cross section assuming direct stratigraphic linkage of the allochthonous Lesser Himalayan Proterozoic metasediments with the basement rocks of the foreland basin. They further assumed that the Tertiary foreland basin terminated against the steeply dipping MBT and the basin does not continue beneath it. Field relations indicate that these assumptions are not justified. Their models did not account for consequent structural influence of these subthrusts Tertiary rocks on the overlying pre-Tertiary nappes.

In the Rangit Window, the Sikkip thrust and the RRT system similar to that of the TKT appear to climb up a ramp either from that part of the Main Detachment Fault located within the low grade Proterozoic floor rocks or may even have ramped up from the MBT located at the tectonic base of the pre-Tertiary rocks that have overriden the northern extension of the Tertiary foreland sediments (Fig. 5b).

Further to the south of the Tamor and Rangit half-windows, tectonic movements are along the Main Detachment Fault, which appears to be located within the low grade Proterozoic floor rocks. Or the movement is along the MBT following a thrust-flat and located at the tectonic base of pre-Tertiary and over the sub-thrust foreland Tertiary rocks. The thrust stack with exposed low grade Proterozoic rocks carries the crystalline nappe floored by the MCT on their back. This has resulted in shaping frontal belt half klippe of crystalline rocks at Mahabharat Lekh and Darjeeling Hills (Fig. 5b and 5c). The pre-Tertiary thrust stack, at this stage of frontal advancement or even earlier as already mentioned, has encroached and overridden the northern sub-thrust extensions of foreland Tertiary sediments. Thus, the floor thrust became the MBT. After following a thrust-flat, the MBT climbed up a ramp close to the frontal belt and thus the MCT and MBT are exposed with a steep northerly dip. Within the exposed part of the foreland Tertiary basin in the frontal zone, the Main Detachment Fault is either located within the early Neogene sequence (Lower Siwaliks) or within the marine to paralic Eocene sediments (Fig. 5a and 5b). The northern belt of tectonised early Neogene sediments represent the parautochthonous zone of ramped up thrust imbricates and the Central Sub-Himalayan Thrust (CSHT) delimits the southern boundary of this zone. At times, the Eocene rocks occur at the tectonic bases of these imbricate thrusts especially in Arunachal Pradesh foothills (Acharyya, 1994). The northerly dipping homoclinal Neogene sequence of the foothills representing the autochthon, is represented by frontal advancement of the detachment level to a minor scale and ramping up of the Neogene pack.

The Tamor and Rangit windows expose different structural levels of the Himalayan nappes. The Tamor window only exposes low grade Proterozoic metasediments and their basement granitoid rocks occurring beneath the high grade crystallines, whereas the Rangit window exposes late Palaeozoic and Proterozoic rocks, which occur structurally beneath a nappe of similar low grade Proterozoic metamorphic rocks which also contain several wedges of basement granitoid rocks. The latter rocks are likely to have been thrust from the segment of the Main Detachment Fault located at the base of the Proterozoic metasediments or within the granitoid basement rocks flooring them. On the other hand, late Palaeozoic basins of Gondwana affinity developed further south were the sites of the MDF for the core rocks of the Rangit Window. Further, all these thrust pile lie tectonically below the high grade crystalline nappe.

The setting and disposition of the NPT in the Siang window is closely comparable to that of the TKT/RRT of the Tamor and Rangit windows. In the Siang window, the MBT is the arched up roof-thrust demarcating the northern boundary of the window, whereas, the rectilinear NPT marks the floor thrust. Thus, the imbricated Palaeogene sediments at the core form a duplex (Fig. 3). The pre-Tertiary rocks immediately overlying the MBT include the Proterozoic metasediments and Permian rocks of Gondwana affinity. These noted differences between these windows may reflect the difference of exposed structural levels of these windows.

THRUST SYSTEM GEOMETRY, EVOLUTION OF DOMES AND EASTERN SYNTAXIS

Pre-collisional Indian continent was effectively Y-shaped with two continental projections, which have exerted fundamental control on the development of the Himalayan thrust stacks (Treloar and Coward, 1991). Collision and thrust stacking was earliest at the point of its NW projection, which collided earliest with the Eurasian continent that ultimately became the western syntaxis. Since the initial collision during early-middle Eocene at the NW projection, the Indian plate has rotated anticlockwise with increased amounts of subduction to the east (Dewey et al., 1989). Contemporaneous with the terminal collision there was extensive tholeiitic to alkaline basaltic flows, acid volcanism in the foreland basin (Sengupta et al., 1996; Acharyya, 1998). The northeasterly protuberance in the Indian continent acted as the indenture when collision occurred in the eastern end of the Himalaya. This has resulted in the development of the eastern syntaxis, which has some similarity in character to the western syntaxis. For the southward propagating thrusts within the Indian plate, the NE indenture with a northerly sense of movement acted as an oblique ramp and developed ramp anticline in the crystalline nappe and in the pre-Tertiary MBT nappe. All the major Himalayan thrust systems are traceable around the Siang antiformal structure. But some of these have been greatly attenuated in width. The Trans-Himalayan granitoid and crystalline nappes are pushed forward to the frontal zone further

SE of the Siang window and they virtually lie against the northeasterly projected Indian shield basement. All the external thrust system and other tectonic features of the Himalaya and those of the Indo-Burmese Range are concealed beneath and truncated by these frontally advanced NW-SE trending Himalayan and Trans-Himalayan nappes (Fig. 1).

The Tuting-Garu dextral tear fault located along the western margin of the Along synform has many similarities with the faults affecting the Palaeogene sub-thrust rocks of the Siang window (Fig. 3). It branches from the NPT floor-thrust, has the same sense of tectonic movement, and not only breaches the MBT but also the MCT and the crystalline nappe. Thus temporally, the tear-fault movement was younger to the MBT as that of the sub-thrusts of the Siang window. Tear faults are also reported from the western syntaxis of the Himalaya and are produced because of change of movement vector of thrusts at the two sides of the NW indenting front of the Indian continent (Coward et al., 1987). The Tuting-Garu dextral tear fault cannot be accounted by the impingement of the NE indenture, which would have resulted a sinistral fault. The dextral tear fault instead is inferred to have resulted because of movement within the sub-thrust Palaeogene rocks as those within the Siang half-window. But it has breached through the overlying Himalayan nappes, and thus might have accommodated late stage differential movements of nappes located on its either side. Thus, the process controlling the development of tear faults at the western and eastern syntaxes are distinct from each other.

The tectonic movements on the Himalayan thrusts along the eastern edge of the NE indenture was towards SSW, which is confirmed by the kinematic indicators present in the rocks here. In contrast, movement on thrusts along the western edge of this indenture was towards SSE, making this a zone of convergence. Major thrust sheets were emplaced over the Palaeogene foreland rocks located within this zone of convergence and close to the eastern syntaxis of the Himalaya. The required crustal shortening was accommodated in the subthrust block by reverse faults and fault-propagation folds of younger age. All these provided unique setting for the Siang dome and are responsible for its typical features.

The close structural similarity between Tamor, Rangit and Siang windows indicate genetic connection in their development. Their isolated nature of occurrence is unlikely to have been caused by type-I interference of folds. Similar domes are common along external fringes of large crystalline thrust sheets and these are also occupied by duplexes. These were formed as a response to the emplacement of the crystalline thrust sheets and subthrust architecture (Mitra, 1986; Hatcher, 1991). In the Siang dome, the high grade crystalline and the low grade metasedimentary sheets are arched up because of the duplex architecture of the sub-thrust Palaeogene rocks. In the Kuru dome, the uparched geometry of the crystalline sheet is associated with duplex structure in the low grade metamorphic Proterozoic rocks (Ray et al., 1989). Horses of deformed granitiod rocks are exposed in Kuru, Tamor and Tista dome engulfing the Rangit window (Fig. 2). In the Kuru and Tista domes, these granitoids have yielded a Precambrian age and possibly represent basement rocks (Sinha Roy and Sengupta, 1986). Thus these duplexes must have been formed when the main thrust motion was over the Proterozoic basins and their basement. Subsequently when the thrust encroached over the Tertiary foreland basin, the thrust motion got transferred to the MBT and the earlier formed duplexes were carried passively on top of the MBT. The presence of marine Eocene and early Miocene open-sea type marine fauna close to the MBT over wide strike length in the frontal belt from eastern Himalaya (Acharyya et al., 1987; Acharyya, 1994; Sinha and Srivastava, 1992), establish their subsurface extension and continuity. The map pattern at the present level, however, does not give any positive indication favouring up-arching of the sub-thrust Tertiary sediments and MBT in the other windows as against that in Siang.

CONCLUSIONS

The low grade pre-Tertiary metasediments underlying extensively exposed high grade crystalline nappe of the Himalaya override the frontal belt Neogene molasse sediments along the Main Boundary Thrust (MBT). In eastern Himalaya, marine Eocene and early Miocene sediments are tectonically concealed and are only exposed as small horses close to and beneath the MBT. The narrow frontal belt Neogene sediments comprise a southern unit of the homoclinally dipping autochthonous Neogene sediment and a northern imbricated parautochthonous zone of the early Neogene sediments.

The low grade pre-Tertiary Himalayan nappe generally occurs as narrow linear frontal belt bounded to the north by the MCT against extensive spread of the crystalline nappe and to the south by the steeply dipping MBT. But at the cores of domal structures, low grade Proterozoic with or without late Palaeozoic metasediments similar to those exposed in the frontal belt reappear from beneath the up-arched crystalline nappe. The largest Siang window, located close eastern syntaxis of the Himalaya is distinctive. It exposes duplex arch of Palaeocene-Eocene sediments interbanded with the Abor volcanic rocks occurring beneath the upwarped and breached the MBT representing their roof-thrust. The Palaeogene duplex is truncated along the North Pashighat Thrust (NPT) representing the floor-thrust against the imbricated frontal belt Neogene sediments. The Siang and other windows of eastern Himalaya have many structural similarities and have evolved similarly in response to emplacement of the crystalline and low grade pre-Tertiary nappe. The Himalayan pre-Tertiary nappe at some stage of their southward advancement encroached over the northern parts of the foreland basin where marine Palaeogene sediments and tholeiitic to alkalic basaltic and acid volcanic rocks are extensively developed. The sub-thrust Tertiary foreland rocks overridden by the pre-Tertiary Himalayan nappe were subsequently affected by movements along a detachment located within the basal sediment column and thrusts ramping up from this level. The foreland basin sediments were progressively thrust southwards over the southward advancing detachment front towards the frontal zone. The detachment level in the process of advance from the inner window to the frontal belt appears to have climbed from basal Eocene to early Neogene level. The early Tertiary foreland rocks became largely concealed under the tectonic cover of older rocks but the structure of the nappe cover is influenced by the architecture of the subthrust Tertiary rocks.

The Siang window located close to eastern syntaxis of the Himalaya was possibly produced by the NE projecting indenture of the Indian continent which acted as an oblique crustal ramp along the two slopes of which Trans-Himalayan, pre-Tertiary Himalayan nappe and subthrust packets of Palaeogene rocks were tectonically propagated. The convergence of tectonic movements produced imbricate thrusts and duplex arch in the Palaeogene subthrust rocks that breached the MBT, passively folded and tear-faulted Himalayan nappe rocks. The sub-thrust Tertiary sediments are likely to be present beneath other windows in the external zones. But these appear to have played more passive role so far as their influence on the structure of the overlying pre-Tertiary nappes are concerned.

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