# CONDITIONS OF COMPACTION AND DEVELOPMENT OF DIAGENETIC MICROSTRUCTURES IN THE DAFLA AND SUBANSIRI SANDSTONES, WESTERNARUNACHAL PRADESH, INDIA

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## Abstract

The Neogene Siwalik sequence of western Arunachal Pradesh comprises northward dipping thrust sheets structurally below the Main Boundary Fault (MBT) and above the Main Frontal Thrust (MFT). The Sub-Himalayan fold and thrust belt comprises four lithotectonic units between MBT and MFT. From oldest to the youngest these units are Kimi, Dafla, Subansiri and Kimin Formations. The Kimi Formation is equivalent to Lower Siwalik; Dafla and Subansiri formations are equivalent to the Middle Siwalik, while the Kimin Formations represent Upper Siwalik respectively. In the Kameng sector, Tipi Thrust is interpreted to be an intraformational thrust within Subansiri Formation; the Dafla Formations are trusted over the Subansiri Formation relatively at a higher structural level.

Compaction and subsequent strong horizontal north to south compression led to the development of numerous zones of cataclasis in the Dafla and Subansiri sandstones. Earlier diagenetic fabrics in the sandstones have been modified considerably due to subsequent development of deformational grain scale microstructures under compression. The Pure Compaction Bands were formed in the initial stage under raised porosity and permeability. These are transformed to Shear Enhanced Compaction Bands and subsequently to Compactional Shear Bands when deformation assumes a simple shear mode under low porosity and permeability value. Higher degree of compaction is evident in the Dafla sandstone compared to that of the Subansiri sandstone which inferred on the basis of the type of the grain contacts, grain packing, frequency of pressure solution seams and segregated micaceous bands.

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**Keywords:** Dafla, Subansiri, Sandstones, Compaction, Microstructures

## Introduction

The Neogene Siwalik Group of rocks are exposed along road and river sections situated between Bhalukpong and Elephant point in the west Kameng District of Arunachal Pradesh, India. The studied sections are bounded between the latitudes N27$^{o}$ 05´ 41´´ and 27$^{o}$00´72 ´´and longitudes E92$^{o}$35´ 38´´ and E92 $^{o}$ 38´56´´ in the toposheet No.83A/8.In this area, fluvial mollase sediments of the Siwalik Group are sandwiched between two major thrust zones- Main Boundary Thrust (MBT) in the north and Himalayan Frontal Thrust (HFT) in the south and are thrusted and folded due to several episodes of diastrophic activity. The present study is confined to the sandstones of Dafla and Subansiri Formations of Middle Siwalik Group and an attempt has been made to understand the diagenetic changes that took place during burial and post depositional deformation conditions.

Diagenesis in sedimentary rocks was discussed by many workers in terms of load pressure, low temperature (~200$^{o}$C) conditions (Petijohn, 1957; Fairbridge, 1967; Larsen et al, 1983; Cojan et al, 2002). However, data related to these aspects on the Sub-Himalayan Siwalik sandstones of Arunachal Pradesh are scanty (Krynine, 1937; Raju, 1967; Johnson et al, 1972; Nautiyal, 1978). In the study area, the field and petrographic study of the sandstones of the Siwalik Group indicate the earlier compositional fabrics have been modified considerably due to subsequent deformation penetrative to the grain scale. Compaction and rock alteration might have transcended beyond the normal limit of the diagenetic changes in specific high strain zones. The basin fills may have a number of structural phases, each showing advanced diagenetic changes with depth. It has been observed that initial burial and compaction followed by strong horizontal compression led to numerous zones of cataclasis in the Dafla and Subansiri sandstones. The foreland propagating lithopackages developed a ramp and flat geometry with a gradual tapering of the wedge of the prism along the thrust transport direction (Fig.2). On the other hand, the horizontal compression initially produced some Pure Compaction Bands (PCB) in the Dafla sandstones. However, when the permeability of the sandstones attained a minimum value, the Shear Enhanced Compaction Bands (SECB) are developed. The Compactional Shear Bands (CSB) developed in the sandstones are longer in extension and pervasive up to the other rocks above and below (Fig.3) (Fossen et al, 2011). There is a close coordination between the compaction of Dafla and Subansiri sandstones, development of compaction bands, reduction of porosity and permeability and development of diagenetic microstructures. This paper focuses on these coordination and interrelationship in the Dafla and Subansiri Formations of Kameng River section of western Arunachal Pradesh (Fig.1).

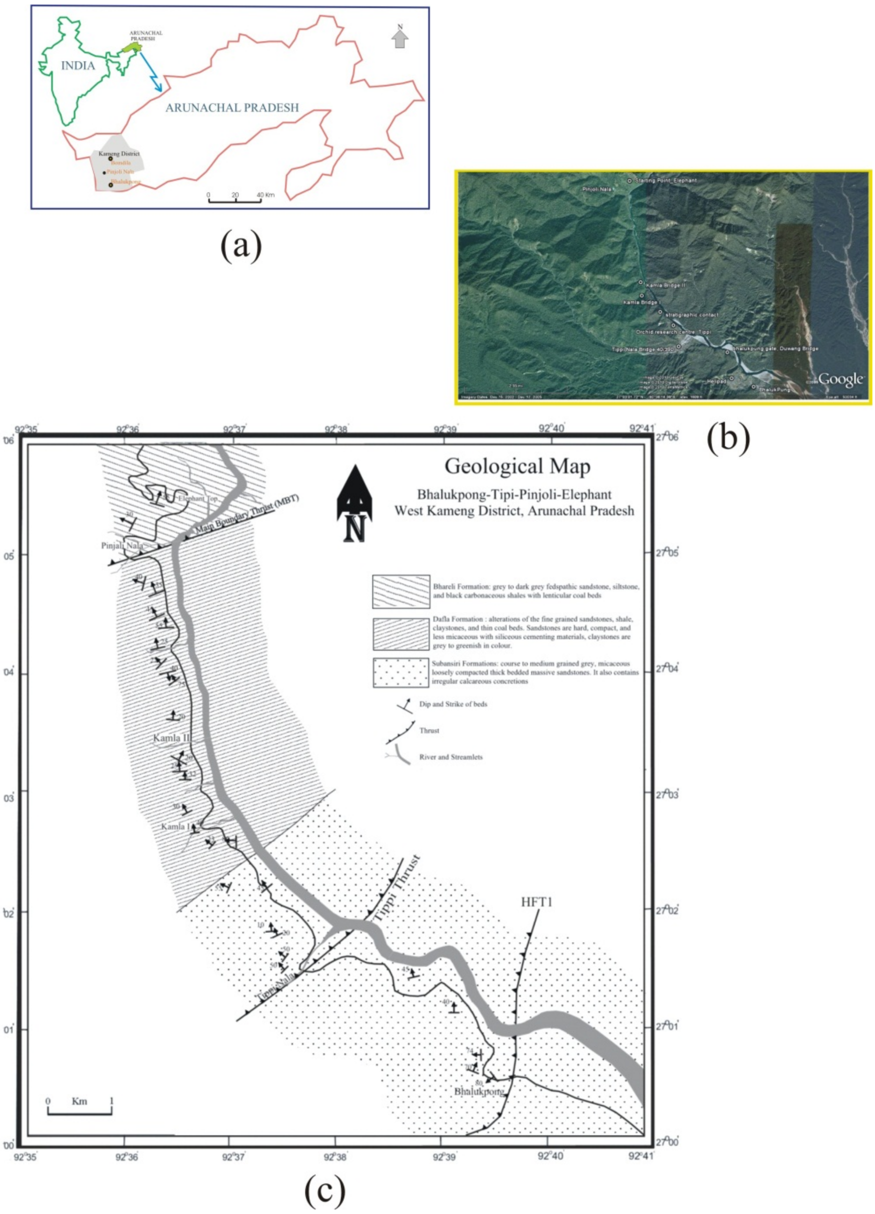
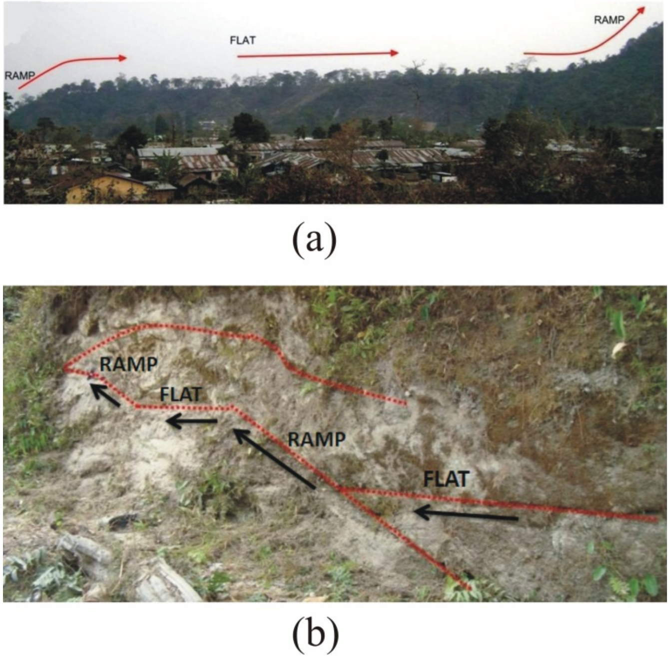


Fig.1. (a) Location maps of the area studied (b) Google image of the Kameng River the study area is from Bhalukpong to Pinjaoli Nala (c) Geological map of the area studied. The Tipi thrust is shown as the interformational thrust in the Subansiri sandstone; the Gondwana-Dafla and Dafla –Subansiri thrusted contacts are shown. HFT -1 is at immediate south of Bhalukpong.

## Geological setting

The Siwalik foreland-fold and thrust belt of western Arunachal Pradesh consist of sedimentary sequence of Miocene and younger ages that are bounded by Main Boundary Thrust in the north and Himalayan Frontal Thrust (HFT) (Nakata, 1971) in the south. The contact between the Siwalik and the Gondwana sequence in the north is however a blind fault without any surface traces (Fig.1). The regionally consistent thrusts developed in the west Kameng District are MBT, Tipi Thrust and HFT (Kelty et al, 2004).Between MBT and HFT, there are four lithostratigraphic units: Kimi, Dafla, Subansiri and Kimin. The strike of these thrusts changes from E-W near the Bhutan -India border to NW-SE at Dikrang River. Kimi Formation is equivalent to Lower Siwalik, Dafla and Subansiri to Middle Siwalik while Kimin Formation is equated with Upper Siwalik (Kumar, 1997).

In the Kameng section, Tipi Thrust is in fact an intraformational thrust within Subansiri Formation contrary to the earlier report (Kelty et al, 2004) and the Dafla Formation is thrusted over the Subansiri Formation at higher structural level (Fig.1.c).



(a)

(b)

Fig.2. (a) The ramps and flats on a larger scale in the Siwalik fold and thrust belt. (b) In the mesoscopic scale, the ramps and flats are shown in the Subansiri sandstones.

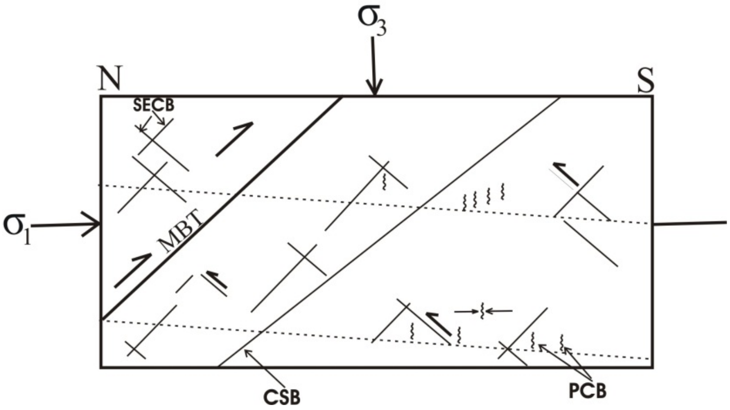


Fig.3. Sketch shows north -south horizontal compression $(\sigma_1)$ responsible for the formation of Pure Compaction Bands (PCB), Shear Enhanced Compaction Bands (SECB) and finally the Compactional Shear Bands (CSB) (as suggested by Fossen et al, 2011)

## Lithology and petrographic characteristics

The Dafla Formation comprises of sandy and argillaceous facies association with thick to medium bedded, hard, compact, jointed sandstone alternating with thin fissile gray shales, compact claystone, carbonaceous shale, coaly lenses with subordinate siltstone laminations (Fig. 4. a, b, d and e). Near the thrusted contact in the overlying Subansiri Formation, the sandy facies grades to argillaceous facies consisting of claystone, thin bedded argillaceous sandstone and dark grey carbonaceous clay with ferrugenous stains.

The Subansiri Formation consists of semi -consolidated to consolidated sandy and argillaceous facies consisting of massive to medium bedded friable, salt and peppery sandstones with pebbly sandstone and current -bedded medium grained sandstone alternating with fissile to compact shale, claystone, sandy -clay and coaly streak (lignite) in sandstone near Tipi Nala (Figs.4. c and f). The woody character of the coaly material indicates the low maturity level of the carbonaceous matter. Soft and friable nature of the sandstone also supports this character.

The study of the detrital minerals of the sandstones indicates that the Dafla sandstones are texturally wacke in nature, mostly quartz-wacke to lithic greywacke, whereas the Subansiri

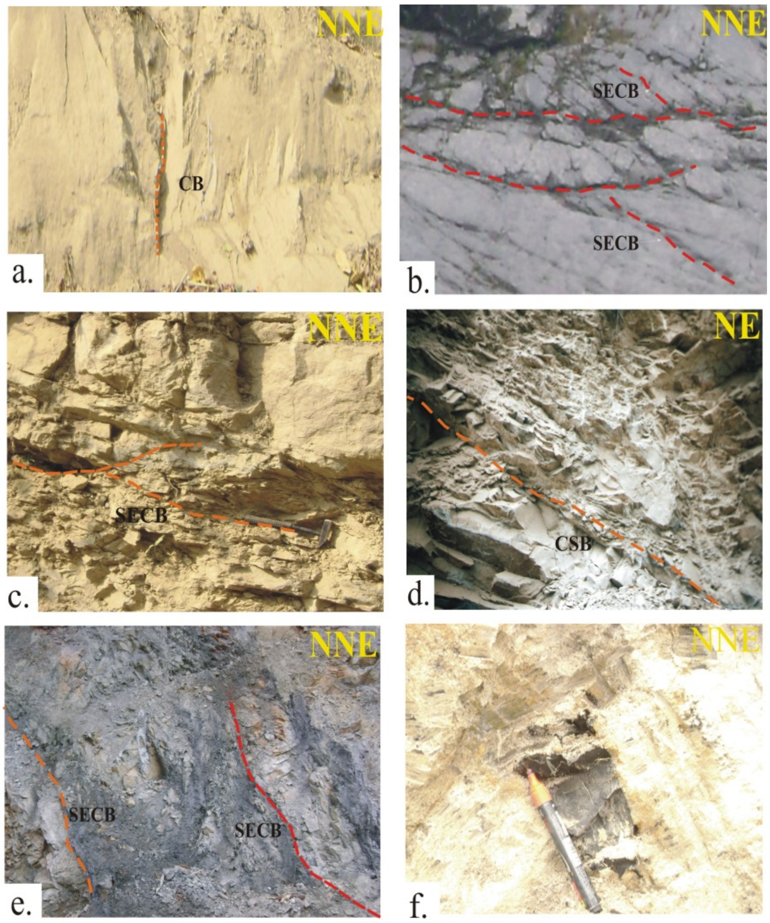


Fig.4 (a) Pure Compaction (PC) band in the massive Dafla sandstone near Kamala River bridge (b) Shear Enhanced Compaction Band (SECB) in Dafla sandstone on 1km south of Kamala River bridge (c) SECB in Subansiri sandstone near Tipi Nala. (d) Compactional Shear Bands (CSB) in Dafla sandstone on 2km south of the Kamala river bridge (e) Carbonaceous shale along the SECB in the Dafla sandstone south of Pinjoli Nala (f) Coaly streak in Subansiri sandstone near Tipi Nala

sandstones show arenitic texture having quartz supported framework grains and classify as quartz arenite and sublithic arenite.

The petrographic study of the sandstones of Dafla and Subansiri Formations illustrate some important mechanical and chemical compactional fabrics (Figs. 5 and 6). 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. Branching of solution seams and quartz grain rearrangement are observed (Figs.5. a & b) and the solution seams transect the grain fabric.

The segregation of mineral matter is a part of the diagenetic differentiation as evident in the sandstones of both Dafla and Subansiri Formations (Fig.5. c). The segregated matter is deposited in open spaces (pores and fractures), irregular microcrystalline bodies replacing the matrix. Mica and quartz bands are segregated into separate layers indicating transfer of ions to the centers of reprecipitation where free energy of such materials is less if they are collected in a larger segregation. It can be inferred as the phylomorphic stage of the diagenesis.

Quartz grains within the deformation band (Fig. 6. g) show no recognizable boundary between original grain and secondary recrystallized grains illustrating the locomorphic stage of the diagenesis.

Complex twinning in plagioclase grains and authigenic clay minerals are seen in the Subansiri sandstones (Fig.5 e). The thick twin lamellae makes an angle with the common lamaller twin bands. This may be the deformation twins developed over slips. Associated diagenetic clay minerals are formed from the labile lithic grains due to transformation under differing pore fluid flow condition.

Incomplete development of the triple point junction is demonstrated by quartz grains in quartz arenites of Subansiri Formation. Dissolution of quartz grains at grain boundaries released silica in solution and recrystallised , forming a compound grain. Triple junctions in compound

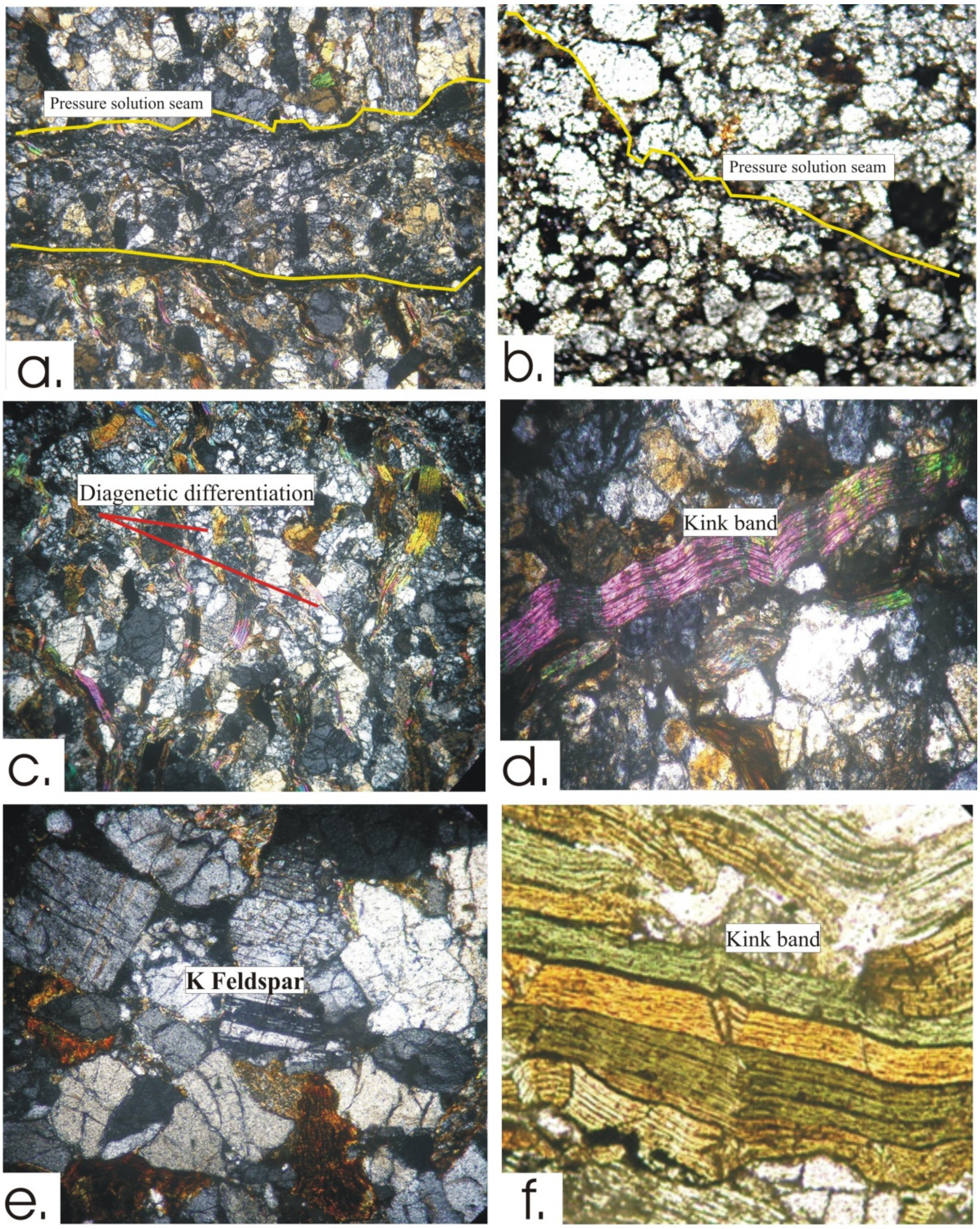


Fig.5( a) and (b) Branching of the pressure solution seams in the Dafla sandstone. The grain fabric is dissected by the solution seams (c) Diagenetic differentiation in the Dafla and Subansiri sandstones (d) and (f). Kink band development in the weakly foliated Dafla and Subansiri sandstones (e) Complex twin in K-feldspar in Dafla sandstones (all photomicrographs cross polarized: 10X).

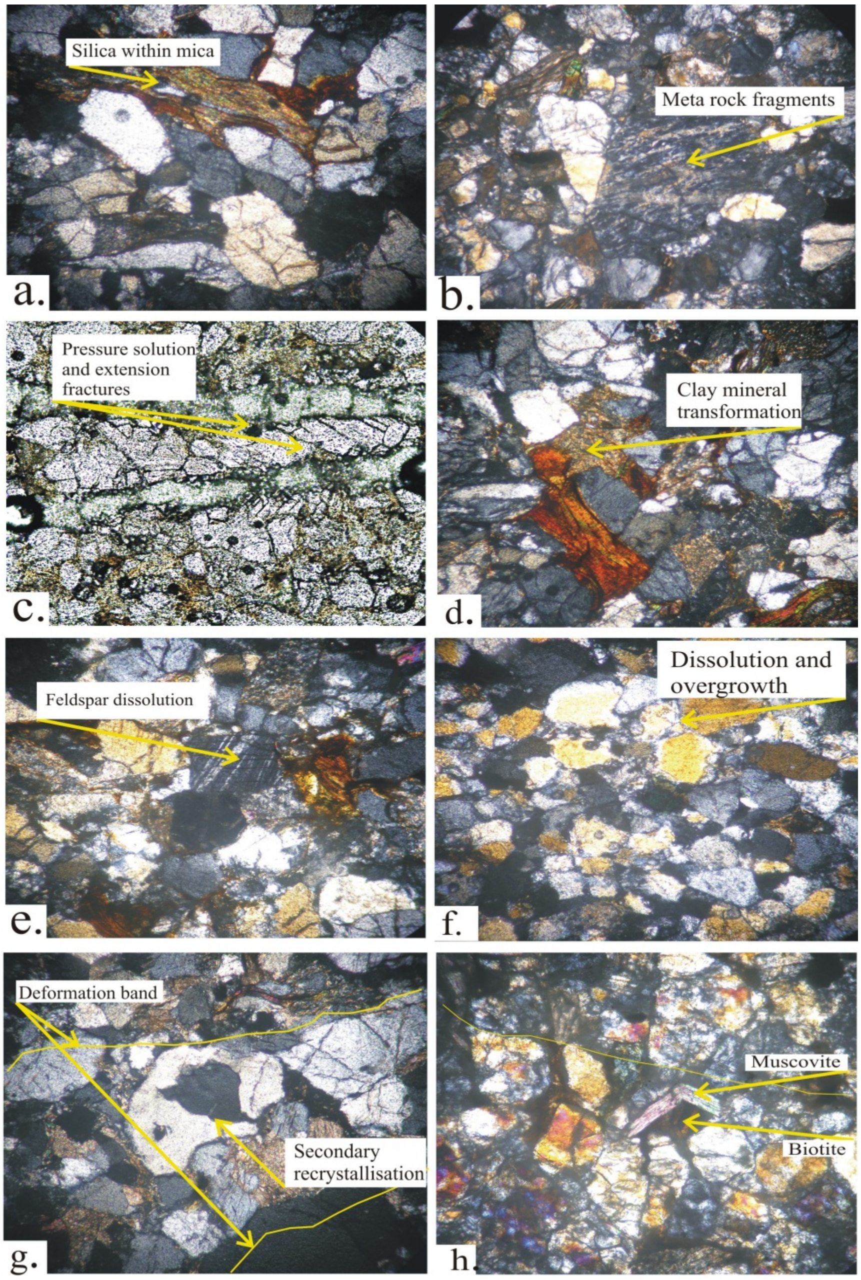


Fig.6. (a) Cleavage produced by pressure solution seams made the Dafla sandstone weakly foliated. Silica within mica is a later growth (b) and (c) Metamorphic rock fragments, pressure solution seams, and extension fractures in phyllites (d) Clay mineral transforming to authigenic mica (e) Secondary dissolution of silica along intra-grain fracture changes the grain orientation. Dissolution of the feldspar twin lamellae along the fracture. (f) Dissolution and overgrowth of quartz forming a triple junction (g) Deformation band showing secondary quartz growth within larger grain (h) Clay mineral transforming to biotite and muscovite. Muscovite shows kink banding (all photomicrographs cross polarized: 10X)

grains show slight variation in optical orientation (Fig.6. f). This illustrates quartz to quartz welding by siliceous cement and can be considered as the syntaxial crystallization.

Clay mineral transformation and ferrugineous cement weld the framework grains in quartz wacke of Dafla Formation (Fig.6.d). Cementation of quartz grains by iron oxide is an example of epitaxial growths. The clay matrix in the intergranular spaces transformed into authigenic clay minerals due to reaction with the mineralizing solutions flowing through the pores at the late stage of diagenesis.

Metamorphic rock fragments with detrital quartz grains are set in argillaceous matrix. The rock fragments show schistosity. Fractures in the grains formed under stress, which distorts the primary foliation and facilitates fluid migration to develop thick quartz lamellae in the lithic grains (Fig.6. b).The clay mineral transformation due to late stage of diagenesis liberates considerable amount of silica in solution and migrates to centers of low free energy conditions. The quartz lamellae within the diagenetic mica indicate this kind of silica precipitation (Figs 4 and 6).

**Development of compaction bands**

When the stress level increases porosity decreases. Under horizontal compression and low level of porosity, PCB will be transformed to Shear Enhanced Compaction Band (SECB). Compactional Shear Bands (CSB) are similar to SECB, but they are longer and they extend to underlying or overlying sandstone units (Fossen et al, ibid). Therefore, when the porosity is considerably reduced, the compaction becomes difficult and the deformation approaches a simple shear. Initially the permeability increases when the band frequency (both PC and SECB) increases. However, within the deformation bands, permeability shows a negative value. This indicates a porosity reduction within the deformation bands and so is the permeability especially within the deformation bands in comparison to the host rock.

PCB forms when the differential stress is at minimum and the yield stress is close to the mean stress. Therefore compaction is needed in the early part of the history of the formation of these bands. When the porosity is reduced considerably within the bands, the shearing becomes more prominent. Factors like mineralogy, grain size, grain shape and grain crushing strength also influence the porosity. At advance state of compaction the pressure solution surfaces/ seams are oriented ~45 $^{o}$ to the slip plane. This orientation indicates that at this advance stage of compaction, strain accumulates by approximately isochoric simple shearing. These deformation bands (CSB) show cm scale shear offsets and are more extensive than the SECB. In the Figs. 3and 4 different compaction bands are shown as a sketch and as developed in the Dafla and Subansiri sandstones in the area studied. It is important to note that pure compaction related instabilities can produce conjugate sets of discontinuities in relatively less porous sandstones at medium depth burial. These discontinuities may be symmetrical at the every stage of deformation with respect to the finite shortening $\lambda_3$ (Choukrune et al, 1987). We have used the term progressive deformation referring that the deformation cannot coaxial in true sense in local scale. This is because the scale enlargement of the stress regime indicates the involvement of local shear even at this stage. Therefore, even when the symmetry at the system boundary refers coaxial, the strain due to local shear gives another picture of non coaxiality.

Pressure solution is a phenomenon of rock water interaction, which (produces cleavage) does not have a yield strength (Engelder and Marshak, 1985). Pressure solution involves mass movement in fluid and can have local deposition or flow of fluid to other locals where dissolved material can be deposited as cements and veins. Diffusional mass transfer processes are strongly temperature dependant and generally takes place at low differential stress. However, volume and grain boundary diffusion are the important components of the pressure solution mechanism (Fig.6)

## Diagenetic microstructures

Low temperature deformation by grain scale crystal plasticity are observed in the form of deformation bands, undulatory extinction and subgrain formation by recrystallisation or crystal plastic strain (Fig. 6.g). These probably marks the upper limit of the low temperature deformation. On the other hand, the rotation of the grains produced weak foliations in phylitic rocks especially in Dafla Formation (Figs 6.b and c). Microscopic to mesoscopic kinks and crenulations of bedding observed in soft clays and shales of Dafla Formation indicating slip along the cleavage planes under enhanced load pressure (Figs. 5b and 6b). These are a special type of flexural slip folds in which the fold hinges have infinite curvature. This is because the radius of curvature equals to zero in these folds. Kinks form in multi layers with high viscosity contrast (sandstones and shales) and bonded contacts (i.e. high frictional resistance to sliding along the contacts. Compression parallel to the layers produces conjugate kink bends at 55 – 60$^o$ to the compression. Loading oblique to the layers (up to 30$^o$) produces asymmetric kink bands (Figs. 5.d and f).Weakly foliated cleavage planes are in fact solution cleavages as observed in the Figs.5.f and 6.a). Secondary intra -grain fracture changes the grain orientation and the dissolution of the feldspar twin lamellae along the fractures (Fig.6 e). Horizontal compression leading to foreland propagating thrust transportation also brought in extension fractures to develop even at the grain scale as observed in the Fig. 6. c.

## Conclusions:

1. In Dafla Formation, the frequency of deformation bands, pressure solution seams, kink bands and diagenetic differentiation are much more pronounced compared to Subansiri Formation in the present area.

2. Diagenesis and maturity of sediments can be correlated on the basis of the temperature dependant changes e.g. lignites in Subansiri and semi bright to bright coaly lenses (lignite-bituminous) in Dafla
3. Pure compaction related instabilities can produce conjugate sets of discontinuities in relatively less porous sandstones at medium depth burial. When the stress level increases porosity decreases. Therefore, when the porosity is considerably reduced, the compaction becomes difficult and the deformation approaches a simple shear.
4. Scope of further specific studies to understand the different generations of cementation history and timing of deformation at meso to microscopic scale is a prerequisite to understand the deformational and diagenetic environment.

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