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Status Report

Brittle and Ductile Deformational Structures in Tectonic Zones: The Research Trends in India

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We review the recent developments of structural geology in India, emphasizing the studies on brittle and ductile deformations in rocks. The Himalayan-Tibetan Mountain system has now become a focal point of tectonic studies, often leading to debatable, but exciting ideas and hypotheses. We provide a glimpse of the Indian contributions towards understanding of the structural processes, such as sequential thrusting, tectonic-surface process interactions and ductile extrusion in the Himalayan range. The Indian craton is crisscrossed by several continental-scale shear zones, marked by intense sheared rocks and intrusives. Some of these shear zones have reactivated later, giving rise to pseudotachylites implying generation of high frictional heat. We present a highlight of the work on these major ductile shear zones.

Key Words : Brittle and Ductile Deformation; Analog Experiments; Thrust Systems; Superposed Folding; Pseudotachylyte

Introduction

In recent years the mechanics of deformational processes has gained a renewed interest in structural geology, especially in view of their applications in interpreting complex structures encountered in the field. An important line of the current research takes a relooks at the shear zone structures with new kinematic and dynamic models. During early eighties the workers formulated a set of geometrical tools, e.g. asymmetric porphyroclast tails, pull-apart structures and fabric relations, to determine the shear sense (Ghosh, 1993, and references therein). Later studies suggest that a firm kinematic analysis needs a deeper understanding of the flow in ductile regimes, which include the flow laws, the mechanics of deformation localization and mechanical interactions of the structural elements (Twiss and Moores, 2007). Similarly, a number of classical problems, such as the estimation of finite strain, mechanics of tectonic fabrics, evolution of buckle fold and boudins have opened up new research fronts in the last couple of decades, inducting fresh theoretical and experimental methods.

A gamut of studies in structural geology deals with the processes of brittle deformation under varied geological conditions. Besides the basic rheological issue of brittle-ductile transitions, there are several topics of research emerging in the recent years, which indeed provide us a better insight of the brittle deformation processes and associated structures, e. g., growth of fractures, development of fault damage zones and fracture-induced deformation localization (Pollard and Fletcher, 2005).

The major trend in structural geology focuses upon the mechanics of crustal-scale brittle failure in extensional and convergent tectonic zones. Using analogue and numerical model experiments several groups investigated the styles of normal faulting in the formation of rift zones (e.g. McClay, 1990). These studies offer new interpretations of the mechanics of intra-continental sedimentary basins, like Gondwana basins in Indian craton. The major linear Gondwana basins: E-W-trending Son-Narmada Basins, NW-SE-trending Mahanadi Basins and NNW-SSE-trending Godavari Pranhita Basins, were earlier believed to have originated from rift-type tectonics (Biswas, 2003). Based on the intra-basinal fault architectures, e.g. cross-basin faults and the basin correlations, recent studies indicate that different Indian Gondwana basins have evolved through different tectonic settings, but maintaining a single kinematic framework (Chakraborty *et al*., 2003). Some of them are of pull-apart,

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Author for Correspondence : E-mail : nibirmandal@yahoo.co.in whereas some others are of rift origin. Similarly, in the recent literature we see a large volume of theoretical and experimental studies on the tectonics of Himalayan structures, leading to several new directions of research, like exhumation of the Higher Himalayan Crystallines, the thrust architectures and neotectonic movements (Law *et al*., 2006). Indian workers have significantly contributed to these developments in the Himalayan geology.

We have an excellent tradition of research with small-scale deformational structures, such as folds (Ghosh, 1966, 1968), superposed folds (Ghosh and Ramberg, 1968; Ghosh *et al*. 1992, 95), deformed lineations (Ghosh and Chatterjee, 1985), boudins (Sengupta, 1983; Mandal and Karmakar, 1989; Ghosh and Sengupta, 1999; Mandal *et al*., 1999). Structural geologists have used different types of theoretical and experimental methods to explain the small-scale brittle and ductile processes. Following the classical theory of Ramberg (1963) and Biot (1957), the mechanics of buckle folding has rejuvenated the interests of new-generation workers with the advent of numerical methods in structural geology. Using finite-element models the process of buckle folding is now relooked at with a view to more complex interactions of different factors, such as nonlinear rheology, initial geometrical perturbations and matrix anisotropy (Ramsay and Lisle, 2000). The method of anisotropic magnetic susceptibility (AMS) has opened a new ground to characterize the tectonic fabrics, especially which are physically unrecognizable (Borradaile and Henry, 1997). Similarly, Electron Back-Scatter Differaction (EBSD) is widely used to study intragranular deformations. Indian structural geologists of the present generation have led the research in the light of these new techniques and concepts.

The present note aims to portray the recent developments of structural geology in India.

The Himalayan Structures

One of the thrust areas in the Himalayan geology aims to model the mechanics of brittle and ductile shear zones. The reason of paying such an emphasis is that the shear zones have dictated several crucial tectonic processes in the Himalaya-Tibet Mountain system, such as the exhumation of deep-crustal materials, geomorphic manifestations, seismic activities and neotectonic movements. These dislocations occur on a wide range of scales, varying from a few millimetres to several kilometres. A number of workers have dealt with the geometry and kinematics of the Main Central Thrust (MCT), a crustal-scale shear zone separating the Lesser Himalayan (low-grade metamorphic) and the Higher Himalayan (high-grade metamorphic) rocks (Dubey *et al*., 2004; Dasgupta *et al*., 2004; Jain *et al*., 2005; Acharyya, 2007, Goswami *et al*. 2009). Estimates suggest that the MCT facilitated a large amount of horizontal shortening in the Himalaya. Srivastava and his coworkers have worked on this thrust zone in the Kumaun Garhwal Himalaya (Srivastava and Tripathy, 2005, 2007). They have investigated mesoscopic shear zones in areas close to MCT, such as Bhagirathi valley. Their kinematic analyses reveal that the shear zones have contrasting kinematics, showing sinistral strike-slip movements. From field mapping, the conjugate trends (NNE to ENE and NNW to WNW) of these shear zones have been deciphered using a statistical analysis of their orientations. Considering the bisectors of the conjugate orientations, they have shown the principal compression to be consistent with the regional convergence direction.

The exhumation process in the Higher Himalaya has remained a subject of great controversy over the last couple of decades. This controversy has recently geared up following a series of important publications that invoke new tectonic models, some of them buttressed by petrological evidences (e.g. Neogi *et al*., 1998). These studies mainly concentrate upon the exhumation of rocks, mechanically isolated between the Main Central Thrust (MCT) and the South Tibetan Detachment Zone (STDZ), though some of the recent studies have reported a petrological continuity across these structural dislocations (Dasgupta *et al*., 2009). The most popular, but quite controversial tectonic models postulates the exhumation process of the high-grade rocks like a mechanical fluid flow between two confined walls, widely known as Channel Flow Model (CFM). Some of the Indian structural geologists have dealt with the CFM to interpret the kinematic transitions across the N-S transects (Jain *et al*., 2005). Using analogue models, Mukherjee and Koyi (2010) have shown the extrusion patterns of ductile rocks from deep-crustal regions beneath the Tibetan plateau to the Higher Himalayas. A Newtonian viscous model has been proposed to show the velocity profile across the tectonic channel in their theoretical studies. Their model explains the kinematic transitions across the Higher Himalayan belt, from thrust movement along the MCT to extensional movement along the STDZ. On the same line of work, their studies have dealt with viscous dissipation, attributed to a number of ductile shear zones with simple shear movement (Mukherjee, 2012 a,b).

The structural evolution in the frontal Himalaya has now become a subject of special interest as it is a unique tectonic setting displaying a complex interplay between brittle and ductile deformational processes. Mukhopadhaya and Mishra (2005) have developed balanced cross-sections along different transects in the NW Himalaya. These sections provide an excellent account of the thrust sequences. The mechanics of FTBs in the Himalaya has remained a lively topic of research in India. Recent studies recognized a number of higher order thrust zones to explain local scale complexities in the structural architecture (Mukul *et al*., 2007, Mukul, 2010, Mullick *et al*., 2009).

In India, a few groups are actively engaged in scale-model experiments to investigate the mutual interactions between the tectonic and surface processes. Sandbox experiments Bose *et al*. (2009) have demonstrated the thrust spacing in FTBs as a function of the stability of tectonic wedges, which in turn depends on the basal friction. Higher basal friction leads the wedge to an unstable state, forming frontal thrusts with increasing spacing. In contrast, the wedges achieve a stable state for low basal friction, and the frontal thrusts progress with a uniform spacing. The experimental findings have been substantiated with the balanced cross-sections from the Subathu FTB in NW Himalaya. Bose and others have also shown the influence of surface erosion in out-off-sequence thrusting, especially under low-basal friction conditions, resulting in focused exhumation in the hinterland (Fig. 1; Bose and Mandal, 2010). The structural geology group of Lucknow University has used the sandbox experiments to demonstrate the evolution of intermontane basins in relation to the frontal thrusting (Agarwal and Agarwal, 2005).

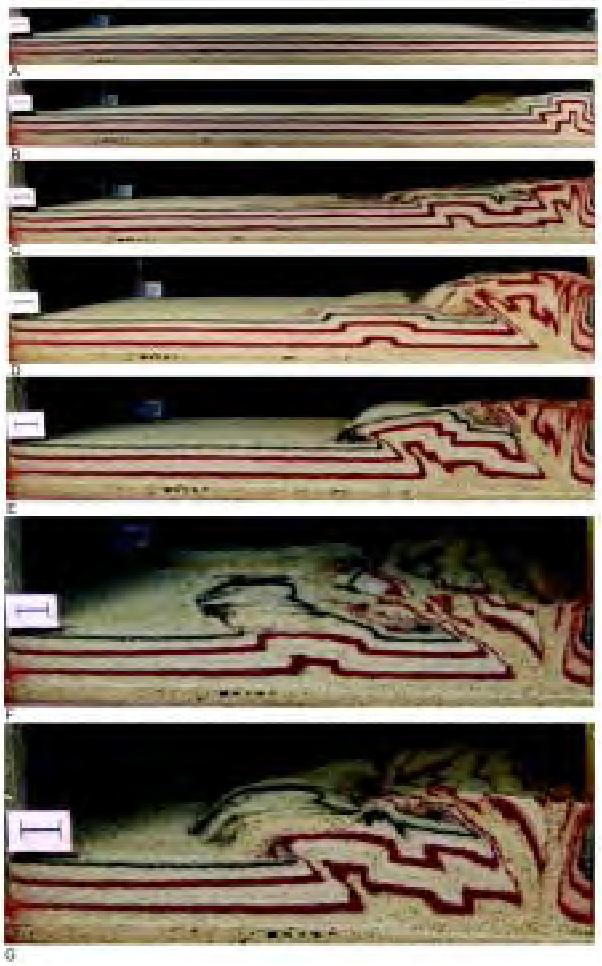

Fig. 1: **Progressive development of thrust structures under the influence of surface erosion in sandbox experiments. Note localization of out-of-sequence thrusts and focused exhumation in the hinterland**

Brittle and Ductile Shear Zones in the Indian Craton

The Indian craton is an excellent museum of crustal-scale ductile shear zones. To name a few, the Phulad shear zone in Delhi-Aravalli Mobile Belt, the Central Indian Suture in Central Indian Tectonic Zone, the Terrane Boundary Shear Zone in Eastern Ghats Mobile Belt, the Salem-Attur Shear Zone and the Palghat-Cauvery Shear Zone in the South Indian Granulite Belt constitute important tectonic zones, separating the cratonic masses in Indian Peninsula. The rocks in these zones are characteristics of extreme shearing forming mylonites (Fig. 2), indicating mostly the thrust-type movement. The Terrane Boundary Shear Zones in the Eastern Ghats Mobile Belt show gradational variations in the shear strain, as reflected from the different types of fabrics related to brittle-ductile and ductile shearing (Biswal *et al*., 2004). The S-C angles have developed from one wall to the other wall, and these allow estimating the magnitude of thrusting in the order of nearly 2 km. The granulite nappes produced during thrusting have undergone retrogression suggesting fluid activity accompanying shearing. A strain analysis indicates that the thrusting was associated with volume changes. Alkali intrusives of a nepheline syenite composition occur along the thrust. The magmatic foliations in the plutons show parallelism with mylonitic fabrics in the sheared host rocks, suggesting their synkinematic emplacement. The Salem-Attur Shear Zone

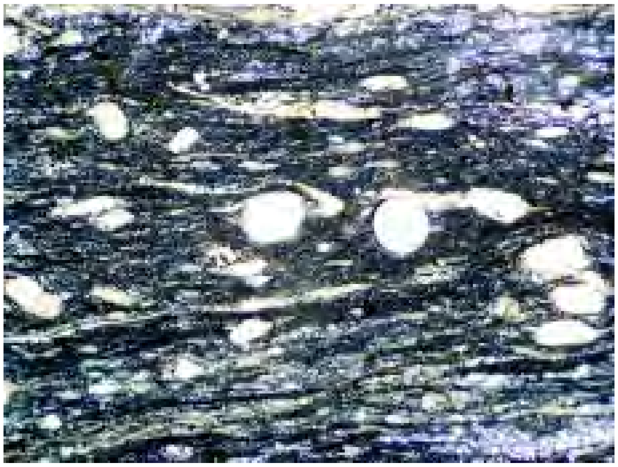

Fig. 2: **A typical example of mylonites indicating the sinistral shear sense. The photo was taken from an exposure in the Central Indian Tectonic Zone**

shows mylonites with prolific static recrystallisation (Biswal *et al*., 2009). The textural features of the mylonites probably owe to its deeper level origin, with post-shearing modifications at the elevated temperatures, similar to an isothermal decompression tectonic setting. The shear zones form an assembly of gently dipping shears, possibly representing a positive flower structure. The charnockite and granulites have been sliced off into several blocks, each representing a definite tectonic history. The pre-exisitng foliations have undergone reorientations due to a block rotation of the thrust slices. Eclogitic rocks are emplaced along some of the thrusts, suggesting deep-crustal exhumation along the suture. The Phulad shear Zone marks a zone of ductile shearing, and consists of number of parallel shear zones lying to the southern extremity of the Delhi belt. The folds in the amphibolites and granulites of the Delhi Belt have been rotated to various extents by the ductile shearing. Along this zone, the granulites have been exhumed in the form of a stack of northwesterly vergent blocks. The Central Indian Suture has piled up several granulite nappes, constituting the Central Indian Tectonic Zone. There are sedimentary belts within the zone, strongly modified by shearing movements. The southern granulite terrain (SGT) forms the southernmost part of the peninsular India characterized by the association of upper amphibolites and granulite facies lithologies. The SGT exposes two crustal-scale shear system popularly known as Cauvery Shear Zone (Chetty and Rao, 2006) and the Achankovil Shear Zone (Guru Rajesh and Chetty, 2006). The Cauvery Shear Zone is an east-west-trending tectonic zone that lies close to the southern margin of Archaean Dharwar Craton. The Achankovil Shear Zone trends NW-SE with a width of about 15km and extends more than 120 km along its strike.

Indian structural geologists have made fundamental contributions to the theoretical interpretations of complex shear zone structures (Fig. 3). For example, based on field observations from the shear zones in Singhbhum Proterzoic Mobile Belt and Kolar Schist Belts, Ghosh and Sengupta (1987) proposed a new kinematic model to show the development of strongly noncylindrical folds in progressive shear deformations, employing the mechanics of buckling in layered rocks. This model has been widely used in structural geology over more than two decades. The Jadavpur University group has continued the research around Phulad shear zone (PSZ) in Rajasthan. PSZ is a long narrow zone of intense deformation running in a northeasterly direction for several kilometres along the western margin of Delhi Mobile Belt. The northeasterly oriented mylonitic foliation has a steep southeasterly dip with a strong down-dip stretching lineation (Ghosh *et al*., 1999, 2003). Detailed analysis of the mesoscopic structures indicates that the deformation in the PSZ was transpressional (Sengupta and Ghosh, 2004). The mylonites show a prominent striping lineation, which is generally parallel to the stretching lineation. The striping lineations occur as fine colour stripes on foliation surfaces of strongly sheared mylonitic foliation in the PSZ. The colour stripes might have initiated at a very early stage of deformation as intersection of a bedding or a colour banding on the foliation surface. In later stages the bedding or the colour banding ceased to be reoriented by external rotation. The foliation became the only active S-surface, and deformation of the colour stripes are controlled entirely by the nature of strain. In strongly sheared rocks the nature of the original layering is greatly modified. Hence a colour striping can remain with very small width even when the foliation and bedding have become parallel. The lineation is transposed and retransposed in response to folding, sheath folding and strong stretching (Fig. 4, Sengupta and Ghosh, 2007). In spite of the complexities of deformation, the sense of shear can be determined from the asymmetry of folds and asymmetric tails of mesoscopic clasts, with a thrusting sense of movement. However, microstructural study of thin section perpendicular to the vorticity vector shows the rotation of a porphyroclast show contrasting sense of movement. This may reflect a complex type of progressive transpressional deformation. However, changing aspect ratios, slip at the clast-matrix interface, orientation of the microfaults in the megacrysts and the presence of microscopic isoclinal folds and sheath folds also create additional confusion during progressive rotation of a clast. In such a situation vorticity analysis of a transpresssional shear zone may not be meaningful (Sengupta and Mahato 2010). A systematic study along several transects across the unit was carried out to examine the state of deformation of the footwall and hanging wall. In the footwall side the coarse-grained granite changes from weakly deformed gneiss to a mylonite as we proceed towards the shear zone. The hanging wall rocks show three generations of reclined folds similar to PSZ. The similarity of the geometry of

Fig. 3: Two generations of reclined fold of Phulad shear zone

Fig. 4: U-shaped striping lineation parallel to first generation sheath fold on a limb of isoclinal second generation fold of Phulad shear zone

structures in the shear zone and its walls demonstrates that the wall rocks did not behave rigidly and the deformation of these units is broadly synchronous indicating thereby the transpressional nature of deformation (Mahato *et al*., 2010). After cessation of ductile shearing, when the rocks were uplifted to a shallower level, the area has suffered some deformation under brittle to brittle–ductile regime. This deformation has affected not only the sheared rocks but also rocks in both the hanging wall and footwall. There are three sets of faults identified in this region, viz. a conjugate set of strike-slip faults, thrust fault and a set of vertical faults (Mahato *et al*., 2010).

Chattopadhyay and Khasdeo (2011) investigated the kinematics of ductile shearing in Gavilgarh-Tan Shear Zone (GTSZ) – a prominent brittle-ductile shear zone in the southern part of Central Indian Tectonic Zone (CITZ). Using the vorticity gauges, e.g. Porphyroclast Hyperbolic Distribution method of Simpson and De Paor (1997), they have estimated the local kinematic vorticity number (W_k) in different parts of the shear zone, and predicted a transpressional system in the GTSZ with strain (and vorticity) partitioning at mesoscopic-to mapscale. Their analysis concludes that the GTSZ has evolved as a wrench (simple shear)-dominated ductile shear zone, flanked by two broad zones of pure shear showing steep orientation changes of stretching lineations. This transpression has been attributed to a phase of oblique collision during Meso-Neoproterozoic orogenesis in the CITZ.

Fault reactivation and its implications in the intra-continental seismicity, hydrocarbon reservoir etc. has been a subject of important research over the last decade. Following a series of recent earthquake events in the Indian craton, this research front, especially seismogenic fault reactivations has gained a fresh motivation. The Neo-Proterozoic reactivation has produced extensive pseudotachylite in the Central Indian Tectonic zone (CITZ) (Fig. 5) and other tectonic belts (Biswal *et al*., 2004). These are dark-coloured, fine-grained glassy rocks, which are considered to be a reliable indicator of seismic fault movement. The pseudotachylites contain clasts with a power-law size distribution, suggesting a melt origin of the pseudotachylites due to friction heating (Ray, 1999). The Structural Geology group at Delhi University has shown the formation of these pseudotachylites as a continued process of shearing movement along the CITZ. Chattopadhyay *et al*. (2008) have demonstrated that the granitic mylonites of GTSZ contain two generations of pseudotachylytes (Pt-M: interlayered with mylonite/ ultramylonite, and plastically deformed after their formation; and Pt-C: associated with cataclasites and internally undeformed), generally concordant with the mylonitic foliation in the host rock. Kinematic analyses showed that mylonites formed under high-temperature (T > 500°C) sinistral shearing at a depth of 15-20 km, followed by a dextral sense brittle-ductile shearing at shallower depth

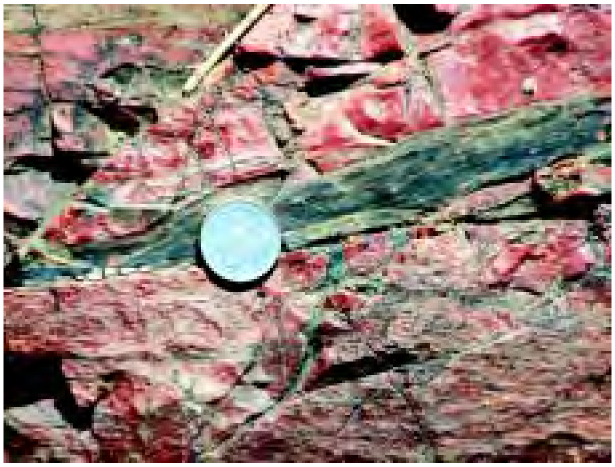

Fig. 5: Occurrence of pseudotachylites in the Central Indian Tectonic Zone. Note later ductile shear deformation within the pseudotachylites

(~11-15 km) that occasionally produced frictional melts along the foliation planes. These pseudotachylytes (Pt-M) were further plastically deformed during on-going shear. Finally, the zone underwent a sinistral brittle shear at a low temperature (~200°C), affecting the gneisses at a shallow depth. The switching of shear sense and decreasing depth of deformation indicates multiphase reactivation of the shear zone with gradual exhumation from depth to shallow level of the crust. Chattopadhyay and Holdsworth (2009) have documented for the first time a deformed pseudotachylyte vein, showing two distinct shear events (dextral shearing and resultant oblique foliation in Pt-M, overprinted by a sinistral kink folding related to later sinistral deformation genetically related to Pt-C, as discussed above).

Roy *et al*. (2008) reported thin, but persistent pseudotachylyte veins within a subvertical, sinistral shear zone at the eastern margin of the Chitradurga schist belt. The pseudotachylyte veins run sub-parallel or occasionally cut across the C-planes of mylonites and ultramylonites. Based on the field evidences, they proposed that the event of pseudotachylyte formation was synchronous to the mylonitization process in response to a catastrophic increase in the shear rate. Mahapatro *et al*. (2009) documented a similar structural association from the WNW-ESE-trending Mahanadi shear zone (MSZ) in the Eastern Ghats Mobile Belt (EGMB).

Ductile shearing of an interbanded litho-assemblage at high temperature produced mylonite and ultramylonite in an extensional-type shear zone. Pseudotachylyte occurs as melt-generating fault veins parallel to the mylonitic C-surfaces and extensional veins cut the foliation at high angle. Melting is evidenced by corroded grains, isotropic glassy phase, dendritic microlites etc. These pseudotachylytes show no ductile overprinting and are interpreted to have formed by brittle deformation post-dating the mylonitic rocks. An occurrence of tectonic pseudotachylyte has been reported from South Almora Thrust zone in Kumaun Lesser Himalayas (Agarwal *et al*., 2011). Pseudotachylyte veins occur within a zone of mylonites, and folded veins are also observed. The authors interpreted that melt was generated by movement of the thrust sheet, which cooled rapidly in contact with host rocks and formed thin pseudotachylyte veins.

Crustal shear localizations are potential zones of mineralization. Chattopadhyay (2010) has reviewed the structural characteristics of orogenic (lode-) gold deposits, with special reference to typical lode-gold deposits of India viz. Kolar, Hutti, Ajjanahalli and Gadag. Using the Mohr-Coulomb fracture criterion and Mohr diagram for stress, it has been shown that dilatant shear fractures (hosting the quartz-gold lode) have formed in the host rocks at different depths, where the fluid pressure facilitated the dilation of tensile fractures. The fluid pressure-induced cyclic fracturing (e.g. 'Fault-valve model' of Sibson *et al*., 1988) has been used to investigate Indian lode-gold deposits. The Kolar gold deposit is best found to fit this model.

Using theoretical and experimental approaches a group of structural geologists in India have dealt with the kinematics of ductile shear zones (Mandal *et al*., 2001; Dasgupta and Mandal 2011). One of the long-standing issues is concerned with the flattening movements in shear zones under constant volume conditions. Based on a continuum mechanical model, it has been shown that long, narrow shear zones, more commonly observed in nature, are unlikely to undergo significant transpression. However, there was no experimental support for this theoretical conclusion. Dasgupta and Mandal (2011) have recently confirmed it from simple analogue experiments.

Small-scale Structures as Kinematic Indicators

One of the major challenges in structural geology aims at establishing small-scale brittle or ductile structures that can be used as reliable kinematic indicators. A variety of tectonic elements, ranging from penetrative fabric to fractures have been targeted as the potential resources for kinematic analyses, and their applications involve rigorous theoretical and experimental tests, backed by field observations. This note presents an overview of this research by the structural geologists in India.

Over the last five years a number of structural geologists in India have been actively engaged in research concerning the fabric analyses and the processes associated with fabric development. These studies follow an integrated approach, taking into account the field evidence, microstructural observations and anisotropic magnetic susceptibility (AMS) analyses. Such an approach have been adopted to solve many complex structural issues, such as recognitions of multiple deformation episodes (Mamtani and Sengupta, 2010) and developing regional tectonic models for different terranes of India - Eastern Ghats Mobile Belt, Aravalli region as well as the Himalaya (Nagaraju *et al*., 2008; Majumder and Mamtani, 2009; Sen *et al*., 2005; Jayangondaperumal *et al*., 2010 a,b; Tripathi *et al*., 2011). Research has also been carried out on the deformation mechanism of magnetite in deformed granite by using anisotropy of anhysteretic remanence magnetization (AARM) data and microstructural investigations involving SEM-EBSD analysis (Mamtani *et al*., 2011). Fractal methods have been used to decipher the conditions of deformation and superposition of fabrics in naturally deformed rocks (Mamtani and Sengupta, 2010; Mamtani and Greiling, 2010). Apart from the above, fabric analysis using magnetic methods has been found to have implications in understanding of rock strength anisotropy as well as other physical properties (e.g., Vishnu *et al*., 2010).

The structural geology group at the IIT, Bombay performed several analytical and analogue models, aiming to decipher the deformation mechanism and ductile shear senses in a number of shear zones and the viscous dissipation related to simple shear (Mukherjee and Koyi 2010a,b; Mukherjee *et al*. 2010; Mukherjee 2011). They dealt with kinematically a number of important deformational features, such as pull-apart structures (Mukherjee and Chakraborty, 2007), flanking microstructures (Mukherjee and Koyi, 2009). Mukherjee (2011) has presented a morphological classification of mineral fishes that are often used as reliable shear sense indicators in ductile shear zones. His studies develop a new set of shear-sense indicators, e.g. trapezoid-shaped mica grains. Their current research focuses upon the mechanism of synkinematic mineral nucleation and intrafolial fold mechanisms.

The use of subsidiary fractures or deformation bands as shear sense indicators is a common practice in structural geology. Many workers have used Riedel shear bands and associated fabrics (called $C^{//}$ foliations) to evaluate the sense of shear in tectonic zones (Ramsay and Huber, 1987, Ghosh, 1993). Ghosh and Chattopadhyay (2008) conducted Riedel shear experiments with homogeneous wet-clay models to simulate surface fracture patterns occurring above a buried strike-slip fault under simple wrenching and transpressional deformation. They found that in wrench-type deformation, R-shears are found to form early (at low finite shear strain) in thin models and link with each other along the principal displacement shear (Y-shear) leading to a through-going fault, parallel to the buried master fault. Antithetic R’ shears form with R shears only in thick models, and under continued deformation two R’ shears join with an R shear to form a ‘penant-vein’ type structure that rotates bodily, opens up and finally looks like a sigmoidal vein with asymmetry antithetic to the bulk shear sense. Under transpression, high-angle R’ shears are cut by R shears in thin models and composite ‘Riedel-within-Riedel’ shears form in thick models with marked angularity between secondary faults and the master fault at depth.

Recent studies have dealt with the basic problems of Riedel shear formation in brittle-ductile shear zones (Mishra *et al*., 2009). According to the mechanics of shear failure, these are likely to form in conjugate sets, forming a low (~15º) and a high (~75º) angle with the shear zone boundary. In fact, the two sets of Riedel bands, called R_1 and R_2 (or R and R’) have been widely reported from field observations. On the other hand, many ductile shear zones contain only low-angle R shear bands, posing a question – how a single set of shear failure can occur in preference to their formation in conjugate sets. Using a set of physical experiments it has been demonstrated that the mechanical anisotropy plays a crucial role in controlling the single versus conjugate sets of Riedel shear. Increasing anisotropy promotes the low-angle shear bands, as observed in many natural shear zones.

Small-scale structures undergo significant modifications either in the course of a single progressive or successive phases of multiple deformation episodes. A line of research in structural geology is concerned with geometrical modifications of buckle folds by flattening strain. Field and experimental observations suggest that buckle folds in single layers initiate with Class 1B, which progressively transform into Class 1C due to intra-layer ductile strains (Ramsay, 1967). A group of structural geologists at the IIT, Roorke has been engaged over considerable time in the research of strain analysis. Their work intends to develop computational methods to use flattened folds for estimating bulk homogeneous strain in the rocks (Srivastava and Lisle, 2004; Srivastava and Shah, 2006). In addition, several workers have shown different other types of geological objects, e.g. elliptical markers, and demonstrated the geometrical methods of using them to determine the finite strain in geological fields (Ray and Srivastava, 2008, Dasgupta *et al*., 2012). Extremely flattened folds are frequently observed in ductile shear zones. The flattening leads to strongly noncylindrical fold geometry, which are called as sheath folds (Ghosh and Sengupta, 1987). There are some problems concerning the mechanics of flattening strain in a fold. Using numerical models it has been shown that folds cannot undergo large amounts of flattening in order to accentuate its hinge curvatures when the viscosity ratio is larger than 10. Furthermore, the initial sinuous geometrical perturbations (normalized to the wavelength) required for the development of noncylindrical geometry must be in the order of 10^{-1} (Mandal *et al*., 2009). Considering these mechanical constraints, a new genetic model has been proposed to explain the mechanics of hinge curvature accentuation, taking into account the role of hinge coalescence. The model has been substantiated with observations from simple analogue experiments.

Developing strain gauges is a classical, but fascinating area of research that dates back to sixties. Ramsay (1967) used linear objects, such as boudinaged belemnite fossils to estimate the magnitude of quadratic elongation as a function of their orientation. Using this method, it is possible to determine the total strain in deformed rocks. However, a basic question is – does the quadratic elongation estimated from a boudinaged object track the actual strain in the bulk rock? Later analogue experimental results suggest that the strains obtained from boudinaged objects significantly underestimate the actual bulk strain (Mandal *et al*., 2009). Different types of boudinage have been considered to test their reliability as strain gauges. Both analogue and numerical model experiments indicate that the shear fracture boudinage structures provide the best estimate for the bulk strain where the error remains less than 10%. Other types of boudinage can yield large errors, exceeding even 50%.

The mechanics of brittle deformations associated small-scale pre-existing cracks or fractures is a classical problem in structural geology and other fields, such as engineering geology. Recently, Misra *et al*. (2009) dealt with similar problems in the Chotanagpur Granite Gneissic Complex, where incipient shear fractures got reactivated during later deformations, resulting in deformation localization at their tips either in the form of dilatational tensile fractures or ductile shear bands. With the help of

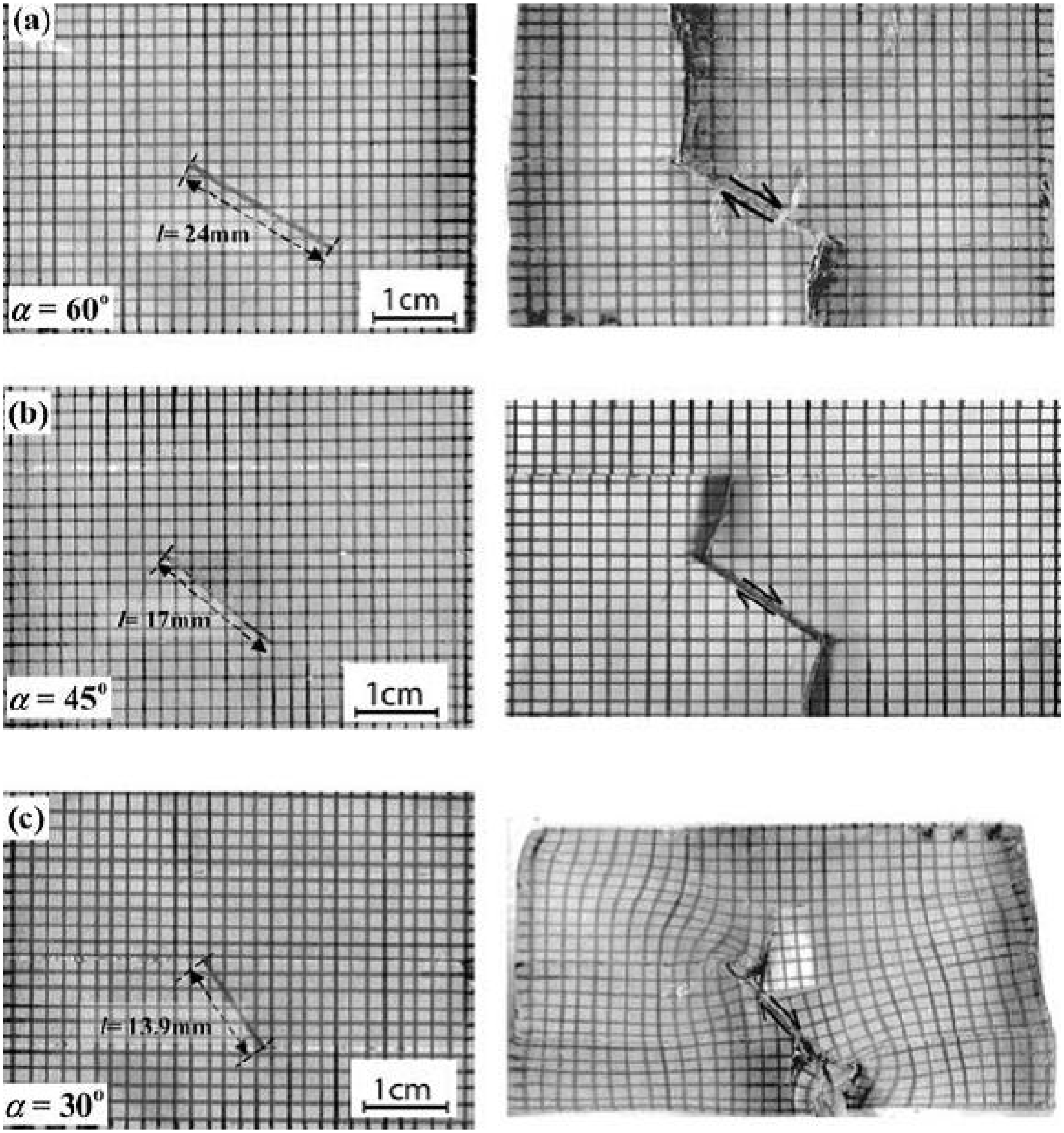

Fig. 6: Analogue experiments on PMMA models showing the brittle to ductile transitions in the deformations at the tips of initial shear fractures

elastic-plastic analogue models they have shown the modes of deformation localization varying from unstable tensile fractures to wing crack and then shear bands (Fig. 6). They have used finite-element models to explain this kind of brittle-to-ductile transition as a function of the orientation of initial shear fractures.

Understanding the rheology of geological materials is a one of the major challenges in the research of modern structural geology. A handful of continuum models prevail in the literature to describe the macroscopic rheology of rocks under specific conditions, e.g. rocks undergoing fractional melting, composite rocks consisting of hard objects and anisotropic rheology due to shape or lattice-preferred orientations of mineral grains. A line of rheological studies has developed in very recent time to characterize the mechanical properties of minerals using the quantum mechanics approach (Dutta and Mandal, 2012, a, b, c). Within the framework of density function theory the first-principle studies show the elastic properties of mineral phases, such as zircon, spinels and their high-pressure polymorphs. This theoretical approach has an advantage to quantify the mechanical anisotropy of mineral aggregates, which is an important parameter controlling the failure behaviour of rocks at high pressures.

Concluding Remarks

Over the last couple of decades the trend of structural geology has undergone a dramatic change, deflecting far away from the real-field observations and leaning heavily towards model-base studies, as lamented by Professor John Ramsay some years back (Ramsay, 1997). It is inevitable that the subject can offer an essence of the science the way it works in nature, not by our considerations only when the field information are extracted with a careful mind. The Indian continental mass is a natural museum with a huge repository of tectonic structures, encompassing virtually all the varieties the structural geologists need for their studies. The research trends that we have discussed in this note reflect that the structural geology in India provide robust field documentations, which constitute the fundamental basis for theoretical or experimental modeling.

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References

Acharyya, S. K., 2007. Evolution of the Himalayan Paleogene foreland basin, influence of its litho-packet on the formation of thrust-related domes and windows in the Eastern Himalayas – A review. Jour. Asian Earth Sci., v. 31, p.1-17.

Agarwal, K. K. and Agarwal, G. K., 2005. A genetic model of thrust-bounded intermontane basin using scaled sandbox analogue models: an example from the Karewa Basin, Kashmir Himalayas, India. Internat. Jour. Earth Sci., v. 94, p. 47-52.

Agarwal K.K., Sharma, A., Jahan, N., Prakash C. and Agarwal, A., 2011. Occurrence of pseudotachylytes in the vicinity of South Almora Thrust zone, Kumaun Lesser Himalaya. Curr. Sci., v. 101, p. 431-432.

Biot, M. A., 1957. Folding instability of a layered viscoelastic medium under compression. Proc. Roy. Soc. Lond., Ser. A, v.42, p. 444-454.

Biswal, T. K., Ahuja, H. and Sahu, H. S., 2004. Emplacement kinematics of nepheline syenites from the Terrane Boundary Shear Zone of the Eastern Ghats Mobile Belt, west of Khariar, NW Orissa: Evidence from meso- and microstructures. Jour. Earth System Sci., v.4, p.785-793.

Biswal, T. K., Sarkar, S., Pal, A. and Chakaraborty U. 2004. Pseudotachylites of the Kui-Chitraseni shear zones of the Precambrian Aravalli Mountain, Rajasthan. Jour. Geol. Soc. India, v. 64, p. 325-335.

Biswal, T. K., Thirukumaran, V., Kamleshwar, R. and Sundaralingam, K., 2009. Study of the Salem–Attur shear zone, east of Salem, Tamil Nadu: a new kinematic interpretation. Curr. Sci., v. 96, p. 1386-1389.

Biswas, S. K., 2003. Regional tectonic framework of the Pranhita-Godavari basin, India. Jour. Asian Earth Sci., v. 21, p. 543-551.

Borradaile, G. J. and Henry, B., 1997. Tectonic applications of magnetic susceptibility and its anisotropy. Earth-Sci. Rev., v. 42, p. 49-93.

Bose, S. and Mandal, N., 2010. Interaction of surface erosion and sequential thrust progression: Implications on exhumation processes. Jour. Geol. Soc. India, v. 75, p. 338-344.

Bose, S., Mandal, N., Mukhopadhyay, D.K. and Mishra, P., 2009. An unstable kinematic state of the Himalayan tectonic wedge: Evidence from experimental thrust-spacing patterns. Jour. Struct. Goel., v. 31, p. 83-91.

Chakraborty, C., Mandal, N. and Ghosh, S. K., 2003. Kinematics of the Gondwana basins of peninsular India. Tectonophysics, v. 377, p. 299-324.

Chattopadhyay, A. and Holdsworth, R. E., 2009. Photo-of-the-month: Ductilely deformed pseudotachylite layer in sheared granite of Gavilgarh-Tan Shear Zone, central India. Jour. Struct. Geol., v. 31, p. 353.

Chattopadhyay, A. and Khasdeo, L. 2011. Structural Evolution of Gavilgarh-Tan shear zone, central India: A possible case of partitioned transpression during Mesoproterozoic oblique collision within the Central Indian Tectonic Zone. Precamb. Res., v. 186, p. 70-88.

Chattopadhyay, A., Khasdeo, L., Holdsworth, R. E. and Smith, S. A. F., 2008. Fault reactivation and pseudotachylyte generation in the semi-brittle and brittle regimes: Examples from Gavilgarh–Tan shear zone, central India. Geol. Mag., v. 145(6), p. 766-777.

Chattopadhyay, A., 2010. A review of the structural Characteristics of orogenic gold deposits, with special reference to Indian gold fields. In: M. Deb and R.J. Goldfarb (Eds.). Gold Metallogeny: An Indian perspective. Narosa Publ. New Delhi & Alpha Science, Oxford, p. 123-153.

Chetty, T. R. K. and Bhaskar Rao Y. J., 2006. The Cauvery shear zone, southern granulite terrain, India : A crustal scale flower structure. Gond. Res., v. 10, p. 77-85.

Dasgupta, N., Mukhopadhyay, D. and Bhattacharyya, T., 2012. Analysis of superposed strain: A case study from Barr Conglomerate in the South Delhi Fold Belt, Rajasthan, India. Jour. Struct. Geol., v. 34, p. 30-42.

Dasgupta, S. and Mandal, N., 2011. Transpression in ductile shear zones under constant volume condtions: Estimates from analogue experiments. Abstract in GSA Annual Meeting 2011, USA.

Dasgupta, S., Ganguly, J. and Neogi, S., 2004. Inverted metamorphic sequence in the Sikkim Himalayas: Crystallization history, P–T gradient and implications. Jour. Met. Geol., v. 22, p. 395-412.

Dasgupta, S., Chakraborty, S. and Neogi, S., 2009. Petrology of an inverted Barrovian sequence of metapelites in Sikkim Himalaya, India: Constraints on the tectonics of inversion. Amer. Jour. Sci., v. 309, p. 43-84.

Dubey, A. K., Bhakuni, S. S. and Selokar A. D., 2004. Structural evolution of the Kangra recess, Himachal Himalaya: a model based on magnetic and petrofabric strains. Jour. Asian Earth Sci., v. 24, p. 245-258.

Ghosh, S. K., 1966. Experimental tests of buckling folds in relation to strain ellipsoid in simple shear deformation. Tectonophysics, v. 3, p. 169-185.

Ghosh, S. K., 1968. Experiments on buckling of multilayers which permit multilayer gliding. Tectonophysics, v. 6, p. 207-249.

Ghosh, S.K., 1993. Structural Geology: Fundamentals and modern developments. Pergamon Press. 598p.

Ghosh, S. K. and Chatterjee, A., 1985. Patterns of deformed early lineations over late folds formed by buckling and flattening. Jour. Struct. Geol., v. 7, p. 651-666.

Ghosh, S. K. and Ramberg, H., 1968. Buckling experiments on intersecting fold patterns. Tectonophysics, v. 5, p. 89-105.

Ghosh, S.K. and Sengupta, S., 1987. Progressive development of structures in a ductile shear zone. Jour. Struct. Geol., v. 9, p. 277-288.

Ghosh, S.K. and Sengupta, S., 1999. Boudinage and composite boudinage in superposed deformations and syntectonic migmatization. Jour. Struct. Geol., v. 21, p. 97-110.

Goswami, S., Bhowmik, S.K. and Dasgupta, S., 2009. Petrology of a non-classical Barrovian inverted metamorphic sequence from the western Arunachal Himalaya, India. Jour. Asian Earth Sci., v. 36, p. 390-406.

Ghosh, S.K., Hazra, S. and Sengupta, S., 1999. Planar, non-planar and refolded sheath folds in Phulad shear zone, Rajasthan, India. Jour. Struct. Geol., v. 21, p. 1715-1729.

Ghosh, S. K., Khan, D. and Sengupta, S., 1995. Interfering folds in constrictional deformation. Jour. Struct. Geol., v. 17, p. 1361-1373.

Ghosh, S.K., Sen, G. and Sengupta, S., 2003. Rotation of long tectonic clasts in transpressional shear zones. Jour. Struct. Geol., v. 25, p. 1083-1096.

Ghosh, S. K., Mandal, N., Khan, D. and Deb, S., 1992. Modes of superposed buckling in single layers controlled by initial tightness of early folds. Jour. Struct. Geol., v. 14, p. 381-394.

Ghosh, N. and Chattopadhyay, A., 2008. The initiation and linkage of surface fractures above a buried strike-slip fault: an experimental approach. Jour. Earth Syst. Sci. 117, 23-32.

Jain, A.K., Manickavasagam, R.M., Singh, S. and Mukherjee, S., 2005. Himalayan collision zone: New perspectives- its tectonic evolution in a combined ductile shear zone and channel flow model. Himal. Geol., v. 26 (1), p. 1-18.

Jayangondaperumal, R., Dubey, A. K., Kumar, B. S. Wesnousky S. G. and Sangode S. J., 2010a. Magnetic fabrics indicating Late Quaternary seismicity in the Himalayan foothills. Internat. Jour. Earth Sci., v. 99(1), p. 265-278.

Jayangondaperumal, R., Dubey, A. K. and Sen, K., 2010b. Mesoscopic and magnetic fabrics in arcuate igneous bodies: An example from the Mandi-Karsog pluton, Himachal Lesser Himalaya. Geol. Mag., v. 147, p. 652-664.

Law, R. D., Searle, M. P. and Godin, L., 2006. Channel Flow, Ductile Extrusion and Exhumation in Continental Collision Zones. Geol. Soc. Spl. Pub., 268p.

Mahapatro, S.N., Tripathy, A.K., Nanda, J.K. and Roy, A., 2009. Coexisting ultramylonite and pseudotachylyte from the eastern. segment of the Mahanadi Shear Zone, Eastern Ghats Mobile Belt. Jour. Geol. Soc. India, v. 74, p. 679-689.

Mahato, S., Roy Chowdhury, M., Darker, M. and Sengupta, S., 2010. Transitional stages of wall rock deformation of Phulad Shear Zone, Rajasthan. Abstract volume, p. 65, National Conference on “Rock Deformation and Structure” at Jadavpur University, 29th to 31st Oct, 2010.

Majumder, S. and Mamtani M. A., 2009. Magnetic fabric in the Malanjkhand Granite (Central India)—Implications for regional tectonics and Proterozoic suturing of the Indian shield. Phys. Earth Planet. Interior, v. 172, p. 310-323.

McClay, K. R. 1990, Extensional fault systems in sedimentary basins: A review of analogue model studies. Mar. Petrol.Geol., v. 7, p. 206-233.

Mamtani, M. A., Piazolo, S., Greiling, R. O., Kontny and František Hrouda, A., 2011. Process of magnetite fabric development during granite deformation. Earth and Planet. Sci. Lett., v. 308, p. 77-89.

Mamtani, M. A. and Sengupta P. 2010. Significance of AMS analysis in evaluating superposed folds in quartzites. Geol. Mag., v. 147, p. 910-918.

Mandal, N. and Karmakar, S., 1989. Foliation boudinage in homogeneous foliated rocks. Tectonophysics, v. 135, p. 133-153.

Mandal, N., Chakraborty, C. and Samanta, S.K., 1999. Boudinage in multilayered rocks under layer-normal compression: A theoretical analysis. Jour. Struct.Geol., v. 22, p. 373-382.

Mandal, N., Chakraborty, C. and Samanta, S.K., 2001. Flattening in shear zones under constant volume: A theoretical evaluation. Jour. Struct. Geol., v. 23, p. 1771-1780.

Mandal, N., Mitra, A. K., Sarkar, S. and Chakraborty, C., 2009. Numerical estimation of the initial hinge-line irregularity required for the development of sheath folds: A pure shear model. Jour. Struct. Geol., v. 31, p. 1161-1173.

Misra, S., Mandal, N., Dhar, R. and Chakraborty, C., 2009. Mechanisms of deformation localization at the tips of shear fractures: Findings from analogue experiments and field evidence. Jour. Geophys. Res., Solid Earth, v. 114, p. 18.

Mukherjee, S., 2011. Mineral Fish: their morphological classification, usefulness as shear sense indicators and genesis. Internat. Jour. Earth Sci., v. 100, p. 1303-1314.

Mukherjee, S., 2012. Simple shear is not so simple! Kinematics and shear senses in Newtonian viscous simple shear zones. Geol. Mag. (In Press).

Mukherjee, S. and Chakraborty, R., 2007. Pull-apart micro-structures and associated passive folds. In: J. Aho (Ed), Ann. Trans. of the Nordic Rheology Soc., v. 15, p. 247-252. 16th Nordic Rheology Conference, Stavanger, Norway, June 13-15, 2007.

Mukherjee, S. and Koyi H. A., 2009. Flanking Microstructures. Geol. Mag., v. 146, p. 517-526.

Mukherjee, S. and Koyi H. A., 2010a. Higher Himalayan Shear Zone, Zanskar Section-Microstructural studies & extrusion mechanism by a combination of simple shear & channel flow. Internat. Jour. Earth Sci., v. 99, p. 1083-1110.

Mukherjee, S. and Koyi, H. A., 2010b. Higher Himalayan shear zone, Sutlej section: Structural geology and extrusion mechanism by various combinations of simple shear, pure shear and channel flow in shifting modes. Internat. Jour. Earth Sci., v. 99, p. 1267-1303.

Mukherjee, S., Talbot, C. and Koyi, H. A. 2010. Estimating the viscosities of two salt diapirs in the Persian Gulf: Hormoz & Namakdan. Geol. Mag., v. 147, p. 497-507.

Mukhopadhyaya, D. K. and Mishra, P., 2005. A balanced cross section across the Himalayan frontal fold-thrust belt, Subathu area, Himachal Pradesh, India: Thrust sequence, structural evolution and shortening. Jour. Asian Earth Sci., v. 25, p. 735-746.

Mullick, M., Riguzzi, F. and Mukhopadhay D., 2009. Estimates of motion and strain rates across active faults in the frontal part of eastern Himalayas in North Bengal from GPS measurements. Terra Nova, 21, 410-415.

Mukul, M., 2010. First-order kinematics of wedge-scale active Himalayan deformation: Insights from Darjiling–Sikkim–Tibet (DaSiT) wedge. Jour. Asian Earth Sci., v. 39, p. 645-657.

Mukul, M., Jaiswal, M. and Singhvi, A. K., 2007. Timing of recent out-of-sequence active deformation in the frontal Himalayan wedge: Insights from the Darjiling sub-Himalaya, India. Geology, v. 35, p. 999-1002.

Nagaraju, J., Chetty, T.R.K., Vara Prasad, G.S. and Patil, S.K., 2008. Transpressional tectonics during the emplacement of Pasupugallu Gabbro Pluton, western margin of Eastern Ghats Mobile Belt, India: Evidence from AMS fabrics. Precamb. Res., v. 162, p. 86-101.

Neogi, S., Dasgupta, S. and Fukuoka, M., 1998. High P-T polymetamorphism, dehydration-melting, and generation of migmatites and granites in the Higher Himalayan crystalline complex, Sikkim, India. Jour. Petrol., v. 39, p. 61-99.

Pollard, D. D. and Fletcher, R. C., 2005. Fundamentals of structural geology. Cambridge University Press. 503p.

Ramberg, H., 1963. Strain distribution and geometry of folds. Bull. Geol. Inst. Univ., Uppsala, v. 42, p.1-20.

Ramsay, J. G. 1967. Folding and Fracturing of Rocks. MacGraw-Hill, NY, 568p.

Ramsay, J. G. and Huber, M. I., 1987. The Techniques of Modern Structural Geology, Volume 2: Folds and Fractures. Academic Press.

Ramsay, J.G., 1997. The geometry of a deformed unconformity in the Caledonides in the NW Scotland. In: Evolution of Geological Structures in Micro- to Macro-scales (*Ed:* S. Sengupta). Chapman and Hall, London, p. 445-472.

Ramsay, J. G. and Lisle, R. J., 2000. The Techniques of modern structural geology, Volume 3: Applications of Continuum Mechanics in Structural Geology. Academic Press.

Ray, A. and Srivastava, D. C., 2008. Non-linear least squares ellipse fitting using the genetic algorithm with applications to strain analysis. Jour. Struct. Geol., v. 30 (12), p. 1593-1602.

Roy, A., Sengupta, S. and Mandal, A., 2008. Synchronous development of mylonite and pseudotachylyte in ductile shear zone: An example from the Chitradurga Eastern Margin Shear zone, Karnataka. Jour. Geol. Soc. India, v. 72, p. 447-457.

Sen, K., Majumder, S. and Mamtani, M.A., 2005. Degree of magnetic anisotropy as a strain intensity gauge in ferromagnetic granites. Jour. Geol. Soc. London, v. 162, p. 583-586.

Sengupta, S. 1983. Folding of boudinaged layers. Jour. Struct. Geol., v. 5, p. 197-210.

Sengupta, S. and Ghosh, S.K., 2004. Analysis of transpressional deformation from geometrical evolution of mesoscopic structures from Phulad shear zone, Rajasthan, India. Jour. Struct. Geol., v. 26, p. 1961-1976.

Sengupta, S., and Ghosh, S.K., 2007. Origin of striping lineation and transposition of linear structures in shear zones. Jour. Struct. Geol., v. 29, p. 273-287.

Sengupta, S. and Mahato, S., 2010. Problem of vorticity analysis from rotating porphyroclast in a transpressional ductile shear zone. Abstract volume, p.76, National Conference on “Rock Deformation and Structure” 29th to 31st Oct, 2010, Jadavpur University.

Sibson, R.H., Robert, E. and Poulsen, K.H., 1988. High-angle reverse faults, fluid pressure cycling, and mesothermal goldquartz deposits. Geology, v. 16, p. 551-555.

Simpson, C. and De Paor, D.G., 1997. Practical analysis of general shear zones using the porphyroclast hyperbolic method: An example from the Scandinavian Caledonides. In: S. Sengupta (Ed.), Evolution of Geological Structures in Micro-to Macro-scales. Chapman and Hall, London, p.169-184.

Srivastava, D. C. and Shah, J., 2006. A rapid method for strain estimation from flattened parallel folds. Jour. Struct. Geol., v. 28, p.1-8.

Srivastava, D. C. and Lisle, R. J., 2004. Rapid analysis of fold shape using Bézier curves. Jour. Struct. Geol., v. 26, p. 1553-1559.

Srivastava, H. B. and Tripathy, N. R., 2005. Shear zone structures from the Main Central Thrust Zone of the Joshimath area, Garhwal Himalaya. Proc. National Seminar on Himalayan Orogeny-Foreland interaction, Paleont. Soc. India, no.2, p. 53-64.

Srivastava, H. B. and Tripathy, N. R., 2007. Geometrical analysis of mesoscopic shear zones in the crystalline rocks of MCT zone of Garhwal Higher Himalaya. Jour. Asian Earth Sci., v. 30, p. 599-612.

Tripathi, K., Sen, K. and Dubey, A. K., 2011. Modification of fabric in pre-Himalayan granitic rocks by post-emplacement ductile deformation: Insights from microstructures, AMS, and U–Pb geochronology of the Paleozoic Kinnaur Kailash Granite and associated Cenozoic leucogranites of the South Tibetan Detachment zone, Himachal High Himalaya. Internat. Jour. Earth Sci., v. 101, p. 761-772.