Status of Research in Structural Geology; the Indian Scene During the Last Five Years

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During the last five years, research in Structural Geology has seen multifarious developments. Experimental and numerical simulations extended our knowledge on deformation pattern of the Earth’s crust, especially on various types of folding mechanisms and strain distribution in shear zones. Experiments on fluid mechanics provided an understanding of the ascent of diamond-bearing kimberlitic magma, the ascent path and geometry of plumes. Study of Anisotropy of Magnetic Susceptibility has come out as a powerful tool to explain strain pattern and quantitative vorticity in deformed rocks, structural control on gold mineralization and in microfracture geometry of impact craters as applied to the Lonar Crater in western India. Regional studies on the Himalaya, Eastern Ghats Mobile Belt, South India, Central India, Rajasthan, and Eastern India advanced our knowledge on crustal deformation pattern, tectonics and assembly of continents, basement structures, fold growth kinematics, thrust-sheet movement and shearing mechanism. Radiometric dates have been estimated from a number of rocks especially to understand the timings of deformation and mineral formation. Palaeostress estimation unravels the stress regime of some geologically significant areas and basins across the country.

Keywords: Stress; Strain; Shock Pressure; Numerical Simulation

Experimental and Numerical Simulations

Shear zones and thrust development continued to draw attention for understanding the nature and distribution of deformation in the Earth crust. Using a combination of physical and numerical modelling, Bose et al. (2014) explore the factors that control localization of thrust initiation and the geometry of tectonic wedges. Some other important studies address the issues of the spatial variations in imbricate thrusting (Saha et al., 2012) and the 3D-geometry of thrust slices and tectonic wedges (Chattopadhyay et al., 2014). Using finite element modelling, Samanta and Deb (2014b) show that unequal mineral transformation rates along the length and width control development of fish-mouth boudins. Role of lower crustal flow, crustal scale compositional variation and mechanical properties of basal décollement surface in the evolution of mountain topography have been studied during the last five years (Mandal et al., 2015). Bose et al. (2015) investigated the possible influence of horst-and-graben structure in the evolution of accretionary wedges. These researches reveal the controlling factors in strength-variation across terrane boundaries in continents.

Analogue modelling has thrown new light on the influence of pure/simple shear ratio in transpressional system, the mechanism of superposed folding and the effect of mechanical anisotropy in deformation. Well constrained experiments by Ghosh et al. (2014) demonstrate development of folds and strain...
distribution pattern in unconfined and/or partitioned transpression. Using numerical and analogue models, Dasgupta et al. (2016) have shown that the influence of pure shear component in a transpressional system decreases non-linearly with increasing the aspect ratio of a shear zone. Their experimental findings suggest that deformation always approaches to simple shear type, i.e., bulk kinematic vorticity ~ 1, for shear zones with large aspect ratios, despite the presence of pure shear component. Bose et al. (2014a) attribute superposed folding as the mechanism for development of the multi-ordered dome-and basin structures, e.g., higher-order Rangit Dome, nested within lower-order Sikkim Dome in the Northeast Himalaya. Chattopadhyay et al. (2014b) elucidate the role of pre-existing anisotropy in the basement rocks in development of extensional fault systems. Misra et al. (2015) highlight the effects of lithostatic pressure and temperature in controlling the style of shear localization around rigid inclusions. Such studies explain the dominance of ductile shear zones in deep-crustal metamorphic rocks containing rigid inclusions, such as, garnet and feldspar porphyroclasts.

Experiments on fluid mechanics reveal that the buoyancy and the viscosity ratio between the ascending fluid and the ambient fluid control the nature of fluid ascent, i.e., continuous or pulsating (Baruah et al., 2013). It has also been possible to experimentally estimate the rate of fluid ascent in diamond bearing kimberlite magma and its role in the dynamics of vertical fracturing- the avenues for the magma transport. Simulation of geometrically varied plumes, rising through different fluid media, shows that the convergence of flow along the ascent paths controls the plume geometry which, in turn, depends on the viscosity ratio between the plume and the ambient fluid phase (Dutta et al., 2014).

The potential of Anisotropy of Magnetic Susceptibility (AMS) has been successfully used for estimation of strain and quantification of the vorticity in deformed rocks (Mamtani, 2014). It is now well known that the strain patterns in shear zones assume complexity with variation in the bulk kinematic vorticity. The scope of AMS studies is further extended to identification of the structural controls on gold mineralization in south India (Mamtani, 2014; Renjith and Mamtani, 2014; Mondal and Mamtani, 2014). In a novel study, Agarwal et al. (2016) use a combination of the AMS, the microfacture geometry and the numerical modelling for estimation of the lower limit of shock pressure in an impact crater. This study reveals that the pristine craters, such as the Lonar Crater in western India, can develop at shock pressure as low as 0.2-0.5 GPa.

Numerical modelling of two- or more- phase systems has considerably improved our understanding of geodynamics. Sarkar et al. (2014) show that the random thermal perturbations occur below the Mid-Oceanic Ridge (MOR). This process leads to magmatic upwelling that triggers the ridge offset in the active tectonic zone and results into segmentation along the Mid Oceanic Ridge. Numerical and computer graphic simulations are powerful tools in development of new methods for stress and strain estimation in rocks. Reddy and Srivastava (2012) propose a new Image analysis method for rapid estimation of strain from the Fry plots. Extensive comparison of different objective variants of the Fry method by Kumar et al., (2014) shows that the Continuous Function Method of Waldron and Wallace (2007) and the Delaunay Triangulation method of Mulchrone (2003) give most accurate finite strain estimates from the Fry plots. Numerical and graphical approaches have been developed for deciphering strain partitioning in Barr conglomerate (Dasgupta et al. 2012). Mondal and Mamtani (2013) use 3-D Mohr circles for recognition of fluid pressure fluctuation.

**Regional Studies**

We identify the following regions where significant work has been carried out: Himalaya, Eastern Ghats Mobile Belt, South India, Central India, Rajasthan and Eastern India.

**Himalaya**

Insights into the mechanical basis for the crustal deformation and the growth of active mountain belt have been the major foci of studies in the Himalaya during last five years (Mugnier et al., 2013; Banerjee et al., 2015). Several contributions address the issues related to topographic variations (Barnes, et al., 2011; Mandal et al., 2015), basement structure (Sen et al., 2015; Srivastava, 2011), spatial disposition of crustal scale thrusts (Bose et al., 2014), and ductile structures in the Himalayan belts. Mechanics of development of brittle and ductile structures has also been explored.
by analogue and numerical modelling (Bose et al., 2014, Mandal et al., 2015). Salient points of studies in the three major lithotectonic subdivisions of the Himalaya are highlighted below:

**Sub-Himalaya**

Sub-Himalaya, the youngest lithotectonic division in the Himalaya, bounded between the Himalayan Frontal Thrust in the south and the Main Boundary Thrust in the north, shows abundant evidence of active deformation (Thakur, 2013). In Himalayan frontal zone, the fold growth kinematics produces high slip rates, weak uplifting of rocks and rapid erosion (Barnes et al., 2011; Mishra and Mukhopadhyay, 2012; Philip et al., 2014). The damage zone of the Main Boundary Thrust (MBT) consists of the imbricate domains that bear the imprints of coaxial refolding and subsequent modification of the folds into sheath-like structures in parts of the Kumaun Himalaya (Shah et al., 2012). Detailed mapping coupled with geometric, kinematic and dynamic structural analysis of the fault zone structures reveal that the MBT represents a sinistral transpressional zone that is partitioned into contractional and wrench domains in Amritpur area, Kumaun Himalaya (Shah et al., 2012). This study also infers an oblique/lateral ramp in the MBT in the Gola river section. Using the soft-sediment deformation structures in the Neogene sediments of the Sub-Himalaya as dynamic archives, Mishra et al., (2013) show that the MBT in Kumaun Himalaya was reactivated during the late Pliocene-early Pleistocene period. Similar soft-sediment deformation structures have also been reported in the Middle Siwalik rocks near MBT in the Sikkim Sub-Himalaya (Kundu et al., 2011).

**Lesser Himalaya**

Most studies in the Lesser Himalaya have focused on understanding the processes of deformation and thrust-sheet movement (Srivastava et al., 2011). A report of pseudotachylite within the South Almora Thrust indicates friction-related heating during the thrust sheet propagation (Agarwal et al., 2011). The brittle structures in the footwalls of the Ramgarh thrust are interpreted as normal faults in the Kumaun Lesser Himalaya (Pant et al., 2012). Bhattacharyya and Ahmed (2016) suggest a direct correlation between the initial width of the Lesser Himalayan sequence and the total minimum shortening recorded in the Himalayan fold-thrust belt. This study also implies that the initial width of the Lesser Himalayan sequence varied laterally.

Tectonostratigraphic units of the Proterozoic Lesser Himalayan sequence (LHS) in north-eastern Himalaya, namely, the Daling Group in Sikkim and the Bomdila Group in Arunachal Pradesh, are studied comprehensively (Saha, 2013). These contributions aim at understanding the nature and extent of Proterozoic passive margin sedimentation, their involvement in pre-Himalayan orogeny and their implications in supercontinent reconstruction. It is deciphered that multiple fold sets and tectonic foliations in the LHS were formed during partial or complete closure of the sea/ocean along the northern margin of Paleoproterozoic India. The older deformation and metamorphism is ascribed to a Paciûc type accretionary orogeny that affected the northern margin of greater India.

**Higher and Tethys Himalaya**

The Deep crustal deformation processes and their role in evolution of the Higher Himalaya have been studied in the Main Central Thrust and the Higher Himalayan crystalline rocks. Some parts of the adjoining Karakoram range have also been studied for a more complete understanding of structure and tectonics of the Himalayan mountain belt. Various micro-structures vis-à-vis brittle-ductile deformation processes are identified and used for understanding the tectonic evolution of the MCT and the Karakoram fault (Bhattacharyya and Mitra, 2014; Moharana et al., 2013; Sen et al., 2012 and Sen et al., 2014). That the strain softening played an important role in ductile deformation along the MCT in eastern Darjeeling-Sikkim Himalaya is demonstrated by Bhattacharyya and Mitra (2011). In a complementary study, Verma and Bhattacharya (2015) attribute the orientational variation of linear structures to the progressive rotation towards the direction of bulk shear along the MCT. Using thermochronological data, Singh et al. (2012) infer an in-sequence thrust propagation in the Central Himalaya. Moharana et al. (2013) point out the practical limitations in demarcation of the Vaikrita Thrust and argue for the redesignation of the Munsiari Thrust as the Main Central Thrust. Detailed structural studies across the Main Central Thrust and the Southern Tibetan Detachment System in the
Alaknanda and Dhauli Ganga valleys, reveal structurally controlled migmatisation and two phases of shear deformation: (a) an older top-to-SW thrust phase throughout the HHC, and (b) a younger top-to-NE downwards normal fault phase in the middle and upper parts (Jain et al., 2013, 2015; Shreshtha et al., 2015). Lahoti et al. (2016) trace the geometry of superposed folding and deformation history in the Chamba nappe. Summarising different lines of evidence, Jain (2016) proposes that the tectonic evolution of the Himalaya occurred due to a repeated sequential subduction and imbrication and associated exhumation of the Indian continental lithosphere.

Analogue models have been used to explain the extrusion process in the Higher Himalayan shear zone in a broader framework of the Himalayan tectonics (Mukherjee, 2012, 2013; Mukherjee et al., 2015). In the continuity, a combined flow and critical taper wedge mechanism is proposed for extrusion of the Greater Himalayan Crystalline slab. As a by-product of flow modelling, a few rheological parameters of Trans-Himalayan gneiss (Sen et al., 2015) and those of the Greater Himalayan Crystallines are deduced theoretically (Mukherjee, 2013). Out-of-sequence deformation in the Greater Himalayan Crystallines is proposed to be climate-driven (Mukherjee, 2015). Various interpretations are proposed for the exhumation and uplift history in the light of low-temperature intracrystalline deformation, flow and critical taper wedge mechanism (Patel et al., 2011; Mukherjee et al., 2012).

It is shown that the greater syntectonic uplift and erosion in Arunachal Pradesh, as compared to Sikkim, allows the Ziro granite gneiss to be exhumed to shallower levels (Saha et al., 2012). Greater convergence rates in the eastern Himalaya may have led to larger mid-upper crustal thickening due to stacking of thrusts over the MBT and MCT, which in turn could have positive feedback on the topography in the Lesser Himalaya, the climatic precipitation and that erosion rates since upper the Miocene-Pliocene period (Saha, 2013).

**Eastern Ghat Mobile Belt**

Structural mapping, strain estimation and SHRIMP-zircon geochronology reveal that a thick-skinned Pan-African nappe (517 Ma) existed at the interface of the Eastern Ghat mobile belt and the Bastar Craton (Sinha et al., 2010). Several lines of evidence from geochemical, geochronological and paleomagnetic studies suggest that an accretionary orogen connected India, Baltica and Laurentia during Paleo-Mesoproterozoic period (Ratre et al., 2010; Pisarevsky et al., 2013). It is argued that the contact between Archean and Proterozoic granulites in this belt is not a suture but an intracontinental orogenic structure (Nanda and Gupta, 2012). Three phases of large scale deformation are recognized in the Eastern Ghat Mobile belt. Integrated field, AMS and microstructural investigations point to the syntectonic emplacement of the anorthosite massif during the third phase of deformation ca. 950-1000 Ma (Nasipuri and Bhadra, 2013). A recent study by Ghosh et al., (2016) demonstrates that the 498-521 Ma old transpressional deformation, recorded in the Rengali province, corresponds to the last phase of tectonic activity along the proto-India-Antarctica join.

**South India**

Combining the paleostress with structural and stratigraphic attributes, Tripathy and Saha (2015) elucidate the evolution of the Proterozoic Cuddapah basin. The stress regimes are tentatively correlated with multiple stages of opening and deformation in the basin. Estimation of palaeostress states from fault-slip data in the Cuddapah basin is found to be useful in constraining the influence of plate-margin stresses on the continental interior (Tripathy and Saha, 2013). Evidence from the outcrops, the structural architecture of the Paleoproterozoic Kandra complex and the geochemical character of subduction-related ophiolites is used for constraining the accretion-collision history along the southeastern margin of the Indian craton (Saha, 2011).

The Salem-Attur thrust belt in Southern Granulite Terrane exhibits a stack of granulite nappes (2604 Ma) that was juxtaposed against the Archaean Dharwar Craton during < 1100 Ma period (Biswal et al., 2010; Sundarlingam et al., 2012). These studies help in understanding the tectonic evolution of the Indian subcontinent vis-a-vis Nuna, Rodinia and Gondwanaland Supercontinent assembly.

**Central India**

In central India, structural studies have largely been inter-disciplinary. The major objectives have been to
understand the tectonics and assembly of continents during the Precambrian Period.

Structural mapping, microstructural studies and kinematic analyses of reveal that the Gavilgarh-Tan Shear Zone is a wrench-dominated sinistral transpressional shear zone (Chattopadhyay et al., 2014a). The final suturing between the Bundelkhand Craton and Bastar Craton occurred along the Central Indian Tectonic Zone (CITZ) ca. 1100 Ma ago. In the southern parts of the CITZ, the younger Sausar tectonothermal events overprint the adjacent high-grade granulites of Ramakona–Katangi Granulite belt. These contributions have an important bearing in understanding the Proterozoic crustal evolution in the central Indian craton (Chattopadhyay et al., 2015).

A system of E-W trending crustal scale vertical shear zones has been identified in the central part of the Bundelkhand Craton (Singh and Bhattacharya, 2010). Furthermore, the large scale quartz reefs are inferred as a Proterozoic crustal scale NE-SW shear system that cuts the craton (Bhattacharya and Singh, 2013). In western Bundelkhand massif, a Precambrian caldera has been identified as a granite collapse breccia near Mohar (Singh S P et al., 2010). The collapse of the granitic mass may have taken place due to the eruption of the felsic volcanic magma in the region. This event was followed by emplacement of the ring dykes that may have created a lubricant layer and facilitated the downward fall of a part of the granitic mass.

**Rajasthan**

Large scale mapping reveals that the bulk of Precambrian basement consists of an intensely deformed gneiss-migmatite terrane and a relatively undeformed granulite-granitoid terrane in the northwestern Indian Shield. Successive folds were developed and modified into sheath like geometry during the ductile shearing in the gneiss-migmatite terrane. The ductile shearing occurred in a general shear type of bulk strain regime due to NNW–SSE-directed subhorizontal compression and resulted in subvertical stretching in the gneiss-migmatite terrane (Srivastava, 2011).

Petrological and structural studies show that the Anasagar Granite Gneiss is a basement that was thrust and domed up during the South Delhi Orogeny (Chattopadhyay et al., 2012). Analysis of the compressional-extensional tectonics in the Granulite Core Complexes of South Delhi Terrane establishes the diachronous nature of the Delhi Supergroup (Mahadani et al., 2015). The South Delhi terrane exhibits a Passive Continental Margin that closed through subduction and collision during Neoproterozoic period (860 Ma). Extension (<700 Ma) and thrusting (800 Ma) contributed significantly to exhumation of the granulites (Singh et al., 2010).

**Eastern India**

Interesting and important results have emerged from studies of the GPS-derived velocities of stations located in the Bengal Basin and in the neighboring active deformation zones (Mullick and Mukhopadhyay, 2011). It is found that the Kolkata-Coco Island baseline shortens at 18.5 ± 1.3 mm/yr, while the baseline between Kolkata and Aizawl and Mizoram shortens at 10.5 ± 1.5 mm/yr. The Kolkata-Siliguri baseline shortens at 8.1 ± 1.5 mm/yr and the Kolkata-Baradighi baseline shortens at 5.2 ± 1.4 mm/yr. The difference in shortening rates between the two stations located in the North Bengal foothill Himalayan zone relative to Kolkata is due to the presence of a highly active transverse zone between the stations. These findings have significant bearing on the tectonics of the northeast region of India.

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