Proc Indian Natn Sci Acad **82** No. 3 July Spl Issue 2016 pp. 435-443

DOI: 10.16943/ptinsa/2016/48459

Review Article

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

A R BHATTACHARYA[1], SANTANU BOSE[2], BARUN K MUKHERJEE[3], MANISH A MAMTANI[4] and DEEPAK C SRIVASTAVA[5]

[1]*Department of Geology, University of Lucknow, Lucknow 226 007, India*

[2]*Department of Geology, Calcutta University, Kolkata 700 019, India*

[3]*Wadia Institute of Himalayan Geology, Dehradun 248 001, India*

[4]*Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, Kharagpur 721 302, India*

[5]*Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee 247 667, India*

(Received on 03 July 2016; Accepted on 14 July 2016)

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 crators as applied to the Lonar Crator 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

**Author for Correspondence: E-mail:* dpkesfes@gmail.com

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 (Mamatani, 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 crator. This study reveals that the pristine crators, such as the Lonar Crator 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; Shreshtra *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 Ghats 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 thrusted 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 neighbouring 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.

Acknowledgements

We are thankful to Professor A K Jain, CBRI, Roorkee for promptly supplying a summary of his contributions. Despite our best efforts, some contributions might have been missed out- this is totally inadvertent and we apologize to the authors.

References

Agarwal A, Kontny A, Srivastava D C and Greiling R O (2016) Shock pressure estimates in target basalts of a pristine crater: A case study in the Lonar crater, India Bulletin *Geological Society of America* **128** 19-28

Agarwal K K, Sharma A, Jahan N Prakash C and Agarwal A (2011) Occurrence of pseudotachylites in the vicinity of South Almora Thrust zone, Kumaun Lesser Himalaya *Current Science* **101** 431-434

Banerjee S, Matin A and Mukul M (2015) Overburden-induced flattening structure in the Himalaya: mechanism and implication *Current Science* **109** 1

Barnes J B, Densmore A L, Mukul M, Sinha R, Jain V and Tandon S K (2011) Interplay between faulting and base level in the development of Himalayan frontal fold topography *Journal of Geophysical Research: Earth Surface* **116** (F3)

Baruah A, Gupta A K, Mandal N and Singh R N (2013) Rapid ascent conditions of diamond-bearing kimberlitic magmas: Findings from high pressure-temperature experiments and finite element modeling *Tectonophysics* **594** 13-26

Bhattacharya A R and Singh S P (2013) Proterozoic crustal scale shearing in the Bundelkhand massif with special reference to quartz reefs *Jour Geol Soc India* **82** 474-484

Bhattacharyya K and Ahmed F (2016) Role of initial basin width in partitioning total shortening in the Lesser Himalayan fold-thrust belt: Insights from regional balanced cross-sections *Journ of Asian Earth Sci* **116** 122-131

Bhattacharyya K and Mitra G (2011) Strain softening along the MCT zone from the Sikkim Himalaya: relative roles of quartz and micas *Jour of Struct Geo* **33** 1105-1121

Bhattacharyya K and Mitra G (2014) Spatial variations in deformation mechanisms along the Main Central thrust zone: Implications for the evolution of the MCT in the Darjeeling–Sikkim Himalaya *Journal of Asian Earth Sciences* **96** 132-147

Biswal T K, Thirukumaran V, Ratre K, Bandyapadhaya K, Sundaralingam K and Mondal A K (2010) A Study of Mylonites from parts of the Salem-Attur Shear Zone (Tamil Nadu) and its Tectonic Implications *Jour Geol Soc Ind* **75** 128-136

Bose S, Mandal N, Acharyya S K, Ghosh S and Saha P (2014a) Orogen-Transverse tectonic window in the Eastern Himalayan fold belt: A superposed buckling model *Journal of Structural Geology* **66** 24-41

Bose S, Mandal N, Saha P, Sarkar S and Lithgow-Bertelloni C (2014b) Thrust initiation and its control on tectonic wedge geometry: An insight from physical and numerical models *Journal of Structural Geology* **67** 37-49

Bose S, Saha P, Mori J J, Rowe C, Ujiie K, Chester F M, Conin M, Regalla C, Kameda J, Toy V, Kirkpatrick J, Remitti F, Moore J C, Wolfson-Schwehr M, Nakamura Y and Gupta A (2015) Deformation structures in the frontal prism near the Japan Trench: Insights from Sandbox Models *Journal of Geodynamics* **89** 29-38

Chattopadhyay A, Bhattacharjee D and Mukherjee S (2014a) Structure of pseudotachylyte vein systems as a key to co-seismic rupture dynamics: the case of Gavilgarh-Tan Shear Zone, central India *International Jour Earth Sciences* **103** 953-965

Chattopadhyay A, Das K, Hayasaka Y and Sarkar A (2015) Syn- and post-tectonic granite plutonism in the Sausar Fold Belt, central India: Age constraints and tectonic implications *Journal of Asian Earth Sciences* **107** 110-121

Chattopadhyay A, Jain, M and Bhattacharjee D (2014b) Three-dimensional geometry of thrust surfaces and the origin of sinuous thrust traces in orogenic belts: Insights from scaled sandbox experiments *Jour Structural Geology* **69** 122-137

Chattopadhyay N, Mukhopadhyay D and Sengupta P (2012) Reactivation of basement: example from the Anasagar Granite Gneiss Complex, Rajasthan, western India *Geological Society, London* Special Publications **365** 219-245

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 *Journal of Structural Geology* **34** 30-42

Dasgupta S, Mandal N and Bose S (2016) How far does a ductile shear zone permit transpression? In: Ductile Shear Zones: from micro-to macro-scales Edited by S Mukherjee and K Mulchrone John Wiley & Sons 14-29

Dutta U, Sarkar S, Baruah A and Mandal N (2014) Ascent modes of jets and plumes in a stationary fluid of contrasting viscosity *International Journal of Multiphase Flow* **63** 1-10

Ghosh G, Bose S, Das K, Dasgupta A, Yamamoto T, Hayasaka Y, Chakrabarti K and Mukhopadhyay J (2016) Transpression and juxtaposition of middle crust over upper crust forming a crustal scale flower structure: Insight from structural, fabric, and kinematic studies from the Rengali Province, eastern India *Journal of Structural Geology* **83** 156-170

Ghosh N, Chakra M and Chattopadhyay A (2014) An experimental approach to strain pattern and folding in unconfined and/ or partitioned transpressional deformation *International Jour Earth Sciences* **103** 349-365

Jain A K (2016) Continental subduction in the NW-Himalaya and Trans-Himalaya *Ital Jour Geosci* 135

Jain A K, Seth P, Shreshtha M, Mukherjee P K and Singh K (2013) Structurally-controlled melt accumulation: Himalayan migmatites and related deformation, Dhauli Ganga Valley, Garhwal Himalaya *Jour Geol Soc India* **82** 313-318

Jain A K, Shreshtha M, Seth P, Kanyal L, Carosi R, Montomoli C, Iaccarino S and Mukherjee P K (2015) The Higher Himalayan Crystallines, Alaknanda – Dhauli Ganga Valleys, Garhwal Himalaya, India. In: (Eds.) Montomoli C, Carosi R, Law R, Singh S and Rai S M, Geological field trips in the Himalaya, Karakoram and Tibet *Journal of the Virtual Explorer* **47** 1-34

Kumar R, Srivastava D C and Ojha A K (2014) A comparison of methods for objective strain estimation from the Fry plots *Journal of Structural Geology* **63** 76-90

Kundu A, Matin A, Mukul M and Eriksson P G (2011) Sedimentary facies and soft-sediment deformation structures in the late miocene-pliocene Middle Siwalik subgroup, eastern Himalaya, Darjiling District, India *Jour Geol Soc India* **78** 321-336

Lahoti S, Kumud K, Gupta Y and Jain A K (2016) Tectonics of the Chamba Nappe, NW Himalaya and its regional implications *Italian Jour Geosci* 136

Mahadani T, Biswal T K and Mukherjee T (2015) Strain estimation of folds, orbiculites and quartz phenocrysts in the Ambaji Basin of the South Delhi Terrane, Aravalli-Delhi Mobile Belt, NW India and its Tectonic implication *Jour Geol Soc India* **85** 139-152

Mamtani M A (2014) Magnetic fabric as a vorticity gauge in syntectonically deformed granitic rocks *Tectonophysics* **629** 189-196

Mandal N, Bose S, Baruah A and Sarkar S (2015) First-order topography of the Himalayan Mountain belt: a deep-crustal flow analysis *Geological Society, London, Special Publications* **412** 5-23

Mishra A, Srivastava D C and Shah J (2013) Late Miocene-Early Pliocene reactivation of the Main Boundary Thrust: evidence from the seismites in southeastern Kumaun Himalaya, India *Sedimentary Geology* **289** 148-158

Mishra P and Mukhopadhyay D K (2012) Structural evolution of the frontal fold-thrust belt, NW Himalayas from sequential restoration of balanced cross-sections and its hydrocarbon potential *Geological Society*, London, Special Publications **366** 201-228

Misra S, Mandal N and Dasgupta S (2015) Role of pressure and temperature in inclusion-induced shear localization: An analogue experimental approach *Jour of Structural Geology* **81** 78-88

Moharana A, Mishra A and Srivastava D C (2013) Deformation style in the Munsiari Thrust Zone: a study in the Madlakia – Munsiari – Dhapa section in north-eastern Kumaun Himalaya *International Journal of Earth Science* **102** 1837-1849

Mondal T K and Mamtani M A (2013) 3-D Mohr circle construction using vein orientation data from Gadag (southern India) – implications to recognize fluid pressure fluctuation *Jour Structural Geology* **56** 45-56

Mondal T K and Mamtani M A (2014) Fabric analysis in massive rocks of the Gadag region (southern India) – implications to decipher time relationship between regional deformation and gold mineralization *Tectonophysics* **629** 238-249

Mugnier J L, Gajurel A, Huyghe P, Jayangondaperumal R, Jouanne F and Upreti (2013) Structural interpretation of the great earthquakes of the last millennium in the central Himalaya *Earth-Science Reviews* **127** 30-47

Mukherjee B K, Sen K, Sachan H K and Paul S K (2012) Exhumation history of the Karakoram fault zone mylonites: New constraints from microstructures, fluid inclusions, and 40Ar-39Ar analyses *Lithosphere* **4** 230-241

Mukherjee S (2012) Channel flow extrusion model to constrain dynamic viscosity and Prandtl number of the Higher Himalayan Shear Zone *International Journal of Earth Sciences* **102** 1811-1835

Mukherjee S (2013) Higher Himalaya in the Bhagirathi section (NW Himalaya, India): its structures, backthrusts and extrusion mechanism by both channel flow and critical taper mechanisms International Journal of Earth Sciences **102** 1851-1870

Mukherjee S (2015) A review on out-of-sequence deformation in the Himalaya *Geological Society*, London. Special Publications **412** 67-109

Mukherjee S, Punekar J, Mahadani T and Mukherjee R (2015) A review on intrafolial folds and their morphologies from the detachments of the western Indian Higher Himalaya. In: Mukherjee S, Mulchrone KF (Eds) Ductile Shear Zones: From Micro- to Macro-scales. John Wiley & Sons, Ltd. pp. 182-205

Mulchrone K F (2003) Application of Delaunay triangulation to the nearest neighbour method of strain analysis *J Struct Geol* **25** 689-702

Mullick M, Mukhopadhyay D (2011) An analysis of GPS-derived velocities in the Bengal basin and the neighbouring active deformation zones *Current Science* **101** 423-426

Nanda J and Gupta S (2012) Intracontinental orogenesis in an ancient continent-continent collision zone: Evidence from structure, metamorphism and P-T paths across a suspected suture zone within the Eastern Ghats Belt, India *Journal of Asian Earth Sciences* **49** 376-395

Nasipuri P and Bhadra S (2013) Structural framework for the emplacement of the Bolangir anorthosite massif in the Eastern Ghats Granulite Belt, India: implications for post-Rodinia pre-Gondwana tectonics *Miner Petrol* **10** 7861-880

Pant P D, Chauhan R, Bhakuni S S (2012) Development of Transverse Fault along North Almora Thrust, Kumaun Lesser Himalaya, India: a study based on field and magnetic fabrics *Jour Geol Soc India* **79** 429-448

Patel R C, Adlakha V, Singh P and Kumar Y and Lal N (2011) A review and few new observations on Geology, Structural and Exhumation history of the Higher Himalayan Crystallines in Kumaon Himalaya, India *Jour Geol Soc India* **77** 47-72

Philip G, Bhakuni S S, Suresh N and Virdi N S (2014) Late Pleistocene Faulting along the growing Janauri Anticline and Seismic Potential in the North-western Frontal Himalaya, India *Him Geol* **35** 89-596

Pisarevsky S A, Biswal T K, Wang X C, De Waele B, Ernst R, Söderlund U, Tait J A, Ratre K, Singh Y K and Cleve M (2013) Palaeomagnetic, geochronological and geochemical study of Mesoproterozoic Lakhna Dykes in the Bastar Craton, India: Implications for the Mesoproterozoic supercontinent *Lithos* **174** 125-143

Ratre K, Waele B D, Biswal T K and Sinha S (2010) SHRIMP geochronology for the 1450 Ma Lakhna dyke swarm: Its implication for the presence of Eoarchaean crust in the Bastar Craton and 1450-517 Ma depositional age for Purana basin (Khariar), Eastern Indian Peninsula *Journal of Asian Earth Sciences* **39** 565-577

Reddy S and Srivastava D C (2012) Rapid extraction of central vacancy by image-analysis of Fry plots *Journal of Structural Geology* **40** 44-53

Renjith A R and Mamtani M A (2014) Domainal petrofabric analysis of micaceous quartzite using BSD data: role of muscovite in LPO evolution of quartz *Jour Geol Soc India* **83** 479-482

Saha D (2011) Dismembered ophiolites in Paleoproterozoic nappe complexes of Kandra and Gurramkonda, south India *Journal of Asian Earth Sciences* **42** 158-175

Saha D (2013) Lesser Himalayan sequences in Eastern Himalaya and their deformation: Implications for Paleoproterozoic tectonic activity along the northern margin of India *Geoscience Frontiers* **4** 289-304

Saha D, Sengupta D and Das S (2012) Along strike variation in the Himalayan orogen and its expression along major intracontinental thrusts – the case of MCT in Sikkim and Arunachal Pradesh, India *Geological Society of India Memoir* **77** 1-18

Samanta S K and Deb I (2014) Development of concave-face boudin in Chhotanagpur Granite Gneiss Complex of Jasidih-Deoghar area, eastern India: Insight from finite element modeling *Journal of Structural Geology* **62** 38-51

Sarkar S, Baruah A, Dutta U and Mandal N (2014) Role of random thermal perturbations in the magmatic segmentation of mid-oceanic ridges: Insights from numerical simulations *Tectonophysics* **636** 83-99

Sen K, Chaudhury R and Pfänder J (2015) 40 Ar–39 Ar age constraint on deformation and brittle–ductile transition of the Main Central Thrust and the South Tibetan Detachment zone from Dhauliganga valley, Garhwal Himalaya, India *Journal of Geodynamics* **88** 1-13

Sen K, Dubey A K, Tripathi K and Pfänder J A (2012) Composite mesoscopic and magnetic fabrics of the Paleo-Proterozoic Wangtu Gneissic Complex, Himachal Himalaya, India: Implications for ductile deformation and superposed folding of the Himalayan basement rocks *Journal of Geodynamics* **61** 81-93

Sen K, Mukherjee B K and Collins A S (2014) Interplay of deformation and magmatism in the Pangong Transpression Zone, eastern Ladakh, India: Implications for remobilization of the trans-Himalayan magmatic arc and initiation of the Karakoram Fault *Journal of Structural Geology* **62** 13-24

Shah J, Srivastava D C and Joshi S (2012) Sinistral transpression along the Main Boundary Thrust in Amritpur area, Southeastern Kumaun Himalaya *Tectonophysics* **532** 258-270

Shreshtha M, Jain A K and Singh S (2015) Shear sense analysis of the Higher Himalayan Crystalline Belt and tectonics of the South Tibetan Detachment System, Alaknanda–Dhauli Ganga valleys, Uttarakhand Himalaya *Current Sci* **108** 1107-1118

Singh P, Patel R C and Lal N (2012) Plio-Plistocene in-sequence thrust propagation along the ain Central Thrust zone (Kumaon-Garhwal Himalaya, India): New thermo-chronological data *Tectonophysics* **574** 193-203

Singh S P and Bhattacharya A R (2010) Signatures of Archaean E-W crustal-scale shears in the Bundelkhand massif, Central India: An example of vertical ductile shearing *Earth Sci India* **3** 215-223

Singh S P, Bhattacharya A R, Hemraj and Shrivastava S K (2010a) Structural development of a granite collapse breccias of Mohar, Bundelkhand massif: An evidence of a Precambrian caldera from the Indian shield *Jour Economic Geol and Georesource Management* **7** 105-117

Singh Y K, Waele B D, Karmakar S, Sarkar S and Biswal T K (2010) Tectonic setting of the Alaram-Kui-Surpagla-Kengora granulites of the South Delhi Terrane of the Aravalli Mobile Belt, NW India and its implication on correlation with the East African Orogen in the Gondwana assembly *Precambrian Research* **183** 669-688

Sinha S, Alsop I and Biswal T K (2010) The evolution and significance of microfracturing in feldspars in low-grade granitic mylonites: A case study from the Eastern Ghats Mobile Belt, India *Journal of Structural Geology* **32** 1417-1429

Srivastava D C (2011) Geometrical similarity in successively developed folds and sheath folds in the basement rocks of the Northwestern Indian shield *Geological Magazine* **148** 171-182

Srivastava H B, Srivastava V, Srivastava R K and Singh C K (2011) Structural Analyses of the Crystalline rocks between Dirang and Tawang West Kameng District, Arunanchal Hmalaya *Jour Geol Soc India* **78** 45-56

Sundaralingam K, Bert D W, Thirukumaran V, Thakur S, Mahadani S, Tanushree and Biswal T K (2012) Deformation, Metamorphism and Geochronology of the Palaeoproterozoic Salem-Namakkal Fold Thrust Belt and Implication for the Gondwanaland Continental Assembly *International Journal of Geology, Earth and Environmental Sciences* **2** 266-283

Thakur V C (2013) Active tectonics of Himalayan Frontal Fault system *International Jour of Earth Sci* **102** 1791-1810

Tripathy V and Saha D (2013) Plate margin paleostress variations and intracontinental deformations in the evolution of the Cuddapah basin through Proterozoic *Precambrian Research* **235** 107-130

Tripathy V and Saha D (2015) Inversion of calcite twin data, paleostress reconstruction and multiphase weak deformation in cratonic interior: Evidence from the Proterozoic Cuddapah basin, India *Journal of Structural Geology* **77** 62-81

Verma A K and Bhattacharya A R (2015) Reorientation of lineation in the Central Crystalline Zone, Munsiari-Milam area of the Kumaun Greater Himalaya *Jour Earth Syst Sci* **124** 449-458

Waldron J W F and Wallace K D (2007) Objective fitting of ellipses in the centre-to-centre (Fry) method of strain analysis *J Struct Geol* **29** 1430-1444.