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Tectonics of Sikkim and Eastern Himalaya

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In India, the Eastern Himalaya broadly refers to the region east of Bhutan, and conventionally, Darjeeling and Sikkim are generally included within its domain. This report is a compilation of some of the publications since 2016, made by, or in collaboration with Indian scientists who have discussed various geoscientific aspects of the Eastern Himalaya. From the stand-point of the geological input to tectonic framework, studies dealing with structural, metamorphic and geophysical aspects have been compiled in this report, based on the publications from Darjeeling-Sikkim and Arunachal Himalayas, which are the Indian components of the Eastern Himalaya.

Darjeeling-Sikkim Himalaya (DSH)

Structure

Microstructural investigations by Ghosh *et al*. (2016) record the dominance of bulging recrystallization near the Daling Thrust (DT; in the Lesser Himalaya), which gradually changes to sub-grain rotation away from DT. In their tectonic model, this increase in deformation temperature away from DT has been correlated to the variations in flow-stress (16-59 MPa) and strain-rate (10^{-12}-10^{-14} s^{-1}). Based on field studies and balanced cross sections, Parui and Bhattacharya (2018) reported ~403 km of shortening in the eastern part of the DSH, at the average rate of ~18 mm yr^{-1}. As the basement ramp is higher in the western DSH (~2 km) than the eastern DSH (~ 0.35 km), the Lesser Himalayan duplex is exposed in the western part only. Along with the field documentation of pre-Himalayan tectono-magmatic features in the Lesser Himalaya, Acharyya *et al*. (2017) reported a ~1850Ma Ar-Ar muscovite cooling age for the pegmatites that intruded the Daling Group. Based on field observations and analogue modeling, Ghosh *et al*. (2018) concluded that the mechanically weak Gondwana sequence played the key role in the localization of the Main Boundary Thrust and Daling Thrust (Location 3 in Fig. 1). Bose *et al*. (2019) documented back-structures (i.e. exposure-scale structures showing shear senses similar to back-thrusts) from the Lesser Himalayan part of the DSH and correlated the observation with structures on the regional-/local- scale. From the fault-slip analyses conducted on the two splays of MBT in the DSH, Patra and Saha (2019) commented on the pre-Himalayan and Himalayan deformation pattern in this region. Pre-Himalayan NE-SW brittle extension was followed by three stages of Himalayan deformation, which includes thrusting events followed by younger strike-slip movements. Singh *et al*. (2017a) conducted OSL dating of the terraces on both banks, present at the confluence of Tum Thang Khola and Tista Rivers (Location 14 in Fig. 1). The authors detected 45 ka and 11.9 ka events that uplifted earlier terraces T3 and T2, respectively. The warping in recent terraces T1 and T0 represent their tectonically active nature.

To investigate the Main Central Thrust (MCT) along the Teesta River valley, Mukhopadhyay *et al*. (2017) incorporated field, microstructural studies with ε_{Nd} and U-Pb geochronology (zircon and monazite) studies. The deformation mechanism in the MCT differs from that of the underlying Lesser Himalayan and overlying Higher Himalayan Crystalline Sequence rocks. The authors also report that the fault zone experienced peak metamorphism (750-800°C) before the intense faulting at 20 Ma (450-700°C), which was followed by an isolated, 11 Ma brittle phase. Based

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on field observations and micro-tectonic analyses Chakraborty and Mukul (2019) presented a conceptual model to delineate the structural break representing the Main Central Thrust in the DSH. Their model shows the MCT to be a mappable shear zone in this region, in spite of having spatially varying thickness along and across the strike.

Srivastava *et al*. (2017) used Real Time Kinematic Global Navigation Satellite Systems data along with field studies to understand various tectono-geomorphic features of the frontal part of the Himalayan orogen exposed at the Gorubathan Recess and Dharan Salient (Locations 15a,b, respectively, in Fig. 1). These authors documented geomorphic features (e.g. warping, geomorphic scarps, topographic growth etc.) formed in response to activity along the Ramgarh Thrust, which defines the orogenic front in this region. Based on the long-time series (1998-2009) of geodetic and static GPS dataset, Mukul *et al*. (2018) concluded that the Lesser and Higher Himalayas equally share the ~9mm yr^{-1} convergence rate. The authors also postulated the presence of a transverse fault that causes the variation in GPS velocities in the eastern and western parts of the DSH. To address the exceptional dominance of strike-slip seismicity in the DSH, Sunil Kumar *et al*. (2019) produced a slip-distribution model following the 18-September-2011 M_w 6.9 Sikkim earthquake. Their kinematic source process modeling refers to a steep NE-SW sinistral source zone within the underthrust brittle Indian plate. They also report that the transpressive stress regime in the crust changes to a pure strike-slip regime in the mantle.

Thirunavukarasu *et al*. (2017) used data from local earthquakes recorded by the Sikkim broadband seismograph network to interpret structural heterogeneity and active faults within the crust, and an actively deforming hotter lithosphere beneath the mountain belt. Data from this network also enabled Paul and Mitra (2017) to identify ramps below Peling and Rangit that are responsible for the arcuate nature of the thrust outcrops in these two regions. Importantly, they identified that the underthrust Indian continental crust below Sikkim was 35-42 km thick. Mitra *et al*. (2018) also attempted to present a comprehensive model of the crustal structure north and south of the Shillong Plateau, encompassing most of northeast India and Bangladesh. Below the eastern Himalaya, north of the plateau, the Moho was interpreted to show a distinct flexure, dipping 30° towards north.

Metamorphism

Studying the Lesser Himalayan rocks at Rangli Rangliot (Location 1 in Fig. 1), Prakash and Tewari (2016) discussed the P-T evolution of metamorphic the rocks in the area using TWEEQU, PerpleX, and petrogenetic grids in the KFMASH system. The reported clockwise P-T-t path has been attributed to decompression of the crust following peak metamorphism at 590°C and 5.8 kbar. Tewari and Prakash (2016) studied polyphase deformation and Barrovian metamorphism related to the MCT zone exposed near the Darjeeling-Mangpu region (Location 2 in Fig. 1). Peak temperatures of 570°C (garnet zone) and 780°C (staurolite zone), peak pressure ranging from 5-7.5 kbar were obtained from geothermobarometric studies. The authors support that the channel flow aided by focused denudation is operating the exhumation process in this region. Subsequently, Tewari and Prakash (2017) incorporated thermobarometry, pseudosection modeling and SHRIMP U-Pb chronology analyses while studying crustal melting in migmatites near Darjeeling (Location 2 in Fig. 1). They obtained peak metamorphic conditions at 7.2 ± 0.5 kbar and 775 ± 20 °C, with evidence of crustal melting at 21 Ma. Prakash *et al*. (2017) applied Perple_X pseudosection modeling in the MnNCKFMASHTO system, and winTWQ results to integrate the deformation episodes (D_1, D_2 and D_3) with metamorphic phases (M_1a, M_1b and M_2) in the Barrovian sequence in the Lesser Himalaya near Darjeeling (Location 2 in Fig. 1). The authors inferred that the regional syn-tectonic low grade M1a phase, (started with D1) and the regional static post-tectonic M1b phase (between D1 and D2) represent the prograde phases, whereas the retrograde M2 phase took place between the D2 and D3 episodes.

Chakraborty *et al*. (2016) reviewed the tectonothermal evolution of the Lesser- & Higher Himalayan sequences in the DSH. Their thermomechanical models involving geochronological and geospeedometry results indicate that the Greater Himalayan Sequence, which is made up of at least two protolith blocks with different P-T-t histories, had a different protolith and metamorphic history from that of the Lesser Himalaya. Based on the data gathered from previous studies, Chakraborty *et al.* (2017) provided a model explaining the nature of tectonic deformation acting in the DSH. In their model, both channel flow (without funnel effect; at higher temperatures) and critical taper (wedge tectonics; at lower temperatures) were operative in this region. However, these two stages were bridged by a deformation phase involving faulting and visco-plastic flow.

Arunachal Pradesh (AP)

Structure

Goswami *et al.* (2016) studied the mylonitized Abor volcanics (Location 6 in Fig. 1) along a branch of the Main Boundary Thrust, exposed at Siang Valley, Arunachal Pradesh. Based on the field evidence, they concluded that these volcanics were generated during oblique-slip thrusting under the influence of the compression exerted by Burmese plate. Singh *et al.* (2019) studied the Abor volcanics of the Eastern Himalayan Syntaxis (Location 11 in Fig. 1). Merging of the results of U-Pb geochronology (zircon), Hf isotopes, XRF and LA-ICPMS analyses indicate that these volcanics were emplaced at ~132 Ma during the initial stage of Gondwana break-up under the influence of Kerguelen Plume. Based on field examples and morphometric calculations, Bhakuni *et al.* (2017) emphasize the role of transverse faults and their interaction with the Himalayan thrusts in the development of neotectonic geomorphic features along the Himalayan mountain front in eastern Arunachal Pradesh. Detailed investigation of fractures by Basa *et al.* (2019) from a fault-bend fold at the Main Boundary Thrust sheet (Location 8 in Fig. 1), Arunachal Lesser Himalaya, shows that fracture spacing is a scale-independent process, but the coefficients of the variation of spacing (C_V) is not. Field studies on the Bomdila Gneiss (Location 7 in Fig. 1), Arunachal Lesser Himalaya by Singh *et al.* (2017b) have led to the demarcation of three deformation phases. The obtained magnetic fabric (SE plunging and sub-horizontal) does not match with any mesoscale foliation, but parallels the F_3 axial plane. Based on this example, the authors conclude that anisotropy of magnetic susceptibility (AMS) study is a helpful tool in figuring out the young/weak deformational phases, which leave no signature in the mesoscopic scale.

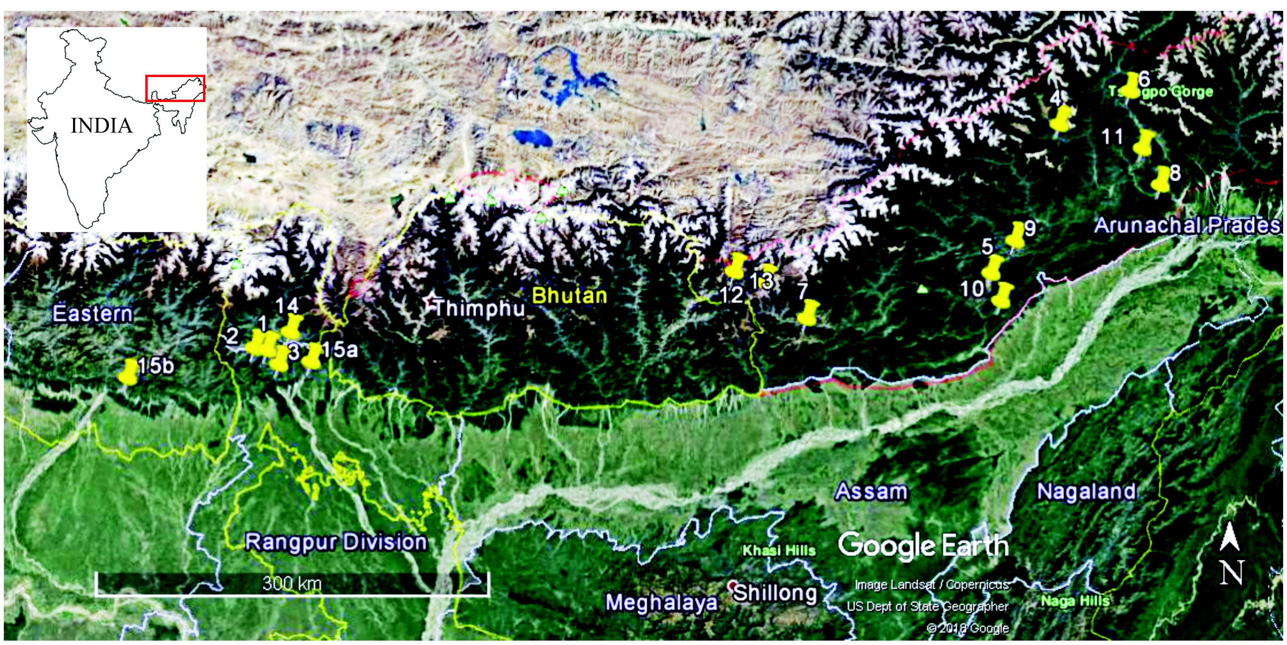

Fig. 1: Google Earth satellite imagery showing the study locations for the following publications mentioned in this report: 1. Prakash and Tewari (2016), 2. Tewari and Prakash (2017), 3. Ghosh *et al.* (2018), 4. Clarke *et al.* (2016), 5. Bikramaditya *et al.* (2018), 6. Goswami *et al.* (2016), 7. Singh *et al.* (2017b), 8. Basa *et al.* (2018), 9. Adlakha *et al.* (2018), 10. Sharma *et al.* (2018), 11. Singh *et al.* (2019), 12. Srivastava and Samal (2019), 13. Taye and Rakshit (2019), 14. Singh *et al.* (2017a), 15a, b. Srivastava *et al.* (2017)

Goswami *et al*. (2018) have described various tectonic features (such as ramp-flat geometry, splay thrusts etc.) from the Siwaliks exposed along the Kameng River section. From field (Location 13 in Fig. 1) and morphotectonc analyses, Taye and Rakshit (2019) deciphered that the Tawang River flows over a region of complex structural configuration. Based on Apatite Fission Track and (U-Th)/He Zircon ages from the Siang Valley, AP, Salvi *et al*. (2017) predicted the presence of an unmapped fault. The authors also support that, since late Pliocene, tectonic-erosion relationship played a key role in shaping up the physiography of the studied location. However, Adlakha *et al*. (2018) obtained the AFT ages to study the exhumation history of a synformal nappe (Location 9 in Fig. 1) in the Higher Himalaya, AP. The results indicate slow exhumation (0.25 ± 0.12 to 0.69 ± 0.25 mm a^{-1}) since Middle-Late Miocene. The authors discarded any link between climate induced focused erosion and tectonic deformation. There are a few geophysical studies that provide information on the subsurface structure of the Arunachal Himalayas; e.g., Priestley *et al*. (2019) reviewed the seismological studies to understand the crustal architecture of the Himalayas at four representative areas including Darjeeling-Sikkim and Bhutan-Northeastern Himalayas.

Igneous and Metamorphic Studies

Basic petrological and geochemical characterization of the granitoids in this area is still in progress. Bhattacharjee and Nandy (2017) studied the following four types/ episodes of granite activity in the western Arunachal Pradesh: *i.* Bomdila Granite – convergent plate margin, where mixing of crustal and mantle sources took place. *ii.* Zimithang Granite – syn-collisional setting; *iii.* Salari Granite – volcanic arc, *iv.* syn-collisional leucogranite intrusion in the Greater Himalayan rocks. Metagranitoids from the Subansiri region were studied by Bikramaditya *et al*. (2018) using U-Pb geochronology, Hf isotopes and geochemical analyses. These granitoids were believed to have originated by partial melting of the Indian passive margin metasediments, and were emplaced during 516-486 Ma. Sharma *et al*. (2018) described the petrography of the volcanic rocks (mostly basalt-andesite and trachite) associated with the Gondwana Group rocks exposed near the Main Boundary Thrust, in and around Lichi area (Location 10 in Fig. 1). The geochemistry of these granites, including major oxides, REE and trace element analyses, suggest a highly calc-alkaline nature, but with signatures both of a pristine MORB and a volcanic arc set-up. Through geochemical analyses of Palaeoproterozoic mafic intrusives from Western Arunachal Pradesh (Location 12 in Fig. 1), Srivastava and Samal (2019) postulated the presence of a large igneous province at ~1.9 Ga. Petrographic and geochemical studies conducted on the Palaeoproterozoic pelites and quartzites of the Bomdila area (Location 7 in Fig. 1) by Rashid *et al*. (2019) indicate the presence of Precambrian felsic crust in this region.

In contrast to these recent igneous studies, metamorphic studies on the area are limited. Clarke *et al*. (2016) studied the inverted metamorphic sequence located along the Main Central Thrust zone at the Siang Antiform, Arunachal Pradesh. Based on the phase relationships in the NCKFMASHTO system, in conjunction with SHRIMP U-Th-Pb zircon and monazite dating, they constrained the timing of three phases of deformation: *i.* >8 kbar at ~550 °C, *ii.* ~640 °Cat ~8.5 kbar (c. 18.5 Ma), *iii.* ~10 kbar at ~750 °C (c. 21.5 Ma).

Current Research Status

This compilation is a status report of the recent (2016-19) studies on the Tectonics of Eastern Himalaya. Although an attempt has been made to incorporate accessible contributions made by Indian geoscientists on the subject, it is possible that some studies have not been mentioned due to oversight; this is completely inadvertent, and we apologize for any such omissions. Nevertheless, our efforts do indicate a significant advance in the knowledge related to the tectonics of Darjeeling-Sikkim Himalaya, including information on subsurface structures. On the other hand, the Arunachal Himalayas are still relatively untapped, and remain a promising target for further investigations from the viewpoint of structure, metamorphism and subsurface structure. The Arunachal Himalaya remains the most prospective region for future research on the tectonics of Eastern Himalaya.

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