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Science of the Himalaya

Mishra (**page 176**) discusses some of debatable issues of intricate Himalayan seismotectonics and seismogenesis in light of past and present researches conducted in different parts of Himalaya. In this commentary, the author suggests that debatable results related to the Himalayan tectonic models, and past and present seismogenesis can be addressed using integrated geoscientific research by deploying multidisciplinary (geology, geophysics, seismology, geodetic, etc.) tools of science of different institutions/organizations of India and overseas. Advances in seismological/geophysical instrumentations, robust computational algorithms, and development of three-dimensional geological models along with availability of skilled geophysical and seismological interpretational acumen of geoscientists can furnish comprehensive information for evolving plausible integrated geo-scientific model of the Himalaya. The author emphasizes on nature and extent of seismogenesis beneath the Himalaya under climate change scenario and suggests a way of conducting research on the subject to understand interrelationship between climate change and its impact on earthquake generating processes and vice-versa.

J. R. Kayal (**page 188**) has reviewed present understanding of the great and large Himalayan earthquakes ($M \sim 8.0$) in India. Although the past great/large earthquakes in the Himalaya are well studied by macroseismic investigations that gave us reliable isoseismal (intensity) maps, due to lack of seismological instrumental data the source zones and tectonics of these earthquakes are not well understood. All the known great earthquakes (1897, 1905, 1934 and 1950) in India occurred before the World Wide Seismograph Station Network (WWSSN) came into existence in 1964, which is now known as Global Seismic Network (GSN). The 1897 great Shillong earthquake is the first event in India that was recorded by few seismic stations in Europe. After this disastrous earthquake, the first Indian seismological observatory was made in Alipore (Kolkata) in 1899, and before the 1950 great Assam earthquake the observatories in India were limited to a few (six to eight) stations only. Thus understanding of source zones, precise location and depth, of these events is much debated.

With the inception of the local microearthquake networks in different parts of the Himalaya since 1980s and upgradation of the networks with digital systems since 2000, our understanding of the Himalayan seismicity and tectonics has increased. In this review, an effort is made to briefly discuss the present understanding of seismotectonics of the Himalayan great and large earthquakes that is not uniform all along the ~2500 km long tectonic belt where the Indian and the Eurasian plates are at head-on collision.

Seismicity in the Darjiling–Sikkim Himalaya (DSH) has been dominated by moderate strike–slip earthquakes and not thrust earthquakes like elsewhere in the Himalaya. Also, hypocentral depths plot below the Main Himalayan Thrust (MHT) prompting seismotectonic models that require the Main Boundary Thrust to reach the Malay Mukul *et al.* (**page 198**) have argued that the deep hypocentres are probably related to transverse strike–slip faults that also generate the moderate strike–slip earthquakes recorded in the region. Seismicity patterns and preliminary dislocation models indicate that the active deformation in DSH occurs on the MHT as well as out-of-sequence deformation in the lesser Himalayan Duplex. The MHT in DSH is locked south of 27°N lat., about 10 km north of the mountain front. Dislocation modelling using a three-fault model involving oblique slip along two thrust faults, including MHT and a transverse, sinistral strike–slip fault best simulates the observed high-precision Global Positioning System surface velocity field. In view of these observations, the role of transverse tectonics in salient-recess transition zones together with dislocation models that allow active slip along the MHT, out-of-sequence thrust as well as transverse strike–slip faults are needed to realistically understand the active tectonics and seismicity in DSH.

Seismic hazard evaluation in the tectonically active Himalaya is crucial because earthquakes pose a continual threat to the safety of the people inhabiting the mountains and adjoining alluvial plain. Reactivation of active faults in the Himalaya reflects intermittent tectonic movements and associated earthquakes. The thickly populated areas of the Indo-Ganga Plain and lesser and outer Himalayan realms are prone to major earthquakes. The losses in terms of life and property would be much higher than for the great earthquakes experienced in the past hundred years, because of the explosive growth of population in the Himalayan region during the last half a century. Palaeoseismological studies carried out by Philip *et al.* (**page 211**) in northwestern outer Himalaya suggest occurrence of large-magnitude palaeoearthquakes. The article reports Late Pleistocene earthquakes along the Nalagarh Thrust (NT) in the Pinjaur Dun and Late Pleistocene–Holocene earthquakes in the Himalayan Frontal Thrust (HFT) in the Kala Amb region. The repeated reactivation of the NT and HFT substantiates high seismic potential of the northwestern outer Himalaya and calls for a extensive study of palaeoearthquakes of this vastly populous mountainous region.

At the beginning of the Cretaceous (144 to 66.4 Ma ago), climates were changing from an episode of global aridity at the end of the Jurassic to much more humid environments throughout Cretaceous. Prior to the Jurassic almost all continents were assembled into the single supercontinent Pangaea, as a continuous block of land that spread from the northern to southern polar regions. The land was surrounded by the vast ocean of Panthalassa (the ancient Pacific Ocean) and the Tethys Sea, which cut a huge wedge into the eastern margin of the continental mass along the equator. By the early part of the Cretaceous, the continents began to split apart in a number of new plates which moved in different directions and finally collided/stitched to the adjoining plates. Northern margin of the Indian plate has witnessed a plate-scale geodynamic activity, within the then Tethys Sea, which ultimately resulted in the evolution of gigantic mountain massifs of the Himalaya and the Karakoram mountains.

Cretaceous is also important for its carbonate platforms which are the largest and most widespread sedimentary units in the geologic column. They developed throughout the Cretaceous in the Tethyan region. Their platforms yield a significant amount of the world's oil and contain major reserves. The Cretaceous reefs were widespread to about 30° lat. and particularly abundant along continental margins bordering the new equatorial ocean passage. With the dominance of rudist bivalves over corals in the middle Cretaceous (Aptian–Albian, 119–97 Ma ago) and Late Cretaceous reef ecosystems, the Cretaceous reefal build-ups consist of communities of rudists, stromatoporoids, algae and some corals with distinct dominance of certain organisms according to their stratigraphic and depositional location. Cretaceous carbonate platforms thus contain important information about changes in fauna, depositional facies, diagenesis and climatic events as they go a long way in providing clues to platform growths and demises. Comparison of different carbonate platforms from diverse tectonic and climatic settings provides a unique test to constrain basic controls on carbonate platform evolution, including effects of biotic changes, eustatic sea-level fluctuations, variations in tectonic subsidence rates, terrigeneous sediment influx and palaeoclimate. Rajeev Upadhyay (**page 223**) discusses the palaeogeographic significance of the occurrence of an important Cretaceous carbonate platform margin of the erstwhile Tethys Sea with abundant rudist-bearing build-ups from the Shyok Suture Zone of the Saltoro Hills of northern Ladakh and eastern Karakoram. The build-ups are associated with volcanic rocks of the Shyok Suture Zone of northern Ladakh and have been correlated with the tropical and subtropical Euro–African–Asiatic regions of the northern margin of the Tethys.

Fault growth, related folding and propagation of fold in the frontal and lateral directions are usually observed in fold-and-thrust belts. The process of active faulting and associated fold growth, lateral propagation and fault segmentation as well as linkage in many tectonically active regions have influenced the shaping of the landscape. The Kumaun Sub-Himalaya region is one of the most active regions falling into Seismic Zone V along the Himalaya. The Kaladungi Fault (KF) – active fault, an imbricated thrust fault of the Himalayan Frontal Thrust (HFT) system provides an excellent example of forward and lateral propagation of fault and related folding in both directions along the strike of the fault. The KF has displaced the distal part of the Kaladungi fan surface resulting into formation of south-facing active fault scarp with variable heights along the front. The variation in heights along the fault is attributed to lateral propagation of fault and associated fold in both directions (i.e. east and west) from centre. The height of fault scarp is ~ 60 m in the east, ~ 200 m in the central part and ~ 80 m high in the west. These clearly testify displacement starting at nucleation in the centre and propagating laterally in an elliptical manner. The northwest and southeast propagation of the KF has resulted into diversion of the Dabka and Baur rivers respectively. The diversion of Dabka and Baur rivers can well be justified by the existence of palaeo-wind-gaps through which these rivers flowed earlier during the Recent geologic past. See **page 229**.

Data on areal extent of glaciers, volume of glacier-stored water, mean annual rate of retreat and loss of glacier mass are useful. However, this information is not easily available due to sparse data, as the Himalayan region is rugged and also experiences extreme weather conditions. Kulkarni and Karyakarte (**page 237**) have reviewed existing data to provide overall estimates of these parameters for the Indian Himalaya. The glacier mass balance is estimated using field and remote sensing-based methods. Volume is estimated by scaling methods. The estimate suggests that the areal extent of glaciers in the Indian Himalaya is 25,041 ±1726 km^2 and glacier-stored water is between 3600 and 4400 Gt. In addition, the review also suggests that glaciers in the Indian Himalaya have lost 13% geographical area and 443 ± 136 Gt of glacier mass in last 3–4 decades. The study also points out that mean annual loss in glacier mass in the Indian Himalaya is accelerated from –9 ± 4 to –20 ± 4 Gt/year from 1975–1985 to 2000–2010. This is significant acceleration in mass loss in the last three decades. It will have an influence on the availability of water in the future.

The landscape of the Himalayan range is dynamically evolving by active interaction of the tectonic processes and the climatically sensitive gradational agents. During Late Quaternary–Holocene period, the region experienced extreme climatic variation affecting fluvial discharge and bed load in response to the glaciation/deglaciation or intensification of monsoon system. Pandey *et al.* (**page 245**) have attempted to understand these climate footprints in the Late Quaternary–Holocene landforms in Dehra Dun, which is a front parallel synformal trough. The glacial-fed and thereby climatically sensitive Ganga and Yamuna rivers drain through margins of the Dun valley with significant drop in stream gradient and the channels become braided. The braided stream suggests fluvio-dynamic equilibrium producing characteristic landforms and has been interpreted as proxy to the climate fluctuation in the upstream catchment. The Dun valley also experienced aggradation of piedmont fans during > 40–10 ka. The variations are exclusively related to the local catchment, provenance and tectonic set-up. The analysis of these landforms in space and time helps in understanding the role of climate fluctuation, proximity of the source to the sink and their effect on gradational processes.

There has been a long-standing controversy on the timing of collision in the Himalaya and Trans-Himalayan Mountains, which has been deciphered between 65 and 35 million years (Ma) using various proxies. The available geological and geochronological data from these mountains have been evaluated by A. K. Jain (**page 254**) to reach the conclusion that these mountains did not evolve by collision of continents of the Indian and Asian plates initially, against the common belief. On the contrary, oceanic lithosphere of the Neo-Tethys Ocean subducted and episodically melted first beneath the southern Asian margin and then produced the intra-oceanic Dras–Shyok Island Arc to generate Karakoram Batholith and subsequently the volcanic island arc. Subsequently, the arc was intruded by the Trans-Himalayan Ladakh batholith since 105 Ma. However, bulk of the Trans-Himalayan magmatism peaked around 56 Ma. As a consequence, there was no direct continent-to-continent fusion in the Trans-Himalaya in the beginning. Timing of the first India–Asia impingement has been better constrained at ~ 56 Ma by comparing ages and products of deep-seated and surface processes: (i) subduction and melting of the Tethyan oceanic lithosphere – the Trans-Himalayan Ladakh batholith at ~ 56 Ma; (ii) subducted continental lithospheric and the UHP metamorphosed Indian crust in the Tso Morari Crystallines at ~ 53 Ma; (iii) biostratigraphy of the youngest marine sedimentation in Zanskar. It is likely that the Himalaya first witnessed its rise and emergence in Tso Morari terrane between 53 and 50 Ma after the continental lithosphere had subducted to ~ 100 km and later exhumed.