

# Neotectonic Movements and Channel Evolution in the Indian Subcontinent: Issues, Challenges and Prospects



Soma Bhattacharya, Harendra Nath Bhattacharya, Balai Chandra Das, and Aznarul Islam

**Abstract** Neotectonics keeps its prominent signatures on river channel evolution. This chapter reviewed emergence, flourishing and advancement of the study of neotectonics, adjustment of fluvial forms and processes to neotectonics within the territory of Indian Subcontinent. Based on this review, we confirm the theme of the volume and suggest profuse scope of further research on the Himalayan Neotectonics and Channel Evolution in the Indian Subcontinent ranging from basin-scale to channel-site scale. We also introduced other chapters of the book.

**Keywords** Neotectonics · Quaternary evolution · Morphotectonic signatures · Dating techniques · Cratonic blocks · Pericratonic Basin · Early Proterozoic mobile belts · The Himalaya · The Indogangetic plain · The Ganga-Brahmaputra-Meghna delta · Indian Peninsular

## 1 Introduction

Neotectonics is a comparatively new branch of study dealing with the earth's deformation process continuing from recent geological time. Obruchev (1948) who used the term 'neotectonic' first "recognised the importance of the recent and active geological processes and proposed a new independent branch of Geosciences" (Pavlidis 1989). The study of neotectonics flourished since the last quarter of the twentieth century, being carried by researchers from different scientific disciplines

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like geology, geodesy, seismology, geomorphology, etc. and the subject is gaining popularity day by day as it permits detailed observation and analysis.

Definitions of neotectonics are varied where scientists try to emphasize the term from different angles; some try to define it from the point of view of time, either relative or absolute; some others from its structural and topographic implications. Such definitions arouse two questions: first, from when exactly neotectonic activity starts and second whether it is really possible to make a distinction between old and recent tectonics.

### ***1.1 Definition of Neotectonics***

If we arrange the definitions of neotectonics provided by various scientists and researchers chronologically we can recognise a trend. Instead of explaining the driving mechanism workers are more interested to define the term on the basis of its manifestation time either absolute or relative. The age of commencement as specified by different scientists for neotectonics varies widely. Obrutschow fixed the age of commencement to early Neogene, (Murawski 1972) whereas Gary et al. (1972) assigned it to Pliocene which was subsequently supported by Bates and Jackson (1980). On the other hand Bloom (1998) also assumed Neogene as the starting age of neotectonism and Vita-Finzi (1986) attributed it to Late Cenozoic. Diebold and Muller (1985) assigned neotectonics to the Quaternary epoch only. However, all these definitions extend the period of neotectonics up to the present time. Therefore, it appears that there is a lack of consciousness among the scientists regarding the actual period of neotectonic activity, as it is really tough to separate Neotectonic from Paleotectonic in field observations.

As a result, the later definitions describe the neotectonics in a relative time frame such as neotectonics start at a different time in different regions. As a consequence, the phrases like, ‘the recent geological past’ (Stewart 2005), ‘current tectonic regime’ (Stewart 2005), after ‘last significant tectonic reorganisation’ (Pavlidis 1989), ‘contemporary stress field’ (Blenkinsop 1986), after completion of ‘the present day configuration of relative plate boundaries and motion’ (Hancock 1986); were used to demarcate the relative age and characteristics of neotectonics.

The International Union of Quaternary Research (INQUA) defines neotectonics “as any earth movements or deformation of the geodetic reference level, their mechanisms, their geological origin, their implications for various practical purposes and their future extrapolations”. According to Pavlidis (1989) “neotectonics is the study of young tectonic events which have occurred or are still occurring in a given region after final orogeny or more precisely after its last significant tectonic reorganisation”. Stewart (2005) defines neotectonics “as the study of horizontal and vertical crustal movements that have occurred in the geologically recent past and which may be ongoing today”.

Therefore in conclusion it can be said that the neotectonics explain movements and structural deformations active when ‘contemporary stress field’ of a region is

established after the 'significant tectonic reorganisation' of the area. This implies that it occurred at different regions at different times. Often active tectonics is used as a synonym of 'neotectonics', though according to Wallace (1986) "active tectonics are tectonic movements which are expected to occur within a future time span of concern to society".

## ***1.2 Implications of Neotectonics***

Neotectonics involves both regional and isostatic deformations. As a result, they are common along the young orogenic mountain belts lying at active plate boundaries. The vertical crustal movements occur due to seismic displacements, glacio-hydro and sediment isostatic movements and also from anthropogenic changes. Mainly recent sediments bear their signature. Neotectonic movement of studies comprises a wide range of timescale. As Morner (1980) says, it includes movements from "instantaneous (seismic),  $10-10^2$  (geodetic),  $10^2-10^4$  yr (Holocene studies),  $10^4-10^6$  yr (Pleistocene studies), up to about  $10^7$  yr if it is necessary to enable us to understand the origins of recorded movements". Neotectonic activities and their effects are generally smaller in scale than the paleo-tectonic activity. Neotectonics and seismological studies are supplementary to each other. It gives ample opportunity to study the role of tectonic activity on landform features through morphometric analysis. Quantitative techniques and analysis of remote sensing data are widely used in neotectonic and morphotectonic studies. Being recent they provide a scope of the investigation, measuring and monitoring of landscape evolution through field observation. Migration or lateral displacement of stream courses, abrupt deflection of streams, dissection and displacement of sub-recent or recent geomorphic feature, valley asymmetry, linear scarp, fan terraces, river terraces, increasing incision of rivers, formation of paleolakes due to ponding of rivers are some of the geomorphic indicators of neotectonics.

## ***1.3 Determination of Age***

Dating of features by field study and laboratory experiment is an important part of neotectonic studies. There are different dating processes- some deriving the relative age and some other the absolute age. Relative age is determined by the laws like the principle of superimposition, the principle of cross-cutting relationship, the principle of horizontality, the principle of lateral continuity, the principle of unconformity and through paleontological studies. Such features are generally identified on exposed vertical sections where the depth of rock mantle or soil cover is very little or they are completely absent. Boring is also done to decipher the stratigraphic relationship. The clast seismic velocity method, the study of weathering rinds, the study of obsidian hydration rind, depth of soil cover, the study of carbonate coatings

and other pedogenic indicators also help to derive the relative age of the surface and near-surface materials. Lichenometry is also a long-used technique of relative dating in geomorphology. All these are qualitative derivation.

To deduct absolute age several methods are used some of them are biological or geological and the remaining techniques are radiometric dating, luminescence dating, cosmogenic dating, chemical dating and paleomagnetic dating. The following table gives an idea regarding these dating techniques (see Table 1).

## **2 Neotectonics and Channel Morphology in Indian Subcontinent**

Being highly dynamic in nature the fluvial systems bear signatures of adjustments to the latest phase of tectonic deformation of the area. As a result, the effect of neotectonics is displayed widely over the drainage basins of the world, though it is very difficult to discrete it from those of paleotectonics and other allogenic changes. Through appropriate analysis of such features, the tectonic and geomorphic evolutionary history of landscapes are summarised, which is the prime aim of this edited volume. The papers accrued in this volume incorporate interesting morphometric analysis to establish the influences rendered by neotectonic movements on channel evolution in the Indian subcontinent.

### ***2.1 Physiographic and Geotectonic Divisions of Indian Subcontinent***

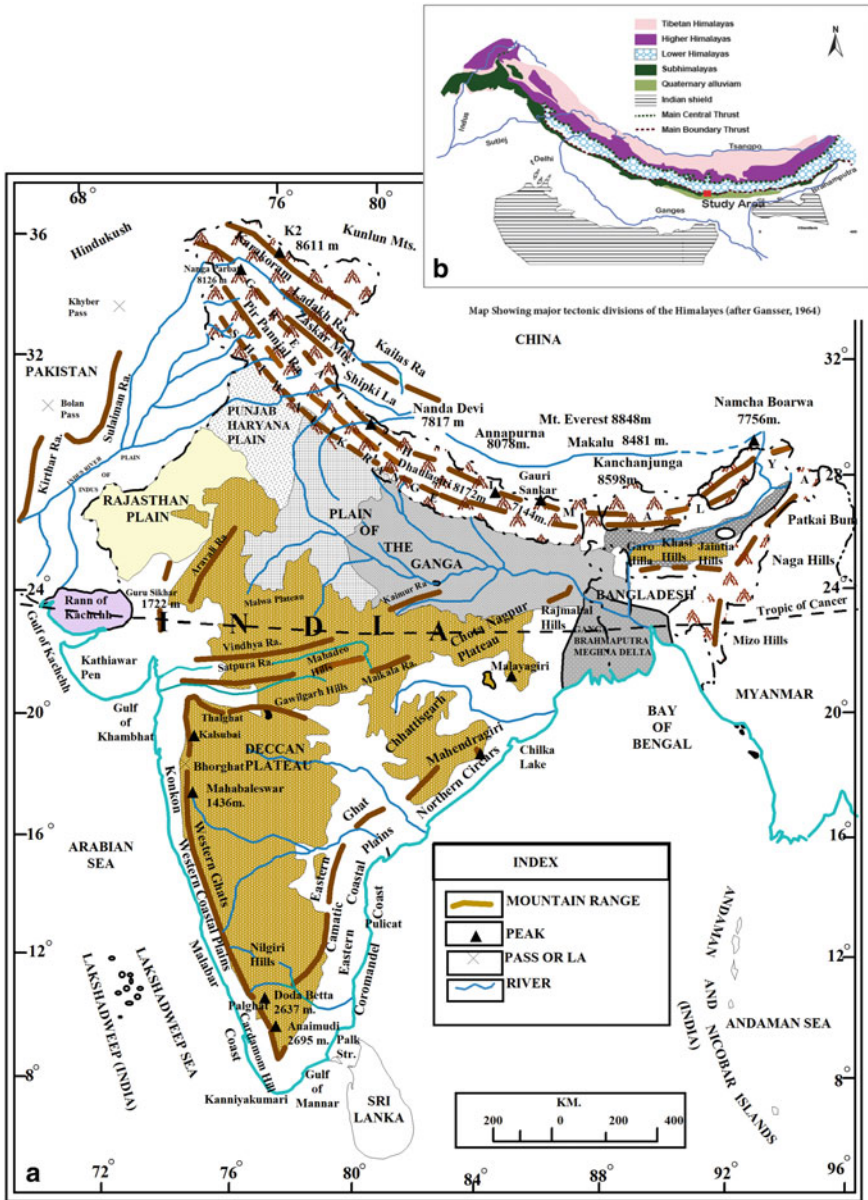
Indian Subcontinent lies in the collision zone of Asian Plate with Indian Plate comprising of the countries of India, Pakistan, Bangladesh, Nepal and Bhutan. It is a surprising land mass embodying rigid and consolidated Paleo-Achaean Cratonic blocks; the Early Proterozoic mobile belts, the lofty Tertiary mountain chain, the Quaternary plains and deltas. The Himalayas, the world's highest mountain containing 10 out of 14 eight-thousander peaks of the world separates Indian Subcontinent from the rest of Asia. The Peninsular India comprises the southern block. In between, there are the largest alluvial plains and deltas of the world—the Indo Gangetic plains and the Ganga–Brahmaputra–Meghna delta (Fig. 1). The subcontinent is highly active tectonically as the Tertiary tectonic evolution has not been seized yet and the Indian plate is still moving towards the Asian Plate (at a rate of  $58 + 4$  mm/year, Freymueller et al. 1996) and to the Sundaland. (at a rate of  $34 + 6$  mm/year, Sahu et al. 2006). The neotectonic activity in the Indian subcontinent can be broadly classified into two—(i) Interplate tectonic activities are those associated with the Himalayas and the Indo-Gangetic Plains which are the direct products of inter plate collision of the Tertiary Era and (ii) Intraplate tectonic activities are those

**Table 1** Different dating techniques

Method	Useful range	Materials needed	References
Radioisotopic $^{14}\text{C}$	35 ka	Wood, shell	Libby (1955), Stuiver (1970)
U-Th	10–350 ka	Carbonate (corals speleothems) Silicate (zircon, mica)	Ku (1976)
Thermoluminescence (TL)	30–300 ka	Quartz or feldspar silt	Berger (1988)
Optically stimulated luminescence (OSL)	30–300 ka	Quartz silt	Aitken (1998)
Cosmogenic	0–4 Ma	Quartz	Lal (1988), Nishiizumi et al. (1991)
In situ $^{10}\text{Be}$ , $^{26}\text{Al}$			
He, Ne	unlimited	Olivine, quartz	Cerling and Craig (1994)
$^{36}\text{Cl}$	0–4 Ma		Phillips et al. (1986)
Fission Track analysis	1 Ky–5 Ma	Apatite, Zircon sphene and Mica	
Chemical Tephrochronology	0–several Ma	Volcanic ash	Westgate and Gorton (1981), Sarna-Wojcicki et al. (1991)
Amino acid racemization	0–300 ka, temperature dependent	–	
Paleomagnetic Identification of reversals	>700 ka	Fine sediments, volcanic flows	Cox et al. (1964)
Secular variation	0–several Ma	Fine sediments	Creer (1962, 1967) Lund (1996)
Biological	0–10 ka, depending upon existence of a local master chronology	Wood	Fritts (1976), Jacoby et al. (1988), Yamaguchi and Hoblitt (1995)
Dendrochronology			
Sclerochronology	0–1000 yr	Coral	Buddemeier and Taylor (2000)

After Burbank and Anderson (2016)

associated with the reactivation of old fold and shear zones of the Indian Peninsular due to breaking, migration and collision of plates.



## **2.2 *Interplate Neotectonic Movements in the Himalayan Region and Resultant Landforms***

It is difficult to specify the age of neotectonic movement in the Himalayan region and separate it from the long continuous paleo-tectonic activity of the region and resultant landforms.

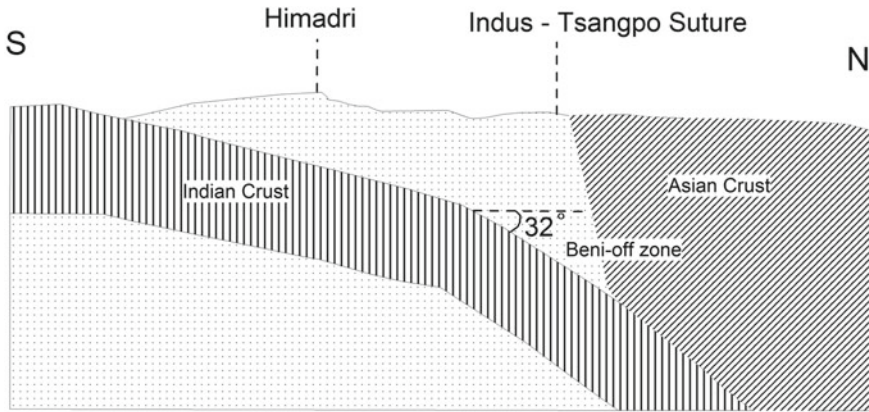
If we follow the definition of Pavlides (1989) as mentioned earlier the ‘neotectonic age’ of India may be considered as started from Late Quaternary after the Siwalik orogeny and formation of Indo Gangetic plain (126 Ma) But for practical purposes, most of the studies on neotectonics are of the Quaternary period extending over Pleistocene through Holocene to Anthropocene age.

The Pleistocene and Holocene earth movements and structural deformations have been termed as neotectonic movements by a group of scientists whereas others prefer to use the term active tectonic though this term is specifically associated with repeated recent or sub-recent earthquakes whose results are directly compatible with seismic analysis and their future extrapolations. The reactivation of old and traditional faults is manifested through different geomorphic markers among which adjustment of drainage lines/systems, terrace building, channel deflection, paleochannels, formation of knick points, waterfalls, lakes, etc. are noteworthy. Analysis of the evolution of such features with the help of different morphometric techniques, topographical sheets and remote sensing data, different dating processes, and study of micro-sedimentological, paleontological and paleoseismic evidence help us to derive the age and character of tectonic deformation. All these geomorphic features not only bear the evidence of structural deformation but also bear the evidence of Pleistocene climatic change. Therefore in searching the clues of earth movement and structural deformation one should be careful about the evaluation of climatic influences also. Quaternary Developments in India, neotectonics, active tectonics and resultant structural and geomorphic deformation can be summarized as follows.

### **2.2.1 A Great Himalaya or Himadri**

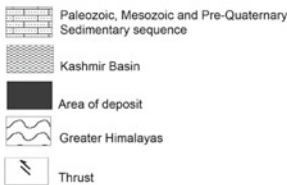
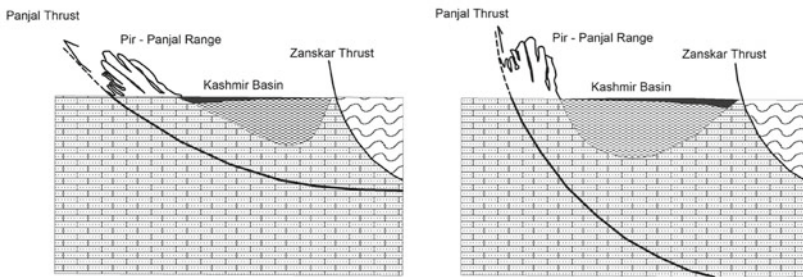
During Quaternary, the Great Himalayas or Himadri was rising at a very fast rate. The rate of uprising in its northwestern part was variable. In Nanga Parbat-Harmosh Massif it was 3–4 mm/year (Whittington 1996), in Karakoram region, it was 2 mm/year (Zeitler et al. 1982) and in intermountain Karewa basin along Pir Panjal range it was 3.5–10 mm/year (Burbank and Jhonson 1982). The rate of erosion was also high though variable from region to region with variation in structure, lithology and climate. The river Indus curved a deep valley in the Nanga Parbat Massif through an incision along the active thrust boundary creating deep gorges (Valdiya 2016). The uplift along the PirPanjal thrust system about 4 million years ago originated the Karewa Paleo Lake ponding the course of the Jhelum River (Valdiya 2016). Valley of Rambiassa in the Southern part of Kashmir valley shows unpaired fluvial terraces and the basin is cut by three northeast dipping faults (Ahmad and Bhat 2012).

These faults have affected the recently deposited soft sediments. It was subjected to subsequent sedimentation of a thickness of 1300 m at a rate of 16 cm/1000 year to 64 cm/1000 year deposited by fluvio-lacustrine or glacio-fluvio-lacustrine and aeolian processes and the thickness of sediment in the basin changed its location due to the movement along Panjal Thrust (Agarwal et al. 2002; Fig. 2) The sedimentation was triggered by the landslides and debris flows activated by the movements along



SCHEMATIC SECTION

**a**



**b**

**Fig. 2** **a** A model depicting the collision and subsequent bending of Indian crust against the Asian crust (after Makovsky et al. 1996, From Valdiya, 2016); **b** Schematic diagrams showing (i) deposition taking place towards south and (ii) towards north of Karewa basin due to movement along Panjal Thrust (after Agarwal et al. 2018)



thrust planes. The faulting of the southern part of Karewa resulted in the formation of finger liketerraces occurring at an elevation of 2700–3000 m (Valdiya 2016). These terraces are known as marg e.g. Gulmarg and Khillanmarg. Around 20,000 yr BP continuing movements on faults formed an opening (Baramula gorge) which resulted in the draining of the substantial part of the lake (Agarwal et al. 1989). The remnants are the Dal and Wular lakes. The area is subjected to subsequent neotectonic movements resulting in the formation of the fold, fault, sand dykes, terraces, etc. The earthquakes changed and reoriented the geomorphic features. Drainage in the area comprises dendritic, anastomosing and parallel. A sudden decrease in the gradient of the area resulted in the development of anastomosing drainage pattern while parallel drainage indicates the presence of linear faults and ridges (Agarwal et al. 2018).

Displacement of debris-flow deposits and offsetting of 1–2 km fan indicates reactivation of Karakoram fault in recent past. The rate of incision of the Indus river in Pakistan increased in the recent past and there are left out strath terraces produced in the process of incision. With the help of in situ cosmogenic  $^{10}\text{B}$  and  $^{26}\text{Al}$  exposure Leland et al. (1998) stated that the rate of incision has profusely increased upto 9–12 mm/year in last 7000 yr before which the rate was 1–6 mm/year. This obviously indicates the occurrences of tectonic movement in the recent past.

Ladakh is a barren land with rugged topography where most of the area lies above the tree line. Unlike other areas Ladakh experienced a decreased rate of the incision. Since 15,000 years BP the region experiences an incision rate of 0.3–0.4 mm/year compared to 2 mm/year in the period between 15,000–22,000 year B.P. (Sharma et al. 1998). This rate is the lowest in Quaternary Himadri of northwest. Huge alluvial fans, talus and scree cones, deep gorges (Fig. 3a), waterfalls, scarp faces, fan terraces dominate the local relief (Phartiyal et al. 2005). A number of lakes of fresh or brackish water are found on either side of the Indus–Tsangpo Suture zone. These lakes probably are the result of tectonic reactivation in the Holocene. Tso Morari Lake is the largest among such lakes. It has a length of about 25 km and an average width of 6–8 km indicating damming of north-northwest-south-southeast trending river and its tributaries by debris avalanches (Shukla et al. 2012). The water from the surrounding region drains into the lake. West of Leh damming of the river Lamayuru by a tectonically induced landslide produced a lake during 35,000–45,000 yr B.P. (Bagati et al. 1996; Phartiyal et al. 2005). Subsequent sedimentation under fluvial and lacustrine environments has turned it into a delta (Mathur and Kotlia 1999).

Spiti Valley in Himadri shows a mature topography with uninterrupted sedimentary cover (outwash plains, alluvial fans, debris cones, fluvial terraces and lake deposits) which holds very good potential to study the Quaternary history, palaeo climate, neotectonic and earth surface processes (Phartiyal et al. 2009). The valley is located in the extensional regime with MCT (Ni and Barazangi 1985; Bhargava and Bassi 1998) in the south and Indus -Tsangpo Suture Zone in the north with several north-south and north northeast-south-southwest trending faults. According to Phartiyal et al. (2009) the north-south trending normal faults (Kaurik-Chango and Leo-Kargil Horst) and their conjugate faults are the cause of slope failure and landslides leading to blockade of river intermittently converting a fluvial regime into lacustrine phase. Tso Lake is another paleolake along the upper course of Yunam

**a****b**

**Fig. 3** Deep Gorge of the river **a** Zaskar in Ladakh; **b** Alakananda in Uttarakhand

Tso river formed due to damming of the river in response to neotectonic activity during Quaternary times (Bohra and Kotlia 2008). Phartiyal et al. (2009) recognized evidence of recurrent earthquakes along the ShyokSuture zone through the study of multiple lenses of paleoseismites in the paleolake at Khalsar. The uplifted and incised fluvial sediments in SekoNascongPaleolake in the upper reaches of the Spiti river

indicate two phases of active tectonic movements in 12,000 year BP and 7000 yr B.P. respectively. In Spiti valley, the N-S trending Smudo fault is one of the very active transverse faults which has displaced fluvial and lacustrine sediments (Shah and Virdi 1997). Mohindra and Bagati (1996) noticed 90,000–26,000 ka old eight levels of seismites in a 120 m thick sedimentary column. In 1975 an earthquake of 6.5 magnitude occurred along this fault. Chamba fault with sinistral strike-slip movement along Ravi river was also a very active fault being subjected to earthquake in 1975, 1945, 1968, 1986 and 1995 (Joshi 2004; Valdiya 2016).

Deflection of the river along lineaments, incision forming deep gorges due to river rejuvenation, formation and disappearance of lakes are geomorphic features found along the great Himalayas in Himachal Pradesh and Uttarakhand due to reactivation of Main Central Thrust and Trans Himadri Detachment fault. Deflection of the Sutlej river in the vicinity of NS trending lineament proves the active nature of the basin (Joshi and Kathyari 2008). A number of lakes have formed along the rivers Gori, western and eastern Dhauli and Kali in Uttarakhand due to damming by landslides and huge moraines and upward movement of footwall made up of Vaikrita crystalline rocks. (Valdiya 2016). At least three lakes have formed due to tectonic reactivation in the eastern Kumaon sector (lake Garbyang studied by Kotlia and Rawat (2004); lake Goting studied by Juyal et al. (2009) and lake Burfu studied by Pant et al. 2006, Kotlia and Joshi (2013). According to their studies, Garbyanglake has formed by movements between 17,000 and 20,000 B.P and 13,000–14,000 year B.P; Goting paleolake has formed earlier than 40,000 yr BP and Burfu were active in between 11,000–16,000 year B.P. Draining of these lakes produced waters cut gorges on downstream of fault crossings (Valdiya 2016).

In Nepal, the movements along the reactivated MCT have generated a youthful, rugged topography with deep gorges and high ranges. In northwest Nepal, tectonic movements have reactivated portions of MCT. The Darma Fault, the Talphi Fault, the Tibrikot Fault and the Dhaulagiri fault are right stepping en echelon faults forming a 170 km long fault system extending from north west to south east (Nakata 1989) resulting in the right lateral displacement of stream courses and ridges. Fluvial terraces, scarps, alluvial fans and fan terraces indicate vertical displacement.

All the major rivers Yamuna, Ganga, Alakananda, Kali, Gandok, Kosi etc. have maintained their courses through rejuvenation. They show nearly vertical deep gorges (Fig. 3b) knick points, waterfalls and rapids along their courses in the southern zone related to MCT. River Tsangpo Brahmaputra has cut a deep valley near Namcha Barwa along the syntaxial bend. In its long course from Tibet to eastern India, it has majestically developed amazingly deep gorges cutting the entire width of the Himalayas through the zone of weakness near the bend.

### 2.2.2 The Lesser Himalaya

The lesser Himalaya presents a gentle relief with wide valleys and meandering rivers indicating a mature topography in between the MCT and MBT. Crossing the Greater Himalayas in deep gorges as soon as the rivers enter the undulating lesser Himalayas

they flow through wide and open valleys. The tributary streams also full of twists and turns, excepting where they enter the trunk stream at a lower level. The wide-open valleys are transformed into narrow gorges of 200–300 m depth in areas of active tectonics of the MBT e.g. Nainital Massif (Valdiya 1988). In many sections, nappes of crystalline rocks overlie the sedimentary rocks. These nappe zones are ideal places for mass movements with resultant ponding of streams into the lake. South central Kumaon is dotted with a number of lakes whose origin can be attributed to faulting along the MBT. The Nainital and Bhimtal are the results of movements along a conjugate pairs of NW–SE and NEN–SWS trending faults showing right lateral and left lateral displacement respectively (Valdiya 2016).

The Bhimtal and Nakuchiyatal, now separated by 52 m thick deposits of lacustrine sediment was once continuous as revealed from paleontological studies (Kotlia 1995; Kotlia et al. 1997). The Dulampaleolake, formed about 30,000 year BP on Saryu River (Kotlia and Sanwal 2004) and Wadda paleolake near Pithoragrah formed about 35,000 years BP (Kotlia et al. 2000) are lakes of the same origin active during the Late Quaternary. Six levels of aggradational terraces along both sides of the Alakananda river in Uttarakhand, structure governed course, fast cascading and deeply incised tributary streams indicate neotectonic movements along North Almora Thrust (Chaudhary et al. 2008; Kothyari and Pant 2008).

There is growing evidence of neotectonics and seismicity in the Lesser Himalayas in Nepal. According to Jackson and Bilham (1994) the rate of uplift is 3 mm/year. Active faults trending NNW and ESE direction are found along older fault lines. Barigad Fault and Sun Kosi–RosiKhola fault show right-lateral strike-slip displacements (Naktala 1989). Some NS trending normal faults are also found. The results of uplift and displacements along such active faults are seen in the rejuvenation and superimposition of young topography on the overall mature topography of lesser Himalayas with offsetting of rivers and ridges, formation of terraces and alluvial fans. The courses of the Bari Gad, Nishi Khola, ThuloKhola and SaniBheri rivers lie along these active faults for about 140 km (Nakata 1989). Fault scarps, elongated depressions are also found. Almost all the streams exhibit paired or unpaired terraces. Generally, three and occasionally six aggradational terrace levels are found (Khan et al. 1982), indicating different pulses of Pleistocene Holocene earthquakes. Such six levels of terraces are also found upstream of the Tehri dam near Srinagar, Uttarakhand along the river Bhagirathi (Valdiya 2016). Active faults with repeated Quaternary slip are relatively straight in nature in Nepal suggesting a near surface steep dip.

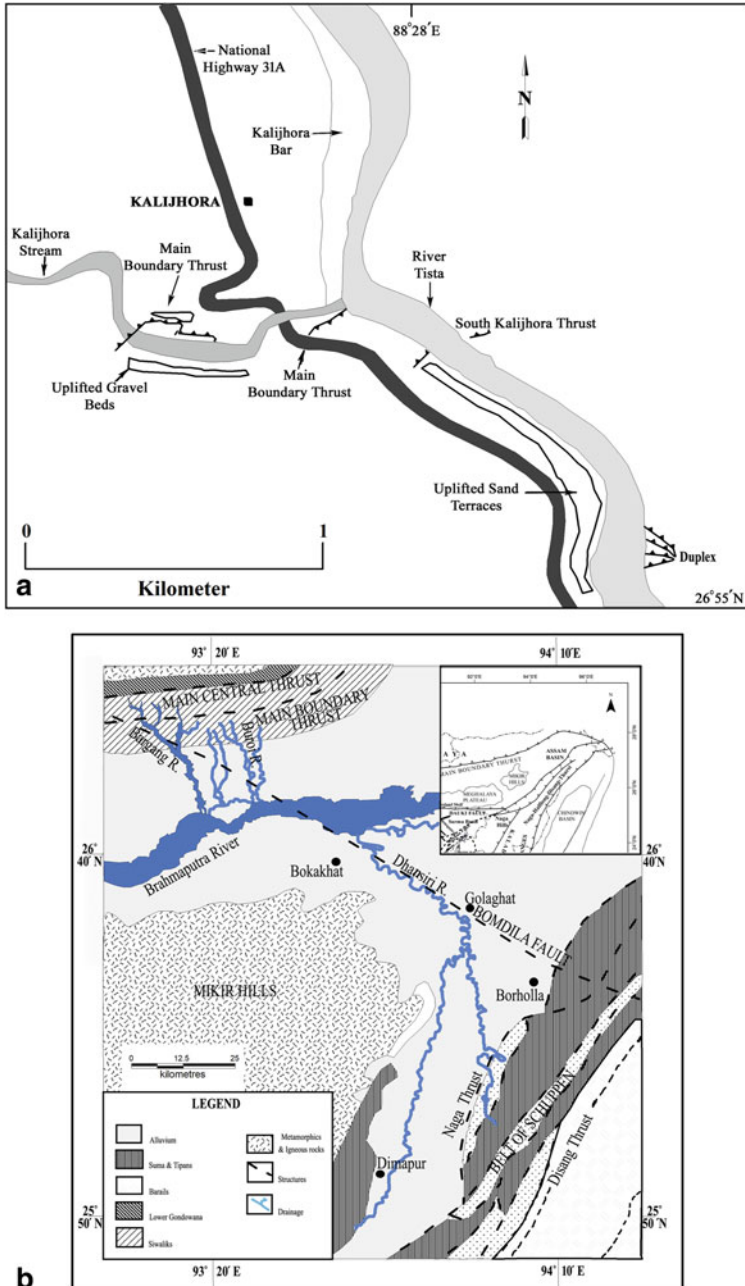
Pokhra and Rar lakes are the results of river ponding. The Kathmandu paleolake essentially a paleotectonic feature was formed in the late Pliocene, as revealed from paleontological studies (Yoshida and Gautam 1988; Sakai 2001), by ponding of Bagmati river due to uplift of Chandragiri Hill along an east–west trending fault (Valdiya 2016). Subsequent movement along a tear fault resulted in the draining of the lake 11,000 years ago (Valdiya 2016).

Neotectonic activity in the lesser Himalayas of Darjeeling and Sikkim are not uncommon. The Tistariver has migrated about 150 m east ward (average rate 13 mm/year) and incised its valley for about 48 m (vertically average rate

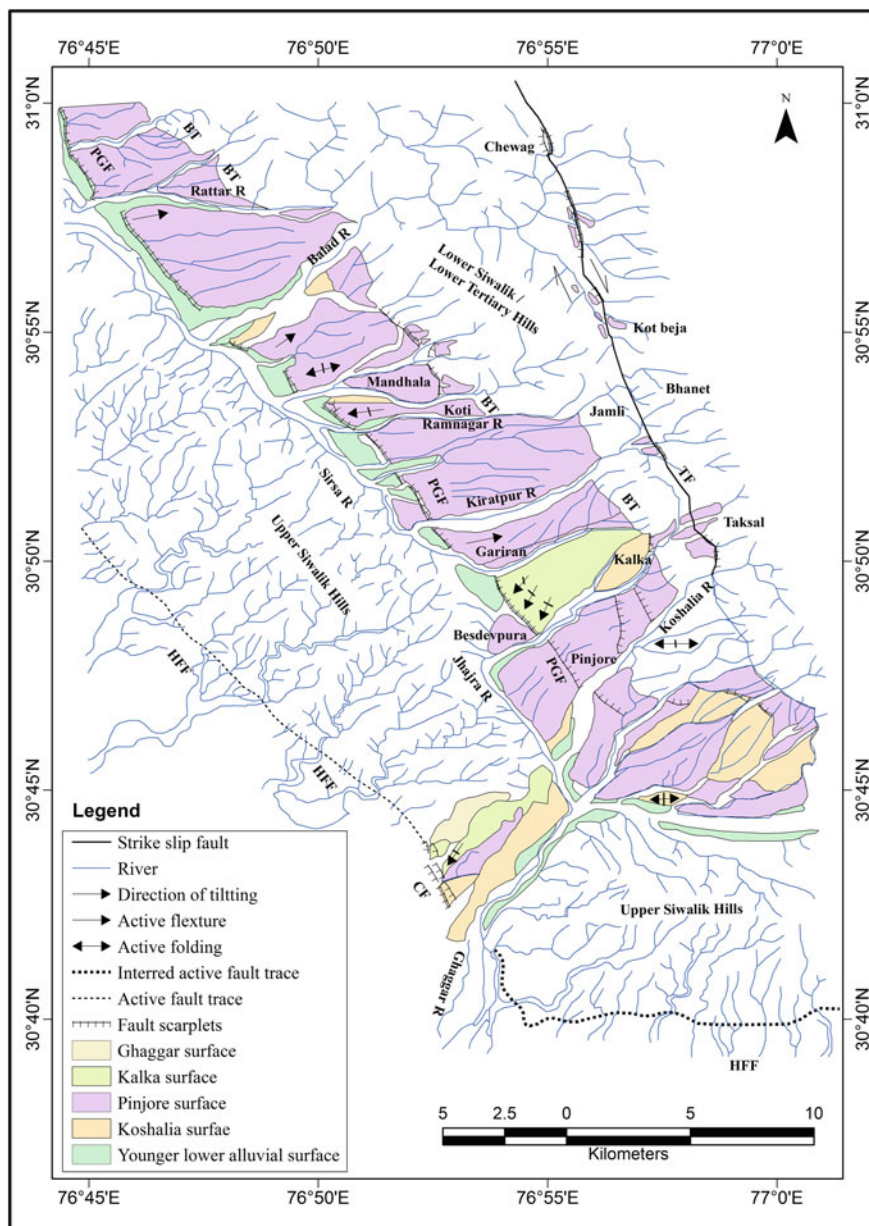
4.4 mm/year) creating unpaired strath terraces between 11,000 and 14,000 years (Mukul et al. 2007). Quaternary unsorted deposits are found along the northern and southern part of Kali Khola a tributary of the Tista at a height of 4 m from the present channel suggests a very recent activity on the MBT (Mukul 2000). Darjeeling sector, the imbricate structure extends southward over a width of more than 30 km (Valdiya 2016). This imbrication has raised the bed of the river Tista leading to the formation of a bar upstream (Fig. 4) (Valdiya 1976). The Lesser Himalayan Duplex is an active structure in the Darjeeling Sikkim, Himalaya with a very pronounced cluster of earthquake epicentres (Kellet et al. 2014). The clustering is prominent along the traces of surface exposures between MCT and MBT (Pandey et al. 1999). The observed seismicity in the Lesser Himalayan Duplex is dominated by moderate frequent thrust and strike-slip earthquakes (Kellet et al. 2014) whereas eastern Nepal records moderate to micro earthquakes along the entire length of Himalayan Wedge (Pandey et al. 1999; de la Torre et al. 2007).

### 2.2.3 The Sub-Himalayas or Siwaliks

The entire sub-Himalaya with foothills lying to the south of MBF is the result of Quaternary tectonic movements. During the late Pleistocene the resurgence of tectonic movement led to the reactivation of MBT and structural development of Siwalik sediments, derived from the subaerial wastes of the mountains, swept down by the numerous rivers and streams. The process was alike that of what present day rivers and their tributaries are doing. Reactivation of MBT and associated reverse fault system brought the older rocks from north to rest over the Siwaliks. The Siwalik sediments were deformed to a series of simple open folds which become more complex as one moves towards the north. Such open synclines west of 79° east longitude form longitudinal intermontane piggy back valleys later filled up to form duns e.g. Pinjaur Dun in Punjab, Dehra Dun in Uttarakhand and Kota Dun in Kumaun and Dung Dun in Nepal separated by piedmont type of foothills. Dun type foothills are the most common features along the sub-Himalayan zone of the central Himalayas including Kumaon and Nepal Himalayas (Nakata 1972) (Fig. 5). The Duns are good archives of alluvial fans and fluvial deposits. Pinjore Dun, a 45 km long and 8–10 km wide valley lying near Chandigarh is drained by longitudinally flowing major tributaries of Sutlej and the Ghaggar Rivers. Aggradation under alluvial fan environment by the processes of mass movement is the prime cause of the initial formation of the Dun later shaped by the streams. The subsequent confinement of the streams into channelized flow due to increased erosion and resultant incision formed different terrace levels. Increased erosion and the subsequent incision may occur both due to climatic change and tectonic movement during Quaternary. Five terrace levels were observed in the Pinjore Dun and along the Ghaggar river as studied by Malik and Nakata (2003). The Kota Dun lies in the eastern part of the Kumaon Himalayas in Uttarakhand. Between the river, Kosi in the west and Baur in the east lies 21 km long Kota Dun with an average width of 5 km. Most of the streams here form antecedent gorges with straight escarpments running in the WNW-ESE direction parallel to each



**Fig. 4** **a** Map showing the tectonic features and associated landforms as uplifted sand terrace and gravel beds in and around Kalijhora in Darjeeling Himalayas, India (after Mukul 2000). **b** Map showing fault guided course of river Subansiri a tributary to Brahmaputra river, Brahmaputra planes, India (after Sarma and Sharma 2018)



**Fig. 5** An example of Dun type of foothill in north western Himalayas (after Malik and Nakata 2003)

other when they cut through the uplifted ridges near the plain (Nakata 1972). Middlemiss (1890) designated these escarpments as warped cliffs. The sedimentation and evolution process of the Kota Dun is more or less similar to that of Pinjore Dun. Dehra Dun is located in the northwestern part of Uttarakhand with an average length of 90 km and an average width of 25 km. The Dun is drained by two major rivers Ganga and Yamuna both of which exhibit a series of river terraces along their course. The characteristic deposits of all the Duns are designated as Dun Gravel, deposited during Late Pleistocene and early Holocene as tectonic movements decreased the gradient of rivers and streams (Valdiya 2018). Reactivation of these faults caused tilting and deformation of the Dun gravel at 15°–20° (Nakata 1972; Valdiya et al. 1992; Rautela and Sati 1996; Thakur and Pandey 2004).

Reactivation also formed newer Duns (Rao 1977) in the Late Holocene after a decrease in stream gradient. All these are related to the neotectonics of the Himalayan Frontal Thrust (HFT). Originating about 1.6ma ago HFT is a series of reverse faults that demarcates the boundary of the Himalayas against the vast expanse of the Indo-Gangetic plain. At someplaces, it is covered by younger alluvium. According to Valdiya (2003), 'where the hidden ridges of the Indo-Gangetic basement impinge the Himalayas, the mountain fronts are ruptured. At these places, HFT is repeatedly reactivated'. But in the sectors where the basement does not touch the Himalayas, there is no surface expression of HFT and the ground of adjoining Indo-Gangetic plain is sinking with the lateral shifting of the river courses, and large tracts of marshy and water logged lands are formed (Valdiya 2003). Whatever it may be the HFT is the tectonically most active part of the Himalayas.

The recent rate of convergence as measured by Wesnousky et al. (1999) based on geological studies of deformed terraces is  $14 \pm 4$  mm/year in western Himalaya near DehraDun. Powers et al. 1998 suggested a rate of convergence of  $1 \pm 5$  mm/yr across the Himalayan Front in Dehra Dun and  $14 \pm 2$  mm/yr in the northwest of Dehra Dun. The rate is 15 mm/year in the central Himalayas (Yeats and Thakur 1998). Numerous faults have been traced in recent investigations along the HFF. In Pinjore Dun the active Chandigarh Fault, Pinjore Garden Fault and Barsar Thrust have vertically dislocated, warped and back tilled the fluvial and alluvial fan surfaces of late Pleistocene and Holocene time (Malik and Nakata 2003). A right lateral offset of streams and younger quaternary terraces proves a prominent right lateral movement along the Taksal Fault in the same region. Black Mango Tear fault in the same region resulted in two large surface rapture earthquakes in the last 650 years (Kumar et al. 2001) as revealed by paleoseismic studies. Oatney et al. (2001) through paleoseismic analysis concluded that two earthquakes have struck along the Sirmurital fault in DehraDun.

Sinuosity along the strike is another conspicuous characteristic of HFT which occurs due to differential movements of different thrust sheets. The convex part of HFT is known as salient whereas the concave part is known as recess. The lift over portions of the thrust sheet is thus connected with the lateral ramps or connecting splays which appear on the surface as transverse faults or tear faults (Srivastava et al. 2012). Yamuna tear fault forced the Giri, Bata and Sukha Rao rivers to take sharp southward bend from their normal south east flow (Srivastava et al. 2012) Such

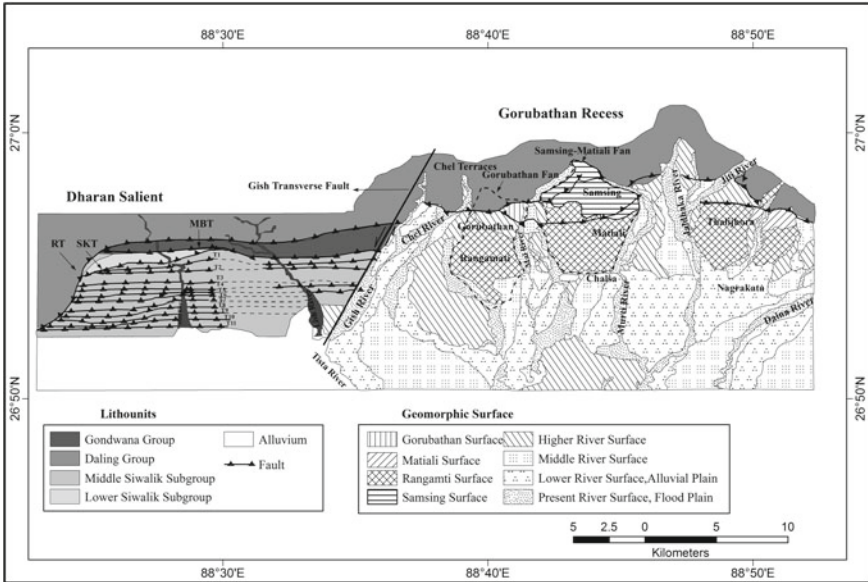


transverse faults are obviously younger in age than HFT. Between the Yamuna and Markanda river exists the Dhanura anticline grew by the merging of three HFT segments and formed a barrier to the drainage arising from the initial northern topography forcing them to get deflected (Sharma et al. 2019).

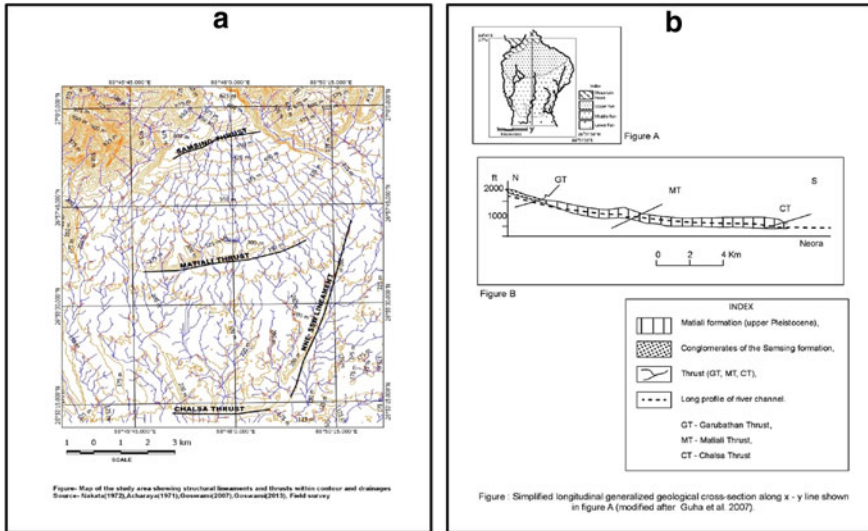
Simple folds cut by faults, branching off from a decollement are the characteristics of Siwaliks in Nepal, rising abruptly from the Gangetic plain to about 2000 m. South eastern Nepal is characterized by active tectonics along MBF and HFF. An active fault near the River TumniKhola on the MBF locally strikes northwest–south east and crosses the east–west active faults on the HFT and extends upto the plains (Nakata 1989). This results in the development of three levels of terraces along TumniKhola. The average slip as calculated by the vertical displacement of terraces is about 1.7 mm/1000 year along HFF (Nakata 1989). A very recent earthquake along an active fault produced a small scarplet of 4.5 m height. Duns are not uncommon in Nepal also like Surkhet-Ghorahi Dun and Dang Dun. Active faulting on the MBF in this region is typically represented by Surkhet-Ghorahi fault which demarcates the northern margin of Surkhet-Ghorahi Dun and extends upto north of Dang Dun (Nakata 1989). Yamanaka and Yogi (1984) deduced the age of terraces of Dang Dun based on radio carbon dating and placed it 20,000–27,000 yr B.P. Gully type of debris flow is a common feature of Siwaliks in Nepal. High rainfall induced mass movement along the steep and precipitous slopes resulted in the development of such features. Sometimes active faulting plays important role in their formation e.g. the region near and along Malai Thrust (Bhandari and Dhakal 2019).

The Siwalik belt is narrow or altogether absent in the eastern Himalayas being buried by metamorphic rocks of the lesser Himalayas (Starkel et al. 2008; Gansser 1964). Nakata (1972) stated that the eastern Himalayas are fringed by piedmont type Foot Hills; which is called Duars and characterized by the formation of Quaternary alluvial fans and fluvial terraces along deeply incised major and minor rivers lying between river Tista in the west and river Jayanti in the east. The major rivers are deeply incised than the minor rivers and discharge their loads in the adjacent alluvial plains. In eastern Himalaya, another pair of salient and recess has been recognized the Dharan salient and Garubathan recess (Mukul 2010) which is a great repository of quaternary alluvium (Fig. 6). This salient recess pair is Non-Dun type which opens to the foreland and the rivers carrying sediments from the recess flush out directly into the foreland (Srivastava et al. 2017). The Garubathan recess (Fig. 7) is an ideal unit to study the deformation of Quaternary sediments as its northern boundary is defined by the Ramgarh Thrust (previously termed as Garubathan Jiti fault (Nakata 1989) and the presence of blind faults 35 km south of the mountain front (Martin and Mukul 2010; Nakata 1989; Guha et al. 2007; Goswami et al. 2012). The Ramgarh thrust bifurcates to the east forming escarpments along Matiali surface, Rangamati and Sumshing surfaces (Nakata 1989). Guha et al. (2007) placed the date of activation of Ramgarh Thrust through radio carbon dating to 34 kybp.

The Matiali scarp shows a dislocation of Quaternary sand and gravel beds of Matiali surface for about 90 m, whereas the uplift along the Rangamati surface is about 70 m and 40 m along samshing surface. These surfaces as designated by Nakata (1972) are nothing but old and abandoned alluvial fans being deeply incised



**Fig. 6** Showing Lithofacies and Geomorphic surfaces of Garubathan Recess and Dharan Salient area at Darjeeling Himalayan Foothill. (after Srivastava et al. 2017)



**Fig. 7** Map of Darjeeling foothill region **a** (Survey of India topographical sheet no. 78 B/13) showing structural lineaments, thrusts and sudden disappearance and resurgence of streams in Tarai region; **b** Generalised geologic cross section along the line NS

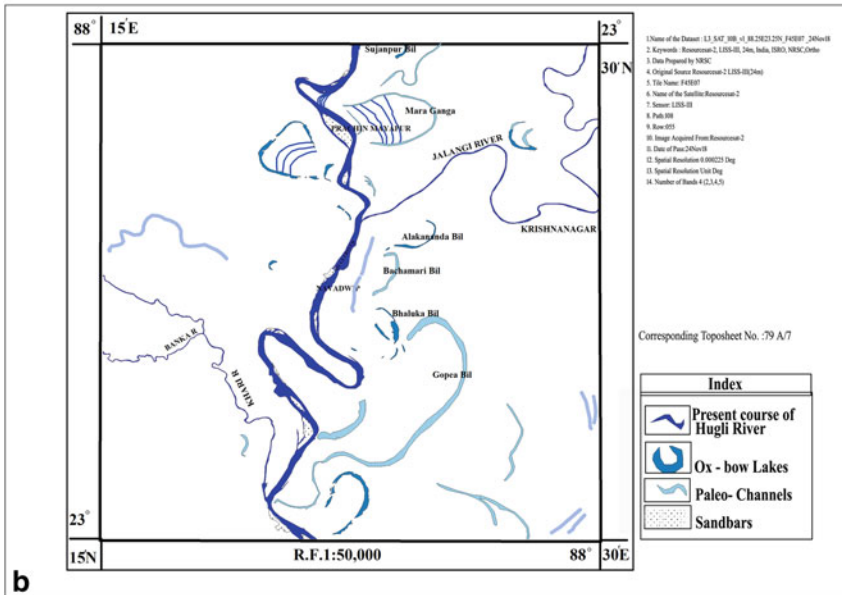
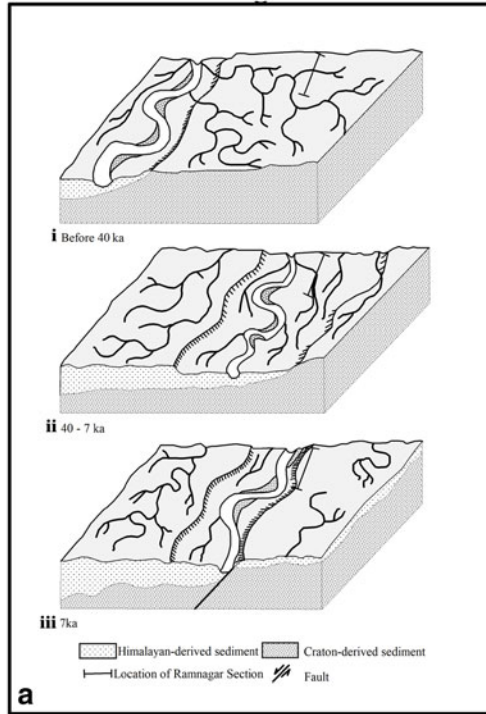
by Chel, Mal, Neora and Murti rivers. The Ramgarh Thrust or Garubathan Jiti fault further extends eastward crossing Jaldhaka River upto Jiti river. South of this line lies the Chalsa thrust which has been attributed to MFT by Nakata (1989) again demarcated by an escarpment (Fig. 8). These east–west propagating faults have not only dissected the alluvial fans but also responsible for the rejuvenation of rivers cutting near vertical terraces along their course.

The Matiali fault was probably active between 24,000 and 11,000 yr B.P (Kar et al. 2014) and whereas repeated activation along Chalsa thrust has been envisaged by Singh et al. (2016), between 41,000 and 48,000 yr B.P; Guha et al. (2007) after 22,000 yr B.P and around 11,000–6000 yr. BP by Kar et al. (2014). Another fault was identified by Nakata (1989). South of Chalsa Fault known as Baradighi fault which tentatively is a blind fault equivalent to MFT (Srivastava et al. 2017). The Righ River terrace of Jaldhaka has been dislocated by Chalsa fault vertically for about 20 m indicating an average slip rate of about 1 m or more per 1000 yr, which is similar to that of Matiali fault. (Nakata 1989). No lateral displacement has been recorded along these active faults of the Himalaya Frontal zone (Nakata 1989).

The Siwalik or the Sub Himalayan tectonics in the east has been studied less compared to the west or north western part. Burgess et al. (2012) have studied a part of the eastern Himalayan MFT zone in detail in Bhalukpong area in eastern Bhutan. Using the age and geometry of uplifted terraces they established a minimum Holocene slip rate of  $23 \pm 6.2$  mm/yr along 10 km wide MFT zone which has been partitioned on three structures–Bhalukpong thrust in the north, growing Bilpara anticline in the middle and Nameri thrust in the south (Burgess et al. 2012).

Strath terraces in the hanging wall of the Bhalukpong thrust, river terraces across the growing Bilpara anticline are the resultant geomorphic features. Bomdila fault is a major tectonic feature in Assam Himalaya extending in NW–SE trend from the Eastern Himalayas to the Naga Hills and directly the courses of rivers Brahmaputra, Dhansiri, Bargang and many others (Sarma and Sharma 2013). An unusually straight course of the river, Dhansiri, north-west ward deflection, knick points, faults scarp are some of the results of neotectonic movements along Bomdila Fault (Fig. 4B). Along Kale river a tributary of the Subansiri river, there was a 15 km long and 5 km wide north–south oriented lake which was formed due to ponding of Kale river by a fault about 20–22 Ka B.P (Valdiya 2016). The reactivation of this fault about 21 Ka B.P. terminated the life of the lake (Srivastava et al. 2009).

Some active faults have been identified in the sub-Himalayan region of Arunachal Pradesh. Devi (2007) detected unpaired terraces along Sinkhi and Dokhoso river and wind gap at a height of about 35 m from the present channel of Senkhi river, linear arrangements of ponds along NW SW indicating paleo channel of Dokhoso river all of which indicates neotectonic activity in the region. There are two active faults along HFT in Arunachal Himalayas; the Banderdewa Fault and the Churachandpur fault have been identified using the GPS Geodetic measurement. (Kumalet et al. 2011). The northward deflection of the south-flowing Singra, Kimin and Ranga rivers along fault lines indicate the presence of active tectonic in the region of Arunachal Pradesh (Devi 2008).



**Fig. 8 a** Channel Migration and incision of river Ganges near Varanasi (i) 40,000 year, (ii) between 40,000 and 7,000 year and (iii) before 7,000 year. **b** Lateral migration of river Ganga with Paleo channels, Ox-bows and Bils, a part of Ganga, Brahmaputra, Meghna Delta, West Bengal, India

The Indian plate bends down as it underthrusts the Himalayas and the slip rate has been calculated from seismic evidence of great earthquakes. The rate is highly variable. In Arunachal Himalayas, the rate of slip has been estimated to  $23 \pm 6.2$  mm/yr whereas the rate varies from 1.5 to 8 mm in the Nagaland and Tripura Mizoram salient and Manipur recess (Jade et al. 2007).

### 2.3 *The Indo-Gangetic Plain*

The Indo Gangetic plain is a fore-deep in front of the rising Himalayas that came into existence in Late Quaternary, due to the breaking of the Siwalik basin into two unequal halves by the Himalayan Frontal Thrust (HFT) or the Main Frontal Thrust (MFT) (Das et al. 2019). The northern 25–45 km wide part evolved to the rising Siwalik Ranges and the southern 200–450 km wide part became a subsiding basin (Valdiya 1998, 2001, 2016) with variable depth, later filled up by the simple process of alluviation.

The highly monotonous plain covers an area of about 777,000 km<sup>2</sup> extending over the largest portion of Sindh province of Pakistan, northern Rajasthan, Punjab, Uttar Pradesh, Bihar, Bengal, Assam in India and the whole of Bangladesh being the largest alluvial plain of the world. The plain is the widest in the west (about 500 km wide) from where the width decreases eastward (about 280 km near Allahabad and 160 km near Rajmahal hills). The plain widens again in Bengal (about 460 km) and narrows in Assam (about 60–100 km). The gradient of the plain is highly imperceptible, the average gradient being only 25 cm per km. The floor of the basin is not uniform structurally being intercepted by ridges or highs and depressions or lows, all of which dip steeply to the north (Wadia 1976). Magnetic, gravity and seismic surveys along with deep drilling have indicated that the floor of the basin is also dissected by faults (Sastri et al. 1971; Fuloria 1996). The basins and depressions extend transversely from northeast to southwest in the central sector and from northwest to southeast in the western sector and are closely associated with faults of considerable extent (Valdiya 2016). Generally, the basin deepens towards north which indicates the bending of the Indian plate under the Eurasian plate. The northern margin of the basin is under considerable tectonic strain. There is evidence of a considerable amount of flexure and dislocation at the northern margin of the trough passing into the zone of various boundary faults at the foot of the Himalayas (Wadia 1976).

The Sindhu basin deepens westward giving rise to Sulaiman and Kirthar Depressions, naturally, the depth of alluvium also increases westward. The eastern part of the plain is intercepted with occasional residual hills of Pre-Cambrian rocks, probably being the extended stumps of the Aravalli Mountain.

The river Indus, according to Wadia (1976) shifted westward for about 130 km as revealed from the records of third century B.C. The past channel now exists as a dried course extending upto Rann of Kutch. The westering of the Indus with all Punjab rivers is a very pronounced phenomena for which different causes have been suggested including neotectonism.

The line joining Mount Kailas, Mount Abu with Mount Girnar seems to have served like a water-divide (Valdiya 2016). It separates the east southeast following Bay of Bengal rivers from the southwest and south-flowing rivers, discharging in the Arabian Sea. This buffer area between the Sutlej river in the west and Yamuna in the east does not have any perennial river and is known as the Punjab Hariyana plain (Singh 1996; Singh and Ghosh 1994). This area is drained by some ephemeral streams. To the east the drainage basins are PathralaNadi and Somb river, whereas Khairikakhala; Fandi Rao, Sukar Rao, Chautang 1, Chautang 2 and Saraswati are the basins towards west (Shrivastava et al. 2011). According to Shrivastava et al. (2011) the area was subjected to neotectonic uplifting and tilting along the Delhi Ambala Subsurface Basement High (a subsurface continuation of Aravalli Delhi Massif) and along HFT. Shallow subsurface sand bodies have been identified by several geologists who reconstructed the ancient channel system of the Punjab and Hariyana plain and provided OSL dates to the buried channels (Saini et al. 2009; Saini and Mujtaba 2010) which is responsible for the youthful nature of the basins. Strong structural control exercised by the northeast southwest and northwest southeast lineaments and resultant various fluvial anomalies as reflected by long straightened course, abrupt changes in the flow direction, water gaps, sharp knee shaped bends have been observed along river Sutlej and Beas and their tributaries along with seasonal rivulets in Bistdoab region. (Bhatt et al. 2008).

A high scarp running along the western side of the Beas river and presence of paleo channels, oxbow lakes, compressed meanders etc. in the west indicate a upliftment of the western side and the upliftment along the HFT is evident in the form of elongated and asymmetric water sheds (Bhatt et al. 2008).

Late Tertiary and Quaternary reactivation resulted in a horst like raising of the Aravallis and a slow rise of the area to NW and W (Ahmad 1986; Valdiya 2016, 1984; Sinha-Roy et al. 1993; Sinha-Roy 2001, Bakliwal and Grover 1988) north–south, northeast–southwest and northwest–southeast trending faults and fractures among which the Sardar Sahar fault, Luni Saki fault, Jaisalmer-Barwani fault are of considerable extent (Sinha- Roy et al. 1993; Balkiwal and Ramasamy 1987; Ramasamy 1999). This tectonic deformation led to drainage disruption including deflection of channels, formation of lakes and ultimate disappearance to the west of Aravalli in Rajasthan and adjoining regions of Hariyana and Gujrat. This tract is the driest part of India and may be described as the Thar Domain. This region which was once fertile riverine land and seat of very old and rich civilisation along the course of the river Saraswati has been converted into a dry land over a period of 10,000 yr or more due to past climatic change and the above mentioned tectonic activity which disrupted the entire drainage pattern of the area. The disappearance of the river Saraswati has been attributed to this tectonic movement which must have caused the deflection of the two Himalayan rivers Yamuna and Satadru, two important feeders of the river (Valdiya 2002, 2016). Due to westward deflection, Satradru finally joined the Beas and the Yamuna with an eastward shift joined the river Ganga. The abandoned course of the river Saraswati is traceable as curvilinear or meandering segments of dry channels as concluded by a good number of researchers from the study of satellite images, the study of paleo-sediments and OSL dating (Ghose et al. 1979; Yashpal et al. 1980;

Ramasamy et al. 1991; Bakliwal and Grover 1988; Valdiya 2002). The present day Ghaghra, the Hakra and the Nara rivers probably occupied the old and abandoned channel of the Saraswati (Valdiya 2016). The drainage of the Luni river was also controlled by E-W, NE-SW, and NW-SE trending fault as revealed by a study of sediments (Valdiya 2016). Neotectonic activity related to block faulting also resulted in changes in recharge of fresh water from base flow and surface flow leading to a drastic change in salinity in the Mendha basin, an important river flowing to Lake Sambhar (Rathore et al. 2008).

The Ganga Basin as a whole exhibits a low geomorphic relief through which the river and its tributaries are flowing in the incised valley with a relatively narrow flood plain. This is a unique feature of the river. Over the Bhangar section (composed of beds of clays of yellow and brownish red colour with calcareous or ferruginous concretions) there is a chain of upland with 14 m high escarpment on the southern bank of the Ganga, which is possibly the result of active fault (Valdiya 2016). Similar escarpments with greater height (20–60 m) are also found along Yamuna in Sengarh Valley which has been attributed to Middle and Upper Holocene time (Singh et al., 1997; Agarwal et al. 2002). In the northern part of Ganga Plain the region lying to the east of the river Ghaggar and west of the river Kosi neotectonic faulting events are associated with the terminal fans, which has been correlated with the segmentation of Indo Gangetic plain (Pati et al. 2015). This area is characterised by coalescing alluvial fans of the rivers Yamuna, Ganga, Sharda, Gondok and the river Kosi formed of very coarse detritus materials predominantly gravels. Pati et al. (2015) refer to the segmentation of the region into blocks and subblocks by fault-guided rivers. The fans are incised and the development of terraces is common. The stratigraphy of the upland interfluvium (Ganga Yamuna Doab) shows deposits that are made up of sloping surfaces, flat areas, small channels, ponds and lakes which are exposed at cliff sections and the ravines of the rivers (Singh et al. 1997). In this doab, the river Ganga made deep incision in response to tectonic activity in the peripheral bulge (Shing et al. 1997). Similar features are also found in the Sikkim-Darjeeling foothill zone along Garubathan recess as discussed earlier in connection with Siwalik Gap. TL dating has revealed that the age of the Ganga mega-fan is in between 3000 and 8000 yr. B.P. and the age of fan terraces developed on it is in between the last 3000–1100 yr. BP (Srivastava et al. 2003).

Near Varanasi on the right bank of river Ganga there is a 750 m long cliff the Ramnagar section; the lithofacies study of which indicates recent tectonic deformation (Shukla et al. 2012). River Gomati also shows the development of such a cliff. The river Ganga here is also subjected to shifting and incision as shown (Fig. 8) by Shukla et al. (2012).

Holocene tectonic activity in and around Kanpur at 2.5, 5 and 8.5 ka controlled the Ganga river and the drainage pattern of the area as a whole (Pati et al. 2006). The change in the course of the river Ganga by about 90° is probably due to the block tectonics and diagonal slip faults (Pati et al. 2006). The long profiles of river Ganga near Patna suggest the presence of a knick zone that has shifted upstream due to incision (Sahu and Saha 2014).

Further east the Gondok and Kosi rivers are tectonically active (Pati et al. 2006). The Gondak mega fan formed by episodic tilting of tectonic blocks followed by an eastward shift leaving natural waterlogs and paleo channels as observed from the study of satellite images, GPR study, OSL dating, morphometry and Pedology (Pati et al. 2015). The Gondak shifted about 105 km east leaving behind the paleo channel of Buri Gondak in between 1735 and 1975. The Kosi mega fan is a flat country like any other flood plain covering an area of 16,000 km<sup>2</sup>. The monotony of the landscape being broken by features like old courses now occupied by much smaller streams, old channel courses, oxbow lakes and in places dunes like mounds. (Gohin and Prakash 1990). The shift in case of the river Kosi is about 105 km over its own mega fan between 1736 and 1964 (Valdiya 2016).

Brahmaputra plain, the north eastern extension of the Gangetic plain is a narrow corridor of 80–100 km width compressed between the eastern syntaxis and the Meghalaya Massif. Geologically it is a part of the Assam Arakan Basin, Assam Plain forming its shelf area while the Naga Patkoi Hills represent the mobile area (Sharma and Sarma 2013; Dasgupta and Biswas, 2000). The Precambrian basement of the Basin is faulted with structural 'highs' and 'lows' and deepens southeastward (Valdiya 1999, 2016). Major tectonic features of the area are the northeast-south west trending belt of Schuppen and nearly east–west trending Jorhat fault (Dasgupta 1977; Narula et al. 2000). The area is tectonically active with north-east south-west trending active faults crisscrossed by another group as revealed by seismic survey of the area (Narula et al. 2000; Kent et al. 2002).

Neotectonic activity along the active faults has grossly affected the drainage pattern and characteristics of the upper Brahmaputra Basin. The overall drainage pattern is parallel and sub-parallel with exceptions indicating immediate response to neotectonism. The annular drainage pattern of the river Dikhu and Jhanzi, paleochannels of Mori Namdang and Mori Dikhou, compressed meanders of Dikhu, Mori Dikhou and Namdang, sharp right angle bends along the rivers Thanzi, Namdang, Dimou Jan, Dorika and Disang and low lying swampy areas along their downstream reaches where they meet the axial river the Brahmaputra all indicate active tectonics (Sharma and Sarma 2013). Most of the major tributaries joining the Brahmaputra from the north have distinct paleochannels as revealed from the study of historical maps and recent satellite imageries (Lahiri and Sinha 2012). Evidence of shifting of river courses and confluences are also not uncommon. As Lahiri and Sinha (2012) concluded that the confluence point of the river Siang, Dibang and Lohit, (from where the river Brahmaputra starts) as shown in the topographical maps of 1915 experienced a shift of about 16 km downstream by 1975 and further 129 km downstream by 1975 and further 19 km in 2005. The recent bank erosion of the Majuli island has also been attributed to neotectonics activity (Lahiri and Sinha 2014).

The drainage pattern over the plains of Bengal is highly dynamic. This is partly due to fluvial adjustment in a land of imperceptible gradient and partly due to neotectonic changes in land level, eustatic changes of sea level due to Quaternary climate change and sediment-isostatic adjustments.

The rivers of North Bengal plain namely Mahananda, Tista, Jaldhaka, and Torsa along with their tributaries, after crossing the pediment zone in deeply incised valleys

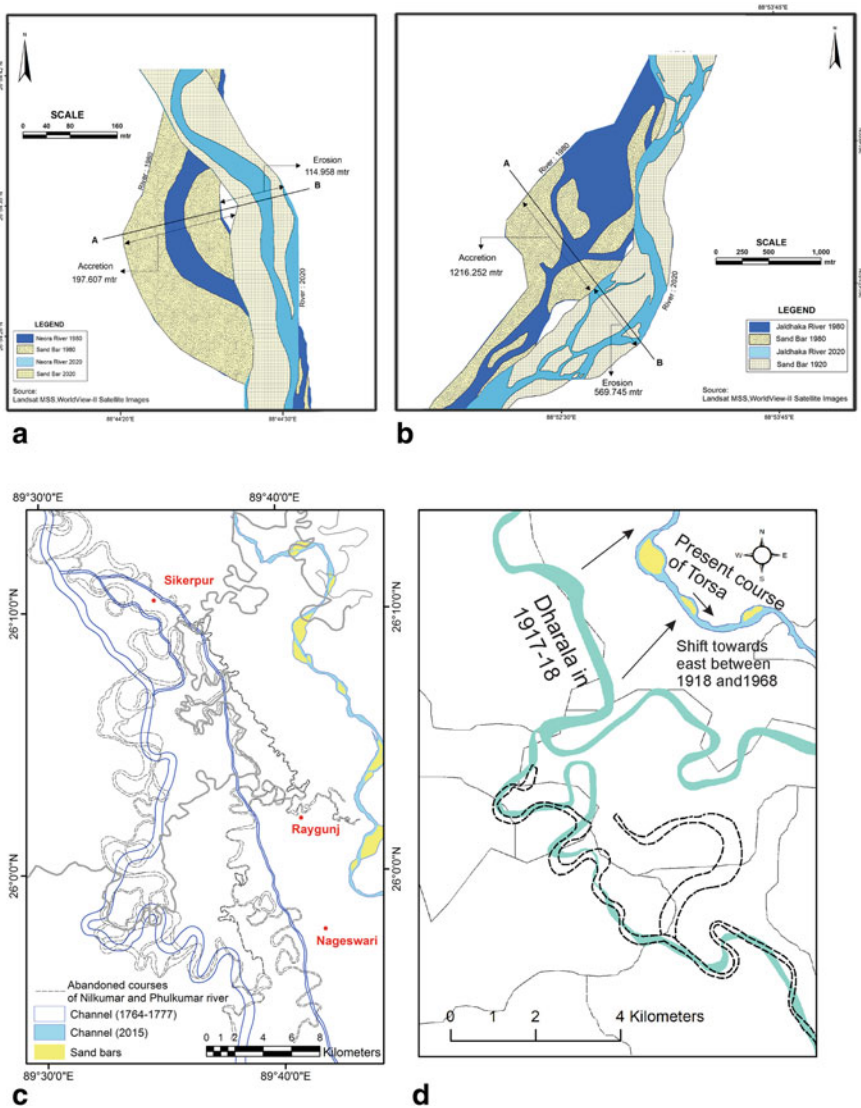




**Fig. 9** Deeply incised course of river Murti with fan terraces in North Bengal plain, India

meet the plain in wide open braided channels (Fig. 9). Following the regional eastward dip they are also migrating eastward through avulsions leaving behind paleochannels, oxbows, etc. (Fig. 10 a–d). The river Tista in 1787 shifted eastward and joined the river Brahmaputra leaving its previous course meeting the river Ganges (Valdiya 2016). Further south in between river Tista and Mahananda there is another group of rivers namely Punarvaba, Kulic, Tangon and their tributaries show structural adjustment and response to the domal uplift of Barind tract and movements along 40 m long Maldah-Kishanganj fault. The Atreyee and Punarbhaba rivers flow through entrenched valleys over Barind tract. The rivers of the western part of the Bengal basin flowing from the eastern flank of Chhotonagpur plateau like Ajoy, Mayurakhi and Damodar along with their innumerable tributaries also show markers of neotectonic adjustments (Barman et al. 2019). An ancient fan delta was developed by the river Damodar, lying at 6–10 m high above the present sea level exists here. This part of Bengal Basin is characterised by numbers of north–south trending normal faults shifting river courses.

The Rajmohol Pahar and the Meghalaya massive with Rangpur saddle in between divide the South Bengal and North Bengal plain. The tectonic settings of South Bengal are highly complex as this is the area where the North or North-East ward migration of the Indian plate gradually changes its direction to East and South-East. Among the major structural and tectonic features is the Hinge zone which marks the periphery of the Indian craton where the Indian plate gradually slopes down to be destroyed ultimately, below the Asian Plate (Bandopadhyay 2019). The Hinge zone is 25 km wide and extends roughly along the line running between Kolkata and Maymensingh. The angle of subsidence varies from 2°–3° to 6°–12° and again decreasing to 1°–2° (Rudra 2018). The Bengal Basin, the Sylhet Trough, Faridpur



**Fig. 10** East ward shift of rivers across North Bengal plane leaving paleo channels and bills

Trough and Hatiya Trough lies over the Benioff zone and Barishal Chandpur gravity high marks the point from where Oceanic crust starts. The Chittagone Tripura fold belt and Chittagone and Coxbazar Fault marks the line approximately along which is present subduction is going on (Alam et al.2003). Dauki Fault marks the Southern end of the Meghalaya massif. A number of NNW SSE trending fault runs roughly between the Rajmohol Pahar and Meghalaya massif, extending up to Sylhet Basin (Fig. 11).

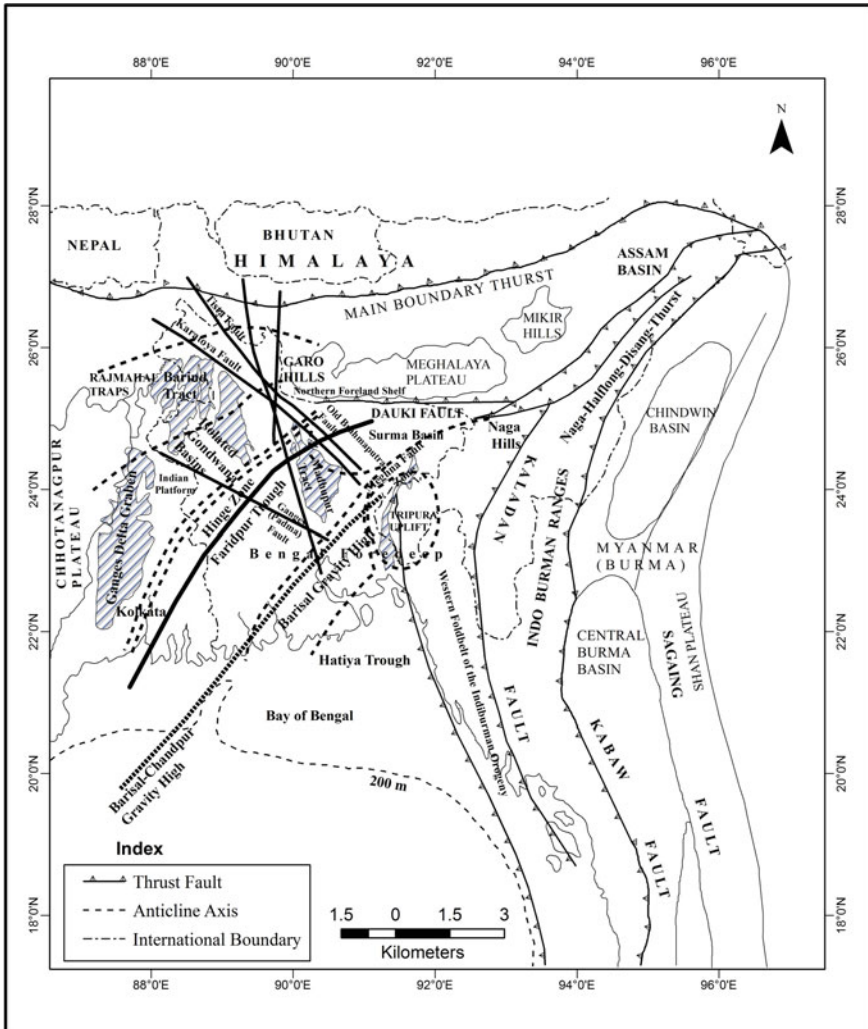


Fig. 11 Geotectonic setup of Bengal Basin (compiled from various sources: Rudra 2018; Rashid et al. 2015; Bandyopadhyay 2019)

Physiographically the Bengal Basin is marked by an uninterrupted plain. The river Brahmaputra and the Ganga enter the deltaic part of Bengal through Rajmahal-Garo Gap. The monotony of the plain is interrupted by the elevated terraces of old alluviums: the barind Tract and the Madhupur tract. The entire Bengal Plain is marked by innumerable distributary channels of the main rivers, paleo channels and abandoned channels indicating lateral shifting, meander bend cut off, oxbow lakes, pools, bills, waterlogged marshy areas (Fig. 8b). Such features though normal in any deltaic region as a part of fluvial adjustment in areas of imperceptible gradient in

case of the Bengal Basin tectonic deformation also plays a vital role in the lateral shifting of rivers and abrupt switching of course through avulsion (Reitz et al. 2015) as it lies over an active plate margin. The subsidence rate has been estimated at 2–4 mm/a by Goodbred and Kuehl (2000). Due to the subsidence of Sylhet Basin and associated reactivation of Dawki Fault the river Brahmaputra frequently (5 times) shifted its course on either side of the Madhupur Tract in the last 8000 years presently flowing between Barind and Madhupur Tract. Goodbred and Kuehl (2000) as revealed by sedimentological analysis of facies. The old course is marked by the river old Brahmaputra on the East of Barind Tract.

The Ganga Brahmaputra Delta is the largest delta in the world covering about 15,000 km<sup>2</sup>. The southern and southeastern part of Bengal Basin, being enclosed by the rivers Bhagirathi Hoogly, Ganga, Padma, Brahmaputra and Meghna is the deltaic part of Bengal Basin. This delta is the output of high sediment influx by the major perennial rivers and their tributaries draining through the highly tectonically active hinterland. The delta building processes are going on Goodbred and Kuehl (2000) established a subsidence of the order of 2–4 mm /yr for the central and coastal part of Ganga Brahmaputra Delta. This subsidence is the obvious result of huge sedimentation and following isostatic adjustments and vis-a-vis. Stanley and Hait (2000) calculated a subsidence of 5 mm/yr against sediment accumulation of upto 7 mm/yr for the western Sundarban Delta.

### 3 Intraplate Tectonic Activity—The Indian Peninsula

Peninsular India is a landmass of great antiquity and is formed of the conjunction of four stable cratonic blocks which remained practically undeformed through the ages. “The cratons are the Dharwar Craton in South India, the Bastar Craton in central India, the Singbhum Craton in eastern India and the Bundelkhand Craton in northern India (Valdiya 2016). These Cratons are separated from one another by the Eastern ghat mobile belt borders the Dharwar and Bastar Craton, the Satpura-Aravalli Mobile belt encompassing the Bundelkhand Craton, and the Chhotonagpur Shingbhum Mobile belt demarcating northern margin of the Singbhum Craton” (Valdiya 2016). This unified and stabilized land mass in the early Permian was subjected to block faulting leading to the development of elongated grabens or basins now occupied by the rivers Damodar, Mahanadi, Son Narmada, Pranhita and Godavari. During the Cretaceous the Indian Peninsular was put through stupendous volcanic eruptions. Lava flows coming out from fissures covered almost the whole of Maharashtra and adjoining regions in Gujrat, Madhya Pradesh, Karnatak and Telengana. Rajmahal Hills, Southern Meghalaya and parts of Sylhet in Bangladesh also bear segregated remnants of Deccan Basalt.

Subsidence due to faulting along the coasts of Peninsular resulted in the formation of Peri Cratonic basins subsequently filled up by marine and fluvial sediments ranging in age from upper Jurassic to Quaternary. They are the seat of Mahanadi, Godavari, Krishna and Cauvery delta, Khambat Bay and the Kutch region. Therefore,

from the Cretaceous, the Peninsular Shield practically did not suffer from any type of major tectonic deformations being subjected to unrelenting activities of exogenous forces turning it into a region of subdued relief excepting the formation and filling of the Pericratonic Basins along the Coast.

### ***3.1 Neotectonics and Associated Channel Adjustments***

As outlined by Plate tectonic theory, it is known that the plate interiors are relatively free from major tectonic disturbances. The Peninsular Shield suffered both from paleo and neotectonic movements. Presently the Shield is also experiencing earthquakes of different magnitudes. The neotectonics and active tectonic deformation have resulted in drainage adjustments as reflected by their anomalous geomorphic indices. The neotectonic movements in the Peninsular area are mainly concentrated along its boundaries.

Quaternary revival of tectonic activity of the Aravalli region has already been dealt in detail in the previous section in connection with the rivers Saraswati and Luni. Ali and Ikbal (2020) from their studies on Ahar watershed area near Udaypur located in the Southern front of the Aravalli Hills concluded that this watershed area is tectonically active.

In the south-east of Aravalli, this uplift rejuvenated the river Chambal which through headward erosion captured the Banas catchment and resulted in 25–30 km shifting of Banas watershed along the Vindhya hills (Sinha-Roy 2001). About 10,000 yr. B.P. the fluvial activity of the river Mahi increased due to neotectonic uplift which is manifested by deeply incised (40–50 m deep) meanders and ravines popularly known as the Badlands of Mahi Valley (Chamyal et al. 2003). The Orang river in the Southern part of Mahi basin deflected southward to join Narmada river leaving its paleochannel as Dhadar river (Raj 2004). River Sabarmati in northern Gujrat also deflected its course southward and met the Gulf of Khambat, leaving its paleochannel now occupied by Rupen River (Sridhar et al. 1994; Ramasamy et al. 1991).

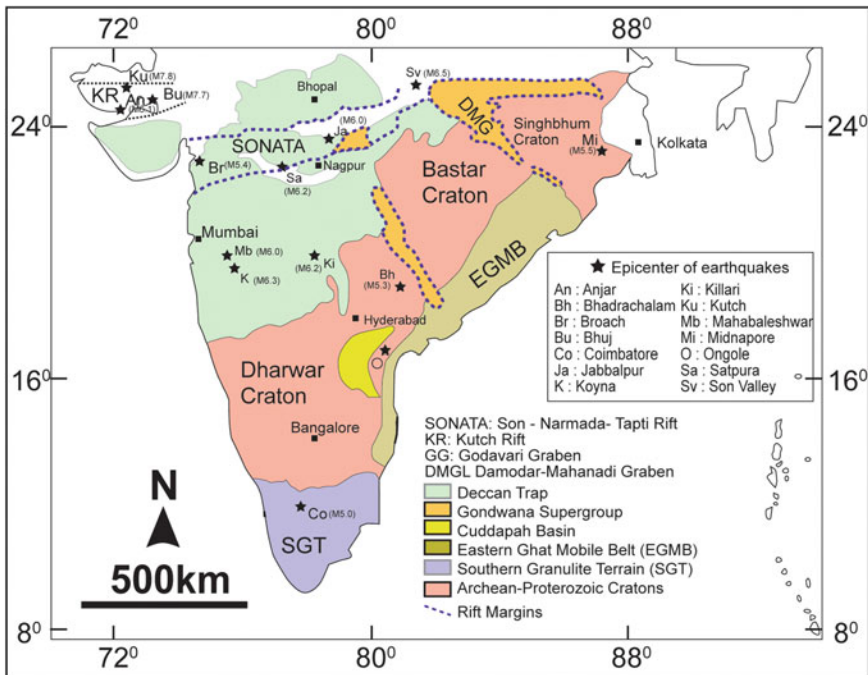
The neotectonic activity of the Aravalli and Vindhyan region is going on. The WNW and ESE and NE-SW lineaments are more persistent pairs of lineaments and have maximum control in the evolution of Quaternary landforms (Roy and Jakhar 2002). The GPS measurements of 2007–2011 of a permanent GPS site at Udaypur suggest that the site moves at a rate of 49 mm/yr towards northeast (Bhu et al. 2014).

The Kachchh (also spelt as Kutch) region is too a tectonically sensitive region and is cut by some major faults. Reactivation of such zones is common and is revealed by river responses like—the reactivation of Kachchh Mainland Fault have resulted in debris flow deposition and formation of colluvial fans towards the north of Northern Hill Ranges (Malik et al. 2001). These fans are deeply incised by youthful streams. South Wagad Fault also is tectonically active which is manifested by the development of strath terraces along the rivers; incised alluvial fans and deflection of channels

(Mukul and Sing 2016). Kachchh region is seismotectonically active being the site of recent and subrecent earthquakes.

The Narmada, Son, Tapi Fault zone also known as Central Indian Tectonic zone extends for about 1000 km from the west southwest to east northeast travelling through the Central part of India is a spectacular structural feature of Indian subcontinent. The zone nurtures the west-flowing Narmada and Tapi rivers and north east-flowing Son river. The region represents a horst-graben structure with Satpura Ranges as a horst separating the Narmada and Tapi valley. The northern margin of Narmada graben is marked by Son Narmada North Fault and southern margin by Son Narmada South Fault and the Gavailgarh Fault marks the northern limit of Tapi graben. This paleo-rift region of Precambrian origin suffered repeated tectonic deformation through ages (Fig. 12).

During Quaternary, the north south compression due to continued northward movement of Indian Plate folded the Tertiary sediments south of Narmada Son Fault into anticlines with steep reverse fault running in east north east to west south west direction (Joshi et al. 2013). Quaternary deformation and reactivation of reverse faults have also been suggested by Mulchandani et al. (2007) through their study of the Kim river basin south of the Narmada Son Fault.

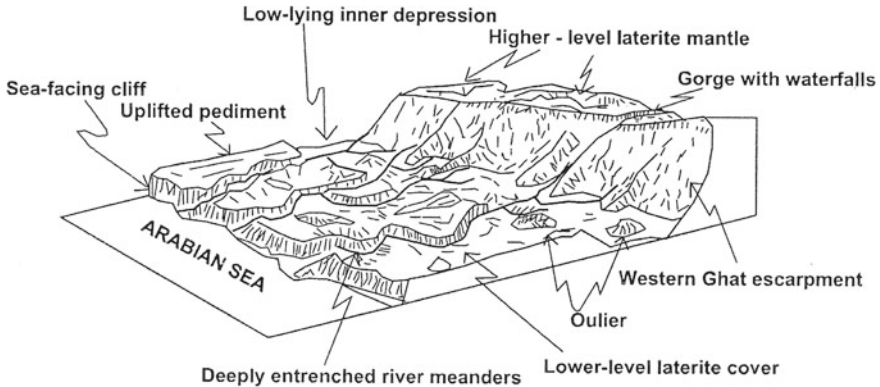


**Fig. 12** Precambrian Cratonic Fragments and mobile belts with major paleo rift zones and earthquake epicenters (after Chattopadhyay et al. 2020)

Parallel drainage, knick points and associated waterfalls, incised meanders, and deep ravines (indicating gully erosion) are the geomorphological indicators of neotectonics along the north-flowing tributaries of the Narmada river (Joshi et al. 2013). However, based on the quantitative morphometric study, they concluded a spatial variation in neotectonic activity. The north south compression in Son Narmada Fault zone in the upper course of the river Narmada near Jabalpur is represented by the shifting river channel near Amarkantak, the Dhuandhar waterfalls, the vertical incision in Bhedaghat (Kothyari and Rastogi 2013). The lower reaches of Narmada also suffered from tectonic deformation during Holocene (Chamyal et al. 2002). Terrestrial Cosmogenic Radionuclide Dating places the age of deep gorges near Dardi waterfalls in Gujrat at about 40,000 yr (Gupta et al. 2007). The Relative Index of Active Tectonics of the Son sub-basin, Bijul sub-basin, Rihand sub-basin and Kanhar sub-basin in Son valley also suggests reactivation of Son Narmada North Fault and Son Narmada South Fault (Dubey and Shankar 2019).

Geomorphic analysis of longitudinal profile, river pattern, valley width valley depth ratio, hypsometric curve and OSL dating of the terraces of the rivers Wardha, Maru, Purna and Arna and their tributaries crossing the Gavilgarh Fault indicates that the fault zone is tectonically active and repeated deformation occurred at about 65–80 ka, 50 ka and 14 ka (Bhattacharjee et al. 2016). The Son Narmada fault zone also suffered from a number of recent earthquakes which roughly associates with Son, Narmada Valley (Choubey 1971) and also Tapi Valley (Copley et al. 2014).

The Sahyadri or Western Ghats stands as a high escarpment on the coastal plain rising abruptly from a height of about 80 m to a height of about 1200 m with a gentle undulating surface topography. The Sahyadri is divided into longitudinal blocks by NW and SSE trending echelon faults which are cut by WNW and ESE trending lineaments (Valdiya 2001). These are all active faults. The west flowing rivers exhibit wide valley, gentle slope, low gradient, meandering course over ridges, cutting into deep gorges with waterfalls and rapids over the escarpment face and flowing in an incised meandering valley with terraces over the coastal plains (Fig. 13). These fluvial features indicate that the Western Ghat and associated coastal area is tectonically active. The Valapattanam river along with its tributaries flowing through the Precambrian terrain of Western Ghat in north Kerala also shows signatures of neotectonic activity of variable magnitude as revealed by analysis of Digital Elevation Model (DEM) and morphotectonic analysis (Jayappa et al. 2012).



**Fig. 13** A schematic section across Western Ghat to Arabian Sea in Konkan-Kanara coastal belt showing landscape differences (after Widdowson 1977)

The Bharathapuzha Basin in the vicinity of Palaghat Gap near Palghat Cauvery Shear Zone exhibits tectonic drainage disruptions along a WNW-ESE fault suggesting that the area is affected by the episodic neotectonic movement since middle Quaternary (Jhon and Rajendran 2008).

The continuous shift of the courses of the Cauvery, Palar and Ponnaiyar rivers indicate ongoing tectonism along (Valdiya 2016) Coromandal Coast.

The Godavari Krishna Delta shows the evolution in four stages, the oldest one dates back to 65,000 Yr BP (Rengamannar and Pradhan 1991). The Mahanadi Delta also shows a developmental history of more than one stage (Bharaii et al. 1991). The Cauvery Delta shows a recession in the delta building process due to Quaternary movement and the morphology of the delta being dominated by paleochannel and distributaries suggesting the presence of neotectonism (Ramasamy et al. 2006).

In Mysore plateau, the tectonic reactivation of persistently weak fault and shear zones resulted in fluvial anomalies along the rivers Cauvery, Bedti, Sharavati etc. being represented by waterfalls, cascades and rapids, upstream ponding of rivers Cauvery, Shimsha, the Kabini and Suvarnabati and deformation of fluvial and lacustrine sediments (Valdiya 2001; Valdiya and Rajagopalon 2000).

Along 13°N parallel between Pulki and Pulicat there is a water divide separating the north flowing and south-flowing streams which indicate crustal buckling (Subrahmanya 1994, 2002). Moreover, the tectonic resurgence of the western edge of the plateau is evidenced by a case of stream piracy by west-flowing Sharavati River (Radhakrishna 1964).

In the Deccan Volcanic Province of Andhra Pradesh and Maharashtra the fluvial characteristics show neotectonic activity on local and regional scale due to intense loading of basalt (Veeraswamy and Raval 2005) and erosional unloading of the same (Sangode et al. 2013). The courses of the Godavari and its tributary Kaddam bear signatures of such neotectonism. The sharp knee bend deflection of the river Godavari and distinctly linear course of the river Kaddam is definitely fault-guided



(Sangode et al. 2013). The rivers also show paleochannels and paleo-confluence location of which is now occupied by Kaddam reservoir lake (Sangode et al. 2013). The lineament guided Terna river basin (a tributary to the Manjra river of Maharashtra) with sharp deflections in the course and other fluvial anomalies indicate the presence of neotectonic activity (Babar and Chunchekar 2008).

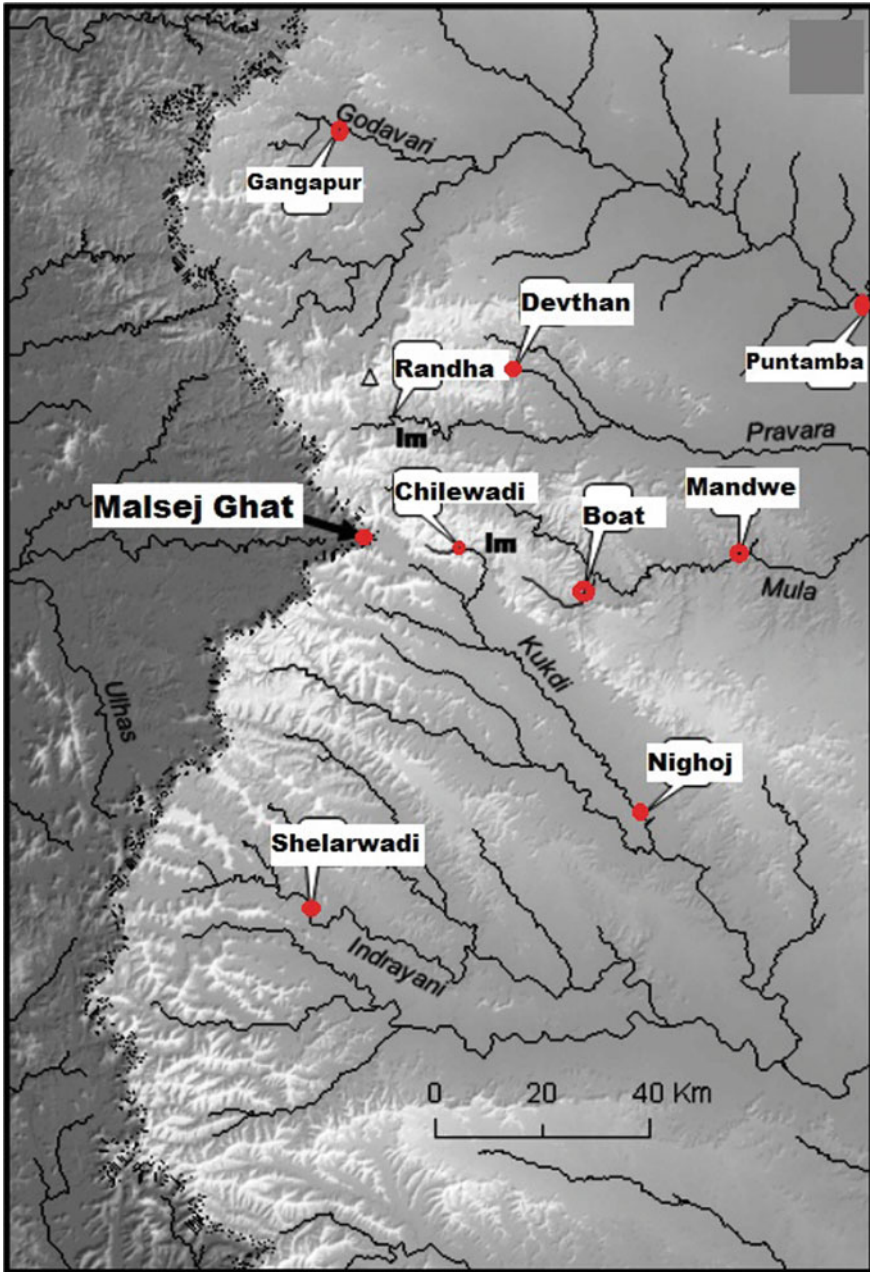
Geomorphic analysis of the streams of Deccan Basaltic Region flowing to the east of the Western Ghat was done by Kale and Shejwalkar 2008. They observed, “some well known knick points with scablands, inner channels, waterfalls and potholes occur on the Godavari river near Gangapur and Punlamba, on the Pravara river at Randha, on the Mandvi river near Chilewadi, on the Kas river near Bote, on the Mula river near Mandwe, on the Indrayani river at Shelarwadi on the Kukdi river near Nighoj and on the Shivaganga river at Baneswar”. These features are common markers of tectonic adjustment by fluvial channels (Fig. 14).

## 4 Modern Earthquakes Effecting Indian Subcontinent

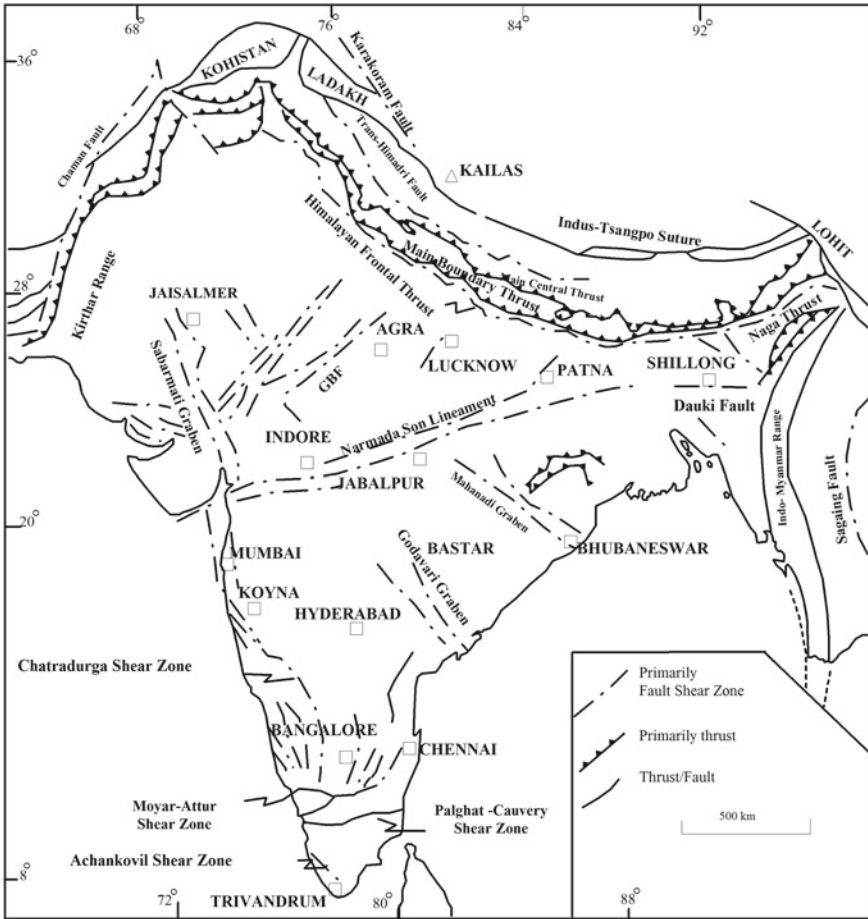
Indian Subcontinent comprising of the Cratonic Blocks with Peri-Cratonic Basins, ‘Early Proterozoic Mobile Belts’, the Tertiary Orogenic Arc and vast alluvial plains evolved from filling of Fore-Deep Basin, is one of the most seismically active areas of the world. Earthquakes of variable magnitudes are frequent with disastrous effects to human society, but earthquakes producing detectable surface deformation are not so frequent. Earthquakes are the result of reactivation of preexisting faults, thrust and shear zones (Fig. 15). They are most common with dense epicenter distribution in the Himalayan Chain particularly in Lesser Himalayas between MCT and MBT (Fig. 16). Verma and Bansal (2016) researchers of Centre for Seismology and Geosciences Division of Ministry of Earth Sciences identified 67 tectonically active faults in India out of which 15 is in the Himalayas, 17 in the Indus Gangetic Plain and as much as 30 in the long-accepted region of stability in Peninsular. The list of major earthquakes with their surface effects is given in Table 2.

## 5 Introducing the Other Chapters

The previous discussion is just an overview which has tried to sum up partly the areas of the Indian subcontinent experiencing neo and active tectonic movements and the resultant drainage evolution and adjustments. In General, it appears that majority of the Neotectonic movements are associated with the evolution of the Himalaya. Thus, we intended to trace out the role of Himalayan Neotectonics on channel evolution in India through this volume—‘Himalayan Neotectonics and Channel Evolution’. To address all corners of the selected topic—‘Himalayan Neotectonics and Channel Evolution’ in detail will need more than an epic volume. The following chapters are the detailed description and analysis of some particular areas with spectacular



**Fig. 14** Map showing the approximate location of major knick points on Upland river (1) near Gangapur on Godavari, (2) near Puntamba on Godavari, (3) near Devthan on Adula, (4) at Radha on Pravara, (5) near Chilewadi on Mandvi, (6) near Bote on Kas, (7) near Mandwe on Mula, (8) near Nighoj on Kukdi, (9) at Shelarwadi on Indrayani, Im represents incised meanders (After Kale and Shejwalkar 2008)



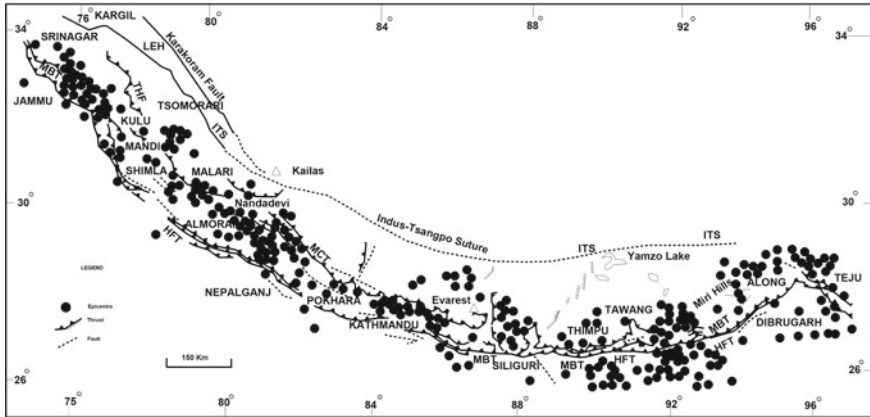
**Fig. 15** Map showing thrusts, faults and shear zones of India some of which are currently active. (from Valdiya 2016)

impressions of neotectonics which can be used as identical examples for the others with minor local variations.

The book contains fifteen chapters all together including the present one. All the chapters disclose different issues related to neotectonics and channel evolution of different parts of the region with the help of modern techniques and methodology.

The Chap. 2 intends to comprehend the role of tectonics and differential uplift in landscape dynamics and erosion rates of the Bhagirathi-Alaknanda catchment. The authors suggested a higher recurrence of landslides and profound fluvial incision as a consequence of tectonics and upliftment between major thrusts.

Tectonic controls on spatial variability of topographic attributes and channel morphological characteristics in the Ladakh Trans-Himalayas are illuminated in



**Fig. 16** Distribution of earthquake epicentres between MCT and MBT (after Valdiya 2016)

Chap. 3. Authors used the ALOS PALSAR Digital Elevation Model (DEM) to elicit watershed and channel parameters related to tectonics.

‘Geomorphic response of the Solani river basin to neotectonics: A study from the western Himalayan foothills, India’, the Chap. 4, investigates the influence of neotectonic on the Solani river basin, using morphometric parameters, seismic events, field evidences, and OSL chronology.

‘Tectonic Control on the Meanders Pattern of Alaknanda River in Srinagar Valley (Garhwal Himalaya), India’ constitutes the Chap. 5 and investigates tectonic control on the meander pattern of Alaknanda River in Lesser Garhwal Himalaya. Using remotely sensed data, AOI map and field survey authors confirm the structural and lithological controls on the abrupt change in the flow direction, incised meandering, offset river channels, paleo-channels, multi-level terraces, knick points, pools in longitudinal profile. Meanders are controlled by faults and lineaments.

The Chap. 6 ‘Significance of Channel Planform Change and Morphometric Indices in the Buri River Basin, India and Bangladesh’ used Shuttle Radar Topography Mission elevation data (3 arc second tiles) to bring out the structural signature on drainage using profile shape, normalized stream length-gradient (SLk) index and basin asymmetry factor (AF). Moreover,  $\chi$ -map and long-term rainfall records were analyzed to show that the Buri is antecedent to all anticlinal axes along its course. The chapter also found that the Buri basin has been tilted to the north and water divides are shifting towards the basin.

The Chap. 7 disclosed the ongoing adjustment of river valleys and channels with the active tectonism of lesser Himalaya. The basin-scale neotectonic signature for some selected rivers in the eastern Himalayan region is mined in the chapter ‘Morpho-tectonic expressions of the drainage basins and channel long profile forms on a selected part of Sikkim-Bhutan Himalayas’.

With the help of “Old Data Inventory, Satellite Images and Sedimentary Architecture” the Chap. 8 analysed the sudden deflections in channel direction around

**Table 2** Major earthquakes in Indian subcontinent since 1819

Date	Location	Magnitude	Epicentre	Effect
2001-01-26	Gujarat	7.7 $M_w$	9 km south-southwest of the village of <u>Chobari</u> in <u>Kuchchh District</u> of <u>Gujarat</u>	0.5 km rupturing along Kuchchh Mainland Fault and some other transverse lineaments (Pande et al. 2003)
1999-03-29	Chamoli district-Uttarakhand	6.8 $M_w$	–	Strike-slip motion along north west south east trending Nandprayag fault (Valdiya 1976–1980) Deformation features in fluvial soft sediments (Pande and Pande 2004)
1993-09-30	Latur, Maharashtra	6.2 $M_w$	–	Deformed the ground surface in a 100 m wide zone (Gupta et al. 1996)
1991-10-20	Uttarkashi, Uttarakhand	6.8 $M_w$	–	Low-angle thrust faulting with varying amounts of strike-slip movement (Ali and Ikbal 2020)
1988-08-06	Myanmar, India	7.3 $M_w$	–	Landslides were reported in India and Bangladesh <u>subsidence of 20 cm</u> (7.9 in) was recorded in <u>Gauhati, India</u>
1967-12-11	Maharashtra	6.6 $M_w$	The <b>1967 Koynanagar earthquake</b> occurred near <u>Koynanagar</u> town in <u>Maharashtra</u>	Probably Anthropocene in origin caused a 10–15 cm (3.9–5.9 in) fissure in the ground which spread over a length of 25 km (16 mi). S
1950-08-15	Assam, Tibet	8.6 $M_w$	The epicentre was located in the <u>Mishmi Hills</u> ,	200 km long rapture and 8 m slip (Khattri 1987, 1998)

(continued)

**Table 2** (continued)

Date	Location	Magnitude	Epicentre	Effect
1905-04-04	Kangra	7.8 $M_s$	epicenter of the earthquake lies within the zone of <u>thrusts</u>	More than 120 km long rapture and 8 m slip (Khattri 1987 and 1998)
1897-06-12	Shillong, India	8.0 $M_w$	–	Two new faults resulting in 18 km long with up through upto 10 m A series of waterfalls and pools along the stream About 11 km long zone marked by surface cracks
1833-08-26	Bihar, Kathmandu	8.0 $M_s$	epicentre located in eastern Nepal about 9.5 km south of <u>Mount Everest</u> (Agarwal et al. 1989)	sand and water vents appeared throughout the central vents of the earthquake area, ground around these sand fissures subsided
1819-06-16	Gujarat	7.7–8.2 $M_w$	–	a 80 km long (possibly as much as 150 km) and 6 m high natural dam across the Puran river known as the Allah Bund, or Dam of God formation of Sindri Lake covering an area of more than 1,000 km <sup>2</sup> due to subsidence of up to 3 m south of the Allah Bund which was later drained out

lineaments or fault lines and intense meandering with sinuosity ranging from 1.20 to 3.12. The existence of micro-terraces and entrenched channel segments encountered structural confinements and certified the positive controls of neotectonics on development of Dharala River.

The Chap. 9 is a ‘Preliminary Study of the Manabhum Anticline: A Possible Key to Better Understanding the Quaternary Tectonics of the Eastern Himalayan Syntaxial Zone’. In this chapter, a detailed geomorphic and geological study of NNW-SSE trending Manabhum Anticline of Naga-Schuppen belt and Mishmi hill has been done to establish the tectonic scenario during Quaternary time. The authors interpret

that the present-day drainage is mainly controlled by the ENE'ly dipping thrust with the considerable effect of the strike-slip fault. They also opined that as Manabhum Anticline is one of the most tectonically active regions during the Quaternary time in South East Asia, it may act as a key to understand the movement of the Indian Plate along the Eastern Syntaxial zone.

The Chap. 10 'Assessment Of Neotectonic Effect On Quaternary Deposits In Darjeeling Himalayas' detected signals of neotectonism from landform and sediments of Darjeeling-Jalpaiguri Sub-Himalayas and southerly adjacent piedmont. A quantitative approach is adopted in this chapter. Sinuosity value less than 1.4 in most of its straight channel segments, minimum gradient on the crest of the Mountain Front Thrust (MFT), the frequent presence of mass-flow products and increase in clast size and share of distal crystalline rocks in clast composition but stable climate indicate towards the uplift of MFT.

Tectonic events of Himalayan Foredeep and its effects on the fluvial landscape with special emphasis on scarps and fans has been discussed in 'Himalayan Foredeep Neotectonics and Deformed Riverscape Landforms: An Integrated Discussion, West Bengal, India', the Chap. 11.

The Chap. 12 'Evaluating the relative tectonic response of the fluvial systems using multi-criteria Entropy Method: A case study of the Rangit Catchment, Eastern Himalayas, India' assess the tectonic response in the fluvial systems using several indices such as the asymmetric factor, hypsometric integral, elongation ratio, stream gradient index and valley width-height ratio for all 16 sub-catchments along with the trunk-stream of the Rangit River. Authors suggest that the left bank tributaries show a higher degree of tectonic control than the right bank tributaries. The Main Central Thrust (MCT), which was active in the Holocene period has prominent control on the basin and channel evolution.

The Chap. 13 'Role of geomorphic drivers and active tectonism on channel oscillation of the Raidak-I River in the eastern Himalayan foothills, India' illuminates the relationship between the riverbank erosion-deposition and geomorphological and tectonic adjustment.

'Morphotectonics of the Chel river basin, Eastern Himalaya, India: Insights from Shuttle Radar Topography Mission digital elevation model-based geomorphic indices' comprises the Chap. 14 which examined the implications of Neotectonic activity on channel characteristics and landform development of Chel river basin. Authors analyzed Shuttle Radar Topography Mission (SRTM) DEM based geomorphic indices and uncovered how the elongated basin shape, hypsometric integral value, basin asymmetry factor, irregular mountain front, presence of V-shaped valleys, and knick points point towards neotectonism and the senile stage of the basin.

The Chap. 15, 'Influence of Neotectonics on Channel Evolution of Kameng River, North-East India' used morphometric and statistical tools and pointed towards the signature of neotectonism on the channel evolution of the Kameng River of North-East India. Due to neotectonic perturbations and associated inclinations of different parts of the basin into different directions, sub-basins became significantly asymmetric. Direction of flow paths of channel links are associated with the orientation of fault lines and lineaments.

## 6 Conclusions

The subject tectonic geomorphology (Morphotectonic Studies) attracted the attention of geologists and geomorphologists in the last few decades starting its journey from the last century, with the overwhelming Davisian concept—‘Landscape is a function of structure, process and stage’, which grasped the central concept of tectonic geomorphology in a very incipient form. This Davisian concept had to wait a long to be tested in the field due to a lack of proper identification tools, age determining techniques and quantification methods and is now gaining popularity day by day.

Studies on neotectonic activity and landform started with the refinement of tectonic geomorphology as a subject. Identification and analysis of geomorphic markers from secondary data are required in the field of neotectonic study obviously being followed by field observations. Innovative tools for identification of such geomorphic markers were not available to the researchers even in seventies and eighties of the last century. Presently high resolution remotely sensed data of different satellite systems of different countries and highly sophisticated software to identify the geomorphic markers are easily available. Now a day remote sensing data is mostly available in digital formats, like Landsat MSS, Landsat TM, Landsat ETM+, SPOT, QuickBird, Cartosat, IKONOS, etc. These digital images are processed with appropriate hardware and software like ER Mapper, Ilwis, Erdas, Geomatica, ArcGis, TNTmips etc. Geo referencing helps to derive the location of the feature on earth and map overlays helps to derive the pattern of change through time. Then ground checking is done to determine the location and exact characteristics of the features on real earth. All these are opening the scope of the subject day by day and young researchers are becoming interested in such studies. Moreover the modernisation of dating techniques is also helping more accurate prediction of data and time which is making the subject more fascinating and innovative. All these undoubtedly indicate a profusely expanding arena of the subject though inaccessibility will remain as a natural hinderance in the field verification and study.

Neotectonic events are in operation in the Himalayas, the peninsular plateau and Indo-Gangetic-Brahmaputra plain with deltaic part of the Indian subcontinent, and river channels in these areas show striking imprints of tectonism in their evolution. Though the Indian subcontinent is much diversified in geological evolution and fluvial response, the tools and techniques to explore the non-linear fluvial behavior in response to geology and stratigraphy are strikingly insufficient compared to the Anglo-European nations of the world. However, in the recent decades developments in high resolution imageries and the GISciences is backing the earth scientists to some extent to explore the newer areas. With this backdrop, present volume initiated fused-avenue of tectonic geology and fluvial geomorphology for a better understanding of rivers and sub-surface tectonics of the Indian subcontinent with special reference to the Himalayan Neotectonics. We hope that this initiation directs to the vast scope and paves the way of further research ranging from basin-scale to channel-site scale on each and every basins, and their sub-basins of different orders in different



hydro-meteorological and tectonic regions of the world in general and in the Indian subcontinent in particular.

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