23 Geomorphic Appraisal of Active Tectonics and Fluvial Anomalies in Peninsular Rivers of the Bengal Basin (West Bengal, India)

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Abstract

The Bengal Basin is one of the largest peripheral collisional foreland basins at the juncture of three converging lithospheric plates (Indian Plate, Eurasian Plate and Burma Plate), carrying signatures of regional scale sesimogenic faults, which is conducive for the frequent and recurrent earthquakes. The recent earthquakes occurred with a magnitude range (M_w) of 3.6–5.7 in the western shelf zone of the Bengal Basin and the seismologists have predicted an event of potential earthquake of M_w 8.2–9.0 due to locked mega thrust. Such activeness of seismic events reflects the vulnerability of densely populated towns and cities located in the Ganga–Brahmaputra–Megna Delta. The main point of research interest is the anomalous fluvial responses to active tectonics in the shelf zone of the Bengal Basin to explore the relative perkiness of regional tectonic uplift or subsidence. Since Palaeogene time, the peninsular river system (viz., Brahmani, Dwarka, Mayurakshi, Ajay, Damodar, Dwarkeswar, Silai and Kasai river basins) was directly influenced by the underlying structure and *en echelon* faults, and several landforms, channel morphology and morphostratigraphical units were distorted and deformed due to seismic shocks. The present study tries to document and understand the significant tectonic elements, geomorphometric anomalies and soft-sediment deformation structures on the alluvial river valleys and Quaternary floodplains using seismic information, proxy data, geomorphic indices of active tectonics, thematic mapping and stratigraphic analysis of depositional facies.

Keywords

Syntectonics · Earthquake · Bouguer anomaly · Seismites · Geomorphic indices of active tectonics · Bengal Basin

23.1 Introduction

Active tectonics is defined as those tectonic processes that produce deformation of the earth's crust and surface on a time scale of significance to human society (Schumm et al. 2002; Keller and Pinter 2002). More recently, much attention has been paid to the role of tectonics in Anthropocene, and active tectonics has become a major concern with much emphasis on earthquake studies (Ouchi 1985; Schumm 1986; Hoolbrok and Schumm 1999; Azor et al. 2002; Jain and Sinha 2005; Kale and Shejwalkar 2008; Sahu et al. 2010; Mahmood and Gloaguen 2014; Anand and Pradhan 2019). The major concern is

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centred on the seismo-tectonic features, earthquake prediction and fluvial responses to tectonic activity. The western shelf zone of the Bengal Basin is considered as one of the important and structural elements of Indian sub-continent (Valdiya 2016) because the basin geosyncline is one of the largest peripheral collisional foreland basins, due to resistance to subduction below the Eurasian Plate and plate convergence. An obvious question in this regard is whether there is any geomorphic evidence to support the view that the western margin of the Bengal Basin has experienced significant and protracted uplift or subsidence from Tertiary to recent times? Alluvial rivers are the active and sensitive element of the fluvial landscape, because any shifts in the tectonic controls can instigate various rapid geomorphic and sedimentary responses from the fluvial system through different complex responses and resilience (Schumm et al. 2002). According to Jain and Sinha (2005), the primary response of rivers to tectonics is manifested as change in channel slope, while secondary changes are reflected in aggradation/degradation and variations in channel morphology.

The imperceptibility slow and secular as well as episodic crustal movements that have been taking place since the beginning of the Quaternary period some two million years ago are described as neo-tectonic activities. Areas involved in or subject to the impact of continental drift and collision of Indian Plate, Eurasian Plate and Burma Plate are particularly prone to persistent tectonic stability and attendant deformation and displacement (Valdiya 1984). Dennis (1972) and Valdiya (1984) mentioned major indicators of neo-tectonic movements: (a) *historical instances* of sunken or buried archaeological sites, (b) *geomorphic features* such as changing the course of river and streams, abrupt drainage swings, raised floodplain, alluvial terraces and anomalous channel gradient, (c) *structural dislocation and deformation* and recent sedimentary deposits, including the dissection of pediments, fans, warping or tilting of recent layered deposits, movement of ground along newly developed or reactivated older faults and thrusts, (d) *altimetric variation* of elevation determined by geodetic measurements and geomorphic indices of active tectonics and (e) *recurrent seismicity*, implying surface or underground episodic or spasmodic movements or rocks or soft-sediment deformation structures along faults.

For geomorphologists, the important factor is that the deformation is impacting a river, and it is the syntectonic response of the river that is of concern. Syntectonics refers to contemporaneous or coeval deformation and river response, which permits discussion of both active tectonic and neo-tectonic impacts on rivers and floodplains (Schumm et al. 2002). It is a largely ignored aspect of tectonic geomorphology, the study of landforms that result from tectonic processes, which has been involved primarily with earthquake effects and prediction. The notable studies of Ouchi (1985), Leeder and Alexander (1987), Yeats et al. (1997) and Holbrook and Schumm (1999) revealed minutely that tectonic deformation causes a notable change in channel slope, which, in turn, is responsible for variations in channel forms, processes and hydrological behaviour of alluvial rivers (Table 23.1). It is estimated that any deformation of the order of few mm ($2-3\ \text{mm year}^{-1}$) can produce anomalous features in a river basin (Schumm 1986; Schumm et al. 2002). In India, earlier studies on the drainage systems of Ganges River Basin have severally highlighted the manifestation of region E–W thrust as kinck points in the longitudinal profiles of the rivers in north and eastern India (Seeber and Gornitz 1983; Valdiya 1999; Jain and Sinha 2005; Malik and Mohanty 2007). In the western part of the Bengal Basin five important large to medium scale studies of tectonic geomorphology have been still performed by Singh et al. (1998), Sinha and Ghosh (2012), Roy and Sahu (2015), Barman et al. (2019), Roy (2019), and Roy and Bera (2019) showing role of marginal faults on the evolution of laterite uplands, old fluvial/deltaic plains and young fluvial plains and correlation among subsurface lithology, gravity anomaly and anomalous drainage behaviour. Finding the research novelties and gaps of previous works, it is now utmost necessity to correlate the geo-tectonic

Table 23.1 Important works on the tectonic geomorphology of fluvial processes and landforms

Sl. no	Authors	Essential remarks on research articles and books
1	Seeber and Gornitz (1983)	Analyzing the river profiles along the Himalayan arc to understand the relative activeness of tectonics
2	Ouchi (1985)	Experimental understanding of variable fluvial responses to sow active tectonics in the alluvial rivers
3	Holbrook and Schumm (1999)	Field-based understanding and thematic modelling of geomorphic and sedimentary responses of alluvial rivers to tectonic warping or tilting in modern and ancient fluvial sedimentary settings
4	Keller and Pinter (2002)	One of milestone works to inter-relate the earthquakes, uplift or subsidence and landscapes; providing separate chapters on geomorphic indices of active tectonics and fluvial anomalous response to uplift or subsidence
5	Schumm et al. (2002)	One of the important books to cover the various aspects of tectonic geomorphology to understand the typical response of fluvial forms to active tectonics in alluvial rivers
6	Jain and Sinha (2005)	Active tectonics in a basin plays an important role in controlling a fluvial system through the change in channel slope
7	Kale and Shejwalker (2008)	Explaining the merit of geomorphometric analysis in response to ongoing post-rift flexural uplift or neo-tectonic activity in the western Deccan basalt Province
8	Goswami (2012)	Exploring the geomorphic evidences of active faulting syntectonic responses in the north-western Ganga Plain
9	Mahmood and Gloaguen (2014)	Assessment of relative active tectonics on drainage systems of Hindu Kush mountain range using GIS and geomorphic indices
10	Nath et al. (2015)	Assessing the earthquake scenario in West Bengal with emphasis on seismic hazard micro-zonation of Kolkata city
11	Das et al. (2016)	Active tectonic response of dryland fluvial system to tectonic—climatic perturbations of Late Quaternary in Kutch Basin, western India
12	Anand and Pradhan (2019)	Geomorphic understanding of active tectonics using morphometric parameters in the Ganga Basin
13	Dubey and Shankar (2019)	Exploring the impact of relative seismic events on drainage pattern in the Sone Valley
14	Das (2020)	Investigating geomorphic expression of tectonic control in Koyna-Warna shallow seismic region of Deccan Traps

elements of the Bengal Basin with recurrent seismicity (earthquakes) and fluvial signatures of floodplains (to realize current seismicity and active tectonics in the shelf zone of the Bengal Basin) considering the maximum numbers of peninsular rivers (flowing over the western margin of basin). The present study of tectonic geomorphology has made a reconnaissance attempt to understand the surface deformation pattern and fluvial dynamics across and along the subsurface faults and lineaments with the help of gravity anomaly, seismo-tectonic elements, geomorphic indices and soft-sediment deformation structures of fluvial facies.

23.2 Geomorphic Setting of Study Area

The geographical extension of the Bengal Basin ranges between 25° and 20°30′ N latitudes and 87°30′ to 90°30′ E longitudes (Fig. 23.1). The sedimentary basin occupies an area of 89,000 km^2 in total about which 57,000 km^2 on land ad 32,000 km^2 offshore up to 200 m bathymetry (Hossain et al. 2019). In Indian sub-continent, one of the important tectonic and structural elements is the Bengal Basin which is one of the largest peripheral colliosional foreland basins,

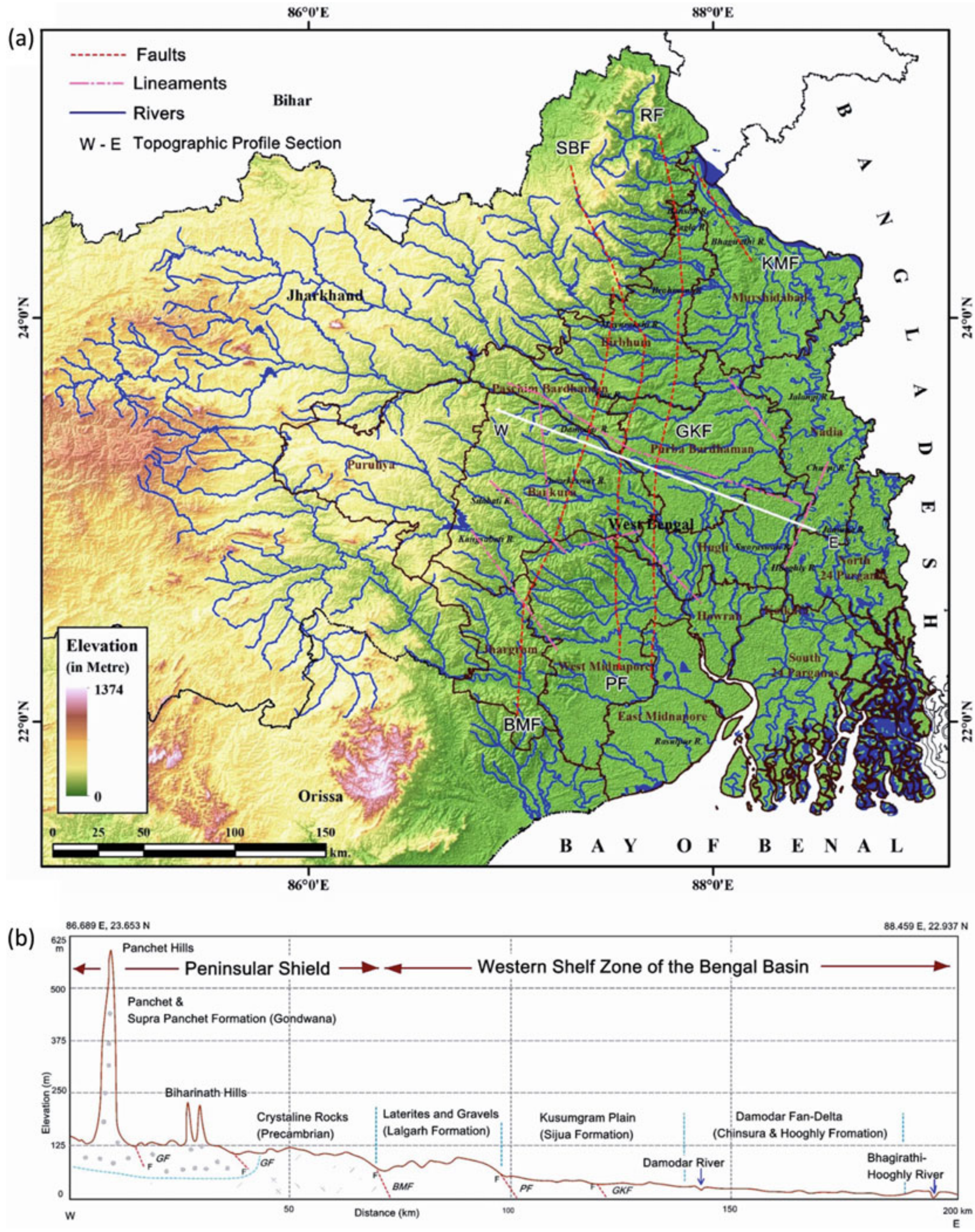


Fig. 23.1 **a** Study area depicting spatial distribution of peninsular rivers in connection with elevation zones and sub-surface faults in the western part of the Bengal Basin, and **b** regional elevation profile W–E showing the occurrences of geomorphic units in association with underlying geology and faults of the Peninsular Shield and Bengal Basin

consisting of Permo-Carboniferous to Mesozoic and Tertiary deposits covered by the Quaternary to Recent alluvium (having ~21 km thick sedimentary succession in West Bengal). From the geomorphic point of view, this basin, occupied by the Ganges-Brahmapurta-Meghna (GBM) Delta, is getting Himalayan and Peninsular sediments at an average rate of 1.1 gigatonne per year (Goodbred and Kuhel 2000). It is found that in these densely populated regions of India and Bangladesh, scientists have found many evidences of active tectonics and the increasing trend of earthquakes due to the resistance to subduction below the Eurasian Plate. The plate convergence, tectonic deformation and seismic activity occur in the intra-plate region, including stable shelf in the western part of the Bengal Basin and results in conjunction with high-angle basement faults of variable trends (NE–SW, E–W, NW–SE) (Roy and Chatterjee 2015).

The Bhagirathi-Hooghly River is the western branch of the GBM Delta and flows more than 500 km from Farraka to Sagar Island. The Bhagirathi-Hooghly River has an undulating catchment area of 66,000 km^2 along the right bank drained by the major tributaries (Fig. 23.1), which are Brahmani, Dwarka, Mayurakshi, Ajay, Kunur, Khari, Damodar, Dwarkeswar, Silai and Kasai (Rudra 2018). These tributaries of peninsular shield area together contribute about 48,410 million m^3 of water annually into the Bhagirathi-Hooghly River. The Ajay (basin area of 6074 km^2), Damodar (basin area of 20,874 km^2) and Mayurakshi Rivers (basin area of 9345 km^2) originate in the Precambrian crystalline metamorphic units of the Chhotanagpur Plateau, and these rivers are flowing west to east direction guiding by the underlying lithology and structure. Other peninsular rivers are originating in the hard rock terrain of plateau fringe and lateritic *Rarh* uplands. A wider extension of the GBM Delta is the 'para-deltas' of western uplands formed by these peninsular tributaries to the Bhagirathi-Hooghly River within its geographic area, and the Damodar Fan Delta is a key morphostratigraphic unit developed through marine transgression and tectonic activity since Pleistocene (Rudra 2018; Mahata and Maiti 2019). Agarwal and Mitra (1991) named that unit as 'palaeo-delta', which occupies the western and northern-most part of the main GBM Delta occurring dominantly west of the Bhagirathi-Hooghly River (Fig. 23.2). To the west, it is bounded by the exposed Pleistocene laterites, Tertiary Formations, Gondwana sediments and Precambrian rocks. The deposition of pebbles and gravels with ferruginous matrix is observed as alluvial fan to fan-delta morphotstratigraphic units of Oligocene to Miocene age, which are assumed to be developed as a result of Basin Margin Fault (BMF) in the interfluves of Ajay–Dmaodar–Dwarkeswar (Mahapatra and Dana 2009; Ghosh 2014). Pleistocene uplands of laterites, elevation range of 40–70 above mean sea level, are carrying main geomorphic signatures of lateritization, neo-tectonics, badlands, complex fluvial incision and ruggedness (Niyogi et al. 1970). Singh et al. (1998) revealed that tectonic evolution of laterite uplands, old fluvial/deltaic plains and young fluvial plains in connection with the subsequent uplift of faulted blocks since ~7 ka in the western margin of GBM Delta.

23.3 Methodology and Database

Tectonic Geomorphology of alluvial rivers may be studied in two ways: (1) the study of landforms and sedimentary features produced by tectonic processes and (2) the application of geomorphic principles and techniques to the solution of tectonic problems (Keller and Pinter 2002). Though geomorphic characterization of the tectonic properties of a landscape is an extremely complex task, but it is now well recognized that the commonly used geomorphic indices of active tectonics (GAT) are powerful methodological tools to evaluate the relationship between tectonics and fluvial hydrogeomorphology at basin scale or reach scale, and to recognize the Quaternary to Recent deformation of fluvial elements and sedimentary structures (Bull and McFadden 1977; Schumm 1986; Holbrook and Schumm 1999; Keller and Pinter 2002; Jain

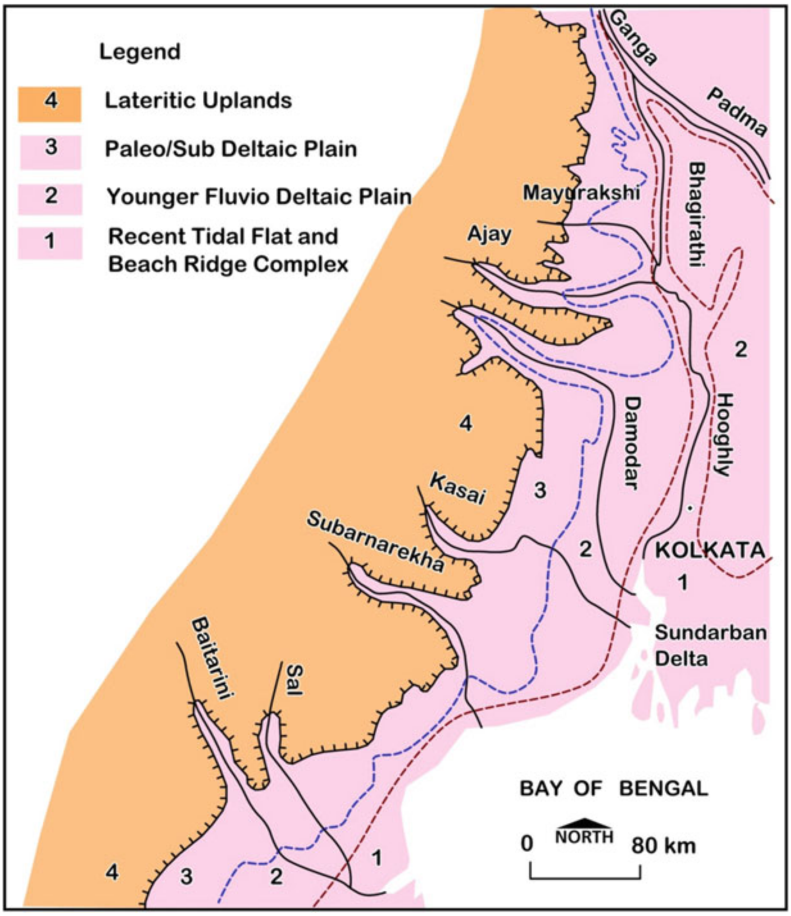


Fig. 23.2 Quaternary palaeogeomorphic units developed in the western shelf zone of the Bengal Basin (modified from Agarwal and Mitra (1991), Singh et al. (1998))

and Sinha 2005; Montenat et al. 2007; Kale and Shejwalkar 2008; Mahmood and Gloaguen 2014; Shanmugam 2016; Anand and Pradhan 2019; Ghosh and Shivakumar 2019; Ayaz and Dhali 2019; Das 2020). These relief, areal, shape and gradient parameters particularly provide useful information about the dynamics of tectonics in the regions underlined by the same rock-type (Keller and Pinter 2002; Kale and Shejwalkar 2008). Quantitative measurements allow geomorphologists objectively to compare different landforms and to calculate less straightforward parameters (GAT) that may be useful for identifying the fluvial response or anomalies (a particular characteristic of an area) to different levels of past or ongoing tectonic activity (Keller and Pinter 2002).

Calculations of a number of geomorphic indices for a large region such as the western shelf zone of the Bengal Basin (from the Rajmahal Basalt Traps to the Kasai River Valley) were made feasible by the analysis of Digital Elevation Model (DEM) of 30-m resolution SRTM (Shuttle Radar Topographic Mission) global data. The spatial scale or unit of geomorphic study is the basin and channel reach of the fluvial system of Peninsular Rivers. Here 12 rivers (viz., Dwarka, Brahmani, Mayurakshi, Ajay, Kunur, Khari, Damodar, Dwarkeswar, Silai and Kasai) and their watersheds (in between the Chhotanagpur Plateau and the Bengal Basin) are selected for GAT analysis. The digital elevation data are used to extract information about the drainage basins, network and profiles using the standard procedures and 3D tools of Global Mapper 21.0 software. A word of caution is added here regarding the longitudinal and cross profiles extracted from the SRTM-DEM data. Because of stepping, anthropogenic interventions and alluvial floodplain of low altitude, the detection of significant breaks and knick zones in the profiles is a not a very simple and straightforward task, especially for low-gradient alluvial rivers. Buffering of path profile (mean elevation error correction using standard deviation) and smoothing of the long profiles using running mean (aka moving average) of 5–11 consecutive elevation values partially reduce the problems but do not eliminate them completely. Next, the extraction of fluvial features is cartographically done from the Survey of India (SOI) topographical sheets of 1: 50,000 scale (viz., 72 P/12, 73 N/1, N/2, N/5 and N/6, 73 M/1, M/6, M/7, M/10, M/12, M/15 and M/16 etc.) using ArcGis 9.3 software. To get micro details and temporal variations of fluvial features, the public domain of Google Earth Pro is used severally. In addition, the sample field studies of selected locations, along the Damodar River Basin, are performed to get soft-sediment deformation features and twisted lithofacies in the alluvial stratigraphy of Holocene to Recent age. To get additional geologic and seismo-tectonic information, the unpublished reports of the Geological Survey of India (GSI) (Ghosh 1992; De et al. 1994; Bhattacharya and Dhar 2003; Shivgotra et al. 2011; Deb and Singh 2011), Bhukosh web portal (http://bhukosh.gis.gov.in/Bhukosh/Public), United States Geological Survey web portal (https://earthquake.usgs.gov/), National Center of Seismology web portal (https://seismo.gov.in/MIS/riseq/earthquake), and important research works (Chandra 1977; Khan and Chouhan 1996; Kayal 2008; Raj et al. 2008; Govindaraju and Bhattacharya 2012; Steckler et al. 2016; Nath et al. 2010; 2014, 2015, 2018; Dey et al. 2019; Singh et al. 2020) are analyzed here.

GAT may detect anomalies in the drainage system or along or across active fault regions. These anomalies are possible due to local changes of topography from tectonic activity resulting from uplift or subsidence. Some of the geomorphic indices most useful in studies of Himalayan active tectonics include (Table 23.2):

(1) The Sinuosity Index (S_I) (Schumm 1956; Mueller 1968) is measured to the deviation of channel from a straight path. Simply it is the ratio of channel length to valley length. Mueller (1968) introduced the topographic and hydrologic sinuosity index to understand the controls of tectonic activity or stream discharge on sinuosity. It is assumed that any tectonic deformation that changes the slope of a river valley may result in a corresponding change in sinuosity to maintain equilibrium channel slope.

(2) The Hypsometric Integral (H_I) (Strahler 1952) is a useful attribute of the hypsometric curve (the area under the curve) to identify the stages of landform development (regarding erosional and depositional sequences), based on a function of total area and total elevation at basins scale. Higher index values of H_I might result from the recent incision of initial landforms formed by deposition in the alluvial rivers.

(3) The Stream Length-Gradient Index (S_L) (Hack 1973) correlates to stream power or energy gradient in response to topographic upliftment or subsidence. It is calculated on the basis of channel slope or gradient of the reach and the total length of channel, measured as horizontal length from the watershed divide to the midpoint of the reach. The S_L index values of the basins are used to discuss the influences of environmental variables on longitudinal river profiles and to test whether the rivers have reached equilibrium or not (Mahmood and Gloaguen 2014).

(4) Drainage Basin Asymmetry Factor (A_F) (Hare and Gardner 1985) is used to recognize the distinct pattern and geometric anomalies of basin in the presence of active tectonics. A_F is a function of the basin area to the right (facing downstream) of the truck stream and the total basin area. The factor is sensitive to tilting perpendicular to the trend of the truck stream. A_F significantly greater or smaller than 50 ($A_F > 50$ implies tilt down to the left of basin, looking downstream) shows influences of active

Table 23.2 Geomorphic indices of active tectonics (GAT) and their calculations

Sl. no	Index	Formula	Variables	Reference
1	Sinuosity Index (S_I)	$S_I = A_L/E_L$	A_L = actual or observed length of stream; E_L = expected length of stream	Schumm (1956); Litchfield et al. (2013)
2	Standard Sinuosity Index (SSI)	SSI = CI/VI, TSI = 100 (VI − 1)/(CI − 1), HSI = 100(CI − VI)/(CI − 1), CI = CL/AL, VI = VL/AL	CI = channel index, VI = valley index, CL = channel length, AL = air length, TSI = topographic sinuosity index, HSI = hydraulic sinuosity index	Mueller (1968); Ghosh and Mistri (2012)
3	Hypsometric Integral (H_I)	$H_I = (E_m - E_{min})/E_{max} - E_{min})$	E_m = mean elevation, E_{max} = maximum elevation, E_{min} = minimum elevation	Strahler (1952); Anand and Pradhan (2019)
4	Stream Length-Gradient Index (S_L)	$S_L = (H_1 - H_2)/(\ln L_2 - \ln L_1)$	H_1 and H_2 are the elevations of each end of a given reach, L_1 and L_2 are the distances from each end of the reach to the source	Hack (1973); Kale and Shejwalkar (2008)
5	Drainage Basin Asymmetry Factor (A_F)	$A_F = 100(A_r/A_t)$	A_r = are of the basin to the right of the trunk stream, A_t = total area of the drainage basin	Hare and Gardner (1985); Mahmood and Gloaguen (2014)
6	Ratio of Valley Floor Width to Valley Height (V_F)	$V_F = V_{fw}/[\{(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})\}/2]$	V_{fw} = width of valley floor, E_{ld} = elevation of the left valley divide, E_{rd} = elevation of the valley floor, E_{sc} = elevation of the valley floor	Bull and MaFadden (1977); Mahmood and Gloaguen (2014)
7	Basin Elongation Ratio (E_R)	$ER = 2 (A/\pi)^{0.5}/L_b$	A = basin area, L_b = length of the basin	Schumm (1956); Kale and Shejwalkar (2008)

tectonics/lithological control or differential erosion, as for example the stream slipping down bedding plains over times (Keller and Pinter 2002; Mahmood and Gloaguen 2014).

(5) The Ratio of Valley Floor Width to Valley Height (V_F) (Bull and McFadden 1977; Bull 1978) is a useful geomorphic index conceived to discriminate between V-shaped ($V_F < 1$) and U-shaped ($V_F > 1$) flat-floored valleys. It is a mathematic function of valley floor width, elevations of left and right valley divides, and elevation of the valley floor. High index values of V_F reflect low uplift rates or stable region and broad valley floors, and low V_F values are associated with local uplift, deep valleys and active incision (Keller and Pinter 2002).

(6) Basin Elongation Ratio (E_R) (Schumm 1956) is basin shape index, which can give information about tectonic deformation of shape with time. It is estimated based on the total area of the basin and maximum length of the basin. Relatively young drainage basins in active tectonics areas tend to be elongated in shape parallel to the topographic slope of a region (Mahmood and Gloaguen 2014).

23.4 Results

23.4.1 Elements and Features of Active Tectonics

23.4.1.1 Geotectonic Settings

Peninsular India lying south of the Indo-Gangetic Alluvial Plain (IGAP) commonly referred to as the Indian Shield reportedly occupied a much wider area than the present triangular shaped region, made up of a diverse mosaic of igneous and metamorphic terrains that have undergone deformation and metamorphism (Hossain et al. 2019). Bengal Basin is situated in the north-western part of Indian Shield, covering West Bengal of India and entire Bangladesh. The Bengal Basin is a classic example of a peripheral foreland basin formed via continent–continent collision (Mukherjee et al. 2009). The basin was initiated at the breakup of Gondwanaland in the late Mesozoic and evolved through the formation of the proto-GBM delta to the present delta starting around 10.5 Ma (Mukherjee et al. 2009). Goodbred and Kuhel (2000) sedimentation in the Bengal Basin was marked by basin-ward subsidence in the middle to Late Eocene causing extensive marine transgression almost over the entire Bengal Basin (Roy and Chatterjee 2015).

The onset of Miocene witnessed a further increase in sediment supply when a huge thickness of fluvial sediments showing alternating and repetitive deposition of sandstone and shale along with swallowing up of the basin from pro-delta to brackish marine with limited marine influence (Roy and Chatterjee 2015). During the Early Pleistocene, shallow marine conditions prevailed only in the deeper part of the eastern Deep Basin. The sea finally receded from the Bengal Basin area possibly in Late Pleistocene. After a brief period of depositional hiatus, the older sediments in the entire basin area were covered completely by a thick mantle of fluvial Holocene alluvium (Roy and Chatterjee 2015). The geological succession of the Bengal Basin (adjacent areas of Peninsular region) is depicted in Table 23.3 and Fig. 23.3.

The main tectonic and structural zones of the basin are identified as (Fig. 23.4): (1) Basin Margin Fault Zone (BMFZ), (2) Stable Shelf Zone (SSZ), (3) Eocene Hinge Zone (EHZ) and (4) Deep Basin (Hossain et al. 2019). The main point of interest is the BMFZ and SSZ, because these geological units are associated with many active faults and west–east flowing peninsula rivers, which have directly influenced the landform evolution, laterite genesis and badlands. The NNE—trending zone of BMFZ demarcates the western crystalline or metamorphic complex of Precambrian age from the shelf sediments. The fault zone is, apparently, the result of distension and down warping of the shelf region during Early—Late Cretaceous, probably, concomitant with the eruption of Rajmahal basaltic lavas. Western portions of this feature are the exposures of Gondwana sedimentary rocks resting on the Precambrian granitic-Gneissic basement (Kaila et al. 1992; Hossain et al. 2019).

To the northwest, the Bengal Basin is separated from the Rajmahal Hills by the approximately N-S running Rajmahal Fault and the Rajmahal Hills of West Bengal and Jharkhand is a fault-bounded small tectonic element (Rajmahal Fault at east and Saithia-Brahmani fault at west) situated in the western edge of the SSZ of Bengal Basin (Hossain et al. 2019). The Tertiary sedimentary prism thickens towards east and merges with the deep shelf beyond EHZ, which is narrow elongated zone that separates the thick post-Eocene sediments in the east from the shelf zone of the west. At western part of Paschim Barddhaman the subsequent break in the basement slope is very conspicuous, and the L basement slope gently tends towwards east, marked by numerous step faults with small displacements (Ghosh and Guchhait, 2018). The formation of Damodar Fan Delta (DFD) and the associated drainage development were largely influenced by these basement faults since Tertiary times (Mahata and Maiti 2019). The deep seismic profile of Beliator—Khandaghosh zone has encountered two *en-echelon* type faults (Garhmayna—Khandaghosh Fault and Pingla

Table 23.3 Generalized stratigraphic succession of the geological units in the western part of Bengal Basin and eastern part of Peninsular Shield

Era	Period	Formation	Lithology
Cenozoic	Quaternary to Recent	Hooghly Formation/Arambagh Formation/Ganga-Kosi Formation. Katwa Formation	Recent to sub-recent oil/alluvium/sandy clay/loose sand/ferruginous sediment with calcretes
		Panskura Formation/Chinsura Formation/Malda Formation/Bethuadahari Formation	Ferrous shale, mudstone/Calc mud/impure limestone, fine to coarse sandstone with floral remains
		Sijua Formation	Ferruginous sandstone clay/thin pebbles bed/impure limestone/green clay/Carbonaceous clay with rich floral assemblage and plant roots
		Barind Formation/Baikunthapur Formation/Lalgarh Formation/Ausgram Formation	Alternating clay and sand beds
	Tertiary	Siwalik Group	Ferruginous sandstone, pebbly grit, red shale, clay, gravel and fossil wood
Mesozoic	Gondwana supergroup	Durgapur Formation	Compact, thinly laminated quartzite, carbonaceous shale with fossils of algae and foraminifera
		Unconformity	
		Rajmahal Formation/Dubrajpur Formation/Supra-Panchet Formation	Traps with inter-trappeans, ferruginous sandstone, red shale/clay stone
		Unconformity	
Paleozoic		Raniganj Formation	Sandstone and shale with thick coal seams
		Barren Measure Formation	Grey shale nodule of iron ores
		Barakar formation	Sandstone with coal seams
		Talchir Formation	Conglomerate, siltstone, shale and sandstone
Proterozoic	Lower to Middle Proterozoic	Manbhum Granite/Kuilpal Granite	Granite containing phenocrysts of feldspar
		Dalma Volcanics	Ultramafics, mica schist, phyllites, quartzites, tuffs, cherts and calc silicates
	Archean		silicified metamorphics, anopthosites, schist, amrble/cal. Granulites/amphibolites/hornblende schist/composite gneiss, biotite gneiss
	Proterozoic	Chhotanagpur Gneissic Complex	

Source Sengupta (1966), Das Gupta and Mukherjee (2006)

Fault), which has affected the entire sedimentary column starting from the surface to the basement (Kaila et al. 1992). The depth basement of the SSZ varies from 4 to 5 km near Khandaghosh to about 7.5 km near Dhatrigram.

Lithospheric flexure and subsidence of the basin (subduction of the Indian plate below the Eurasian and Burmese plates) are occurring at a rate of 2–4 mm/year in Mukherjee et al. (2009). As a result of the resistance to subduction flow below the Eurasian plate and plate convergence, intense deformation and seismic activity occur in the India intraplate region, including on the stable shelf in the western part of the Bengal

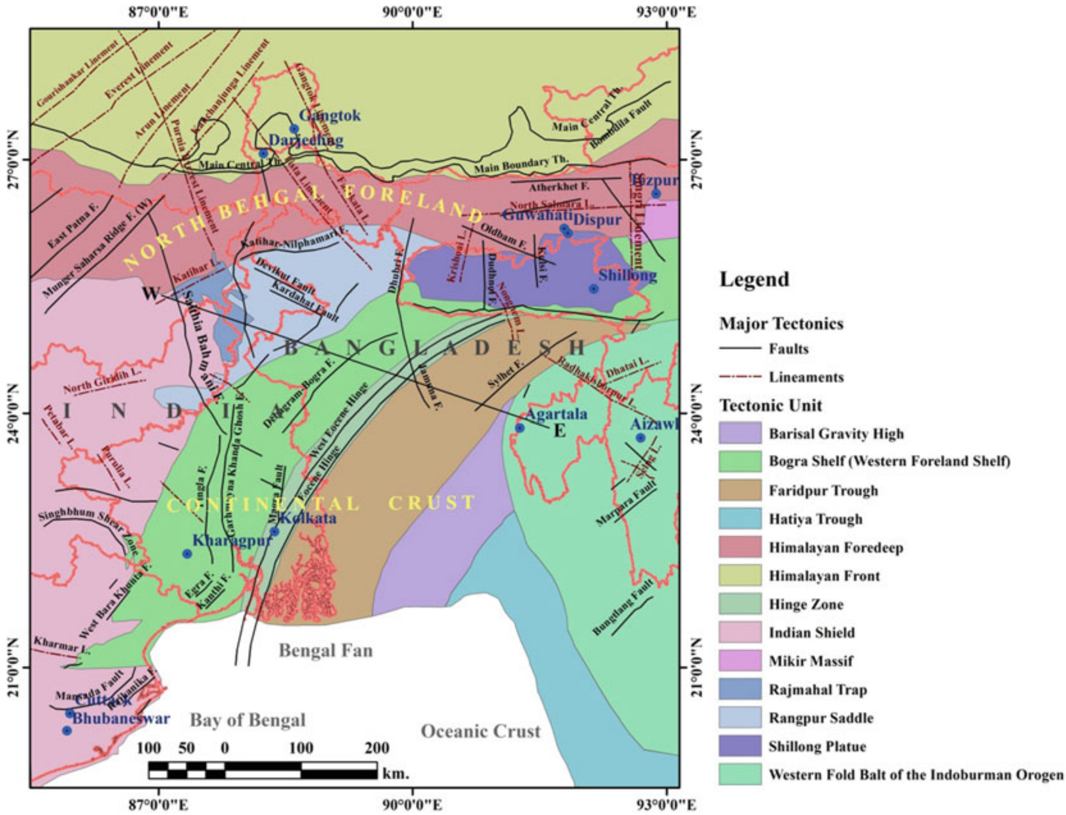


Fig. 23.3 Geological configuration of the Bengal Basin and adjacent areas of India and Bangladesh (modified considering Sengupta 1966; Das Gupta and Mukherjee 2006; Nath et al. 2010, 2015)

Basin (Fig. 23.4), resulting in folding of strata and brittle deformation via high-angle basement faults (Mukherjee et al. 2009; Roy and Chatterjee 2015). The SSZ has further been subdivided into the Baharampur terrace, the Baidyapur depression, the Contai terrace from north to south, the Dinajpur slope, the Rangpur Saddle and the Bogra slope from west to east (Nath et al. 2014). The Bogra slope represents a monocline plunging fold gently sloping towards the southeast of the EHZ and the width of it varies from 60 to 125 km (Nath et al. 2014, 2018).

The western sub-basin of the Bengal Basin (BMFZ and SSZ) shows the occurrence of laterite and lateritic soils, the protoliths of which include ferruginous sandstone, red shale, grit and gravel beds (mainly Lalgarh Formation) containing dicotyledonous fossil woods (Roy and Chatterjee 2015). Moving eastward, red soils change over to grey alluvium along the BMFZ, which is a zone dislocation running along the N15°E–S15°W trend and marked by the crowding of gravity contours (Roy and Chatterjee 2015). Since Palaeogene, it may be expected that the river systems and landforms of West Bengal were directly influenced by the numerous faults and lineaments of Bengal Basin, viz., Garhmayna—Khandaghosh Fault (GKF), Chottanagpur Foor-hill Fault or Basin Margin Fault (BMF), Jangipur-Gaibardha Fault (JGF), Pingla Fault (PF), Debagram—Bogra Fault (DBF), Saithia—Brahmani Fault (SBF), Rajhamal Fault (RF), Malda—Kisanganj Fault (MKF), Purulia Shear Zone (PSZ) etc. The most prominent tectonic feature is the NE–SW trending Eocene Hinge Zone (EHZ), which is 25 km wide and extends to a depth of about 4.5 km below Kolkata city (Nath et al. 2014, 2018). The western margin of

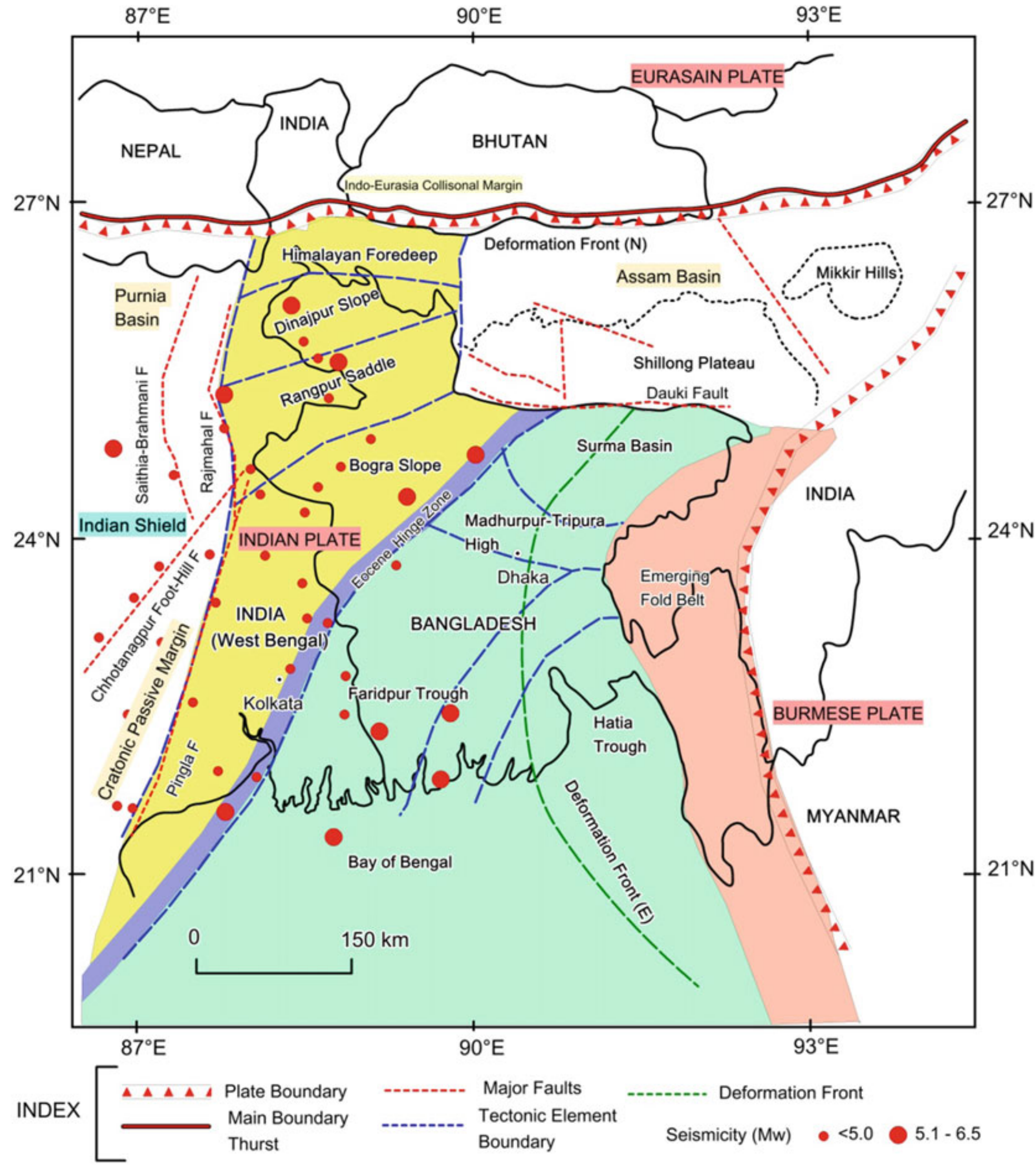


Fig. 23.4 Tectonic elements and divisions of the Bengal Basin with plate boundary, major faults, thrust and seismic events ($M_w > 4.3$) (modified considering Mukherjee et al. 2009; Hossain et al. 2020; Singh et al. 2020)

the Bengal Basin is marked by two interesting features: (1) a series of basement ridges buried under the alluvium bordering the eastern margin of the Precambrian shield area and (2) a series of normal faults and fault-line scarps along the eastern margin of this zone of shallow basement ridges (Sengupta 1966).

23.4.1.2 Bouguer Anomaly

Bouguer anomalies are most sensitive to the mass distributions and hence are influenced by the nature of underlying geological formations. In areas underlain by masses with relatively higher density, Bouguer anomalies are reflected as gravity highs and vice versa (Verma 1985). Bouguer anomalies are negative over elevated areas, showing inverse relationship to topography, i.e. higher the elevation, more negative is the Bouger anomaly. The negative values under elevated areas, therefore, give indirect evidence in support of the root formation. To the east of Singhbhum and Hazaribagh region significant low Bouger anomaly is attributable to large thickness of Tertiary to Quaternary sediments of the Bengal Basin (Verma 1985). The Bouger anomaly map of the Raniganj coalfield shows that the central part of the Gondwana basin is oval shaped. The deepest part of the basin is located few km southwest of Asansol and has a residual anomaly of −32 mgal (Verma 1985; Kayal 2008). Southern part of this coalfield is bounded by a steeply dipping fault (Southern Boundary Fault) and it appears that faulting in the basement is mostly responsible for deposition of sediments in the Bengal Basin. Central Indian Tectonic Zone (CITZ) may have played a role in the postulated collapse of the crust south of the Shillong Plateau, following the outpouring of the Rajmahal lava flows, and in the development of the E-W down-basin faulting in this area (Das Gupta and Mukherjee 2006). Its impact on the West Bengal Shelf is marked by the presence of a depression zone with a monoclonal terrace (viz., Radha Monocline, Baidyapur Depression and Contai Monocline) each to its north and south. From the presence of a number of important riverine alignments, some of these faults may be mid active even to this day (Das Gupta and Mukherjee 2006). The shelf zone is occupied by a wide NNE-SSW gravity low, reflecting structural high or depressions underlying the basin (Reddy et al. 1993; De et al. 1994; Roy and Chatterjee 2015). The most easterly of the alignments links the N-S stretch of the Jalangi River with similar stretches of the Hooghly River Shantipur to Kolkata.

Seismic refraction studies indicated that the alluvium in the Birbhum and Purba-Paschim Barddhaman areas directly overlies the Gondwana sediments and/or Archaeans. In the north of Durgapur the maximum thickness of Gondwana sediments in the extended Raniganj is of the order of 2.8 km. In this area surveyed by De et al. (1994), Bouguer anomaly values range from + 40 mgal in the north of Illambazar to −35 mgal in the east of Bolgona (Fig. 23.5). The ESE-WNW trending gravity low takes a turn towards south near panagarh and continues up to southwest of Bishnupur forming three isolated lows (of the order of −10 mgal) near Sonamukhi, Layakbandh and Bishnupur (in between Basin Margin Fault and Pingla Fault). These gravity lows and crowding are found over the Tertiary sediments in the marginal zone of the Bengal Basin geosynclines, where the thickness of Tertiary columns is expected to about 200 m and is affected by the underlying basement faults. Then, the gravity high structure (from Siuri to Bishnpur) occurs over the shelf zone of the Bengal Basin, reflecting a series of buried basement ridges, aligned NNE – SSW under thick alluvium (De et al. 1994). There is a continuous fall of gravity values over the Bengal Basin shelf province, identified as two prominent lineaments—the marginal zone and fault scarp zone of the Bengal Basin. This fault scarp zone is characterized by a series of normal, down-to-basin, en echelon faults (Basin Margin Fault, Pingla Fault and Garhmayna-Khandaghosh Fault) limiting the western boundary of the Bengal Basin. Faulting probably has occurred at different times during the accumulation of huge thickness of Tertiary sediments of West Bengal (Sengupta 1966).

23.4.1.3 Pattern of Earthquakes

Seismological data of the events that took place in the Bengal Basin during 1918–1989 have revealed an increased frequency of earthquakes in the last 30 years (Khan and Chouhan 1996). The increase in seismic activity is an indication of fresh tectonic activity or propagation of fractures from the adjacent seismic zones (Khan and Chouhan 1996). The Bengal Basin is located at a junction point of the three lithospheric plates viz. the Indian Plate, The Eurasian Plate and the Burma Plate posing high seismic susceptibility in the region. The major earthquakes, that have been affected the Bengal Basin since nineteenth century, are as follows: (1) Cachar earthquake M_W 7.5 (10 January 1869), (2) Bengal

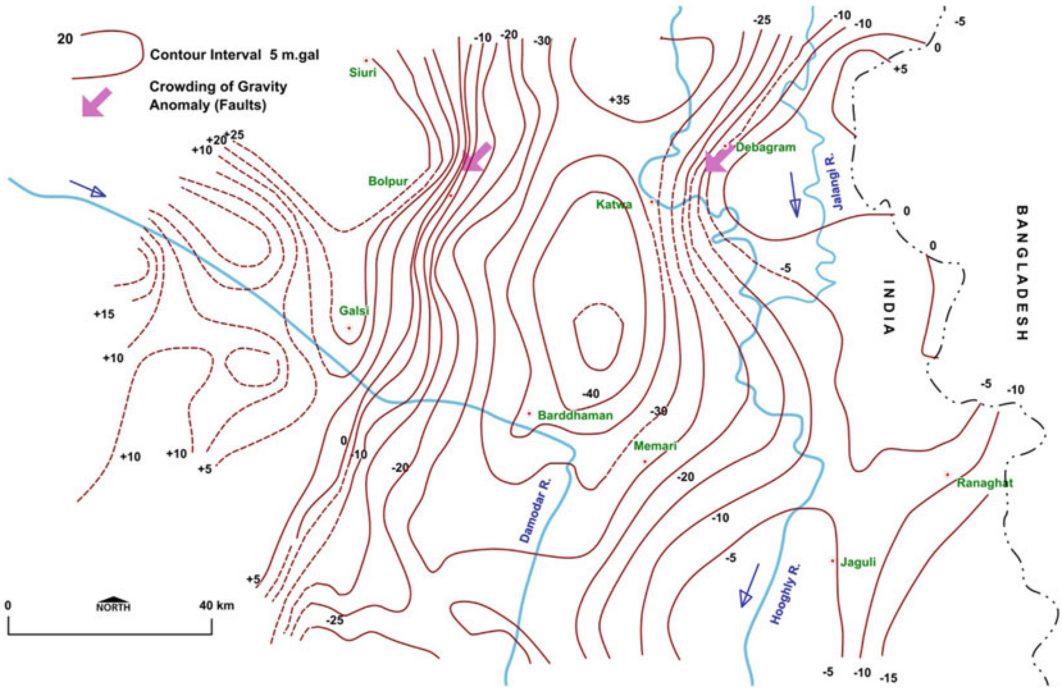


Fig. 23.5 The trend of Bouguer anomaly (interval 5 mgal) in the western part of the Bengal Basin, showing crowding of contours coincided with faults (modified from Das Gupta and Mukherjee 2006; Roy and Chatterjee 2015)

earthquake M_W 7.0 (14 July 1885), (3) Great Assam earthquake M_W 8.7 (12 July 1897), (4) Srimangal earthquake M_W 7.6 (8 July 1918), (5) Dhubri earthquake M_W 7.1 (3 July 1930), (6) Bihar-Nepal earthquake M_W 8.3 (15 January 1934) and (7) Assam earthquake M_W 8.4 (15 August 1950) (Khan and Chouhan 1996). The state of West Bengal has recorded a history of earthquake activity dating back to the past three centuries. Most of the earthquakes occur in Himalayan ranges in the northern part of the state or deep earthquakes within the Bengal Basin. The seismic hazard zonation map published by the Bureau of Indian Standard has classified the whole Indian Territory into four zones (zone II to V), and megacity Kolkata falls in the boundary of zones III and IV, indicating high seismic risk (Govindaraju and Bhattacharya 2012).

Many scholars assume that the shelf zone of the Bengal Basin is stable, but the sediments below the surface are the contributing factor in the ground failure and are capable of amplifying the ground motion, thus enhancing the hazard potential during a strong earthquake (Nath et al. 2015). The 1737 Kolkata earthquake, the 1885 Bengal earthquake of Mw 6.8, the 1897 Shillong earthquake of M_w 8.1, the 1918 Srimangal earthquake of M_w 7.6, the 1934 Bihar-Nepal earthquake of M_w 8.1, the 1935 Pabna earthquake of M_w 6.2 and the 1964 Sagar Islan earthquake of M_w 5.4 caused widespread damage in the Kolkata City and its surroundings (Nath et al. 2015). Magnitude measures the energy released at the source of the earthquake and intensity measures the strength of shaking produced by the earthquake at a certain location. A way to measure the size of an earthquake is to compute how much energy is released. The amount of energy radiated by an earthquake is a measure of the potential for damage to man-made structures using the empirical equation, $E = 10^{1.5Mw + 4.8}$ (where E is energy released in joule) (Fig. 23.6). The magnitude scale portrays energy logarithmically to approximately base 32. For example, a magnitude 6.0 earthquake releases about 32 times as much energy as magnitude 5.0

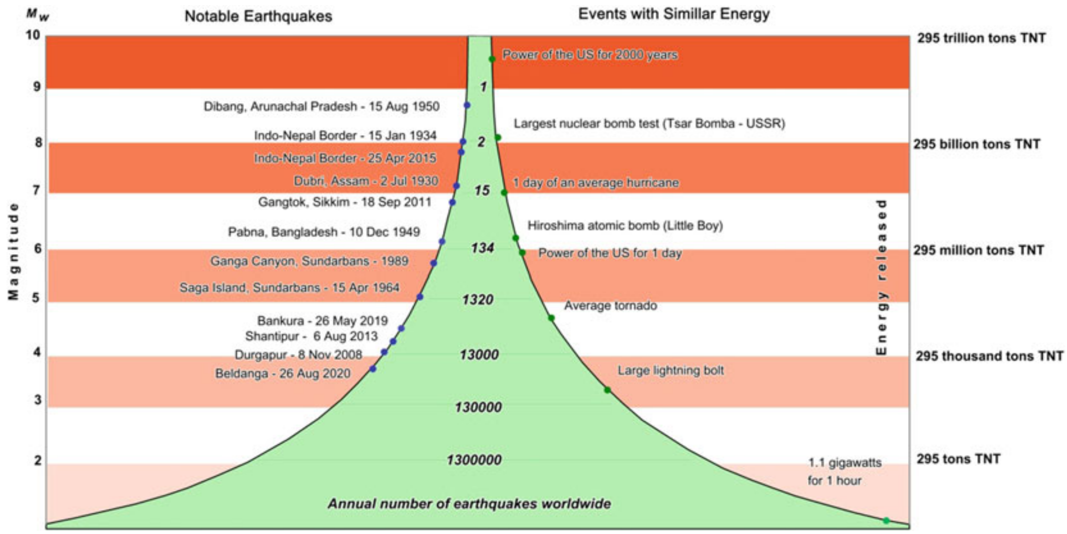


Fig. 23.6 Earthquake magnitudes of the Bengal Basin and energy release (comparing with TNT explosion) and comparison with other natural and man-made events (diagram source USGS earthquake public domain)

earthquake. The table of notable earthquakes is presented here with magnitude, energy equivalent and energy release (Table 23.4). The recent recurrent earthquakes of $M_w > 4.0$ depict that these events are evidence of active tectonics under the thick alluvium of the Bengal Basin and either the GBM delta itself or the substructure of hard strata underlying the Bengal Basin still has the capability of generating occasional earthquakes.

Recently, a mild tremor shook the Bengal Basin region when a shallow-depth earthquake of M_w 4.9 (hypocentral distance 130 km) with epicentre at 23.47° N, 87.12° E (near Bankura town) struck at 11:40 a.m. local time on 6 February, 2008 (Raj et al. 2008). Approximately 2 years ago, an earthquake of M_w 4.0 (hypocentral distance 15 km) was also recorded on 13 December, 2005, with its epicentre located at 22.31° N, 87.64° E (nearer to PF) (Raj et al. 2008). While there is a perceptible vulnerability at least, a bigger earthquake occurs, the recent earthquakes indicate a neo-tectonic activity along the underlying seismogenic source. On 28 February, 2018, another earthquake of Mw 4.8 (hypocentral depth of 7 km) was triggered in the shelf zone of Bengal Basin, having epicentre at 22.6° N, 87.7° E (over PF) (Dey et al. 2019). Strong to moderate ground shaking was felt in the epicentral zone and in surrounding districts of East Midnapore, West Midnapore, Jhargram and Bankura. Again the moderate size of the earthquake was triggered between the PF (to west) and the GKF (to its east). Changes in the stress patterns within the continental interior flexural loading of the thick sediments along the basin margin can reactivate these faults, resulting in significant seismic hazard to nearby regions and cities. Occasional light-to-moderate intra-plate earthquakes have occurred in the past, beneath this region of the western Bengal Basin (Dey et al. 2019). Given the ~7 km focal depth of the earthquake, it originated on the east dipping Pingla Fault (PF). In general observation the nodal planes could be the fault plane, but the similarity in orientation of the NNW-SSE striking nodal plane with PF, suggest this to b the fault plane of this earthquake (Dey et al. 2019). That earthquake ruptured a segment of the Precambrian gneissic basement fault (~4 km^2 fault area) in contact with the eastward thickening sedimentary layer. It is found that that earthquake occurred in response to intra-plate stresses due to the N20°E motion of the Indian plate, and the E-W flexure of the basement due to sediment loading in the Bengal Basin (Dey et al. 2019).

Table 23.4 A summary of major earthquakes that occurred in the tectonic blocks of the Bengal Basin and estimation of earthquake energy magnitude equivalent during trigger

Sl. no	Date	Location	Earthquake Magnitude (M_w)	Energy equivalent to Kilo-watt-hour (kWh)	Compared release of energy during explosion of TNT (kg)
1	2 July 1930	Dhubri, Assam	7.1	808,532,532	1,338,260,744
2	15 January 1934	Indo-Nepal Border	8.0	15,984,442,704	26,457,008,613
3	21 March 1935	Pabna, Bagladesh	6.2	40,897,569	67,692,528.85
4	10 December 1949	Kishoreganj, Bangladesh	6.0	21,071,599	34,877,129
5	15 April 1964	Sagar Island, West Bengal	5.2	1,484,900	2,457,767
6	12 August 1969	Bankura, West Bengal	5.7	7,792,871	12,898,545
7	23 June 1980	Sundarbans, West Bengal	5.0	765,063	1,266,312
8	26 March 1981	Chingrakhali-Bhairabnagar	4.9	549,158	908,951
9	12 June 1989	Sundarbans, West Bengal	5.7	7,792,871	12,898,545
10	20 June, 2002	Jayachari-Rajshahi	5.1	1,065,853	1,764,171
11	20 October, 2003	Purulia	4.3	75,109	124,319
12	6 February, 2008	Beliator, Bankura	4.3	75,109	124,319
13	8 November, 2008	Durgapur	4.2	53,913	89,236
14	5 January, 2009	Bangaon	4.2	53,913	89,236
15	6 August, 2013	Shantipur	4.5	145,779	241,290
16	15 December, 2015	Chas, Jharkhand	4.1	38,698	64,053
17	28 August, 2018	Hooghly	4.7	282,942	468,317
18	28 July, 2019	Kenda, Jharkhand	4.1	38,698	64,053
19	8 April, 2020	Bankura, West Bengal	4.0	27,777	45,977
20	26 August, 2020	Beldanga, West Bengal	3.8	14,311	23,688

Note 1 kWh is equivalent to the energy of 1000 J used for 3600 s; TNT—Trinitrotoluene, $C_6H_2(NO_2)3CH_3$, equivalent is a convention for expressing energy, typically used to describe the energy released in an explosion or earthquakes

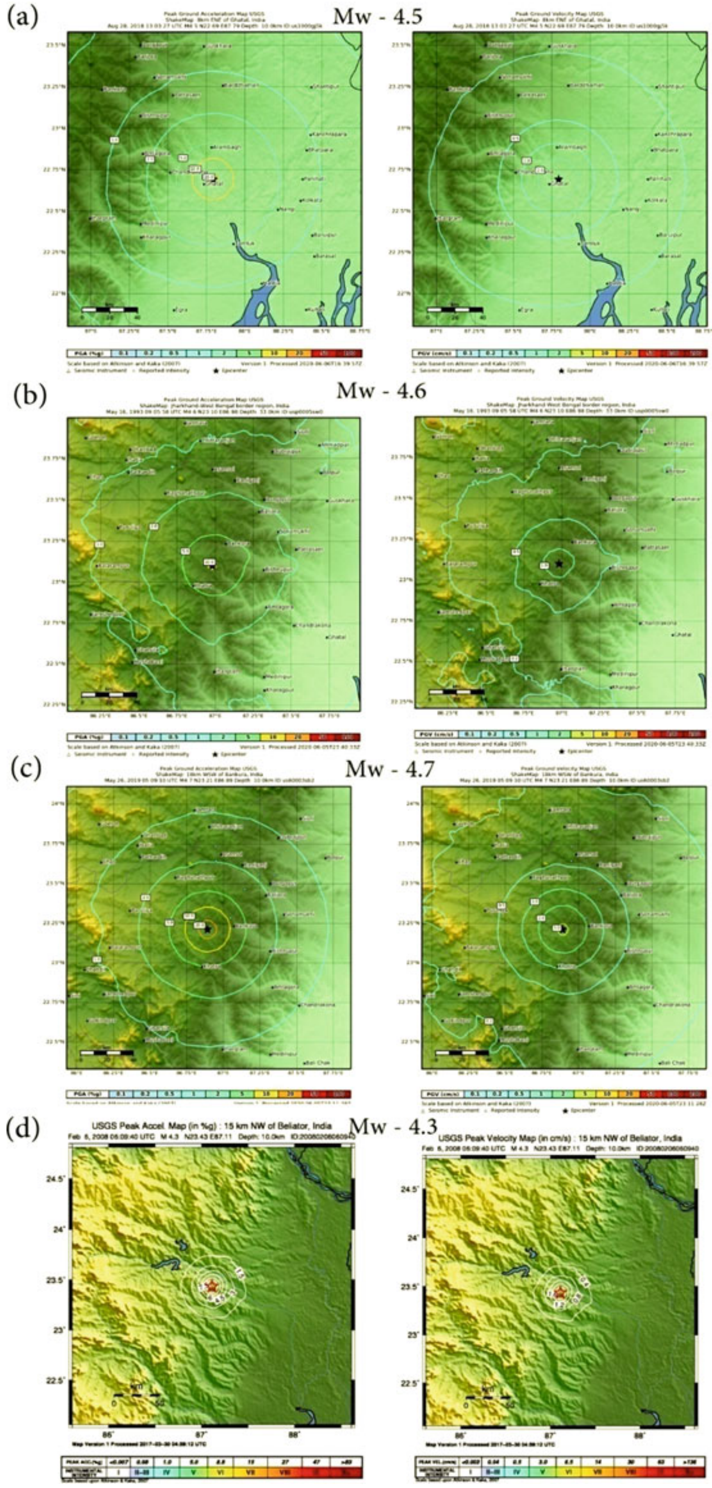
Steckler et al. (2016) estimated a potential earthquake of M_w 8.2–9.0 in the eastern part of Bengal Basin. The peak ground acceleration (PGA) and peak spectral acceleration (PSA) are estimated during those earthquakes by the USGS (United State Geological Survey), and the maps are presented in Fig. 23.7 to the observed spatial extension of earthquake shaking in the Bengal Basin.

23.4.1.4 Seismites

To explore the alluvial signatures of active tectonics, the geologists and geomorphologists are getting clues from the seismites which are principally fluvial sedimentary beds and structures deformed by seismic shaking. Seilacher (1969) first proposed the genetic term 'seismites' to interpret earthquakedeformed bed of soft-sediment deformation structures (SSDS). The genetic term 'seismites' have the following characteristics: these units differ from ordinary marine slides by the soupy top layer and by lack of a basal slip surface. It seems more plausible to connect them with seismic shocks acting on gently dipping muds in which compaction gradually increased down from the water–sediment interface (Shanmugam 2016). In this case, the sliding process may not have had time to develop fully so that deformational structure became 'frozen' in an embryonic stage, without resulting in a major lateral transport (Shanmugam 2016). Depending on mud consistency and paleoslope, as well as strength, duration and type of the shock, quite different structures may result. In perfectly horizontal mud layers, or under weaker shocks, for instance, nothing but the liquefied zone would form. The standard vertical alluvial sequences for seismites composed of the following four division: (a) soupy zone (top), (b) rubble zone, (c) segmented zone and (d) undisturbed sediment (bottom) (Seilacher 1969; Suter et al. 2010; Shanmugam 2016). SSDS as water-escape structures, aqueous environments being alluded to because it within these soft-sediment deformations chiefly raised by liquefaction, which involves a change of state from solid like to liquid like in cohesionless grain mass. The principal features of SSDS include load cast, imbricate structure, deformed cross-bedding, pseudonodule, convolute laminates and clastic dyke (Montenat et al. 2007; Suter et al. 2010).

The fluvial facies of floodplains have numerous layers of sandy silt or silty materials, which are the most sensitive sediments with contrasted granulometry, such as alternately homogenous fine sands or silts and argillaceous beds (Montenat et al. 2007). Various fluidization and fluid expulsion phenomena may occur independent of seismicity (e.g. over-pressure of fluid due to loading by sudden deposition of a thick depocenter; channel deposits; mud-or debris-flows etc.); water escapes often associated with gravity deposits, generating convoluted beds (turbiditic sediments). To investigate SSDS, the Quaternary alluvial sections of the Damodar River are taken into consideration. From Rhondia (23°22′ 19″ N, 87°28′ 41″ E) to Palla (23° 09′ 47′′ N, 87° 59′ 57″ E), majority of the field evidences were collected and, in these stretch of river valley, the imprints of tectonic activity are indicated by sand dykes, independent mounds, load casts and deformed beds of clay or sandy-silt (Fig. 23.8). A well-preserved sand dyke and sill horizon was observed within a section of Quaternary lithofacies, exposed near Tirat-Harabhanga village (23° 36′ 45″ N, 87° 03′ 33″ E). The feature was observed at the base of >5 m thick section consisting of semi-compact sandy-clay and clay horizon (F_{cl}). The horizon shows the intrusion of the overlying host sandy clay section by sand dykes and sills (1–5 cm width) in varied directions. The sand dykes are water escape structure formed by vertical shear stress during earthquakes. The litho-section (>4 m depth) of Haripur village (23° 10′ 31″ N, 87° 48′ 24″ E) unveiled a very well-preserved seismites section in the study area. The Haripur seismites section with a total thickness of approximately 1 m consists of undeformed clay silt layer at the base. The undeformed clay-silt (F_m) layer is overlain by an enormously deformed clay-silt layer (5 – 30 cm). The sand silt layers at the periphery of this layer are partially oxidized and these too are variably deformed. The deformation within the layer has been observed in the form of crumbled, churned, sometimes detached, contorted, overturned and intricate folded bands of

Fig. 23.7 A series of thematic maps showing peak ground acceleration and peak velocity observed during shallow-focus earthquakes in western part of the Bengal Basin: **a** M_w 4.5 (near Ghatal on 28 August, 2018), **b** M_w 4.6 (near Bankura on 16 May 1993), **c** M_w 4.7 (near Bankura 26 May, 2019) and **d** M_w 4.3 (near Beliator 6 February, 2008) (maps derived from USGS earthquake public domain)



clay-silt and fine sand. This deformed layer is again overlain by a thin deformed layer of clay-silt and fine sand approximately 30–40 cm above the previous deformed layer.

The Bhaluksundha (23° 35′ 08″ N, 87° 11′ 05″ E) Quaternary section (>4 m depth) shows yet another type of seismites exposure in the left bank of Damodar. A twisted medium sand dyke intrudes into silty clay horizon along with prominent number of small horizon. Seismites section exposed near Satyanandapur shows a deformed and disrupted clay-silt layer overlain by undeformed sand layer. Lobate discontinuous structures are observed within the deformed layer. Section exposed near Kamalpur area (23° 07′ 55″ N, 88° 00′ 34″ E) displays intricately overturned and folded unconsolidated sand layers. The glimpses of small-scale load structures are formed due to gravitationally unstable density gradient during earthquakes and overloading. Additionally, small-scale slump structures and multiple deformed laminations are formed also by gravitational body force during earthquake. A similar SSDS was observed in Idilpur (23° 13′ 28″ N, 87° 49′ 42″ E), at left bank of Damodar, displaying deformed lamination of lower clay-silt layer and underlain by deformed sand layers. The deformed and folded unconsolidated sandy-silt layers and gravels of various litho-sections suggest profound control of active tectonics on the sedimentary structures of Damodar River Valley (Fig. 23.9).

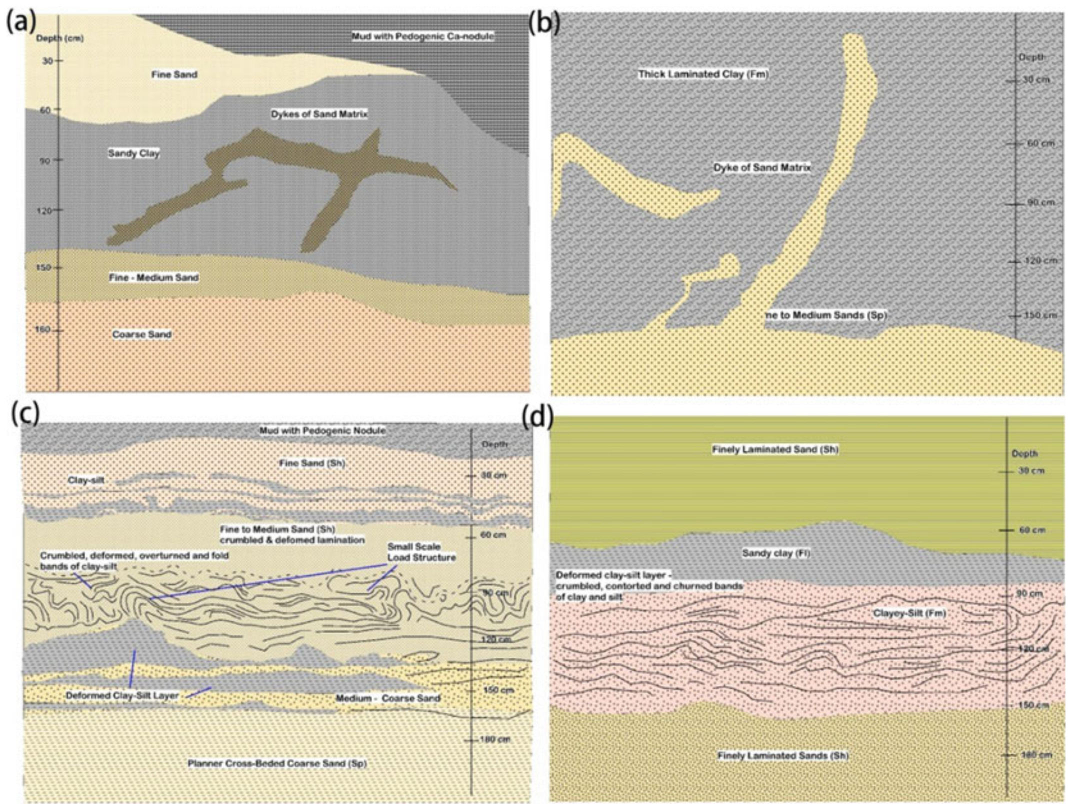


Fig. 23.8 Soft-sediment deformation structures and seismites in Quaternary sections: **a** intrusion of sand dykes in sandy clay (F_{cl}) deposits in varied directions at Tirat-Harabhanga, **b** elongated sand dykes intruded in thick laminated clay-silt deposits (F_m) at Haripur, **c** glimpses of deformed clay layers and small scale load structures formed due to gravitationally unstable density gradient at Kamalpur and **d** glimpse of deformed, overtuned and folded unconsolidated clayey silt and sand layers at Idilpur

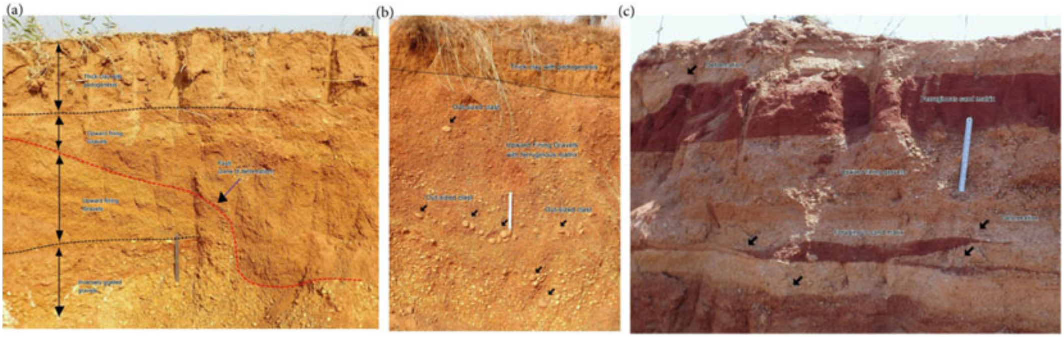


Fig. 23.9 Tertiary sediment deformation structures at Hetodoba, Durgapur: **a** deformation and warping of gravel lithofacies and a trace of fault along deformation, **b** occurrence of out-sized clasts in upward finding gravel facies due to seismic shock, and **c** deformation of ferruginous sandy matrix in litho-section of gravels (length of scale 30 cm)

23.4.2 Standard Sinuosity Index

Understanding the syntectonic modification of river systems is one of key assessments in tectonic geomorphology. The fluvial system is very sensitive element of earth surface and a large magnitude of earthquake either ruptures or deforms the surface, or when ground shaking modifies the fluvial forms and processes. Achievement of 'grade' means that a tectonically induced change in an alluvial river can induce changes in other characteristics of the system. Like the longitudinal profiles, local anomalies in channel character can result from the variations in lithology, geological structure, hydrology and so on, but such anomalies can also result from tectonic activity. To understand the tectonic adjustment of river between faults (mainly Basin Margin Fault, Pingla Fault and Garhmayna-Khadaghosh Fault), the geomorphic index of Standard Sinuosity Index (Mueller 1968) is used in the selected stretch of the peninsular rivers. Meandering nature of the river is occurred to maintain a channel slope (minimum expenditure of energy) in equilibrium with discharge and sediment load. As channel slope is controlled by the tectonic deformation, so the variation of meander growth and sinuosity is very obvious in the active floodplains. A river meanders when the straight-line slope of the valley is too steep for equilibrium—the sinuous path of the meander reduces the slope of channel. Any tectonic deformation that changes the slope of a river valley may result in a corresponding change in sinuosity to maintain the equilibrium channel slope (Keller and Pinter 2002). In many cases, it is found that where meandering rivers cross tectonic upwraps, they tend to be less sinuous on the upstream flank and more sinuous on the downstream flank.

The Brahmani River shows very straight course of channel (less sinuous) due to the effect of Rajmahal Fault (RF). Upstream of RF, the SSI is estimated about 1.109 and it reduces to 1.075 at downstream of RF (Fig. 23.10). The hydraulic sinuosity index (HSI) varies from 47.33 to 57.97%, whereas topographic sinuosity (TSI) index reduces from 52.67 to 42.03%. The upstream course of Dwarka River is guided by the Saithia-Brahmani Fault (SBF) along the Gondwana Basin and Rajmahal Basalt Traps (North West–South East orientation of lineament). SSI shows a low value of 1.029, signifying a straight course of tectonic control (TSI—90.24%). While downstream of SBF, SSI increases to 1.123, reflecting hydraulic dominance on sinuosity (HSI—52.67%). The channel reaches of Mayurakshi River between SBF and GKF (Tilpara Barrage to Gunur) shows straighter course (SSI—1.026 to 1.085) due to tectonic control on river. The topographic control on river sinuosity is well proved by high TSI (>73%).

Similarly, the geotectonic system of BSM, PF and GKF has profound impact on channel

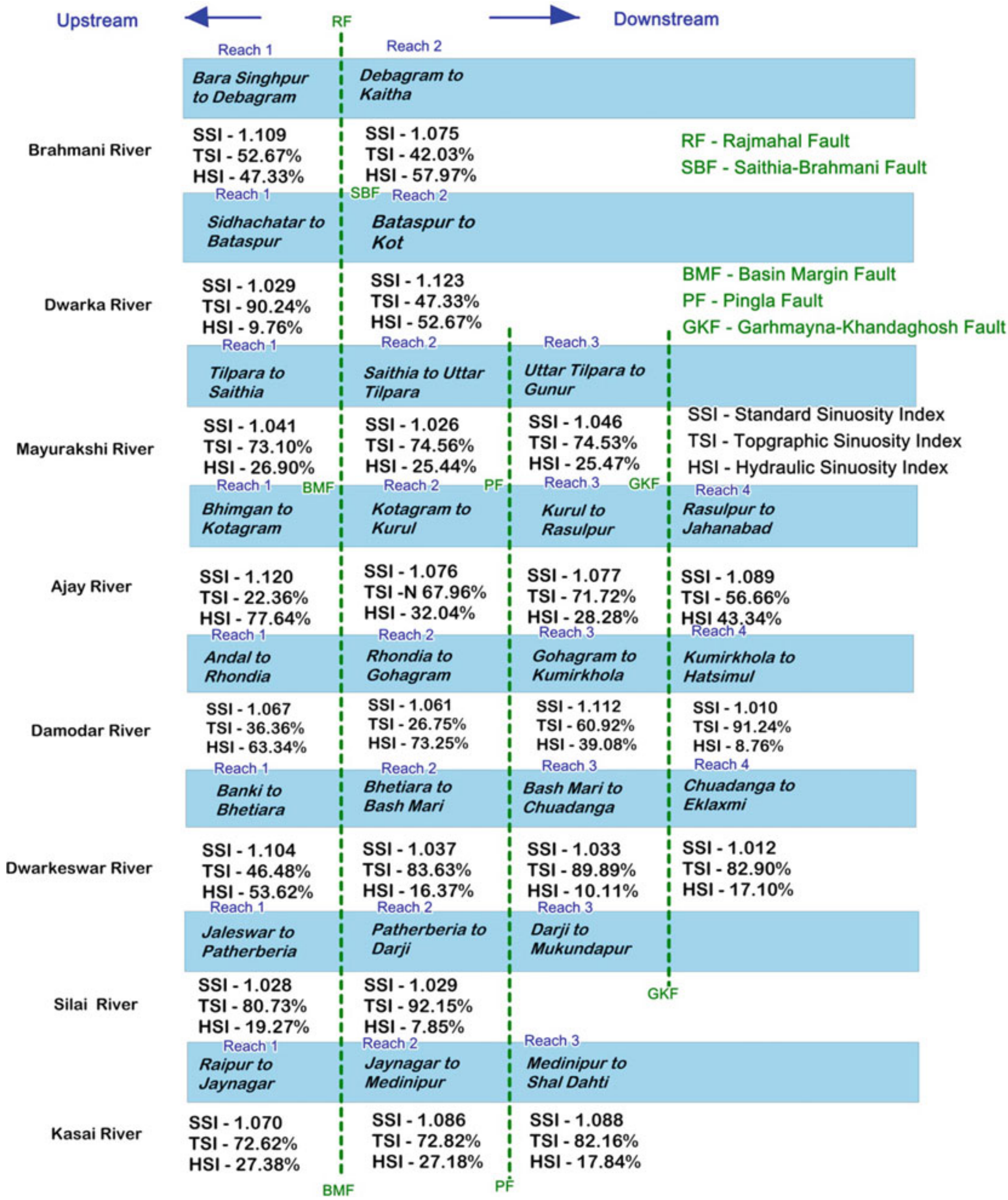


Fig. 23.10 Comparing standard sinuosity index (SSI), topographic sinuosity index (TSI) and hydraulic sinuosity index (HSI) in the alluvial rivers in response to Rajmahal Fault (RF), Saithia-Brahmani Fault (SBF), Basin Margin Fault (BMF), Pingla Fault (PF) and Garhmayna-Khandaghosh Fault (GKF)

sinuosity of Ajay River, showing channel deflection and straightness (Fig. 23.11a). SSI varies from 1.120 to 1.089 at downstream end. Upstream of CF the sinuosity is controlled by hydraulic variables, which reflect in high HSI (77.64%). Downstream of CF, the sinuosity is adjusted by topographic control, as reflected in TSI (56.66–71.72%). The reach between PF and GKF shows more straightness than other reaches (SSI < 1.076). The Damodar River shows prominent deflection of channel course across the faults, maintaining straight alluvial channel (SSI—1.067 to 1.112). The reaches between BMF and PF show more hydraulic control than topographic control, as reflected in HSI greater than 63.64%. While the downstream of PF and GKF (Gohagram to Barddhaman), the sinuosity decreases from 1.112 to 1.010 due to tectonic control (TSI—60.92 to 91.24) (Fig. 23.11b). In this reach, the development of several fluvial terraces, incision, channel narrowness and faults is observed. The channel reach of Dwarkeswar River, between Banki to Eklaxmi, does not show any considerable variation of SSI (1.104–1.012). It may be the resultant effect of BMF, PF and GKF, maintaining a straight course (Fig. 23.11 c). The TSI is estimated as 46.48% at upstream of BMF, but it increases considerably and reaches up to 89.89% at downstream. Similar tectonic control on channel sinuosity is well traced in Silai and Kasai River as well. SSI of Silai River (Jaleswar—Patharberia—Darji) is estimated as 1.028 due to effect of BMF and numerous lineaments, showing very high value of TSI (80.73–92.15%). Very less hydraulic control on sinuosity is observed in Kasai River and SSI varies from only 1.070 to 1.088. Downstream of BMF, TSI increases from 42.03 to 82.16%, marinating a straight course of channel across the terraces of laterites and gravels.

23.4.3 Stream Length—Gradient Index

The Stream Length—Gradient Index (S_L) correlates to stream power. Total stream power available at a particular reach of channel is an important hydrologic variable because it is related to the ability of a stream to erode its bed and transport variable because it is related to the ability of a stream to erode its bed and transport sediment. Total or available stream power is proportional to the product of the slope of the water surface and discharge. The slope of the water surface generally is approximated by the slope of the channel bed, and there is a good correlation between total channel length upstream and bankfull discharge which is thought to be important in forming and maintain rivers (Keller and Pinter 2002). Variations in S_L index reflect the downstream variations in discharge and stream power, but more commonly the lithologic or tectonic controls on channel slope of a given reach. S_L index has been widely applied as proxy to identify areas of anomalous uplift within a landscape. In this study, the reaches of peninsular alluvial rivers (mainly west to east flowing Kasai, Siliar, Damodar, Khari, Ajay, Dwarka and Brahmani Rivers) across or along the Basin Margin Fault (BMF), Pingla Fault (PF), Garhmayna—Khandaghosh Fault (GKF), Saithia—Brahmani Fault (SBF) and Rajmahal Fault (RF) are considered for S_L index analysis and long-profiles.

In the region of Bankura and Paschim Medinipur districts, the fluvial system of Silai and Kasai Rivers has developed well-integrated drainage network and badlands over Quaternary laterites and floodplain alluviums, showing glimpses of fluvial anomalies in channel planform (e.g. more towards straight than meander) and drainage pattern (e.g. annular growth due to tectonic bulge). In this region, the tectonic control of BMF and PF is well traced in the channels and topographic irregularities. The mean channel slope or gradient (S_c) of Silai River varies from 0.00532 to 0.00007 m m^{-1} within the stretch of 64.2 km. In this stretch, the elevation of channel bed varies from 341.96 to 31.18 m and the index values of S_L range between 210.91 and 27.71 m. Across the BMF, the S_L shows high value, i.e. 115.19 to 341.96, which is the reflection of topographic control on high channel gradient. The trace of micro convexity is observed in the long profile curve of river, showing the effect of neo-tectonic uplift. BMF and lineaments have profound impact on the enrichment of kinetic flow energy of incision and low entropy of fluvial system (as regain of power due to uplift). In that stretch of Silai River, maximum concentration of gullies and badlands (at Bagnada and Ganagani) is recognized, showing progressive erosion of relief. Between BMF and PF, the River maintains low energy profile (S_L—27.71 to 42.20 m) with

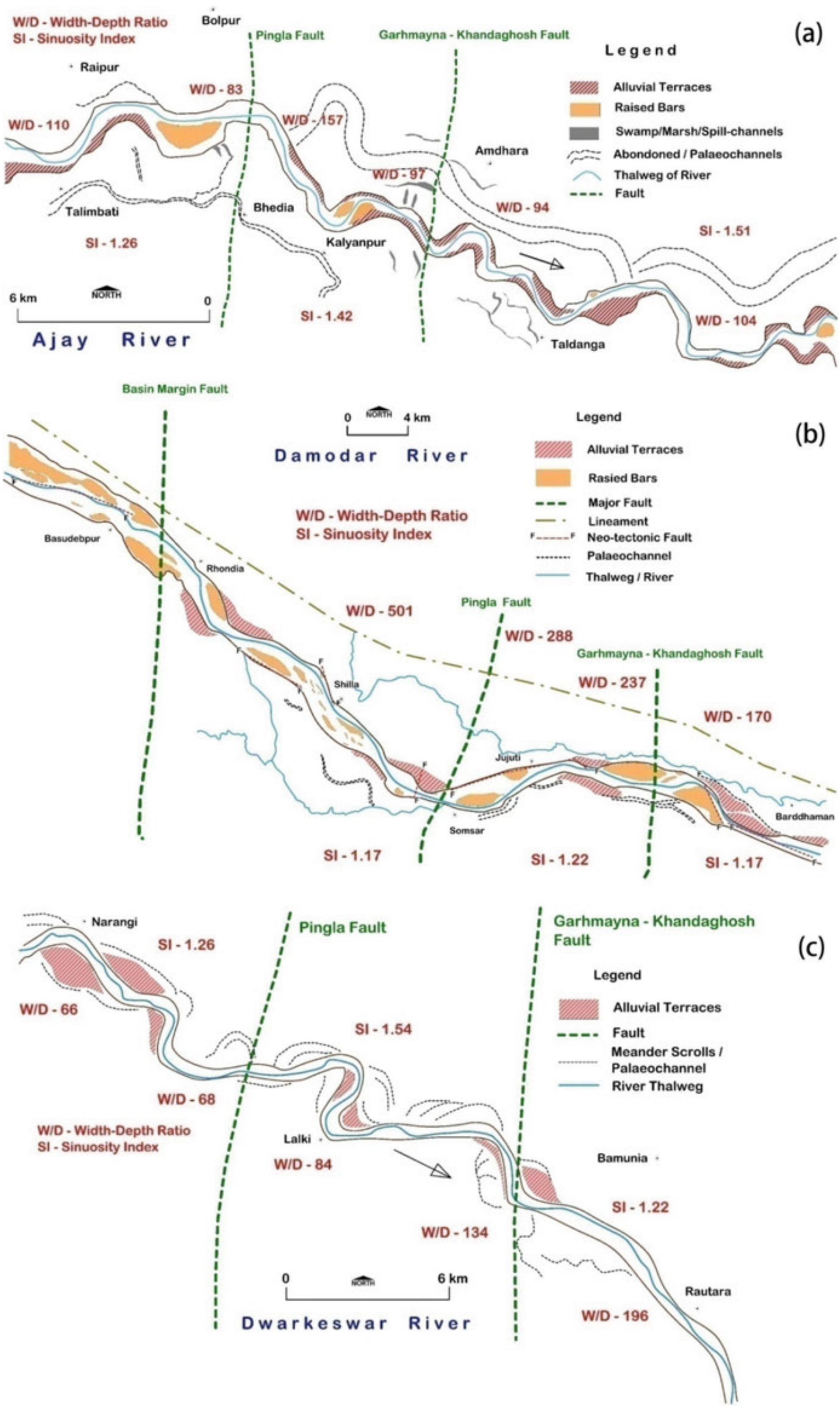


Fig. 23.11 Fluvial responses (viz., width-depth ratio, sinuosity index, alluvial terrace, channel shifting, palaeochannels etc.) to active tectonics across Basin Margin Fault, Pingla Fault and Garhmayna-Khandaghosh Fault in **a** Ajay River, **b** Damdoar River and **c** Dwarkeswar River

ample aggradations (downstream of fault) and valley widening.

Accordingly, Kasai River shows the same kind of signatures, having mean S_c variation of 0.00277 to 0.00058 m m^{-1} within a stretch of 99.2 km. The elevation of channel bed decreases from 136.47 m to 67.86 m and S_L varies from 275.16 to 21.06 m. In the upstream of BMF, the Kasai River is flowing over the Precambrian crystalline complex and Tertiary formations, adjusting the channel profile with underlying geology (Fig. 23.12). Within first 14 km stretch of study reach, the major lineament controls the steep channel gradient, as suggested from high S_L of 147–275 m. Between BMF and PF, the curve of S_L shows four distinct pulse ($S_L > 100$) and convexity of long profile is traced at the locations as a result of occasional channel cut-and-fill sequences (a sign of quasi-equilibrium). The variable change of slope and bed elevation may be the resultant effect of neo-tectonic bulge between BMF and PF. Similar effect is observed in the sub-basins of Silai and Kasai Rivers. Purundar River (a tributary source of Silai) is controlled by a major lineament over laterites, as reflected from high S_L ($S_L > 150$ m). The convexity of profile is well traced in the long profile, showing frequent pulse of S_L towards downstream (S_c variation of 0.00925–0.00007 m m^{-1}). Accordingly, the Tamal River (a tributary source of Kasai) shows bed elevation variation of 78.449–19.84 m within a stretch of 44 km and the index values of S_L decreases from 205.47 to 17.45 m in that stretch. The upstream shows frequent S_L pulse ($S_L > 70$ m) profile convexity and low entropy channel gradient. This river is local base level controlled, showing frequent sign of incision and deposition.

Leaving the sedimentary formations of Gondwana the Damodar River shows considerable variation of channel slope and planform in between Durgapur and Barddhaman (a stretch of 153 km). The mean bed elevation drops from 104.79 to 27.115 m, and S_c varies from 0.00109 to 0.00036 m m^{-1}. Throughout the long profile, S_L index shows frequent high amplitude pulses ($S_L > 100$ m) and profile convexity due to effect of faulting (Fig. 23.13). The reach between BMF and PF shows two separate convexities in long profile, as reflected in S_L of 52.55–110.49 m. There is a considerable increase in channel gradient (0.00033–0.00072 mm^{-1}) between Panagarh and Gohagram. In upstream of GKF, there are considerable topographic expressions (e.g. palaeochannels, raised bars, swamps and abandoned channels) of floodplain subsidence. The subsidence is reflected in low value of S_L, viz., below 50 m. Below GKF, the channel gradient is suddenly increased and convexity of bed elevation profile is clearly visible. It reflects low entropy, high fluvial incision and sudden trigger of high energy due to upliftment along GKF. S_L increases up to 136 m and reduces to 55 m at the vicinity of Barddhaman town. This stretch of Damodar (between Somsar and Belkash) shows increasing straightness of channel ($S_I < 1.1$), unparallel alluvial terraces, narrowness of thalweg and traces of Quaternary faults along the river banks.

Similarly, the tectonic effect of BMF, PF and GKF is observed in the Ajay River, and there is a noticeable variation of S_L (174.91–27.97 m). Five distinct S_L pulses are recognized between BMF and PF, and the convexity of long profile is clearly visible in three parts (Fig. 23.13). These anomalies of channel gradient and stream power are the reflection of tectonic deformation due to these faults. The stretch between PF and GKF shows considerable variation of cut-and-fill sequences, incision of bed (exposure of underlying laterites at Illambazar—Panagarh Bridge) and high energy gradient, forming alluvial terraces of laterite gravels and badlands in the Illambazar Formation. Below the GKF, the river floodplain shows high entropy (S_c variation of 0.00088 to 0.00034 m m^{-1}), subsidence and fluvial aggradations ($S_L < 60$ m), forming abandoned channels, spill channels, swamps, overbank flooding and southern lateral shifting, high sinuosity ($S_T > 1.2$) and raised channel bars. Something differently the Khari River (smaller than Ajay and Damodar) shows the feature of tortuosity, which is a channel property of a curve being tortuous (twisted having many turns) between PF and GKF (Fig. 23.14). It is found that S_L, across PF, shows high S_L ($S_L > 80$ m)

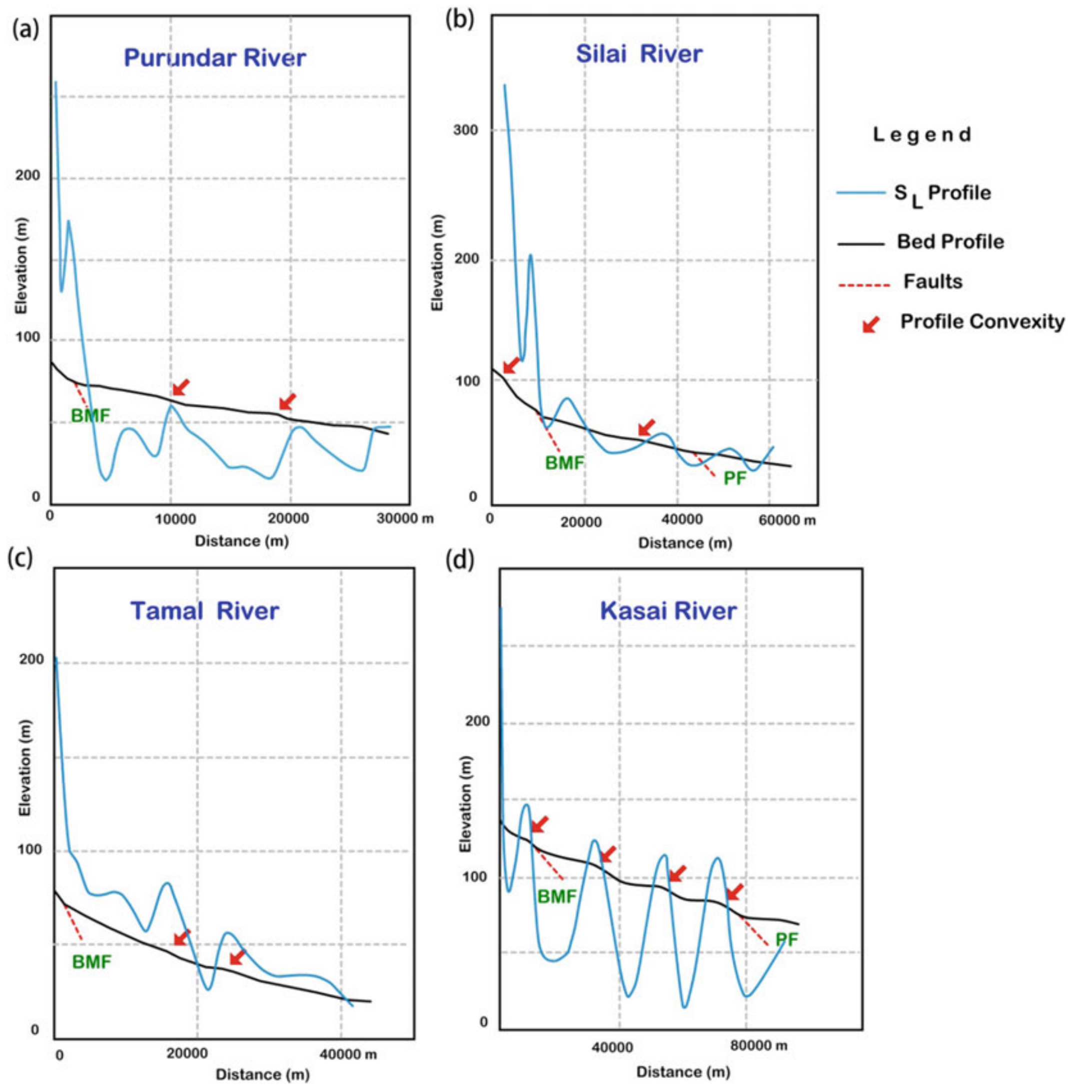


Fig. 23.12 Variations of longitudinal profiles (trace of convexity) and recurrent pulses of S_L values with the effect of Basin Margin Fault (BMF), Pingla Fault (PF) and Garhmayna—Khandaghosh Fault (GKF) in **a** Purundar River, **b** Silai River, **c** Tamal River and **d** Kasai River

and convexity in bed profile, showing the effect of topographic control on channel steep gradient. The development of meander neck-cutoff and numerous fluvial terraces of different topographic levels may be controlled by high fluvial energy (during peak monsoon flow) driven by tectonic uplift. Below GKF, there is a steady decrease of S_L (85–13 m) and the high entropy features of floodplain aggradations are quite prominent, as the development of abandoned channels, high sinuosity ($S_I > 2.0$) and overbank flooding (due to regional subsidence). A similar situation is also observed in Kunur River (Fig. 23.15).

The Dwarka River is flowing along the SBF, crossing the Rajmahal Basalt Traps and Gondwana Formation. The role of SBF is quite prominent, restricting the oscillation of river along a lineament (Fig. 23.16). The channel slope varies from 0.00335 to 00,027 m m^{-1} within the riverbed elevation range of 70.35–

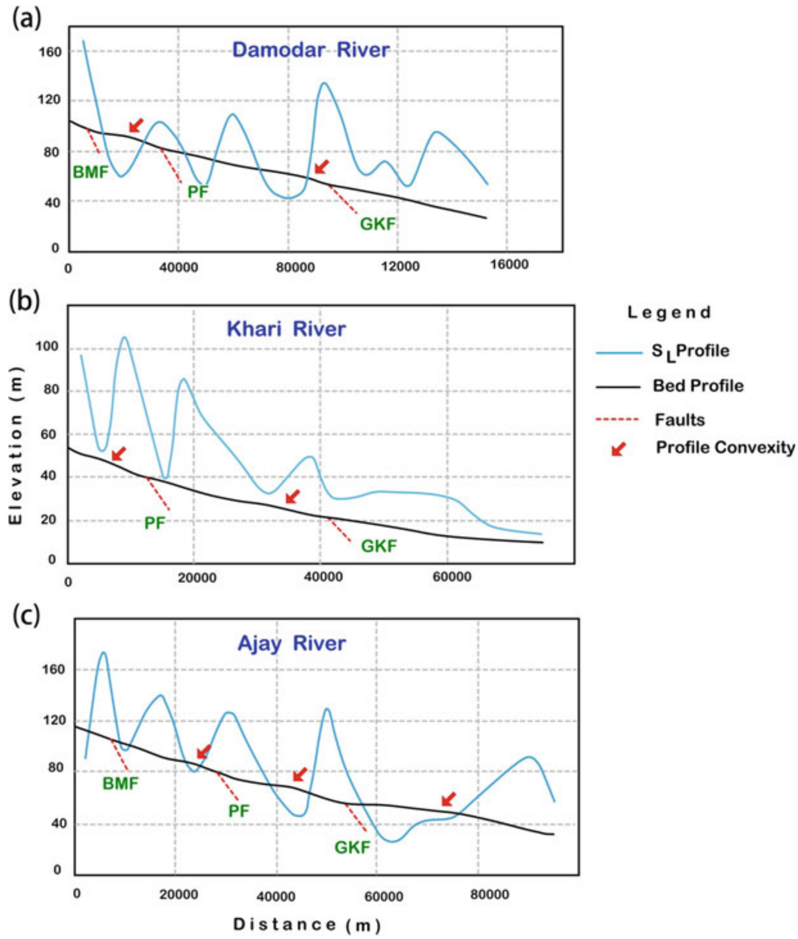


Fig. 23.13 Variations of longitudinal profiles and bed elevations (traces of convexity in relation to zone of deformation by faults) generating recurrent pulses of S_L values with the effect of faults in **a** Damodar River, **b** Khari River and **c** Ajay River

8.37 m. In the initial reach of 15 km yields S_L value of greater than 40 m and it increases up to 71 m. A distinct convexity of elevation profile is traced, reflecting the control of tectonic uplift on high channel gradient and generating several pulses of S_L and cut-and-fill sequences in the channel. The upstream degradation shows narrow and deep valley and alluvial terraces, and downstream degradation shows migrating meandering thalweg, valley widening and raised bars. The influence of basalt trap structure and RF is clearly observed in the Valley of Brahmani River, having S_L range of 354–47 m. The channel slope of Brahmani (bed elevation range of 126.11–46.74 m) reduces from 0.00931 to 0.00036 m m^{-1} within the stretch of 23 km. A prominent convexity, due to uplift along RF, is observed and is traced along the channel elevation profile. Due to this knick point effect, the index value of S_L escalates up to 354 m, indicating low entropy of fluvial system and high fluvial incision with development unparallel terraces. Below RF, the S_L reduces to less than 50 m, developing aggradational landforms, flooding, valley widening and raised channel bars.

23.4.4 Hypsometric Analysis

The distribution of the elevations within a basin provides information on the balance between external processes (which tend to lower the landscape) and internal processes (which tend to create relief). One of the most useful parameters that describes and analyzes the distribution of

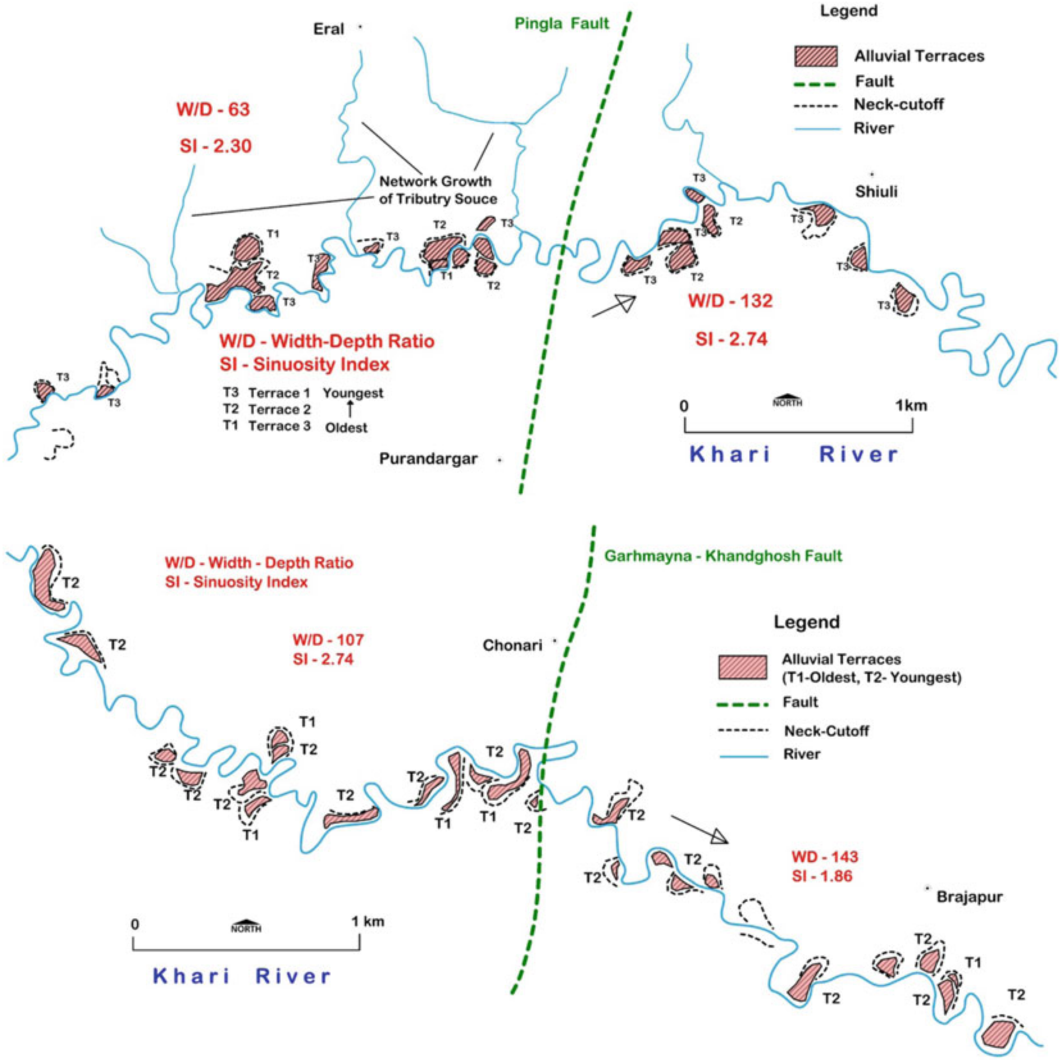


Fig. 23.14 Geomorphic map of Khari River showing upstream and downstream fluvial anomalies (mainly development of terraces and neck-cutoffs) in relation to Pingla and Garhmayna—Khandaghosh Faults

elevations in an area is hypsometry. Hypsometric integral (H_I), a dimensionless parameter, is proposed by Strahler (1952). The advantage of H_I is those users calculate and compare different sins of different areas irrespective of scale. Hypsometric analysis (or area-altitude analysis) is the study of the distribution of horizontal cross-sectional area of a landmass with respect to elevation. The index values of H_I have been used to differentiate between erosional landforms at different stages during their evolution. H_I is an indicator of the present volume as compared with the original volume of the basin. High H_I indicates that most of the topography is high relative to the mean representing a youthful topography stage (Keller and Pinter 2002). Intermediate to low H_I represents more evenly dissected drainage basin, indicating a mature stage of development.

Considering six sub-basins (elevation range of 177–32 m from mean sea level) of the Silai—Kasai drainage system, it is found that the index values of $H_{\rm I}$ increase from 0.362 to 0.558, with mean of 0.441 (Table 23.5). In addition, the hypsometric analysis of Bagnada and Gangani

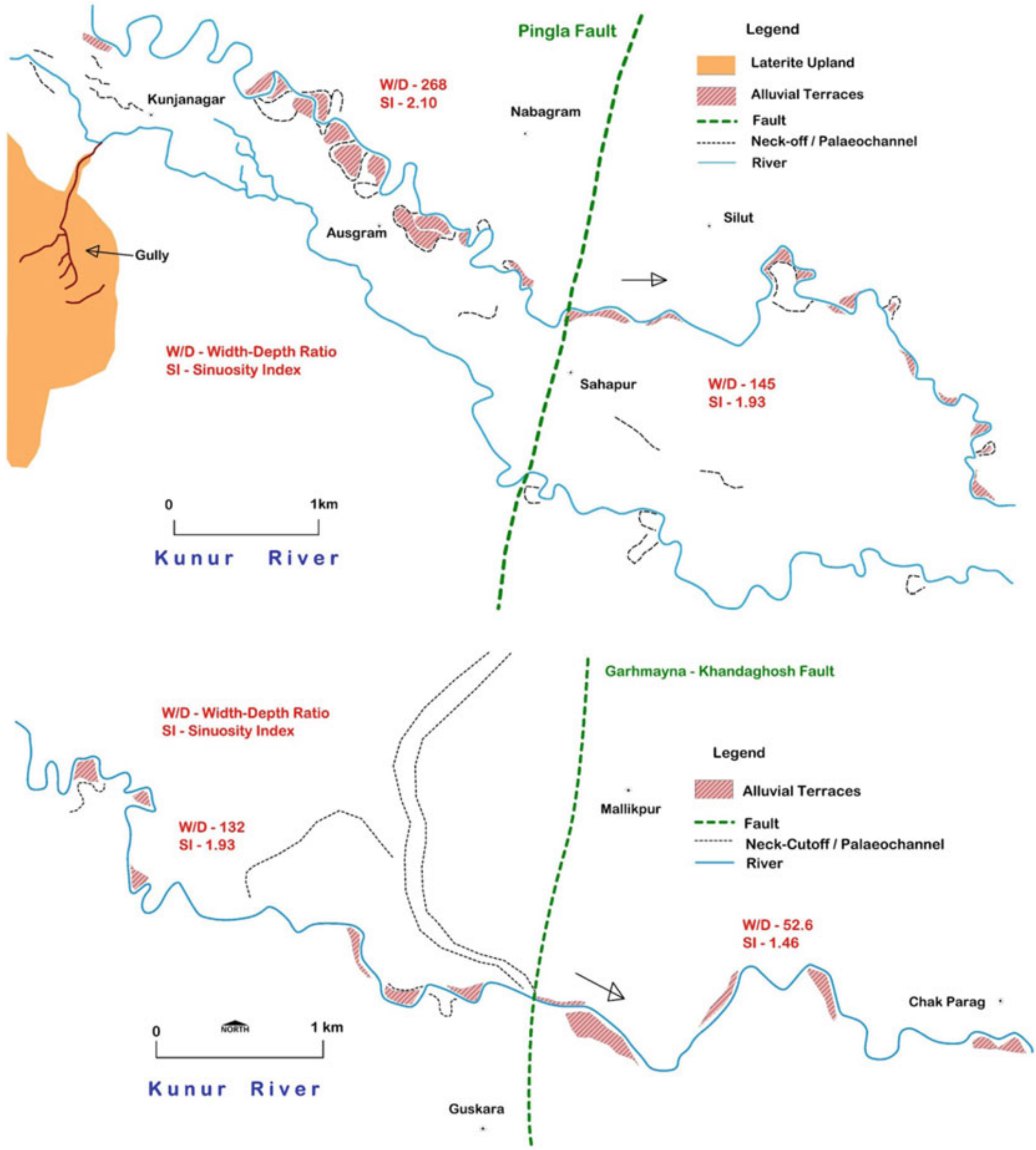


Fig. 23.15 Geomorphic map of Kunur River showing fluvial anomalies (upstream development of alluvial terraces and downstream decrease of sinuosity and width-depth ratio) and in connection with Pingla and Garhmayna—Khandaghosh Faults

badlands suggests relatively high values of H_I, ranging from 0.481 to 0.593. The three sub-basins (elevation range of 120–46 m from mean sea level) of the Dwarkeswar River show H_I range of 0.410–0.451, reflecting mature equilibrium stage of landform development. In the six sub-basins (elevation range of 165–44 m) of the Damodar—Ajay interfluves, H_I varies from 0.396 to 0.619, reflecting mature to youthful stage. The four sub-basins of the Mayurakshi River show H_I range of 0.434–0.480. Similarly in the four sub-basins of the Dwarka—Brahmani interfluves, the index values vary from 0.448 to 0.501, suggesting a mature stage.

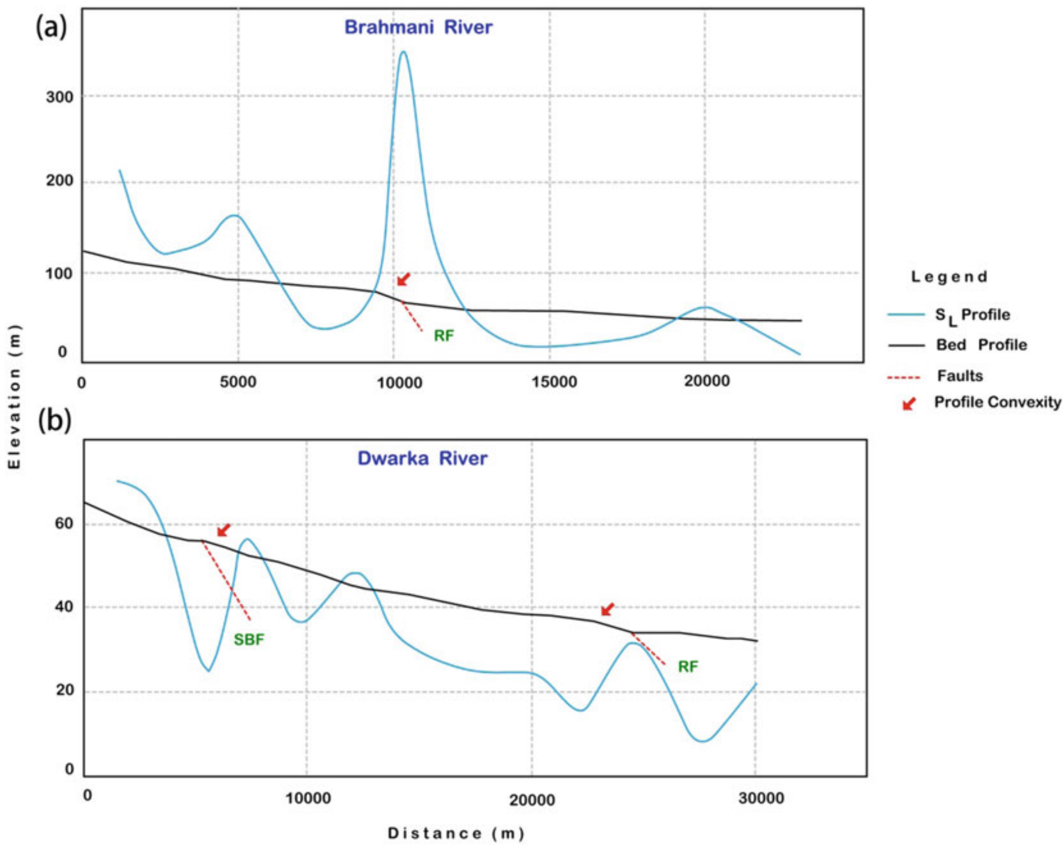


Fig. 23.16 Variations of longitudinal profiles and bed elevations (traces of convexity in relation to zone of deformation by faults) generating recurrent pulses of S_L values in connection with Rajmahal Fault (RF) and Saithia-Brahmani Fault (SBF)

Table 23.5 Summary result showing geomorphic indices of active tectonics in the peninsular rivers of the Bengal Basin

Peninsular river system	SSI range	S_L range (m)	H_I range	A_F range (%)	E_R range
Brahmani—Dwarka River System	1.029–1.123	354–8	0.421–0.5	35.73–53.25	0.530–0.633
Mayurakshi River System	1.026–1.046	165–22	0.433–0.480	63.35–79.24	0.434–0.550
Ajay—Damodar—Dwarkeswar River System	1.012–1.112	175–27	0.396–0.619	43.33–64.58	0.442–0.751
Silai – Kasai River System	1.028–1.088	341–17	0.362–0.578	39.06–70.97	0.367–0.779

Note SSI—standard sinuosity index, S_L—stream length—gradient index, H_I—hypsometric integral, A_F—basin asymmetry factor and E_R—basin elongation ratio

This index is similar to the S_L index in that rock strength or sediment resistance as well as other tectonic factors affect the value. High H_I (>0.5) generally means that not as much of the uplands have been eroded and may propose a younger landscape and dissected relief, possibly produced by active tectonics. The occurrence of gullies and badlands in the lateritic interfluves of these peninsular rivers has proved the active phase of fluvial incision. In this case, the high H_I could also result from recent incision into a young geomorphic surface formed by the deposition. Comparing the H_I values, two groups can be identified with respect to the convexity or concavity of the hypsometric curve: (1) Class A basins with convex hypsometric curves (0.51–0.62) and (2) Class B basins with concave—convex hypsometric curves (0.36–0.50). The range of higher to lower values of hypsometric integral suggests that vast amount of mass is subjected to denudational process while loss of materials has been eroded (Anand and Pradhan 2019). The lower HI values in the basins resulted due to the high kinetic energy of runoff, which dissected the lateritic landscape and floodplain alluvium due to high erosional activities. The values of H_I, less than 0.3, mean a fully stabilized watershed in respect of base level of erosion and the value, greater than 0.6 indicate watershed highly susceptible to fluvial erosion due to regional uplift. In this analysis, the range of H_I ($0.3 \leq H_I \leq 0.6$) reflects that the sub-basins of peninsular rivers are moderately susceptible to incision (control of moderate active tectonics or regional up-warping or tilting), maintaining mature equilibrium to slightly dis-equilibrium stage of landform development in the western shelf zone of the Bengal Basin.

23.4.5 Drainage Basin Asymmetry Factor

To understand the geometric or basin planform change due to active tectonics or lithological control, the factors of drainage basin or valley asymmetry can give some clues about the migration of river or amount of asymmetry in the basin. Using the geomorphic index (viz., asymmetry factor), the users calculate tectonic tilting of the basin and their direction and how much tilting is taking place in comparison to other basin (Fig. 23.17). For most of the stream networks that formed and continued in stable setting, the asymmetry factor (A_F) should equal about 50 (neutral value). The minor rivers of floodplain or pediments or plateau fringe are very sensitive to minimal tectonic up-warping or down-warping. So, A_F is sensitive to tilting perpendicular to the trend of the trunk of high-order river in the basin. Any drainage basin with a flowing trunk stream subjected to a tectonic rotation will most likely have an effect on the tributaries lengths. According to Keller and Pinter (2002), assuming the tectonic activity caused a left to the drainage basin, the tributaries to the left of the main stream will be shorter compared with the ones to the right side of the stream with an asymmetry factor greater than 50, and vice versa.

The four sub-basins (areal coverage of 2.69–9.12 km^2) of the Dwarka—Brahmani interfluves show an anomalous range of A_F, i.e. 33.53–53.25%, depicting the role of RF and SBF in the drainage basin orientation (Table 23.4). The four sub-basins (areal coverage of 8.55–9.85 km^2) of the Mayurakshi River depict A_F range of 38.78–43.37% (values much lower than 50), reflecting tilting of left side of the basins. In the six sub-basins (areal coverage of 17.90–810 km^2) of the Damodar—Ajay interfluves, A_F varies from 43.33% (left tilting) to 64.58% (right tilting). The influence of PF, GKF and BSF makes the trunk streams to tilt more left side of the basins. In the sub-basins (areal coverage of 10.47–159.11 km^2) of Dwarkesar River, it shows anomalous behaviour (complex response) of A_F which varies from 43.18 to 64.25% within the tectonic blocks of PF and GKF. The sub-basins (areal coverage of 52.82–257.54 km^2) of the Silai–Kasai interfluves show again anomalous nature of A_F, which varies from 39.06% (tilting left) to 70.97% (tilting right). In this study, A_F significantly greater or smaller than 50 shows prominent influence of active tectonics or lithological control or differential erosion, as for example, the stream slipping

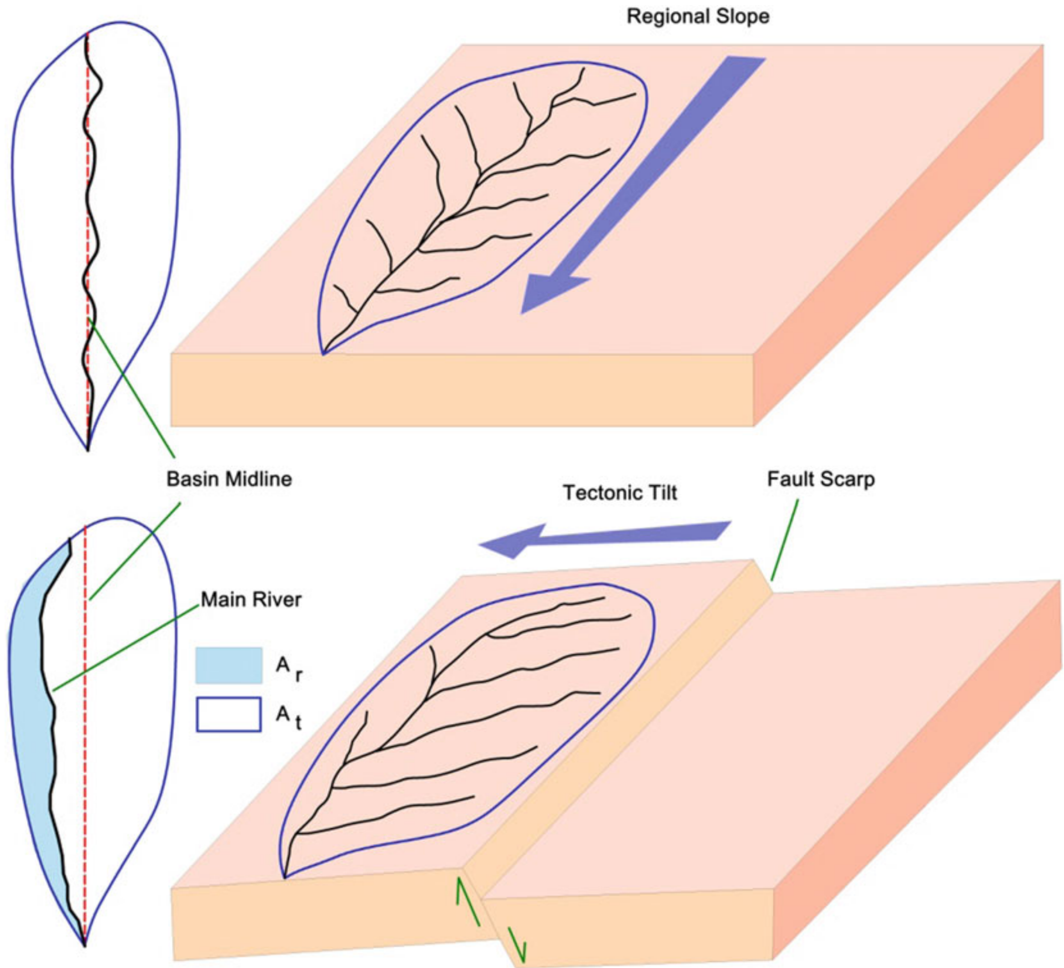


Fig. 23.17 A diagrammatic representation of tilting of river basin due to tectonic deformation and quantitative measure basin asymmetry factor (A_r and A_t)

down bedding plains over time (Hamdouni et al. 2008; Mahmood and Gloahuen 2014). The tectonic blocks between BSF, PF and GKF have differential topographic levels (may be included by fault scarps), occasionally characterized by steep sides and flat floors. The steep sides are created by displacement on faults such that the valley floor moves downs relative to the surrounding margins, or conversely the margins move up relative to the floor. This movement results in basin tilting and causes the river to migrate laterally and deviate from the basin midline. Also, structural control of the orientation of bedding may play a role in the growth of basin asymmetry and tilting of bedding allows for preferred migration of the valley in the down-dip direction, producing a symmetric valley (Cox 1994; Mahmood and Gloahuen 2014).

Valley floor width-to-height ratio (V_F) (Bull and McFadden 1977) is a geomorphic index conceived to discriminate asymmetric valley shapes due to regional tectonic activity. Because uplift is associated with incision, the index is thought to be a proxy for active tectonics where low values of VF are associated with higher rates of uplift and incision. Deep V-shaped valleys (VF < 1) are connected with linear active down-cutting streams distinctive of areas subjected to active tectonics, while flat-floored (U-shaped) valleys (VF > 1) show an attainment of the base level of erosion (may be local), mainly in response to relative tectonics quiescence (Keller 1986; Keller and Pinter 2002; Mahmood and Gloahuen 2014). In this study, a distance between 2 and 4 km is set to measure the geomorphic index along the river valleys, taking more than one cross-sections of DEM upstream of faults for mean value derivation. The sub-basins of the rivers are mainly taken into consideration.

23.4.6 Basin Elongation Ratio

The index of elongation ratio (E_R), introduced by Schumm (1956), is a measure of basin shape included by regional tectonics. Relatively young drainage basins in active tectonics areas tend to be elongated in shape. The elongated shapes are transformed into circular basins, as tectonic activity reduces with time and continued topographic evolution (Bull and McFadden 1977). The reason of this transformation is because the drainage basin widths are much narrower near the active deformation area where the energy of the stream has been directed primarily to downcutting; by contrast, a lack of continuing rapid uplift permits widening of the basins upstream from the active fault zone. The E_R value nearer to 1 suggests highly elongated basin with regional impact of active tectonics. In the sub-basins of the Silai–Kasai interfluves, the index values of E_R vary from 0.367 to 0.779, suggesting an anomalous nature of basin elongation (Table 23.4). The sub-basins of Dwarkeswar River show ER range of 0.409–0.750, reflecting a trend of basin elongation between BMF and PF. In the six sub-basins of Damodar–Ajay interfluves, E_R varies from 0.442 to 0.841, showing control of BMF, PF and GKF on the growth of elongated basin shape. The sub-basins of Mayurakshi River show a trend of semi-circular to elongated basin (upstream of SBF), as reflected from E_R (0.434–0.550). E_R ranges between 0.421 and 0.633 in the Dwarka–Brahmani interfluves, reflecting also semi-circular to more elongated basin shape due to adjoining impact of RF and SBF. It is observed that the basins, situated upstream of PF and SBF (zone of active deformation), show considerable basin elongation, suggesting tectonic uplift of laterite block and the downstream of PF, the inconsistent nature of basin shapes is observed, reflecting quasi-equilibrium fluvial system in response to active tectonics (with regional variations of subsidence and uplift in western shelf of the Bengal Basin).

23.5 Discussion

Where tectonism has been persistent for long periods of time active deformation will produce a channel response that will be superimposed on the long-term tectonic effects. Major valley deformation or total disruption of the river system can be the result of long-term tectonism. It is proposed that stream gradients and valley floor altitudes do not change progressively through geologic time, but rather relatively brief periods of instability and incision are separated by long periods of relative stability (grade). In the terrain, the tectonic forces act as geomorphic extrinsic threshold, and the landform elements of fluvial systems depicts complex response to that event at variable time scale. From the study, it is realized that due to variability of spatial scale of river basins each basin can react differently against same seismic event, producing anomalous landforms in the valleys. For example, when a small drainage basin, like Kunur or Khari, was rejuvenated, the system responded not simply by incision but by hunting for a new equilibrium by incision, aggradation and renewed incision. The rivers of shelf zone do not maintain a steady-state equilibrium, which involves fluctuations about an average (can be traced in stream length–gradient index), but a metastable equilibrium occurs when an external influence, like earthquakes or slow tectonic warping/tilting, carries the fluvial system over some threshold into a next equilibrium regime, forming several landforms (e.g. neck cutoff, alluvial terraces, migration of thalweg, channel shifting, valley narrowness, low sinuosity etc.).

The most commonly cited evidence of fluvial response to deformation is the formation of alluvial terraces in the alluvial valley. The parallel to unparallel terraces are recognized in the rivers of Ajay, Khari, Kunur, Damodar and Kasai at different elevation levels reflecting channel shifting and incision (Figs. 23.14, 23.15 and 23.18). It is found that convex shape of terrace elevation profile between BMF and PF depicts the deformation by uplift, and concave shape between PF and GKF, also to downstream of GKF, signifies regional subsidence. The recurrent occurrences of floods in Ajay, Kunur, Khari, Kasai and Silai Rivers are observed in the region of floodplain subsidence. The uplift occurs between BMF and PF and base level falls, influencing the grade and the cut-and-fill sequences of the sub-basins. The seismic events disrupt the equilibrium of the system, a river may incise through its floodplain in order to reach a new graded profile and begin cutting a new floodplain. The old floodplain becomes a river terrace—an inactive bench stranded above the new level of the river. Repeated episodes of downcutting may preserve several terraces above a river. Faults are as likely to cut the surface of a fluvial terrace as any other landform. The river valley of Damdoar shows several glimpses of Quaternary faults in the terraces between PF and GKF (Fig. 23.11b). The fault cut a given surface (generating steep bank height), and this faulting is known to postdate the age of the terrace surface.

The achievement of grade means that that a tectonically induced change in an alluvial river can induce changes in other characteristics of the system. Longitudinal channel profiles and local anomalies in channel character can result from variations in geology, hydrology and mostly tectonic warping. Where streams flow across tectonic upwraps, erosion across the crest of the warp can generate sufficient sediment to change the local channel pattern from meandering to braided downstream, as reflected in the Damodar River (Fig. 23.19). In addition, because of the dependence on slope, longitudinal titling of just a few tenths of a per cent also can change the pattern of a river (a 0.1% change in slope is equivalent to differential uplift of 1 m over a distance of 1 km). The meandering rivers, like Khari and Kunur, cross-tectonic downwarps between PF and GKF (Ajay—Damodar interfluves), and they tend to be more sinuous on the upstream flank and less sinuous on the downstream flank. It has been suggested that overbank flooding can be anomalously frequent downstream of subsidence. The control of sinuosity is obvious in the peninsular rivers, showing standard sinuosity index nearer to unity, means straight course in between faults. In general, the river meanders (high oscillation in active floodplain) due to minimum expenditure of energy in response to valley slope, but the tectonic deformation of shelf zone increases the valley slope to the extent that alluvial river is confined within the active valley with minimum oscillation, reflecting relatively high energy gradient of Brahmani, Dwarka, Mayurakshi, Ajay, Damodar, Dwarkeswar, Silai and Kasai compared with the floodplains of Bhagirathi-Hooghly River. The domal uplift across Kasai and Silai Rivers shows annular growth of drainage pattern and anomalous nature of sinuosity (Fig. 23.20). There is an increase in sinuosity on the downstream side of uplift as the valley floor is steepened. On the upstream side of the uplift channel, more straightening is observed. In the upstream side of uplift (BMF and PF), the suspended sediment-load rivers, like Kunur and Khari, more development of neck-cutoff and palaeochannels is observed (it aids more degradation), and these will straighten the river downstream.

The Damodar River Valley has witnessed many past seismic events as crossing over the faulted graben of Gondwana sedimentary basin. The deformation of Quaternary sediments (seismites and SSDS) exposed in the banks and nearby areas has sufficient indications and evidences of active seismic activity. The general and almost linear NW-SE and WNW-ESE trend (sinuosity nearer to unity) of the main channel is possibly controlled by tectonic units between BMF, PF and GKF. It is observed that below

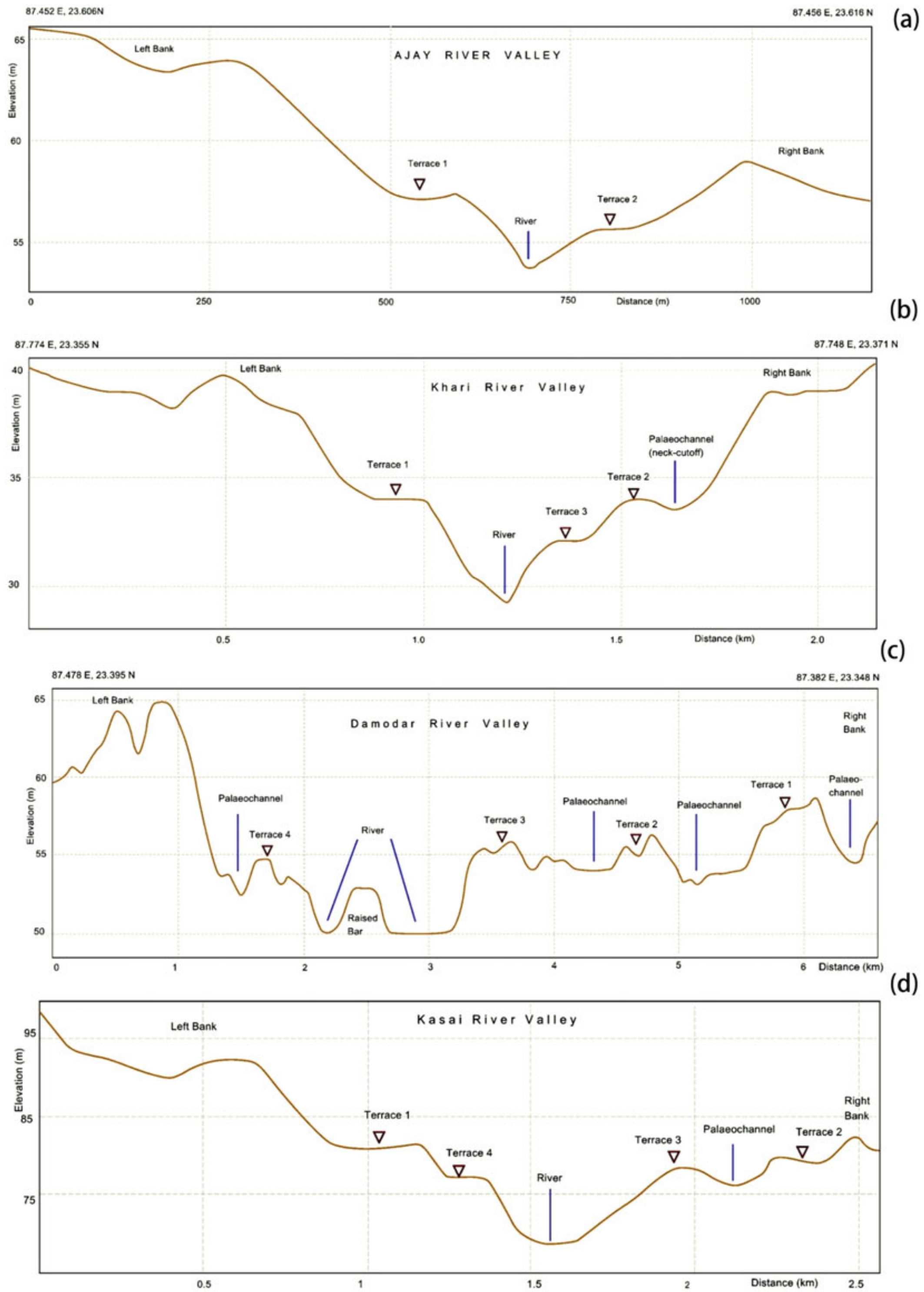


Fig. 23.18 Representation of channel cross-section to depict the alluvial terraces of different topographic levels in **a** Ajay River (near Deul), **b** Khari River (near Asinda), **c** Damodar River (near Shilla) and **d** Kasai River(near Dubli)

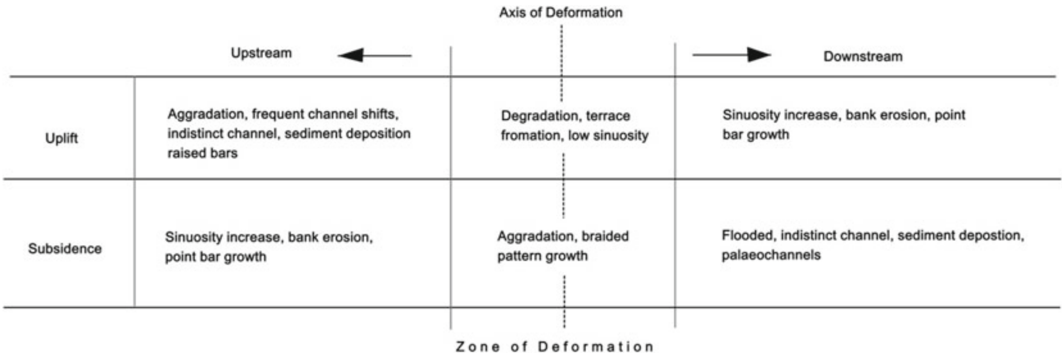
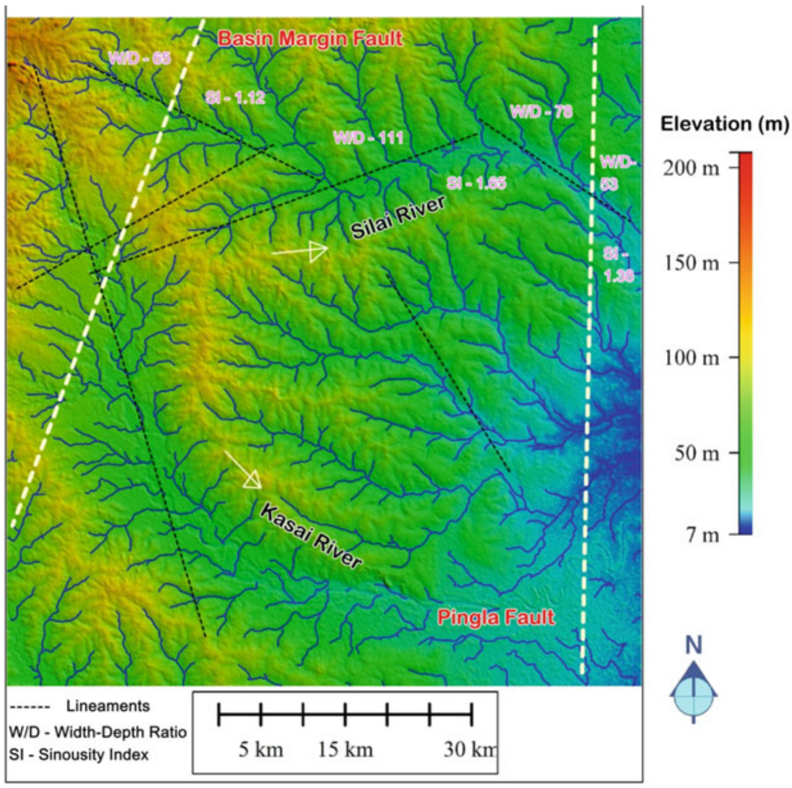


Fig. 23.19 Possible fluvial response to active deformation (uplift or subsidence) observed in the study areas

Fig. 23.20 Elevation map showing tectonic control (faults and lineaments) on drainage development in the Silai–Kasali interfluves



BSF, the width-depth ratio (>100) of the main channel increases from Durgapur to Jujuti, showing bank erosion and raised bars possibly due to recurrent seismic activity. The floodplain signatures of palaeochannels, abandoned channels, low lying depressions, swamps and channel shifting reflect the evidence of subsidence between Rhondia and Jujuti. These features might have been caused due to reactivation of PF and GKF, as reflected from the recurrent earthquakes of M_W 3.6–4.7. These seismic shocks can develop seismites (sand dykes) and SSDS (deformation of clay and sandy-silt beds) in the fluvial facies. The course of Damodar while traversing through Barddhaman becomes WNW-ESE trending and the width–depth ratio also steadily decreases with maintaining linearity up to Palla. From Palla locality, the river takes a sharp and southerly dip and continues to flow further in SSW direction up to Jamalpur. The linearity of course and sudden perpendicular bend might be because it is flowing on a definite tectonic plane, which had a definite role in the evolution of Damodar Fan Delta. Local faulting or dislocations within the Quaternary lithofacies as observed near Rhondia, Gohagram, Haripur and Idilpur are direct evidence of prevalence of active seismicity in the shelf zone of the Bengal Basin. The anomalous development of valley narrowing and linearity, alluvial terraces, sudden rise in bank height, swamps, and raised point and mid-channel bars can be recognized as syntectonic response of Damdoar fluvial system.

23.6 Conclusion

Alluvial rivers have multiple responses (rather more complex responses) to active tectonics of the Bengal Basin, and some are closely interrelated. The concentration here is on individual alluvial rivers' responses, which include those rivers that flow through their own sediments and are not bedrock confined. Apart from seismicity and tectonic elements of the Bengal basin shelf zone, considerable information and documentation of tectonic geomorphology are gained by examining drainage patterns, channel morphology and soft-sediment deformation. Epeirogenic tilting on the ancient deposits or underlying Tertiary Formations has a profound effect on channel slope as reflected from variations of stream length—gradient index between subsurface faults. Deflections of river across the faults are evident in Mayurakshi, Ajay, Damodar and Dwarkeswar Rivers, showing frequent changes of active channel and linear orientation over the floodplains. Low-gradient rivers (mainly suspended-sediment load) are especially sensitive to tectonic movements, such that even very subtle deformation can alter the courses (abandoned channels) and forms (meander cut-offs and terraces) of rivers, like Kunur and Khari. The value of standard sinuosity index is estimated nearer to unity (<1.15) in all peninsular rivers, showing the dominance of topographic control (TSI > 70%) on river sinuosity between the tectonic blocks. The index values of S_L (> 100) and H_I (0.4 to 0.6) show recurrent pulses of stream gradient due to uplift and mature to youthful stage of landform development in the sub-basins of peninsular rivers. Other parameters of basin symmetry factor and basin elongation ratio show also the seismic effect on fluvial landforms, signifying relatively moderate tectonic activity over the basin margin. The recurrent occurrences of earthquakes in and around the Bengal Basin prove the relative activeness of fault planes or scarps, which triggered low to high magnitude earthquakes in BMF, PF, GKF and EHZ in Anthropocene.

The present study has tried to explore syntectonic responses of alluvial rivers to active tectonics in the western shelf zone of the Bengal Basin. The direct implication of the above is that the Quaternary terrain that forms >75% of the total study area is vulnerable (possibility of ample liquefaction) to the effects of a medium to high magnitude earthquakes. The major towns or cities, like Asansol, Bankura, Durgapur, Bardhaman, Bolpur, Medinipur and Kolkata, are situated in the close vicinity of tectonic elements and earthquake epicentres. Apart from that, currently, DGPS (differential global positioning system)-based geodetic surveys and DDS (deep seismic sounding) seismic refraction surveys are strongly recommended in the active deformed zones of alluvial river basins. Seismic microzonation of important towns and cities can provide better information of seismic vulnerability in contagious areas and faulted blocks. Suitable measures should be taken to regularly monitor recurrent seismic activity by installing seismograph on or near the dams and barrage, which are situated adjacent to basin margin faults. There are needs for more interdisciplinary fundamental research to comprehend the effect of fault scarps on alluvial rivers or deformation of alluvial terraces and sediments using sophisticated techniques and instruments. These studies can provide indication and information about the relative activeness of seismicity in the Bengal Basin.

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