

*The Himalayas have no direct continuation either towards the west or to the east. The singular syntaxial bends on both extremes preclude a straightforward continuation of the Himalayan elements.*

—A. Gansser (1964, p. 256)

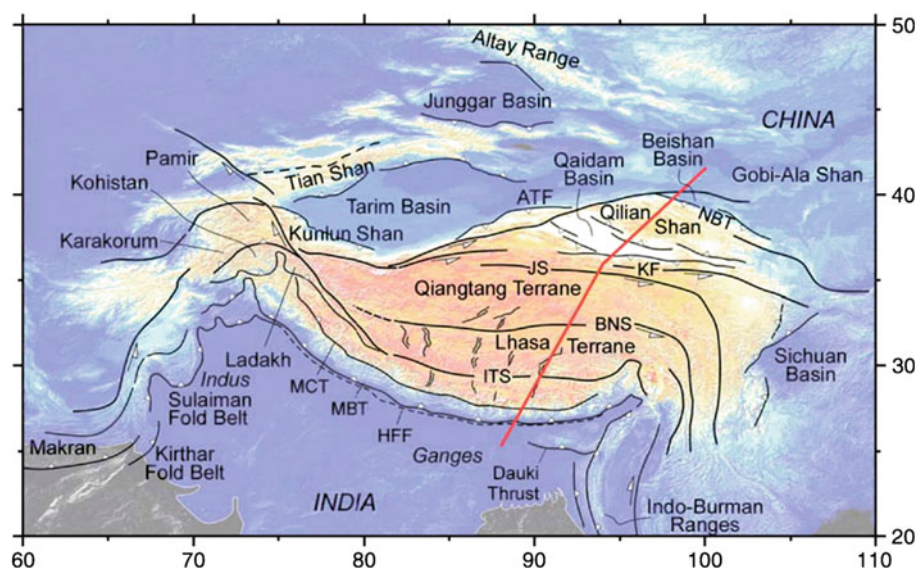
The conspicuous continental climax on earth, the Himalaya, is situated on the south edge of the elevated Tibetan Plateau. The extensive alluvial plains of Indus (Sindh or Sindhu), Ganga (Ganges), and Brahmaputra or Yarlung Tsangpo (or *Zangbo* = river in Tibetan) delimit this mountain range from the south. Together with the Karakoram mountains, bordering the Himalaya on the northwest, this orogenic belt meets and fuses with the Pamirs, from where several other Asiatic mountain chains diverge (Figs. 1.1 and 2.1). The Himalayan Range abruptly encounters an impressive syntaxial bend around Mount Nanga Parbat (8,125 m) at its northwest extremity, from where the Hindu Kush, Sulaiman, and Kirthar ranges continue to the south or southwest. There is another similar sharp syntaxial twist around Mount Namche Barwa (7,756 m) at the southeast end of the Himalaya, from where the Arakan mountains swing to the south or southwest.

The three great antecedent rivers—Indus, Ganga, and Brahmaputra—have been witnessing the Himalayan evolution and rise since the time of its embryonic growth about 50 Ma (Patriat and Achache 1984). The Brahmaputra and Ganga embrace this majestic mountain range from the north and south, respectively, and make a thousands-of-kilometers-long detour before ultimately merging and debouching into the Bay of Bengal. Although, like the Brahmaputra, the Indus also collects its waters from the environs of twin shimmering lakes—Manasarovar (*Mapam Yumco* in Tibetan) and Rakas (*La'nga Co* in Tibetan) in Tibet—it flows at first towards the opposite direction (i.e., to the west), and then comes very close to the tributaries of the Ganga, with a trifling aerial distance in the dead levels of their common alluvial plain, and briskly conveys its waters and sediments into the Arabian Sea near the Gulf of Oman.

## 2.1 Tibetan Plateau

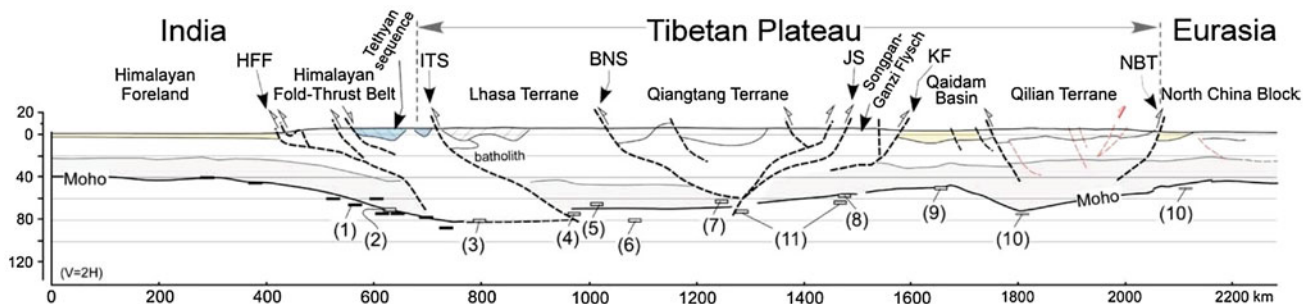
The Tibetan Plateau with the Himalaya and neighboring ranges constitutes by far the widest and highest orogenic system on earth. The changes in its orography and earth's climate are intimately linked to this collisional event (Rowley 1996). The south face of the Himalaya is characterized by verdant vegetation, however, the plateau (Fig. 2.1) is essentially a vast (about 2.5 million sq km) cold desert with an altitude variation from 4,000 to 5,000 m. The plateau attained its altitude as a result of underthrusting of the Indian plate below Asia (Argand 1924).

Tibet is neither a mere “high plateau” nor just a “median mass,” but an intensely folded mountain country with several east–west trending fold belts (Stöcklin 1980). Its crustal thickness frequently exceeds 70 km (Fig. 2.2), which is almost double the normal thickness of the continental crust. It is assumed that the Indian lower crust is underplated below Tibet. In this process the lower crust experienced multiple slicing and stacking leading to the anomalous crustal thickness of Tibet, whereas the decoupled Indian upper crust was thrust towards the south, forming the Himalaya. The Tibetan Plateau is made up of a number of microcontinents, flysch complexes, and island arcs. These smaller younger plates were gradually broken down from the ancient large Indian plate and they moved towards Asia. In this process, the microcontinents successively collided with the Eurasian plate and were subducted beneath it from the Paleozoic Era (Chang and Cheng 1973, p. 264). The most important of them are the Qilian Shan, eastern Kunlun–Qaidam, Songpan–Ganzi, Qiangtang, and Lhasa terranes, distributed from north to south, respectively (Fig. 2.2).



**Fig. 2.1** Tectonic map of the Tibetan Plateau and surrounding regions. Color shades show elevation. Red line shows the position of the profile (Fig. 2.2). ATF Altyn Tagh Fault, HFF Himalayan Frontal Fault, MBT Main Boundary Thrust of Himalaya, MCT Main Central Thrust, ITS

Indus-Tsangpo Suture, BNS Banggong-Nujiang Suture, JS Jinsha Suture, KF Kunlun Fault, NBT North Border Thrust. Source Jiménez-Munt et al. (2008). © Elsevier. Used by permission



**Fig. 2.2** Crustal structure along the profile inferred from geological and geophysical data. Bars show some Moho depth. Source Jiménez-Munt et al. (2008). © Elsevier. Used by permission

The northernmost Qilian Shan terrane is constituted of complexly deformed early Paleozoic arcs, which were formed at the south margin of the North China craton, and they were subsequently offset by the Altyn Tagh fault in the Cenozoic (Yin and Harrison 2000).

The eastern Kunlun-Qaidam terrane is bounded to the north by the southern Qilian suture and to the south by the Anyimaqen-Kunlun-Muztagh suture. It consists of the Kunlun batholith of Meso- to Neo-Proterozoic gneisses, schists, and marbles, which were unconformably overlain by Neoproterozoic stromatolitic strata and Cambrian to Ordovician carbonates (Yin and Harrison 2000).

The triangular Songpan-Ganzi terrane lies north of the Jinsha suture and south of the Anyimaqen-Kunlun-Muztagh suture. The terrane is positioned between the eastern Kunlun-Qaidam terrane to the north and the Qiangtang terrane to

the south. It mainly comprises a thick, deep marine turbidity succession of Triassic age, generally named the Songpan-Ganzi flysch complex, which is actually distributed in a much wider area than the Songpan-Ganzi terrane (Dewey et al. 1988; Yin and Harrison 2000).

The Qiangtang terrane is delimited by the Jinsha suture from the north and the Banggong-Nujiang suture from the south. It is made up of metamorphic rocks of eclogite and blueschist facies, belonging to an Early Triassic age. These rocks are separated from the overlying Paleozoic-Mesozoic sedimentary sequence by low-angle normal faults. The Paleozoic rocks contain a tillitic sequence, like the Talchirs in the Indian subcontinent, as well as Permian limestones alternating with volcanic rocks, whereas the Triassic rocks are represented by carbonates interbedded with continental siliciclastic and volcanic rocks. The Jurassic succession

unconformably overlies the last sequence and is made up of volcanics and limestones (Dewey et al. 1988; Yin and Harrison 2000; Mascle et al. 2012).

The Lhasa terrane is the southernmost microcontinent, whose north boundary corresponds to the Bangong–Nujiang suture and the south border is the Indus–Tsangpo suture. The Lhasa terrane is composed mainly of Ordovician and Carboniferous to Triassic shallow marine clastic deposits, resting on the Mesoproterozoic to Early Cambrian basement (Yin and Harrison 2000, p. 218). The Permian strata contain some tillite beds similar to the Talchirs. Presumably, the Lhasa terrane drifted away from the north part of Gondwana during the Triassic, and collided with the south margin of the Qiangtang terrane between the Late Jurassic and middle Cretaceous epochs (Dewey et al. 1988). The Cretaceous to Tertiary Gangdese batholith, intruding into the rocks of the Lhasa terrane, and constituting its south margin, is related to the north-dipping subduction of the Indian plate (Chang and Cheng 1973).

## 2.2 Indus–Tsangpo Suture Zone

The Indus–Tsangpo or Yarlung Zangbo suture zone is the north tectonic boundary between the Himalaya (Indian plate) and Tibetan Plateau (Lhasa terrane). The boundary is generally marked by a topographic depression, along which the Indus and Zangbo rivers flow in opposite directions (Heim and Gansser 1939).

The Indus–Tsangpo suture zone is a narrow (less than 15 km) belt of oceanic rocks, representing obducted remnants of the Tethys Sea (Ding et al. 2005). The suture zone consists of almost vertical tectonic slices (called exotic blocks) that are intensely deformed and dislocated (Diener 1895, 1898; von Krafft 1902; Heim and Gansser 1939). At a few places, these rocks constitute klippen over the south-lying Tethyan sequence. The suture is rather a discontinuous zone consisting of a wild flysch containing blocks of Permian limestone, Early Triassic pelagic limestone, lenses of serpentinite, Late Cretaceous pelitic calcschist, and pillow and massive alkali basaltic lava. This zone also comprises ophiolites as thin sheets and obducted masses, radiolarites with basic lavas, and some blueschists, recording a pressure of about 1 GPa and a temperature range of 350–450 °C (Mascle et al. 2012). Along the central segment of the suture, Mesozoic sediments of the Tethys Himalaya are metamorphosed. There are post-metamorphic granitic intrusions aligned south of the suture (Gansser 1977). To the east of the Kailas Valley, the metamorphic flysch overlies the non-metamorphic and almost horizontal Kailas Conglomerate along the Great Counterthrust (Heim and Gansser 1939, p. 188). The complex geometry of the Indus–Tsangpo suture zone resulted from the following sequence of events:

(1) nappe movements, (2) shortening and isoclinal folding, and (3) backfolding (Burg 1992, p. 42).

## 2.3 Himalayan Orogen

The 2,400 km long and from 250 to 400 km wide Himalayan fold-and-thrust belt occupies about 600,000 sq km of area. It is positioned between 75° and 95° east longitude, and 27° and 35° north latitude. The Himalaya frequently surpasses 6,000 m contour level, and out of 14 eminent summits exceeding 8,000 m, 11 of them stand on this range, and the remaining three also belong to the neighboring Karakoram mountains. Most of these stupendous Himalayan peaks are congregated towards the center of the range from where the ridgeline altitude gradually decreases to the east and west (Mingtao 1982, p. 10). But this decline is halted abruptly by the two mighty marginal peaks: Nanga Parbat anchoring the Himalaya on the west where the Indus River drains its waters, and Namche Barwa standing at the east tip where the Brahmaputra flows through its foot and creates many gorges and forced meanders. To the southeast, the snow-clad Himalayan ridgeline lies at a distance of about 100 km from the alluvial plains (foreland) and that distance gradually increases to the northwest and reaches about 150 km. The Himalayan topography exhibits self-affine characteristics. An analysis of roughness of this landscape exhibits signs of multifractality as a result of the many intertwined processes shaping the landscape's form (Rodríguez-Iturbe and Rinaldo 2001, p. 233).

The Himalayan mountain range displays a perfect southwards-convex arcuate bulge (Heim and Gansser 1939, p. 1) with a radius of about 1,500 km and the center around 90° east longitude and 42° north latitude. Its present festooning curves are exactly opposite to those of the Alps with which it is connected by the transitional ranges of Iran and Hindu Kush. As compared to all other mountain belts resulting from subduction or collision, the Himalaya with its associated ranges is unique in that it lies on the subducting portion of the plate (Argand 1924). The Himalayan arc is comparable with an island arc, but it is located on land and is linked with the other arcs between Indonesia on the south-east to the Mediterranean on the northwest. It is intriguing why the Himalayan arc should result from simple underthrusting, its size and radius be comparable to those of island arcs, and be part of the island arc chain (Ollier and Pain 2000, p. 131).

The Himalaya—the young and restless giant (Valdiya 1998)—stands splendidly between the Lhasa terrane to the north and the Indian craton to the south. The north portion of the Indian shield with some Gondwana continental deposits formed the south border of the Tethys Sea. The Himalayan orogen incorporated all three elements, that is, the Tethys

sediments, Indian shield, and Gondwanas. After the collision along the Indus–Tsangpo suture zone, the tectonic activity was partially transferred towards the south. The subsequent major event was the formation of the Main Central Thrust, a deep intracrustal fracture in the Himalaya. The next large event occurred still farther south, where the frontal faults developed, respectively, in the Lesser Himalaya and Siwaliks. They represent a shallower intracrustal feature. As do many other mountain belts, the Himalaya displays a relay of orogenic activity from the deeper inner belt to the shallower outer belt (Gansser 1977). Thus, the Himalayan orogen has evolved from intense continental deformation, leading to extensive crustal shortening and thickening, large-scale thrusting and folding, polyphase metamorphism, anatexis, and granite intrusion, together with cryptic and fleeting episodes of exhumation, uplift, and erosion.

## 2.4 Ganga Foreland Basin

The immense alluvial level plains of the Ganga extend between the mighty Himalaya to the north and the ancient Indian tableland to the south. Early attempts to obtain the thickness of alluvium were unsuccessful (Box 2.1). Based on aeromagnetic and gravity studies, Sen Gupta (1964) found Bouguer and isostatic anomalies to be largely negative over the Gangetic plains, but they become increasingly positive over the high (5,000 m) Himalayan peaks. He found the basement depth in the alluvium to vary from about 1,500 m near the northern fringe of the Indian shield to about 9,000 m near the Himalayan foothills. Seismic surveys revealed an unconformity marking the base of the Tertiaries and underlying limestones at a depth of 1,800 m near Bareilly. Positive anomalies are also recorded to the south of the Gangetic Plains, in the northern Indian shield. In other words, the Ganga Basin is flanked on the north and south sides by positive anomalies and the situation is similar to the gravity profile across the Pacific-type arcs and deep oceanic trenches. In this case, the gravity minima of the Ganga Basin correspond to those over deep trenches and the Himalayan positive anomaly to the positive gravity over the island arcs (Sen Gupta 1964, p. 324). Gutenberg and Richter (1954, p. 66) also compared the Himalaya with the Pacific arc based on their investigation on the depth of earthquake foci. They noted that the foredeep of the Himalayan arc is represented by the very deep alluvial depression of the Ganga.

### Box 2.1: Early Boreholes in the Ganga Basin

Oldham (1893, pp. 432, 434) described a borehole sunk at Lucknow, in the Ganga Basin, to a depth of 407 m, or about 300 m below sea level. It passed

through the alluvium with alternations of sand and sandy silt with occasional bands of calcrete without approaching the bedrock. A similar borehole driven at Kolkata, between 1835 and 1840 down to a depth of 140 m below sea level, also passed through the alluvium without reaching the hard rock.

## 2.5 Basement Structure of Ganga Basin

The Ganga Basin uniformly dips towards the northeast, where the overlying sediments reach a thickness of 9–10 km (Misra and Phukan 2005). The Bouguer anomaly map also shows a relatively uniform regional slope towards the north with its values ranging from 60 mGal in the south to a maximum of 210 mGal near the Nepal border. The basin becomes shallow to the east and west (Ahmad and Alam 1978; Singh 1999). The basement configuration reveals a gradual increase in thickness from south to north, indicating a maximum thickness of about 8,000 m in the extreme north margin of the basin (Fig. 2.3). The following main tectonic divisions are found in the Ganga Basin from east to west, respectively (Ahmad and Alam 1978, pp. 586–589).

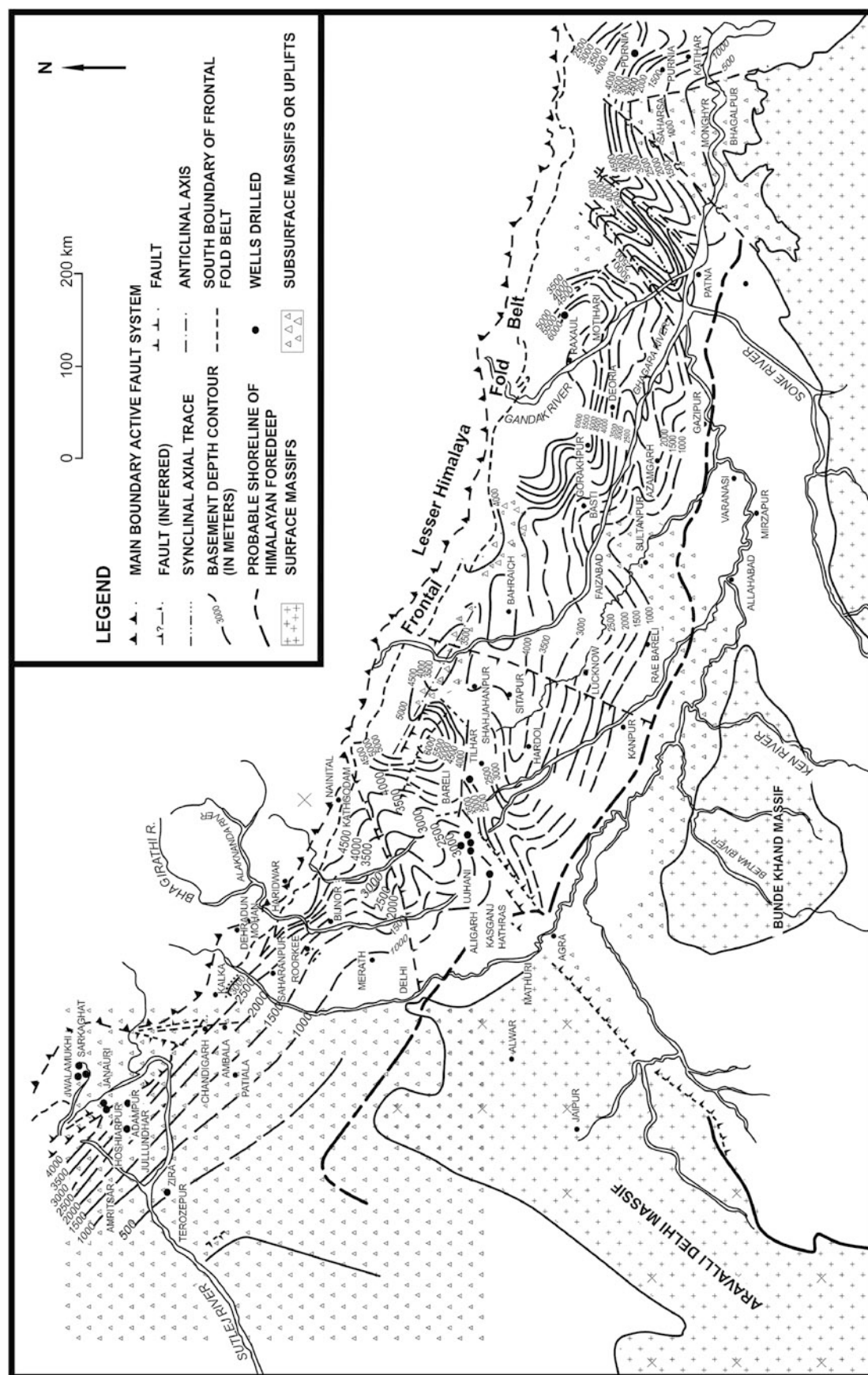
The Monghyr–Saharsa Ridge (Fig. 2.4) forms a NNE–SSW trending structural high and could be the northwards extension of the Satpura Range. The sedimentary cover (mainly the Siwaliks) on the ridge is less than 3,000 m thick.

The East Uttar Pradesh Shelf lies between the Monghyr–Saharsa Ridge to the east and the Faizabad Ridge to the west. To the south of it the Vindhyan and Satpura groups of rocks crop out, and to the north the shelf seems to merge with the Gandak Depression. The inferred rocks to be met with are the Satpura Crystallines, Vindhyan, and Siwaliks.

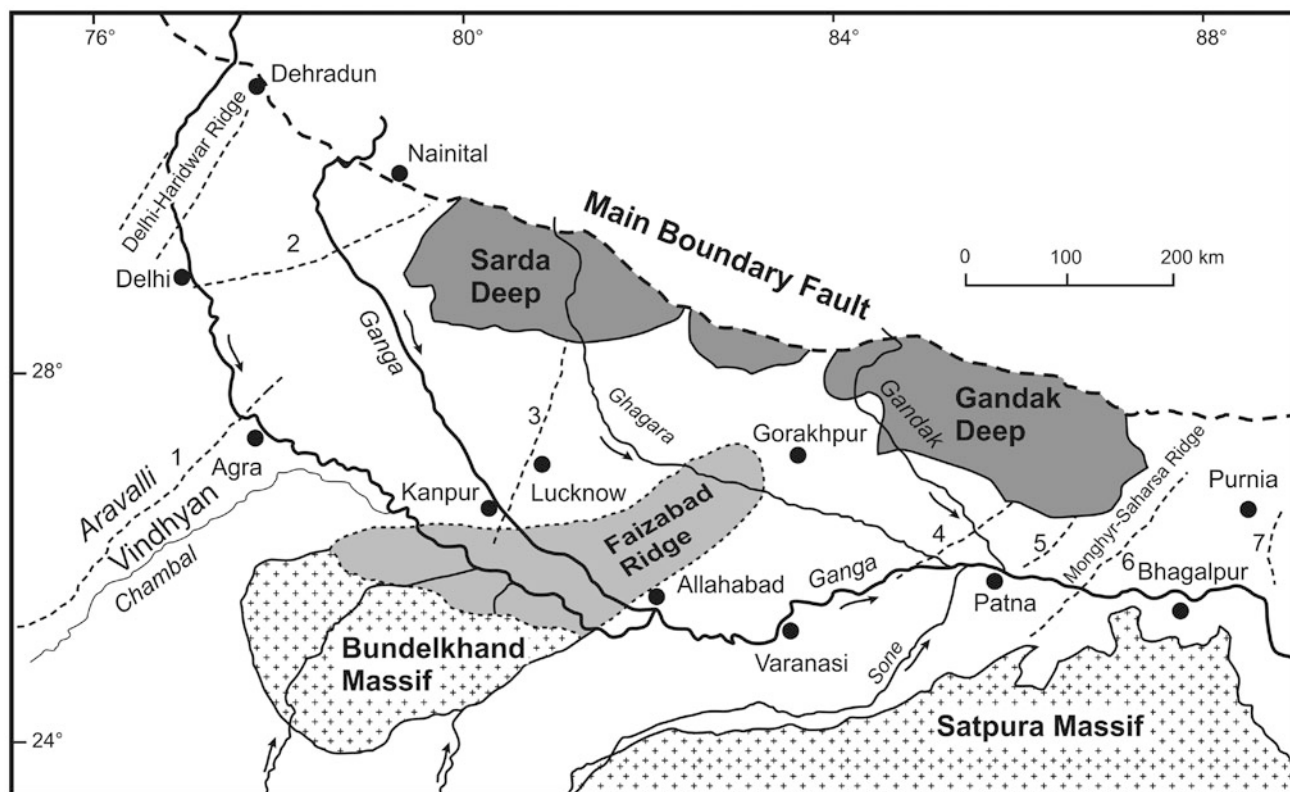
The Gandak Depression (or Deep) lies between the East Uttar Pradesh Shelf and the Himalayan frontal ranges (Siwaliks). In this depression are found more than 6,000 m of Vindhyan, Mesozoic, Paleocene, and Neogene deposits on the Satpura Crystalline base. The Raxaul well drilled in the northern zone of the depression encountered some basement gneisses (? Satpura and Bundelkhand). They are overlain by a succession of purple shales, slates, and quartzites (? Vindhyan). This unit was unconformably followed by the Lower, Middle, and Upper Siwaliks which were finally succeeded by the Gangetic alluvium.

The NE–SE trending Faizabad Ridge (Fig. 2.4) is the most prominent structure of the Ganga Basin. It is made up of Bundelkhand Granitoids and inferred to have a thin Neogene cover. Six boreholes drilled in the West Uttar Pradesh Shelf revealed a complex structure with folds and faults (e.g., the Moradabad Fault). To the west of the Moradabad Fault, the shelf is made up of the Delhi Group





**Fig. 2.3** Basement depth map of Ganga Basin. *Source* Modified from Ahmed and Alam (1978). © Wadia Institute of Himalayan Geology. Used by permission



**Fig. 2.4** Subsurface geology and tectonic framework of the Ganga Basin. Numbers indicate the major subsurface faults identified from geophysical investigations. 1 Great Boundary Fault, 2 Delhi–Moradabad Fault, 3 Lucknow Fault, 4 West Patna Fault, 5 East Patna Fault,

6 Monghyr–Saharsa Ridge Fault, 7 Malda–Kishanganj Fault. *Source* Modified from Sinha et al. (2005). © Wadia Institute of Himalayan Geology. Used by permission

(Basement) unconformably overlain by a Lesser Himalayan sequence. It is again followed with an unconformity by the Middle and Upper Siwaliks grading into the Gangetic alluvium. To the east of the fault are the basement rocks of the Aravalli Group, which are unconformably followed by a Lesser Himalayan sequence, and again with an unconformity by the Middle and Upper Siwaliks, respectively. The Upper Siwaliks gradually pass into the overlying alluvium. In this shelf, the pre-Siwalik unconformity constitutes a northeasterly dipping homocline, varying in depth from 620 (to the south) to 4,200 m (near the Indo–Nepal border).

The Sarda Depression is the north extension of the West Uttar Pradesh Shelf. It contains more than 6,000 m of sediments represented by Vindhyan, Mesozoic, and Paleogene and Neogene sediments.

The Delhi–Haridwar Ridge is the northward extension of the Delhi fold belt and marks the western limit of the Ganga Basin.

The basement is represented by metamorphic and igneous rocks, which can be followed southwards to meet the Bundelkhand massif (Misra and Phukan 2005). These rocks are succeeded with an unconformity by the Vindhyan. The deposition over the crystalline basement took place in the

Mesoproterozoic. Then there was a gap until 600 Ma. At that time, the sediments were transformed to low-grade metamorphic rocks. During the Mesoproterozoic–early Paleozoic, shallow marine mixed siliciclastic and carbonate sequences of passive margin were accumulated. Throughout the early Paleozoic, between the ridges in the Sarda and Gandak depressions, thick shallow marine glauconitic sediments were also deposited. These sediments were laid down in a peritidal platform, with spatial variation of lithofacies from supratidal to subtidal as well as from shallow offshore shoal to fluvial. In the Ordovician, there was a regional uplift followed by a major rift phase during the Permo–Carboniferous era. Subsequently, thick Gondwana sediments were deposited in the depression between Purnia and east of the Monghyr–Saharsa Ridge (Sinha 2005). Then, the region experienced a long hiatus until an important Cretaceous transgression. The hiatus caused widespread erosion, and some basic intrusives were also emplaced at the base of the sedimentary sequence, near Raxaul, towards the northern margin of the Gandak Depression. They can be correlated with the Rajmahal volcanics (Fuloria 1969). The transgression, in turn, was followed by another hiatus that lasted up to the onset of the Tertiary.

Owing to progressive flexing of the Indian plate, the south margin of the foredeep migrated southwards. In this process the north margin of the foredeep was deformed and the foredeep wedges were accreted to the south. The general trend of the foredeep is parallel to the Himalayan front. The sediments accumulated in the foredeep consist of the Tertiary siliciclastics. Except the Paleogene marine Subathu, the rest of the Tertiary sediments are fluvial and consist of many fining-upwards sequences (Sinha 2005).

During the India–Asia collision, a major inversion took place and the pre-existing basement faults were reactivated. The displacement along these faults resulted in the development of linear highs and lows. In the Neogene foredeep area, during the Mesozoic and early Paleogene the region experienced denudation and peneplanation; as a result the sediments were removed from the highs and survived only in the areas of linear lows across the basin. The wedge-shaped Tertiary package gently dips due north and it attains a thickness of about 6,000 m in the proximity of the foothills (Sinha 2005).

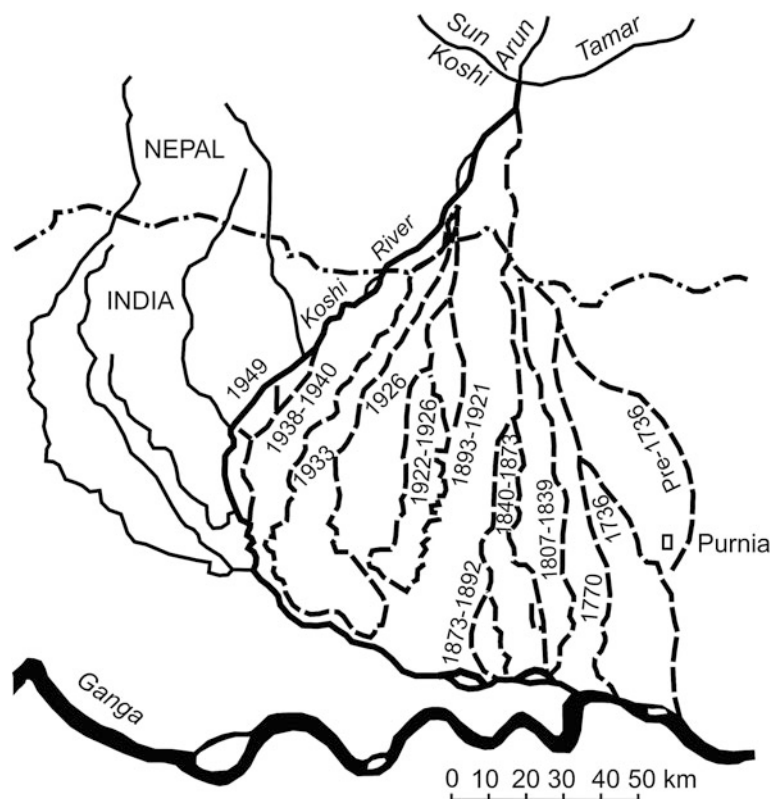
## 2.6 Unstable River Courses

Many and great have been the alterations in the drainage lines of the Indus, Ganga, Brahmaputra, and their tributaries. For example, in Vedic times, the portion of the river that flowed to

the Punjab was known as the Saraswati, and that which joined the Ganga was called the Yamuna (Oldham 1886; Radhakrishna and Merh 1999). At the beginning of the nineteenth century, the Brahmaputra broke away from its old course and flowed west of the Madhopur jungle to join the Ganga, and the new channel was named the Jamuna (Oldham 1886, p. 341). In August 1787, the Tista River deserted the Ganga and joined the Brahmaputra (Shillingford 1893).

The Koshi (Kosi or Kusi, *Kaushiki* in Sanskrit) River is the most devastating one. The river has frequently shifted its channel (Fig. 2.5) and formed a megafan. In the past 250 years, it has migrated westwards by about 150 km via more than 12 channels. In the past, before the construction of the Koshi barrage in 1963, there were some attempts to train the river (Box 2.2). The main cause of channel shifting is the deposition of an enormous amount of sediment load on the Ganga Basin from denudation of the Himalayan ranges. The main channel of the Koshi River oscillates between the Brahmaputra to the east and Gandak (Gandaki) to the west, and the pivot is at Chatra, in Nepal (Fergusson 1863). The oscillation periods are long and slow towards the west whereas they are sudden and devastating while moving towards the east. In the late 1880s and early 1890s, the Koshi River suddenly shifted its main channel on the borders of Nepal and much of the floodwater was thrown eastwards, towards Purnia and Dinajpur. During the rainy season of 1893, severe floods occurred in the Koshi River (Shillingford

**Fig. 2.5** Channel shifting by the Koshi River. Source Modified from Duff (1992)





1893, pp. 1–2). The waters in the Ganga and Brahmaputra rivers interact in a complex manner during flooding (Box 2.3).

### Box 2.2: Past Attempts to Train the Koshi

Shillingford (1893, p. 14) described the following case of river training works:

In North Bhagalpur, there is an extensive embankment of earth in places some 5–10 m high, called the Bīr Bandh, extending from the foot of the Belkār (Beltar) or outer range of hills in Nepal southwards into Bhagalpur district, about 80 km in length, it runs nearly parallel with the present course of the Kusī (Koshi) which approaches it towards its south end. Dr. Buchanan Hamilton and others considered it to be a fortification, a theory shown by Dr. Hunter to be highly improbable, but it may possibly be a dyke to prevent Kusī (Koshi) overflows from flooding the lower country to the west and carving out fresh channels ... Dr. Buchanan Hamilton conjectures that this earth-work was constructed by Lakṣmaṇa II, about the close of the 12th century, the only reasons assigned for the supposition being that tradition stated it to have been built by a Lakṣmaṇa and “as the works were never completed and have the appearance of having been suddenly deserted, it is probable that they were erected by Lakṣmaṇa the second, who in the year 1207, was subdued and expelled from Nadiya by the Moslems.” Probably he refers to the detached portions at its southern end, cut away by river action, when alluding to its incomplete and abandoned appearance. This extensive embankment cuts off the sources of the Dīmṛā and Tīljugā (Trijuga) rivers from the Kusī (Koshi), and intercepts all flood-waters of the latter river from entering the channels.

### Box 2.3: Backflows in Ganga and Brahmaputra

In the first month of inundation when there is much water in the Brahmaputra River, the Ganga above Jaffirgunj flows backwards, and the Echamati at Pubna flows into the Ganga, instead of flowing out of it. During that period there is a considerable amount of deposit in its bed. But, during the last month of the rainy season, when the water in the Brahmaputra River has nearly run off, an immense water body previously spread over the floodplains rushes into the partially deserted bed of the Brahmaputra, which acts as a wastewater reservoir, and clears out the sediments deposited in the earlier months (Fergusson 1863, p. 337).

After the construction of the Koshi barrage, the river was trained to some extent. However, in 2008, the Koshi breached its embankments and followed an earlier course towards the east, bringing about much devastation in Nepal and India.

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Dhital, M.R.

2015, XXIV, 498 p. 304 illus., 107 illus. in color.,

Hardcover

ISBN: 978-3-319-02495-0