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ORIGINAL PAPER

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Extensional tectonic activity in the cratonward parts (peripheral bulge) of the Ganga Plain foreland basin, India

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Abstract Flexural subsidence of the Indian lithosphere created the foreland basin in front of the emerging Himalayan mountain belt. The continued northward push of the Indian plate and thrust sheet loading in the Himalayan orogen caused an up-warping along its cratonward margin, in the form of a regional gentle bulge. In the cratonward peripheral bulge small-scale to moderate size deformation features, e.g., gentle folds (up-arching of the sediment layers), extensional normal faults and uplifted tilted blocks, and incised river channels with 20–60-m-high cliffs, developed. Cliff sections of many rivers in this cratonward part of the foreland basin expose deposits of latest Pleistocene–Holocene age and show evidences of active tectonics in the last few thousand years: vertical uplift leading to deep incision of the river system, development of prominent fractures cutting through the sedimentary succession, bending and tilting of the strata, and tilted blocks. In the Late Quaternary relaxation phase of the Himalayan orogen-foreland, there is increased vertical tectonic activity in the region of the peripheral bulge. The vertical uplift in this part of the Ganga Plain foreland basin caused the rivers (including the axial rivers) to make further deep incision without shifting from their courses. During periods of increased tectonic activity in the Himalayan region, i.e., the addition of thrust slices more rapidly, probably caused the maximum down-bending in the proximal part of the Ganga plain foreland basin. The high amplitude and asymmetric nature of this foreland basin is partly controlled by extensional tectonism.

Keywords Active tectonics · Extensional tectonic peripheral bulge · Foreland basin · Ganga plain

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Introduction

Foreland basins are produced by the lithospheric bending in response to an orogenic load, and the asymmetric space thus created in front of the emerging mountain belt is occupied by various extents of sediment fill. The depositional processes of the foreland basin are controlled by the tectonic activity in the orogen (Fraser and DeCelles 1992).

The Ganga Plain is an example of an overfilled present-day active foreland basin that has a prominent peripheral bulge where sedimentation is taking place essentially by fluvial processes (Singh 1996). The fluvial geomorphology, sedimentation, Quaternary depositional history (Geddes 1960; Mukerji 1963; Pal and Bhattacharya 1979; Singh 1987, 1992, 1996; Joshi and Bhartiya 1991; Sinha 1995), and tectonic framework (Sastri et al. 1971; Rao 1973; Lyon-Caen and Molnar 1985; Covey 1986; Miall 1988; Burbank 1992; France-Lanord et al. 1993; Mugnier et al. 1994; Raiverman et al. 1994; Virdi 1994) of the Ganga Plain and the adjacent Siwalik Hills have been discussed in the past few decades.

The sediment fill of the Ganga Plain foreland basin is an asymmetrical sediment wedge, only few tens of meters thick in the south and up to about 5 km thick in the northernmost part. The sediments of the Ganga Plain foreland basin are deposited on a gently north sloping lithosphere, which is made up of metamorphosed Precambrian basement, Late Proterozoic sediments, or Phanerozoic Gondwana sediments (Singh 1996). The general information regarding the basement of the Ganga Plain is based on gravity surveys and a few boreholes drilled through the sediment cover. It suggests a gently north-sloping lithosphere that forms the basement of the foreland sediment

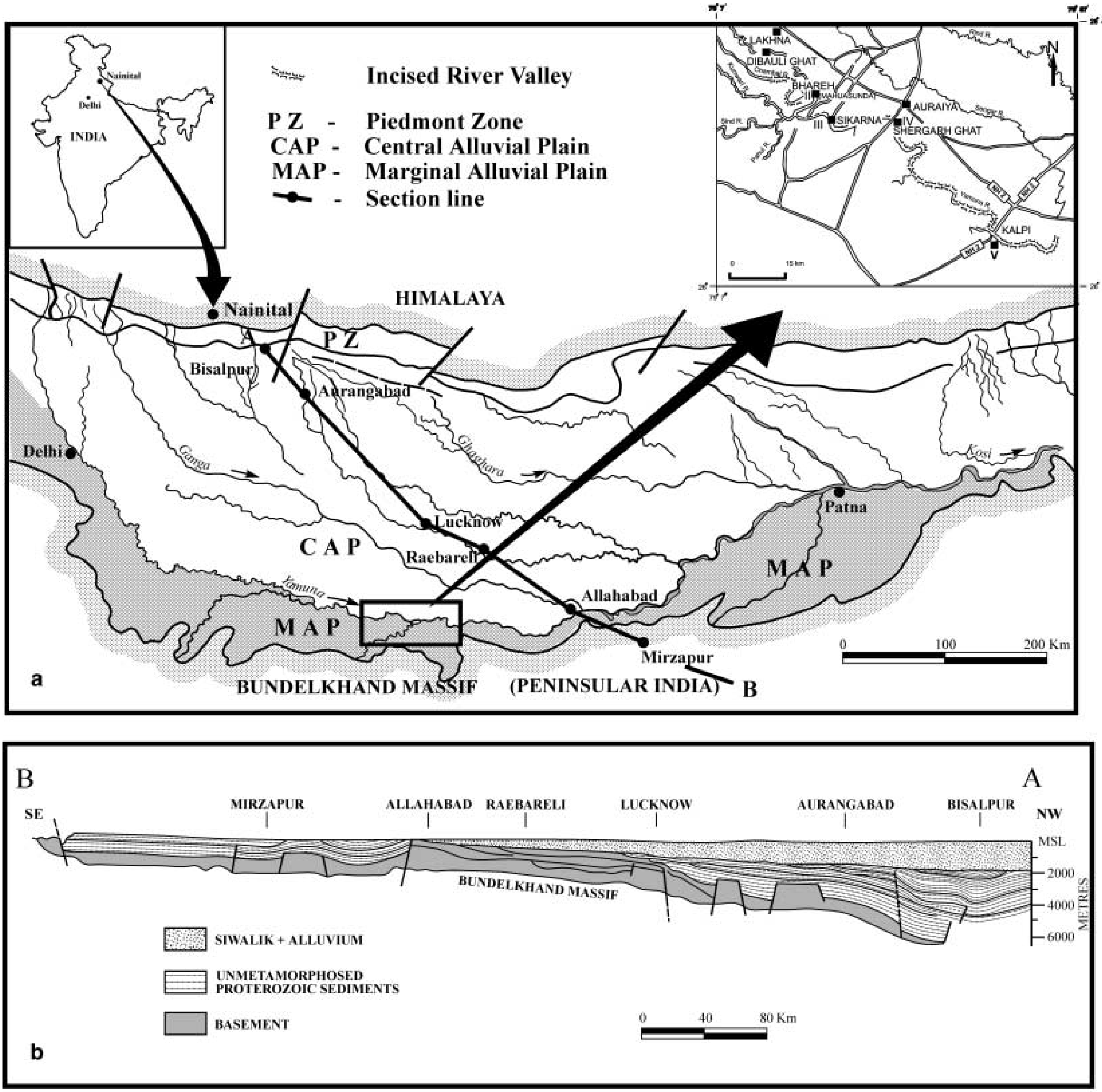

Fig. 1 **a** Location map showing the major localities in the Central Alluvial Plain and Marginal Alluvial Plain, the boundary between the two is marked by the axial rivers (Yamuna in the west and Ganga in the east after Allahabad), India. *I–IV* (in the *inset, top right corner*) Positions of the sections shown in Fig. 2. The line of cross section of *II* is also shown (*A–B*). **b** Cross section shows the sediment fill of the Ganga Plain foreland basin. Sediments are shown partly above the basement, partly above the Late Proterozoic sediments (modified after Karunakaran and Rao 1979)

fill (Sastri et al. 1971; Rao 1973). A geologic cross section of the foreland basin, based on geological data and information from a few boreholes, is shown in the Fig.1a, b. This cross section exhibits a wedge-shaped sediment fill of the foreland basin, thickening in a NW direction, close to the Himalayan orogen (Fig. 1a).

The neotectonic activity in the Ganga Plain has been recorded in several studies (Singh and Rastogi 1973; Singh and Bajpai 1989; Mohindra et al. 1992; Mohindra and Prakash 1994; Singh and Ghosh 1994; Srivastava et al. 1994; Kumar et al. 1996; Prakash et al. 2000). This has been interpreted on the basis of displacement of the Siwalik Hills, the skewness of fan surfaces, the preferential alignment of the rivers, sudden changes in the direction of river courses, nick points and distortion of meanders, straightness of the rivers, presence of escarpments, and asymmetrical terraces. It was documented that, in the southern part of the Ganga Plain, the intensity of neotectonic activity is relatively high, especially in the form of deep incision by rivers and ravine (bad land) development, tilted blocks, up-warps, and open fractures

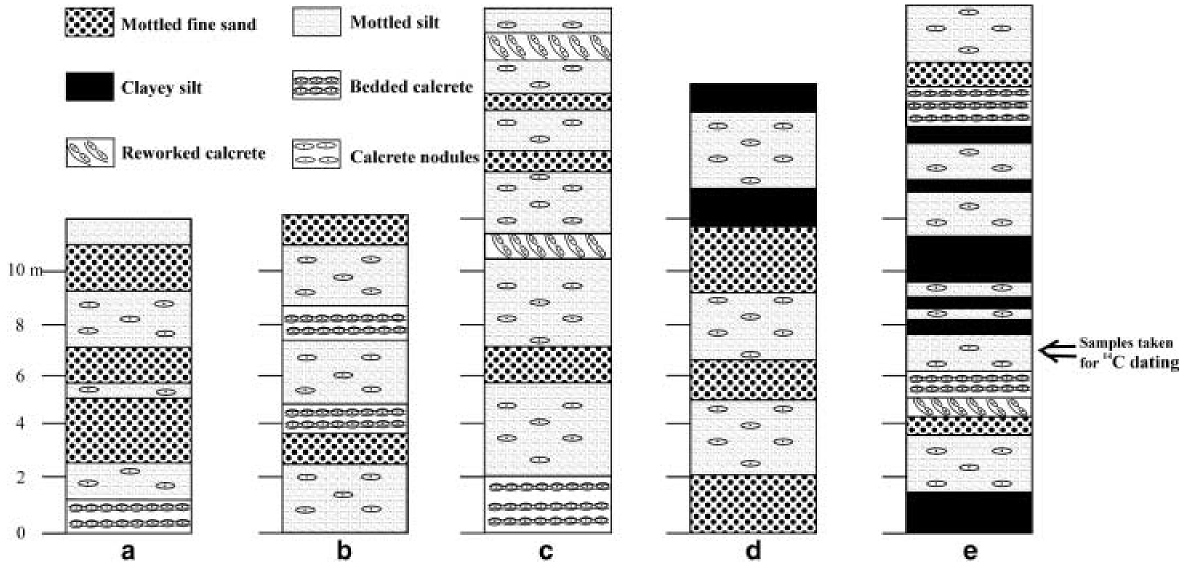

Fig. 2 Sedimentological logs of the cliff sections exposed at **a** Dibauli Ghat, **b** Mahuasunda, **c** Sikarna, **d** Shergarh Ghat, and **e** Kalpi

(Singh 1996; Singh et al. 1999b). The neotectonic activity observed in the Ganga Plain is of Late Pleistocene–Holocene age. In India, the term neotectonic activity is generally used for the tectonic activity of Quaternary age.

The fluvial processes and the tectonic activities chiefly control the sediment fill in this region. The thicknesses of the alluvial fill are highly variable because of the presence of a number of active basement faults (Sastri et al. 1971; Rao 1973; Bajpai 1989; Singh 1996, 1999). All along the width, the Ganga Plain is identified into three distinct zones: the piedmont zone, located close to the Siwalik Hills; the central alluvial plain, located between the piedmont zone and the axial river; and the marginal alluvial plain, the area between the axial river and the craton (Fig. 1a). The rivers in the southern part of central alluvial plain flow parallel to the foreland basin axis, i.e., W–E to NW–SE, and along their courses they show evidence of block uplift and river incision. The rivers of the marginal plain flow in SW–NE and W–E directions, mostly exhibiting vertical cliffs on either side of the river channels. The heights of the cliffs are up to 50–60 m above the rivers beds and offer an opportunity to study the sedimentary and tectonic features in Late Quaternary deposits. These cliffs are often dissected by cross fractures, which at many places are quite symmetrical and evenly spaced, and make 60–80-m-wide triangular faceted blocks.

The purpose of the paper is to document the salient tectonic features seen in the Late Quaternary sediment fill of the southern part of the Ganga Plain foreland basin, namely in the southern part of the central alluvial plain and the marginal alluvial plain, which show evidence of prominent extensional tectonics. An attempt is made to develop a generalized model for the tectonic evolution of the peripheral bulge (forebulge) of the Ganga Plain foreland basin.

Neotectonic features

Surface expressions of the neotectonic activity in the area of study are observed in the form of kilometer-scale undulations with a relief of 5–10 m. These undulations are more prominent in the marginal alluvial plain where the undulatory landform looks similar to the drumlin landscape of the periglacial regions. As already mentioned, most of the rivers in this area exhibit features that are related to tectonic control (Singh et al. 1996). Further, the rivers are incised to expose 5–20-m-high cliffs exposing Late Pleistocene–Holocene deposits, which exhibit neotectonic features in the form of open fractures and tilted beds in the sedimentary layers. The dips are invariably away from the river channels and define gentle arching of the sedimentary layers. Exogenic mass movement can be excluded as a reason for the dips in the sedimentary layers because this process would produce dips towards the river channel. In the following we describe the neotectonic features observed in the cliff sections in the area of study. Evidence for neotectonic activity is observed along the Rivers Yamuna and Chambal and their main tributaries, which fall in the Etawah, Jalaun, Auraiya, and Kanpur Dehat districts of Uttar Pradesh. The cliffs exposed along these rivers invariably show triangular faceted blocks that are regularly spaced, and are mostly back tilted by 2–3° (away from the river channels). The sedimentary layers within them are up-arched and attain a maximum dip of about 8–10° on the flanks.

At Dibauli Ghat, near Lakhna (Fig. 1), the exposed cliff section of Yamuna River is dominantly composed of mottled silt units with dispersed calcrete nodules (Fig 2a). A few horizons of bedded calcrete are also present. Layers of silty fine sand are rare in this section. The Yamuna River in this section follows an ENE–WSW

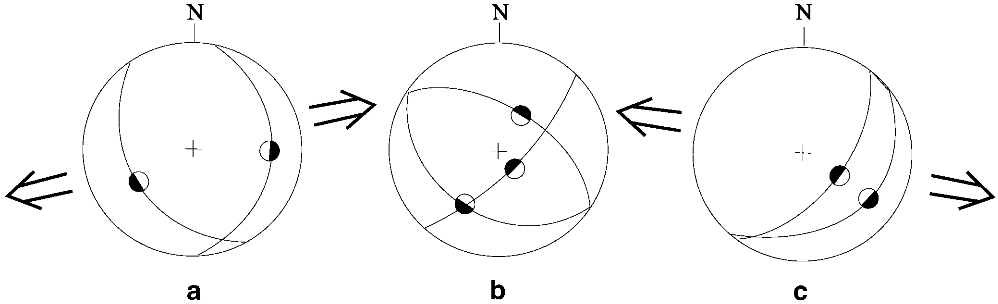

Fig. 3a–c Stereographic projection of fracture systems. *Filled half circles* represent hanging wall going downwards. **a** Two sets of fractures two of them are dipping moderately towards each other at Dibauli Ghat (*n*=30). **b** Three sets of symmetrical fractures dipping around 50° towards each other, whereas the third set is oriented NE–SW and dips around 75° towards NW at Mahuasunda (*n*=40). **c** Two sets of asymmetrical fractures oriented in NE–SW direction dipping 26° to the NW and 55° in a SE direction at Sikarna (*n*=30). All the plots represent the mean directions of the data recorded along the cliffs

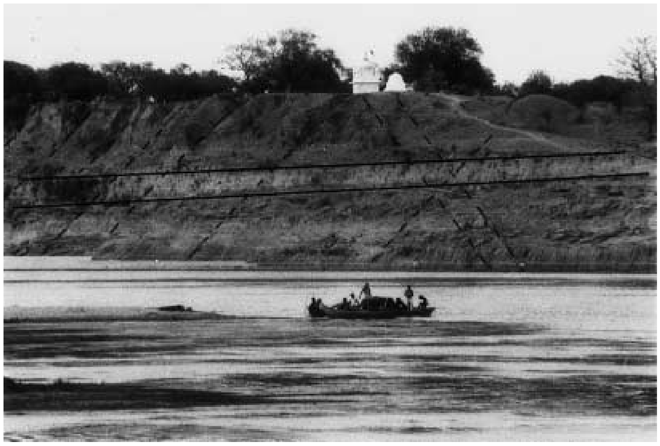

Fig. 5 Cliff section exposed at Sikarna. Note the asymmetric nature of the triangular faceted blocks along the west bank of the Yamuna River

Fig. 4 High cliffs (10–20 m) exposed on the west bank of River Chambal at Mahuasunda near Bhare. Note the wide stretch and triangular shapes in the cliffs. The fractures are seen at the basal part of the cliff and they continue in to the erosional surfaces of the facets

trend, and cliffs of 15–20 m and 5–8 m heights are exposed on the NNE and SSW banks, respectively. Two sets of fractures are observed in these sedimentary successions. One of them is oriented NW–SE, dipping 40° due SW, and the other is oriented N–S, dipping 30° towards the east (Fig. 3a). The fractures in this section are mostly millimeter scale wide and are filled with calcrete.

At Mahuasunda, near Bhare (Etawah district), the cliff section along the Chambal River shows development of bedded calcrete at the base followed by a mottled silt horizon. This, in turn, is overlain by a succession of interbedded mottled fine sand and mottled silt horizons (Fig. 2b). In this area, the Chambal River follows almost a N–S trend and has nearly vertical cliffs of about 10–20 m height on the west bank and 3–10 m height on the east bank of the river. The cliff section stretches for about 1 km and is systematically traversed by three sets of fractures (Fig. 4). Two of them strike N60°W–E30°S, dipping around 50° towards each other; whereas the third set of fractures are oriented almost NE–SW, and dip 75° towards the NW (Fig. 3b). These fractures are often open-type fractures with 2–3-cm-wide gaps across. Sometimes the fracture planes are sealed by calcrete and run throughout the height of the cliffs. The directional measurements of the fractures are made all along the length of the cliff (in all, 35 measurements have been made in about a 1-km stretch). The sedimentary layers are gently up-arched and the regional surface slopes away (back rotated) from the river channel.

In the cliff section near Sikarna on the Yamuna River, a bedded calcrete horizon is present at the base. The rest of the succession is composed of mottled silt units with an abundance of calcrete nodules (Fig. 2c), along with a few horizons of silty fine sand, with channel fills of reworked calcrete. The Yamuna River here follows the NNW–SSE to N–S tectonic direction and the heights of the cliffs on the west bank range between 15 and 25 m (Fig. 5). The asymmetrical triangular blocks seen in the cliff section are separated by two sets of fractures, both striking in a NE–SW direction; one dipping 26° in a NW direction and the other dipping 55° in a SE direction (Fig. 3c).

At Shergarh Ghat, near Auraiya, the succession is composed of mainly calcrete nodule-bearing mottled silt and mottled silty fine sand units. Up to 1-m-thick clayey silt bands are present near the top (Fig. 2). The Yamuna River follows a N–S trend for a considerable distance downstream. The height of the cliffs on the west bank

Fig. 6 Cliff section exposed at left bank of river Yamuna at Shergarh Ghat near Auraiya. The calcrete nodule bearing mottled silt and mottled silty fine sand units are cut by conjugate fractures. Note the tilt in the blocks away from the river channel (river flows on to the *left-hand side of the photograph*)

Fig. 7 Cliff section exposed on the right bank of Yamuna River at Kalpi. Note the up-arching of the sedimentary layers (maximum in the central part and gradually diminishing on the flanks towards the *left-hand side of the photograph*) is prominent. The fractures are highlighted by the *dashed lines*

ranges between 20 and 25 m, and on the east bank between 5 and 10 m. The symmetrical to asymmetrical blocks of the cliff are bounded by a conjugate set of fractures, oriented in a NE–SW direction throughout the cliff section (Fig. 6).

At Kalpi, the exposed cliff section shows three depositional events (or successions) each made up of several lithological units (Singh et al. 1997; Fig. 2e). The lowermost event consists of clayey silt and mottled silt units, capped by a bedded calcrete horizon. The second event is composed of alternating units of mottled silty fine sand and clayey silt subunits capped by a bedded calcrete horizon. The third event is a silty succession with few lenses of mottled fine sand. The Yamuna River shows an E–W orientation and the triangular, faceted cliffs are present on both sides of the river (Fig. 7). The

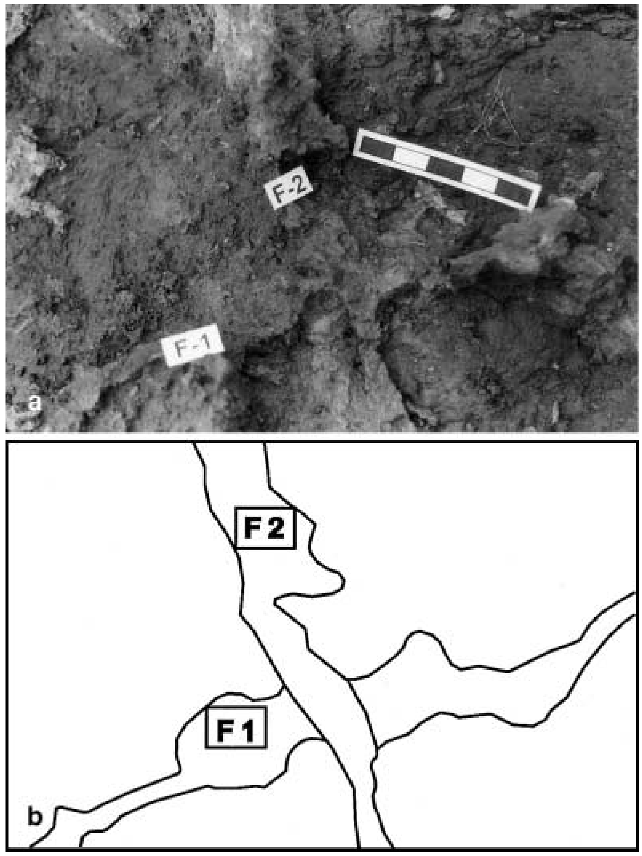

Fig. 8 **a** Photograph showing the calcrete filled fractures at Yamuna River section (right bank), near Kalpi, and **b** the drawing of the fractures

cliff height ranges between 15 and 30 m on the right bank (southern side). The succession of the cliff is traversed by two 2–3-cm-wide sets of calcrete-filled fractures. The whole section is very systematically traversed by these fractures, which run throughout the height of the cliffs. One set of fractures is oriented in a NW–SE direction, dipping 80° towards the NE, whereas the other set of fractures is oriented in a ENE–WSW direction, dipping 70° towards the NNW.To get an idea of the timing of the activation of these fractures, the calcrete of these fractures has been dated using the ^{14}C-method. The calcrete of NW–SE-oriented fractures gives ^{14}C age of 21,500±270 years B.P. (BS-1319), whereas the calcrete fill of ENE–WSW-oriented fractures gives a ^{14}C age of 10,460±140 years B.P. (BS-1318; Fig. 8). These data indicate that the fractures opened at different times during the Latest Pleistocene–Early Holocene, and filled with calcrete at different times.

Near the road bridge of NH2 on the Sengar River, a tributary of the Yamuna River in the Ganga–Yamuna doab (upland interfluve), a well-developed 10-m-thick section is exposed on the right bank (southern side) of the river. The cliff shows two sets of fractures oriented NNE–SSW and NNW–SSE. The sediment layers show marked bending and back tilting of the blocks. The fractures cut across the sediment deposits. A horizon of calcrete conglomerate with molluscan shells gave a ^{14}C age of 9,960±80 years B.P. (BS-1324) for the lamellibranches exposed in the cliff.

The data presented above demonstrate that the fractures are prominently developed in all the sections of the study area and have been responsible for the origin of triangular faceted blocks in the cliffs of the rivers. Furthermore, there are well-defined bending of the sediment layers and tilted blocks away from the river channels. The most consistent feature of the region is incision of all the active channels, suggesting a vertical uplift of the area. The heights of the cliffs along the rivers are of different magnitude and appear to have kilometer-scale amplitude. This feature, as discussed earlier, is caused by the large-scale undulations present in the interfluve area in the whole of the Ganga Plain, and there is a marked difference in the thickness of the sediment fill across the rivers (Bajpai 1983; Singh and Bajpai 1989). The radiocarbon dates of the molluscan shells and thermo-luminescence (IRSL, infrared stimulated luminescence; BGSL blue-green stimulated luminescence) dates of sediments of the cliff sections give ages of Late Pleistocene to Holocene (Singh et al. 1999, unpublished data of several sections). The areas of high cliff usually show deep gullying and erosion as compared with the adjacent parts of low cliffs where no gullying is apparent. The lithosphere in the peripheral bulge of the Ganga Plain in the study area is made-up of gneissic granites, and the sediments are derived from these basement rocks exposed in the cratonward part of the Ganga Plain.

AMS analysis as evidence of tectonic disturbance

AMS analysis is practically useful for all rock types and especially for sediments that have only minor deformation, and where the effect of deformation is hard to record. In order to study the tectonic activities in the Ganga Plain foreland basin sediments, a preliminary analysis was done on four representative samples (Hrouda et al. 1990; Tarling and Haruda 1993; Mamtani et al. 1999).

The directional data for these samples is shown on the stereoplots (Fig. 9). These samples show a very well-defined magnetic foliation and a pronounced magnetic lineation oriented in a NNW direction, which corroborates with the fracture system recorded here.

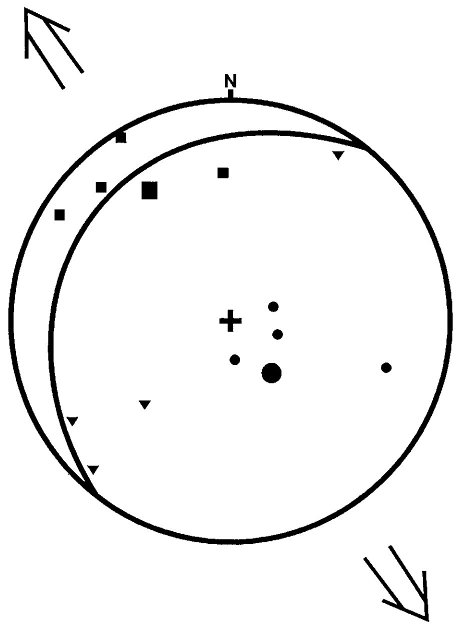

Fig. 9 Stereoplots (lower hemisphere) of the magnetic directions of the samples from the Kalpi cliff section. The magnetic lineation is represented by the *squares* (k_{max}), and the pole of the magnetic foliation is represented by the *dots* (k_{min}); $n=4$

Discussion and conclusions

The foreland basins are considered to have formed by elastic (Lyon-Caen and Molnar 1985) or visco-elastic deformation of the lithosphere (Beaumont 1981), in an overall contractional regime. Fraser and DeCelles (1992) considered the tectonism to be the first phase of foreland basin development and the later modifications were achieved by the sedimentation pattern. Garfunkel and Greiling (1996, 1998) argue that the foreland basin development is controlled by the shape and geometry of the orogenic loads. The two-phase model of Heller et al. (1988) suggest that, during the phase of increased thrust-sheet loading in the orogen, basin subsidence is most rapid. Increased loading in the orogen also causes down-bending of the under-thrusted lithospheric plate and, in response to this increased loading in the orogen on the cratonward parts of the basin, a peripheral bulge is produced. Sometimes the peripheral bulge includes the sediment cover of the foreland basin above the lithosphere. The phase of increased thrust-sheet loading is followed by a phase of lithospheric relaxation, when erosional removal of the mass in the orogen takes place and maximum sediment is received from the orogen into the foreland basin.

In the case of the Ganga Plain foreland basin, the last major thrusting event is considered to be around 500–700 Ka, when rocks of upper Siwalik age (Pliocene–Early Pleistocene) were uplifted by about 2 km (Singh 1996). Based on the nature of the sediment fill (Himalayan sediments overlapping the cratonic sediments), the southward migration of the Ganga Plain during the Late Quaternary is considered to be the activity that caused the peripheral bulge in response to the last thrusting event in the Himalaya (Singh and Bajpai 1989). During the last 500 Ka the basin has been in a relaxation stage. The lithosphere near the peripheral bulge on the cratonward side of the Ganga Plain in the study area is made up of gneissic granites with tens of meters to a few hundred meters-thick sediment cover derived from these basement rocks. In this study, essentially, the tectonic

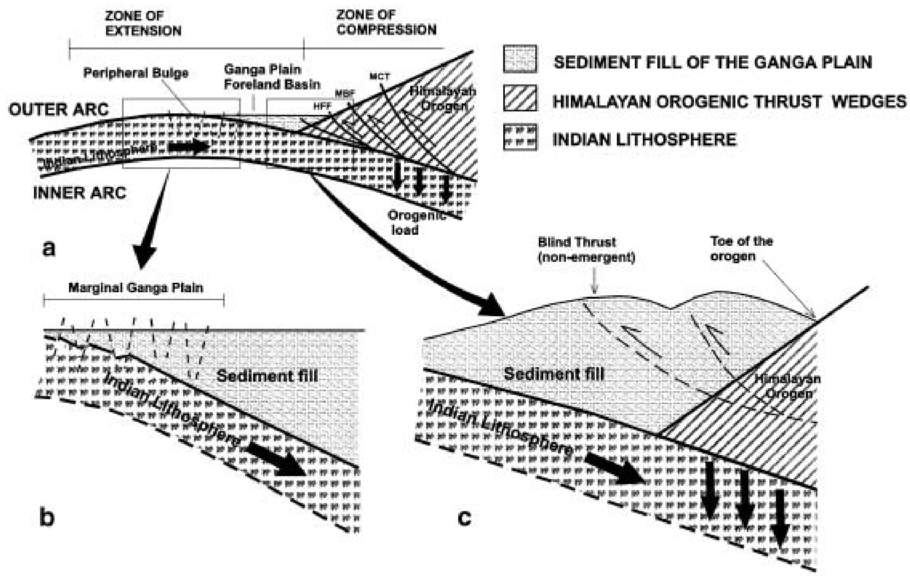

Fig. 10 **a** Schematic cross section of Indian lithosphere and Ganga Plain foreland basin. **b** Active tectonic features of marginal Ganga Plain. **c** Tectonic features at the toe of the orogen, marked by the presence of few blind thrusts. *MCT* Main central thrust; *MBF* main boundary fault; *HFF* Himalayan frontal fault

features of the sedimentary cover of the peripheral bulge are investigated.

The stratigraphy of the upland interfluvial area in the southern part of the Ganga Plain (peripheral bulge region) is made up of deposits of sloping surfaces, flat areas, small channels, and ponds and lakes that make distinctive depositional facies, termed doab (upland interfluve deposits; Singh et al. 1999a). The main rivers flow mainly in a W–E direction following the major tectonic lineament direction. They are highly incised, and expose vertical cliffs whose heights vary from one place to another. The entire region is affected by fractures (mostly in conjugate sets), bending, up-doming, and back tilting of blocks. The cliffs along the course of the river channels are made up of blocks that are symmetrical with triangular facets. The blocks are back tilted (2–3°), and the sedimentary layers attain dips of 8–10° away from the river on the flanks. In the entire studied area, the triangular facets of the cliffs show conjugate systems of fractures oriented mainly in NNE–SSW and NNW–SSE directions and are often filled with calcrete (sometimes up to the entire height of the vertical blocks), e.g., the Kalpi section. In the lower part of many cliff sections, fracture planes filled with calcrete, are visible and, in the upper part, they have erosional surfaces that are responsible for producing the triangular facets in the cliffs (Fig. 4). These fractures dip with moderate to steep angles (30–70°), and are both synthetic and antithetic in style.

Shallow boreholes drilled through the marginal alluvial plain at different places encountered the basement at different depths. In areas where the rivers follow the sites of lineaments and normal faults affect both the basement and the alluvial fill, the thickness of sediment fill across such faults exhibits large variation (Bajpai 1989; Singh and Bajpai 1989; Singh 1996, 1999). This indicates that the Indian lithosphere behaved in a brittle manner. The main tectonic trend in the region of the peripheral bulge of the Ganga Plain developed roughly perpendicular to the extension direction of the Indian lithosphere (roughly NNE; Molnar and Tapponier 1975; Ni and York 1978). A set of interlocking array of conjugate faults, which are both synthetic and antithetic, developed within this extensional domain, near the peripheral bulge. These faults are oriented either perpendicular to or at a high angle to the regional trend of the axial rivers (roughly WNW–ESE). The evidence of syn- and post-depositional extensions can best be seen in the form of calcrete-filled cross fractures dissecting the deposits in the cliffs that have tectonically deformed sedimentary fill.

Modeling of the peripheral foreland basins, in general, is based on the assumption that the nature of the crust is viscoelastic (Beaumont 1981) or elastic (Lyon-Caen and Molnar 1985). However, the Ganga Plain foreland basin exhibits characteristic geometric features, prominently developed in the central and southern parts of the basin, indicating partly brittle behavior of the crust. This is mainly based on the fact that the sediment cover is up to 5 km and the basement shows vertical faults. In our model, the colliding Indian lithosphere behaved rigidly in the peripheral bulge region. The down-bending of the lithosphere because of the thrust sheet loading in the orogen induced extension and normal faulting in the distal part (at the outer part of the bent lithosphere) of the foreland (Bradley and Kidd 1991). The effects of lithospheric extension are pronounced in the distal parts (peripheral bulge) of the foreland. Displacement along important gravity faults in the lithosphere of the peripheral bulge region is of tens of meters to a few hundred meters in magnitude (Bajpai 1983; Singh and Bajpai 1989; Singh 1996). Studies of neotectonic activity in the Ganga Plain (Singh et al. 1996) demonstrate that it can be identified in three regions, running as parallel belts from north to south, each with its characteristic features. The northern part, the piedmont plain, and the adjacent Siwalik Hills are characterized by a contractional regime, evidenced by thrust-sheet movement and blind thrusts (buried under the sediment cover), and a conjugate system of strike-slip faults (mostly in NE–SW or NW–SE directions). The central part, the central alluvial plain, is characterized by NW–SE- and WNW–ESE-trending lineaments, which have partly acted as normal faults (Singh 1996), and are evidence of lithospheric extension. The southern part, the marginal alluvial plain, shows mainly W–E lineaments, with strong evidence of normal faults and graben-like features, which is strong evidence of lithospheric extension (Fig. 10). Some of these extensional faults affected the sediment fill alone, whereas others extend into the basement (Singh and Bajpai 1989). The extension in the Indian lithosphere is related to the down-sagging of the distal part of the lithosphere caused by the increased orogenic loads of the Himalaya (Fig. 10), as a result of which the outer arc of the Indian lithosphere probably produced extensional normal faults in roughly a E–W direction. This fact is supported by the highly entrenched E–W aligned river valleys in the axial zone of the Ganga Plain and also by the presence of fractures in roughly a E–W direction (Fig. 3b). Another prominent set of fractures, normal to the peripheral bulge, are also observed, oriented in NW–SE and NE–SW directions in several cliff sections exposed along the rivers (Fig. 3a, c) of the Ganga Plain. These fractures are also recorded in few AMS analyses, which show a strong magnetic lineation oriented in NNW direction (Fig. 9).

During the present relaxation phase (Heller et al. 1988) of the Ganga Plain foreland basin (since about 500 ka), there has been increased tectonic activity in the peripheral bulge, the cratonward margin of Ganga Plain. However, the axial rivers have not shifted orogenward as conceived in the general models of the foreland basins (Heller et al. 1988; Burbank 1992), but have responded by making incisions in their own deposits. There is a net deposition in the peripheral bulge region (Singh et al. 1997) and not erosion as conceived in generalized foreland basin models during a relaxation phase (Heller et al. 1988). The entire peripheral bulge region is an area of extensional tectonics, which has also led to the down-faulting and preservation of sedimentary sequences. Wicks et al. (2000) recorded similar fracture patterns around the Black Hills foreland uplifts in Cretaceous sequences of the western USA. It seems that down-flexing of the Indian lithosphere generated extensional stresses in the cratonward distal part of Ganga Plain foreland basin. In the peripheral bulge region, extensional tectonics led to the development of both synthetic and antithetic fractures that are vertical to high angled on the surface, but die out at depth and also cause back tilting of blocks by a few degrees in places.

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