Holocene tectonic movements and stress field in the western Gangetic plains

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Using the soil-geomorphic approach recently, distribution and degree of development of surficial soils have been used to identify four tectonic blocks – Piedmont, Upper Ganga–Yamuna, Lower Ganga–Yamuna and Ganga–Ramganga blocks in the region between the Yamuna and Ramganga rivers in the western Gangetic plains.

Luminescence dating of the soils from different blocks has been used to constrain timing of block movements. For example, the Lower Ganga–Yamuna, Ganga–Ramganga and Upper Ganga–Yamuna blocks were uplifted at 8.5 ka, ~5 ka and ~ 2.5 ka, respectively. Also the shifting of the Ganga River from the Upper Ganga–Yamuna block to the Ganga–Ramganga block took place at about 2.5 ka. The Ganga–Ramganga block was tilted westward at about 1 ka causing a shift of the Ganga River in that direction. Additionally, a number of smaller movements are inferred during the last 500 years or so.

Holocene compression directions from west and south-west were inferred from tilting of large blocks. Further, the thickness of Tertiary sediments over the Precambrian rocks in the Gangetic plains was used for finite element modelling of the stress pattern for the region. It suggests that the fault pattern retains signatures of compression from both the west and the south-west and their orientations are strongly affected by the confining nature of the southern boundary and subsurface Aravalli Ridge in the west.

ACTIVE tectonic/palaeoseismic studies undertaken so far in the Himalayas and its foreland, the Indo-Gangetic basin are:

(i) Instrumental recording of earthquakes (summary given in Gupta[1]).
(ii) Geomorphic evidence based on identification of active faults and recent deformations[2–6].
(iii) Instrumental recording of actual movements in different parts of the Himalayas[7–10].
(iv) Study of soft sediment deformation in lacustrine deposits to infer palaeoseismic events[11–14].
(v) Dating by thermoluminescence technique of fault gauges to determine the last major activities along the MBT and HFF[15].

Workers at University of Roorkee have adopted another approach using soil for inferring neotectonic activity in the Indo-Gangetic plains[16–18]. Recently, a number of workers have used soil to date activity of faults (see reviews by McCalpin[19] and Yeats *et al.*[20]). They have trenched across the fault zone and prepared stratigraphic sections, especially in regions with arid/semi-arid climate marked by a low rate of sedimentation. In sections, development of soil and horizons with coarse sediments has been taken as periods of quiescence and activity of faults, respectively. However, major parts of the Indo-Gangetic plains are marked by relatively subhumid to humid climate and a high rate of sedimentation. Here a different approach using soil for deciphering tectonic activity of the region was adopted[16–18]. In this technique, soil-geomorphic units are mapped and relative degree of soil development in each unit is determined by various pedological techniques and a soil-chronoassociation[16] is erected for the region. From these studies tectonic blocks are deciphered and uplift/subsidence and tilting of blocks are interpreted on the basis of distribution of soil-geomorphic units. Absolute dating of soil provides absolute dates of activity of tectonic blocks. In this study an example of application of this new technique in the western Gangetic plains is presented. Also, an attempt has been made to model stress conditions in the region using finite element method.

Soil investigations and tectonic movements in the present area have been studied by Kumar *et al.*[18]. In the present paper, a revision of these aspects is proposed based on recent fieldwork, luminescence dating and finite element modelling.

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General features of the study area

The study area constitutes the western part of the Gangetic plain and lies between latitude 27°15'N to 30°30'N and longitude 77°10'E to 79°10'E (Figure 1). Ganga, Yamuna and Ramganga are the major rivers in the area, which flow in the southerly direction in the northern parts, turning eastward in the southern parts. Courses of these rivers reflect broadly the regional surface gradients in these plains.

Major soil-geomorphic units and faults in the study area have been identified using satellite data and topographic sheets (Figure 2). Field visits were carried out to determine the soil characteristics of these units.

Major soil-geomorphic units

Morphologically, four major landforms are recognized. These are: piedmont, plains associated with rivers, interfluves and aeolian plain. A number of soil-geomorphic units with soil characters varying within small ranges were deciphered within each landform.

Piedmont

In the study area, piedmont is a steeply sloping, narrow (10–25 km wide), elongated landform, drained by many parallel to sub-parallel seasonal streams. These streams are generally small and braided in character. They flow

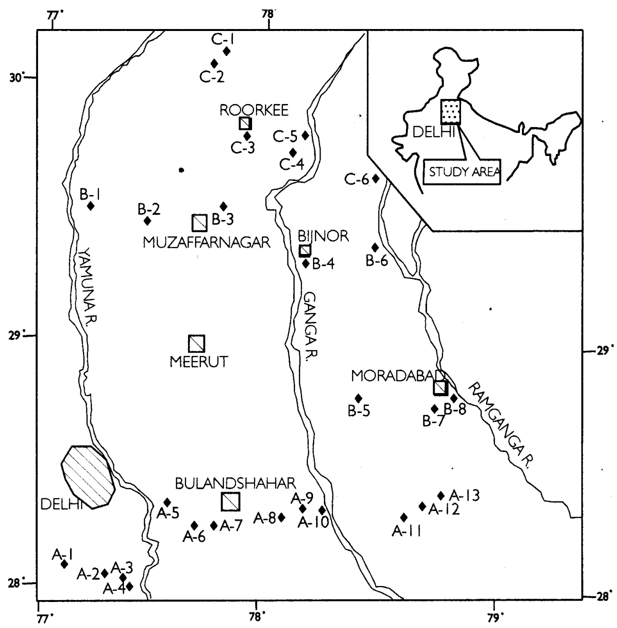

Figure 1. Location map of the study area. Locations of investigated pedons are also shown.

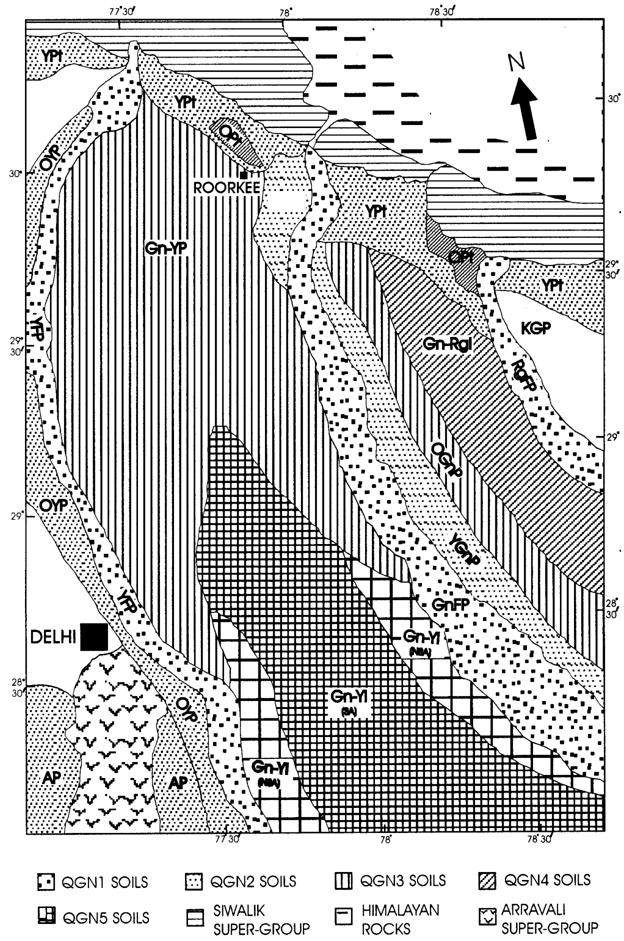

Figure 2. Soil-geomorphic map of the study area. GnFP, Ganga flood plain; YGP, Young Ganga plain; OGnP, Old Ganga plain; Gn-RgI, Ganga–Ramganga interfluve; KGP, Kosi–Gola plain; Gn-YP, Ganga–Yamuna plain; Gn-YI, Ganga–Yamuna interfluve; SA, Salt affected; NSA, Non salt affected; YPt, Young piedmont; OPt, Old piedmont. Modified after Kumar *et al.*[18].

for some distance in a slightly incised course, whereafter the channel ceases to exist. However, larger streams like the Ratmau, Solani and Khoh continue further south and join major rivers like the Ganga or Ramganga. Some streams form well-developed small fans between the Ganga and Khoh rivers.

Within the piedmont zone, two soil-geomorphic units, viz. (i) younger piedmont (YPt) and, (ii) older piedmont (OPt) have been recognized. The YPt is overlain by poorly developed soil and sediments deposited from many braided streams traversing this area. The OPt is overlain by moderately to well-developed soil.

The OPt is present as a triangular uplifted block, bound by minor faults between the Yamuna and Ganga rivers. Small rivulets, showing dendritic drainage pattern, originate from the block and have removed soil from most of the unit, exposing older coarser sand. The uneroded and non-dissected portion of the unit has moderately well-developed soil covering less than 10%

of the area of the block. At a few locations, south of the town of Roorkee, soil of this unit is preserved in small patches below soil of the Ganga–Yamuna plain as a palaeosol. The OPt is present as a rectangular block between the Khoh and Ramganga rivers. It is being eroded and the material is being spread out as a thin sheet of sand further south, which is included in the YPt.

Plains associated with rivers

These plains are overlain by poorly to moderately developed soil and their clear association with some rivers can be identified from satellite images. These include the Yamuna plain, Ganga plain, Ramganga flood plain, Ganga–Solani plain and Ganga–Yamuna plain.

Yamuna plain: The Yamuna river, a major perennial tributary of the Ganga river, enters the Gangetic plain along the Yamuna Tear Fault. The channel patterns changes from braided to meandering, 35 km after the river enters the plain. In the area, the Yamuna plain is slightly incised and guided by the Yamuna Fault along the western boundary. Two soil-geomorphic units, old Yamuna plain (OYP) and Yamuna flood plain (YFP), are recognized from this geomorphic unit. The OYP is a flat surface lying in the western part of this geomorphic unit. The plain is characterized by the weakly developed soil and presence of salt efflorescence at a few places. It does not continue further downstream of the study area due to highly entrenched nature of the channel. The YFP is marked mainly by entisols and numerous abandoned channels.

Ganga plain: The Ganga enters the plains at Hardwar along a tear fault forming a megafan[21]. The Ganga plain has been divided into three soil-geomorphic units – old Ganga plain (OGnP), young Ganga plain (YGnP) and Ganga flood plain (GnFP). The first two form uplands, whereas the last has a slightly entrenched nature.

Both OGnP and YGnP are marked by palaeochannels, which on extension to the north-west meet the active channel at Hardwar. The OGnP has heavy loamy soil, whereas the YGnP has sandy soil. Aeolian activity has reworked alluvial soil of the YGnP into sand mounds up to 3 m high.

The GnFP is characterized by a braided channel in the proximal 50 km in the plains, then a straight channel for about 20 km and ultimately a meandering river. The river course is guided by the Balawali and Ganga Faults. The GnFP is bound by the Ganga Fault with a bluff of 10 to 20 m on the west and low cliffs on the opposite side. Oxbow lakes, abandoned old channels and alkalinity are common features.

Ramganga flood plain (RgFP): The course of the Ramganga river is guided by faults and all through its course, it flows in a number of straight stretches punctuated by sharp turns, before joining the Ganga river.

Ganga–Solani plain (Gn-SP): This is a small unit with sandy to loamy sand soil. It slopes 0.6 m/km due southwest and is marked by waterlogging due to high water table in the southern parts.

Ganga–Yamuna plain (Gn-YP): This is a large (100–120 km × 70–80 km) soil-geomorphic unit, gently sloping towards the south (slope < 0.1 m/km) and marked by numerous palaeochannels of the Ganga and Yamuna rivers forming an integrated anastomosing pattern (Figure 3). Palaeochannels are of two types. Type 1 palaeochannels have sandy zones with sand piled up by wind into linear ridges running several kilometres and with a relief of 2 to 5 m higher than the adjoining areas. Type 2 palaeochannels are now occupied by underfit smaller streams. These palaeochannels seem to have been widened slightly by erosion along their boundaries. Mostly the palaeochannels are very wide (500–800 m) suggesting their formation by large rivers. Also some of these palaeochannels when extended northwards meet the

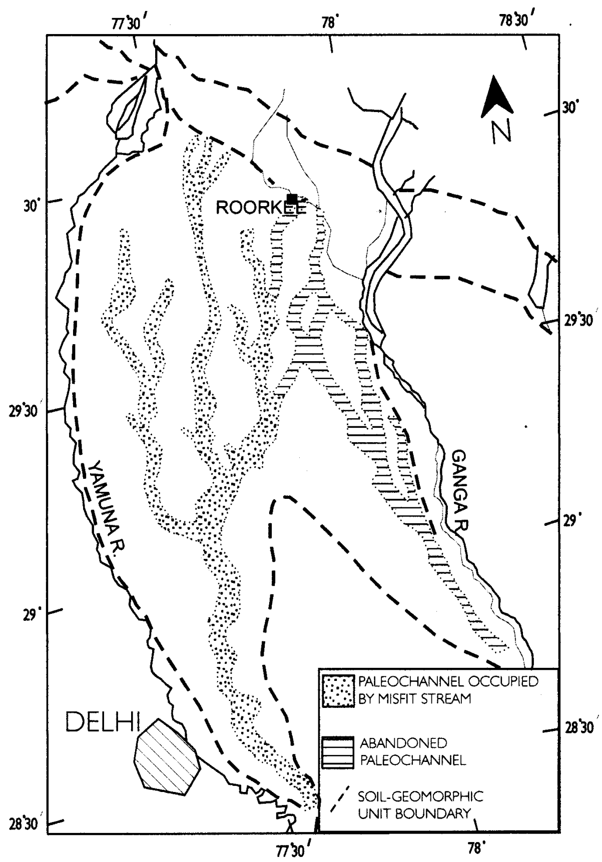

Figure 3. Palaeochannels in the Ganga–Yamuna plain. Modified after Kumar *et al*.[18].

point where the Yamuna and Ganga rivers debauch from the Siwalik Hills into the plains, indicating that these rivers were active on this unit in the past, which is upland in nature presently.

Interfluves

Interfluves are upland areas and occur at the highest level with respect to river flood plain levels in the adjoining areas and are overlain by moderately to strongly developed soil.

Ganga–Yamuna interfluve (Gn-YI): This unit lies in the southern part of the study area and has been earlier called the Ganga Upland[22]. This unit has been divided into two soil-geomorphic units: (a) Salt-affected sub-unit (Gn-YI (SA)) and (b) Non-salt affected sub-unit (Gn-YI (NSA)).

The Gn-YI (SA) unit occupies the central part of the Gn-YI and salt efflorescence in this sub-unit exhibits patchy distribution (in micro depressions) as shown by Landsat images. Soil of this subunit is moderately to strongly developed with extensive development of calcrete.

The Gn-YI (NSA) unit occupies areas of the interfluve close to the rivers Ganga and Yamuna and soil of this unit is similar to that of the salt-affected unit, except for the fact that salt efflorescence is absent and minor amount of calcrete is present.

Ganga–Ramganga interfluve (Gn-RgI): This unit is rectangular in shape with a width of 20 to 25 km and covered with heavy loamy soils. The unit is higher than the adjoining areas by 2 to 4 m and has an undulating topography with a relief of about 1.5 m in the northern parts due to erosion.

Aeolian plain (AP)

This plain occupies a higher level than the OYP and is bound on the western side by outcrops of the Aravalli Hills. It is characterized by coarse textured soil, absence of natural drainage and a gentle slope towards the east.

Tectonic features

Distribution of geomorphological features and soil helped to delineate faults and tectonic blocks. Four major fault-bounded tectonic blocks are recognized: Piedmont Upper Ganga–Yamuna, Lower Ganga–Yamuna and Ganga–Ramaganga Blocks (Figure 4 *a*).

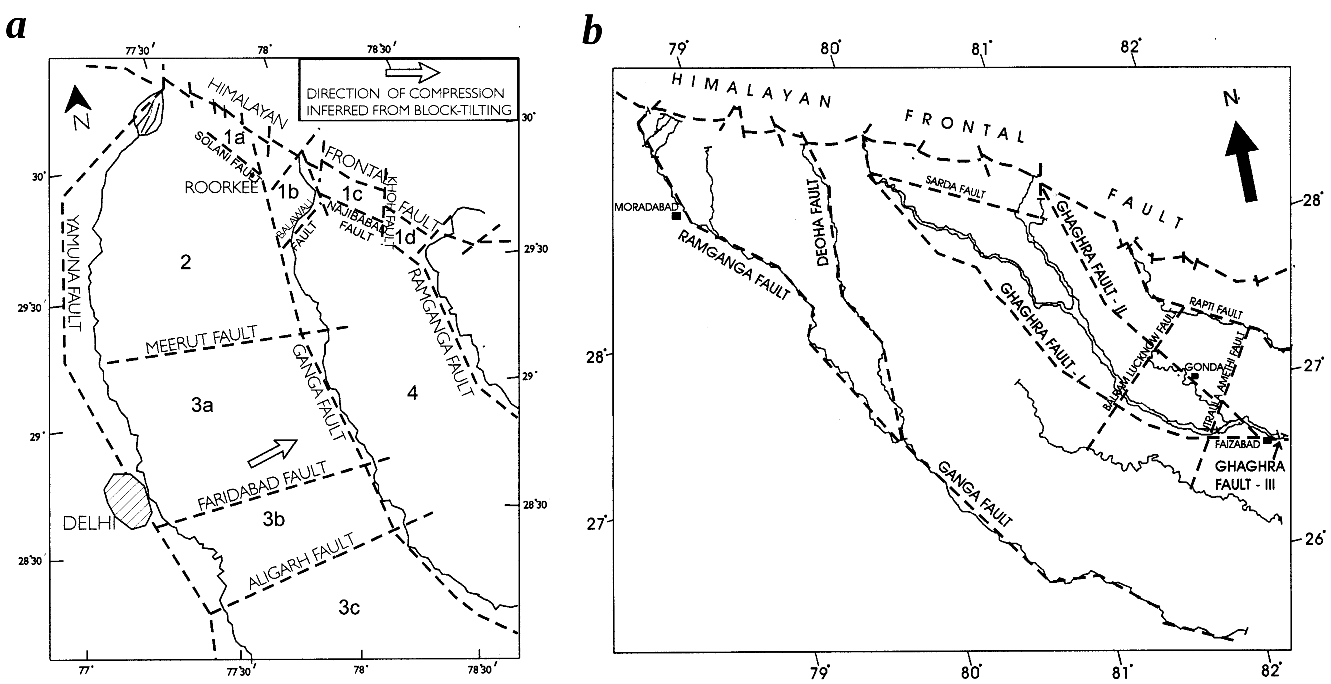

Figure 4 *a*. Surficial faults and tectonic blocks identified in the present area. 1, Piedmont Block; 1a, Solani sub-block; 1b, Solani–Ganga sub-block; 1c, Ganga–Khoh sub-block; and 1d, Khoh–Ramganga sub-block; 2, Upper Ganga–Yamuna Block; 3, Lower Ganga–Yamuna Block, 3a, Modinagar sub-block; 3b, Khurja sub-block; and 3c, Etah sub-block; 4, Ganga–Ramganga Block. ***b***, Surficial faults and tectonic blocks in the region between the Ramganga and Rapti rivers. Patterns formed by Ramganga–Deoha–Ganga Faults and Ghaghra I–III faults have convexity to the south-west and for V's in the north. After Srivastava *et al.*[17].

Faults

Himalayan Frontal Fault: This set of faults separates the geomorphic systems of the Siwalik Hills and the Gangetic plains. This set has been mapped by a number of workers in different areas[3,16,23]. In the present area, these faults trend NW-SE and are offset by some transverse faults like the Yamuna Tear Fault and Khoh River Fault near Najibabad.

Solani and Najibabad Faults: These faults define the southern boundary of the OPt unit. The Solani Fault was earlier delineated by Meijerink[24].

Yamuna Faults: The contact of the YFP with the Aravalli Hills in the west is marked by a set of faults lying in a curve with convexity to the SWW. This set of faults was earlier recognized by Singhai *et al.*[23].

Ganga Faults: This set of faults lies in the middle of the study area marking the contact between the Gn-YP and Gn-YI to the west and south, and GnFP to the northeast. This set of faults starts from the foothills, west of Hardwar, forming the northern boundary of the uplifted OPt and lies along the course of the Ratmau stream. It continues along part of the Solani river and Ganga river courses in N-S direction. These turn near Aligarh to take NW-SE direction. That gives a convexity to the faults to SWW and the curve is sub-parallel to the Yamuna set of the faults. The eastern/northern side of the faults represents the downthrown side with a throw of ca. 20 m and the upthrown block is marked by the presence of a dissected zone or steep cliffs close to the fault. Intersection of the Ganga, Balawali and Solani Faults forms a 'V' with edge point southward (Figure 4 *a*). Almost similar pattern is repeated further east by Ramganga–Deoha–Ganga Faults and Ghaghra I–III Faults (Figure 4 *b*).

Meerut Fault: This fault probably trends E-W defining the northern limit of the Gn-YI unit. This fault roughly coincides with the northern boundary of the subsurface Delhi–Hardwar Ridge.

Ramganga Fault: This fault controls the course of the Ramganga river, which flows in straight stretches of 20 to 120 km and separates the Gn-RgI soil (QGN4) in the west from the Kosi–Gola plain soil in the east (equivalent to QGN2 and QGN3, ref. 18).

Balawali Fault: This fault has an escarpment of about 30 m in the north which decreases to around 10 m in the south within 30 km and the fault terminates against the Ganga Fault. This fault is short in extent and represents the western boundary of the uplifted OPt east of the Ganga river.

Faridabad and Aligarh Faults: These faults trend approximately E-W and lie in the western continuation of the basement Moradabad High. The Yamuna and the Ganga rivers show a compression of meanders and a decrease in width of flood plain, respectively between these faults.

Tectonic blocks

Four major tectonic blocks separated by faults are recognized from the area. These blocks have behaved independently and have been subjected to uplift/subsidence and tilting at different times. The blocks are: Piedmont, Upper Ganga–Yamuna, Lower Ganga–Yamuna and Ganga–Ramganga Blocks.

The Piedmont Block lies in the foothill region and is further divided into four small sub-blocks–Solani, Ganga–Khoh and Khoh–Ramganga and Solani–Ganga sub-blocks. The first three sub-blocks are parallel to the trend of the Siwalik Hills and are 10 to 25 km wide. These are overlain mainly by the YPt (poorly developed soil) and at a few places by OPt (moderately to well developed soil) soil-geomorphic units. The Solani–Ganga sub-block is triangular in plan with its narrow end pointing southward. Though overlain by a plain associated with rivers, tectonically it is in continuity with other piedmont sub-blocks.

The Upper and Lower Ganga–Yamuna Blocks are overlain mainly by the soil-geomorphic units of Gn-YP and Gn-YI. Within the Lower Ganga–Yamuna Block, three sub-blocks are recognized: Modinagar, Khurja and Etah sub-blocks. The Faridabad and Aligarh Faults bounding the Khurja sub-block continue probably beyond the Ganga Fault into the Ganga–Ramganga Block. Though both the Upper Ganga–Yamuna Block and Modinagar sub-block have tilted to the east leading to large shifting of the Yamuna river towards the east (from OYP to YFP), Khurja sub-block has in the recent past tilted very slightly to the west, resulting in tightening of meanders of the Yamuna river and a decrease in the width of the flood plain of the Ganga river over this sub-block. The Ganga–Ramganga Block has been subjected to tilting to the west leading to shifting of the Ganga river in that direction.

Degree of soil development and soil chronoassociation

Field soil morphology and micromorphology have been used to evaluate the degree of soil profile development in the study area. Based on the degree of development, the soil on different soil-geomorphic units has been grouped into five members, QGN1 to QGN5, of a soil-chronoassociation, with QGN1 being the youngest (Table 1).

Table 1. Soil chronoassociation members with dates of soils from different sources/methods given in brackets

Member	Range of age assigned	Soil-geomorphic units included
QGN1	< 0.5 ka	Yamuna flood plain, Ganga flood plain (0.29 ka*[,a]), Ramganga flood plain
QGN2	> 0.5 ka	Old Yamuna plain, Young Ganga plain (1.03 ka*[,b]), Ganga–Solani plain, Younger Piedmont, Aeolian plain
QGN3	~ 2.5 ka	Old Ganga plain, Ganga–Yamuna plain (2.5 ka[36,c], 2.6 ka[36,d])
QGN4	~ 5 ka	Older Piedmont (4.85 ka[37,a]), Ramganga–Ganga Interfluve
QGN5	~ 8.5 ka	Ganga–Yamuna Interfluve (8.5 ka*[,a], 8.3 ka[38], 6.5 ka[3])

[a]GLSL date; [b]IRSL date; [c]TL date; [d]Radiocarbon date of calcrete; Archaeological evidence[16]; *This study, Table 2.

Kumar *et al.*[18] identified a sequence of soil decreasing in degree of development from the Ramganga–Ganga interfluve (most developed) → Old Ganga plain → Young Ganga plain → Ganga flood plain (least developed), occurring from east to west on the Ramganga–Ganga tectonic block. Also a sequence of soils with increasing degree of development from the Young Piedmont (least developed) → Ganga–Yamuna plains → Ganga–Yamuna interfluve on the Ganga–Yamuna tectonic block from north to south was deciphered. However, due to very limited absolute dates from different soil-geomorphic units, correlation between the soils from the two tectonic blocks was tentative. Now, with a reasonable number of luminescence dates, a better soil chronoassociation has been constructed. Our soil chronoassociation given here differs from that given by Kumar *et al.*[18] in that the Old Piedmont and Ganga–Ramganga interfluve (~ 5 ka) are younger than the Ganga–Yamuna interfluve (~ 8.5 ka). Srivastava *et al.*[17] had inferred that a dry, cold climate has prevailed in these plains till about 6 ka giving rise to soil with pedogenic calcrete and salt efflorescence and later climate became warmer and wetter. The absence of pedogenic calcrete and salt efflorescence in the Older Piedmont and Ganga–Ramganga interfluve soil also supports such a younger age for the soil.

Luminescence dating of soil

In the present study, optically stimulated luminescence (OSL) dating technique has been used for dating soil. Here, both infrared stimulated luminescence (IRSL) and green light stimulated luminescence (GLSL) options were employed. The OSL technique was preferred over thermoluminescence (TL) technique, because in the former technique only the charges which are rapidly removed by light exposure are sampled (see Godfrey-Smith *et al.*[25]; Hutt *et al.*[26]) and fluvial sediments like the present one may have been exposed only for short periods. Comprehensive overviews of principles and application of OSL dating have been given by several workers[27–33].

Sample preparation: The sample preparation for both fine grain polymineralic fraction and mineral inclusion technique began with prewash with 1N HCl and 30 to 40% H_2O_2 to remove the carbonates and organic fraction. A fine-grain polymineralic fraction of 4 to 11 μm was separated using Stoke's separation in acetone medium for samples of GnFP and Gn-YI. About 40 aliquots for each sample were prepared, depositing and drying equal volumes of this suspension into aluminium discs. The coarse-grain fraction of YGnP was extracted by drying and sieving the desired grain size from the sample (typically 90 to 105 μm). Grains were then density-separated to float quartz fraction. The mineral separates were then treated with 40% HF to etch the alpha skin and then dried and mounted by sprinkling onto stainless steel discs with silikospray silicon as binding material.

Measurement technique: For the dose rate measurements, thick source alpha counting[27] was used for uranium and thorium estimation and potassium was estimated using Atomic Absorption Spectrometer.

IRSL and GLSL measurements were made on Daybreak 1150 automated TL/OSL system. IRSL analysis was carried out using Schott BG 32 + Corning 5-58 IR rejection filters and GLSL analysis was made using 2 × U340 filter. The aliquots were short-shined to read the normalization values. They were then given a range of additive beta doses and preheated to 220°C for 1 min to remove the unstable signal component. The main signal was read by shining source for 1 min, which reduced the signal to nearly its residual value. The signal so read was normalized with its short shine value to deal with disc to disc scatter.

To obtain equivalent dose, growth curves (luminescence intensities vs applied beta doses) were constructed using linear/exponential fits extrapolated to the residual level. A plot of equivalent dose vs shine-down time (exposure energy) was derived to check for the existence of 'shine plateau'. The OSL ages were determined from the plateau value.

Results

Figure 5 provides a typical IRSL and GLSL experimental data-set. Table 2 provides luminescence data. Since

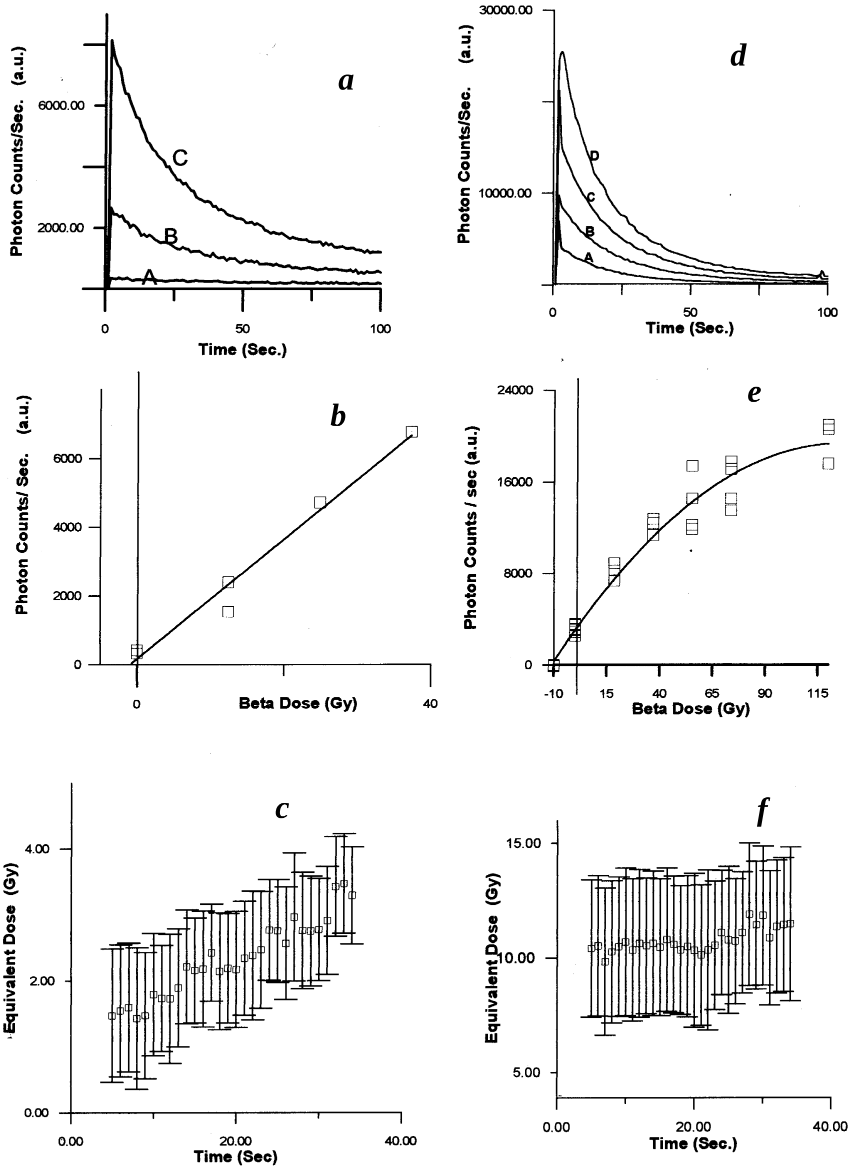

Figure 5. GLSL decay curves (***a***), growth curve (***b***) and equivalent dose plateaus (***c***) for the sample from the Ganga flood plain (taken as zero age). Curves A–C in ***a*** represent natural aliquot and aliquots irradiated to doses 12.4 and 37.3 Gy, respectively. ***d–f***, GLSL decay curves, growth curve and equivalent dose plateaus for sample from the Ganga–Ramganga interfluve. Curves A–D in ***d*** represent natural sample and those irradiated to doses of 18.4, 36.8 and 120 Gy, respectively.

Table 2. Dose rate data and tentative luminescence dates

Soil-geomorphic unit and sample, location	Horizon	Depth (cm)	U^{238} conc. (µg/g)	Th^{232} conc. (µg/g)	Dose rate* (Gy/ka)	Equivalent dose[@] (Gy)	OSL age (ka)
Young Ganga plain (Sajadpur)	A	38	3.62 ± 1.03	11.84 ± 3.51	4.942	5.3 ± 0.8	1.03[b]
Ganga flood plain (Sultanpur)	A	26	5.19 ± 1.36	13.46 ± 5.25	6.081	1.7 ± 0.15	0.29[a]
Ganga–Yamuna interfluve (Khurja–Sikarpur Highway)	AB	27	4.11 ± 0.35	14.09 ± 1.28	4.583	10.634	1.99[a]
Same as above	BC	56	3.60 ± 0.48	11.87 ± 1.84	4.170	38.607	8.5[a]

[a]GLSL date; [b]IRSL date.

*In the estimation of dose rate, alpha efficiency value ‘a’ assumed as 0.1; Cosmic ray dose flux, 150 µGy/a as suggested in Aitken[27]; moisture content 10%, 15% and 20% for C, A and B horizons, respectively.

[@]Equivalent dose is estimated using additive dose method. The source strength was not calibrated and its value was assumed to be 3.5 Gy/min for fine-grained and 5.5 Gy/min for coarse-grained samples as suggested by the manufacturer. Hence the estimated equivalent dose and the estimated ages are tentative and carry an accuracy of ± 25%.

the soils of YGP and GnFP are very young, the IRSL dates for samples from A-horizons of these soils can be taken as their calendar ages. However, GLSL 8.5 ka date of the sample from BC horizon of the Gn-YI is taken as its age. The GLSL 1.99 ka age of sample from AB-horizon of this soil is stratigraphically correct, but this does not reflect the age of the soil, as this has been affected by pedogenesis significantly. Also it suggests that in case of well-developed soil, samples from A and B horizons should not be used and only samples from BC/C horizons that are least affected by pedogenic alteration, should be used for dating soil. Thus the luminescence dates for Gn-YI, and YGnP and GnFP are 8.5 ka, 1.0 ka and 0.29 ka, respectively.

Modelling stress conditions using finite element method

Finite element method is a very effective technique in solving complex problems like states of stresses and deformations in a body under active stresses. In the present study, a three-dimensional finite element modelling of the western Gangetic plains has been carried out using a computer package SESAM marketed by Veritas Sesam Systems[34]. The following steps/assumptions were involved in the modelling:

(i) The Indo-Gangetic basin is a vast trough with a maximum thickness of Tertiary sediments (> 8 km), which thins from north to south. These sediments overlie Precambrian Vindhyan Sediments and Bundelkhand Gneiss, extending northwards from the Peninsula. We have taken basement contour map of Eremenko and Negi[35] for the present area (Figure 6), digitized it using ILWIS package and used it for finite element modelling. The northern boundary of the plains, i.e. region north of the Himalayan Frontal Fault has been taken as a rigid mass for modelling purposes.

(ii) Discretization of the body (sediment-fill) – In the present case a very coarse mesh has been adopted. The whole body has been discretized into 27, 8-nodal, 3-D solid elements. The total number of nodes is thus 78 (Figure 7).

(iii) Elastic properties – The elastic properties of the sediment-fill have been taken as: Modulus of elasticity = 1000 kg/cm^2; Poisson's ratio = 0.35, weight density = 1800 kg/m^3.

(iv) Movements – Earlier two directions of compression of the Holocene sediments of the Upper Gangetic plains, i.e. from west to east (Kumar *et al.*[18]) and from S55°W to N55°E (Srivastava *et al.*[17]) have been postulated. In the present study, two cases (I and II) with eastward and north-eastward movements have been analysed. The loads equivalent to 10 cm displacement on the eastern border and 16.6 cm on the north-eastern border for the cases I and II have been applied.

(v) Initial stresses – No initial stresses have been accounted for. The analysis provides the additional stresses and deformations, which would be developed due to movement.

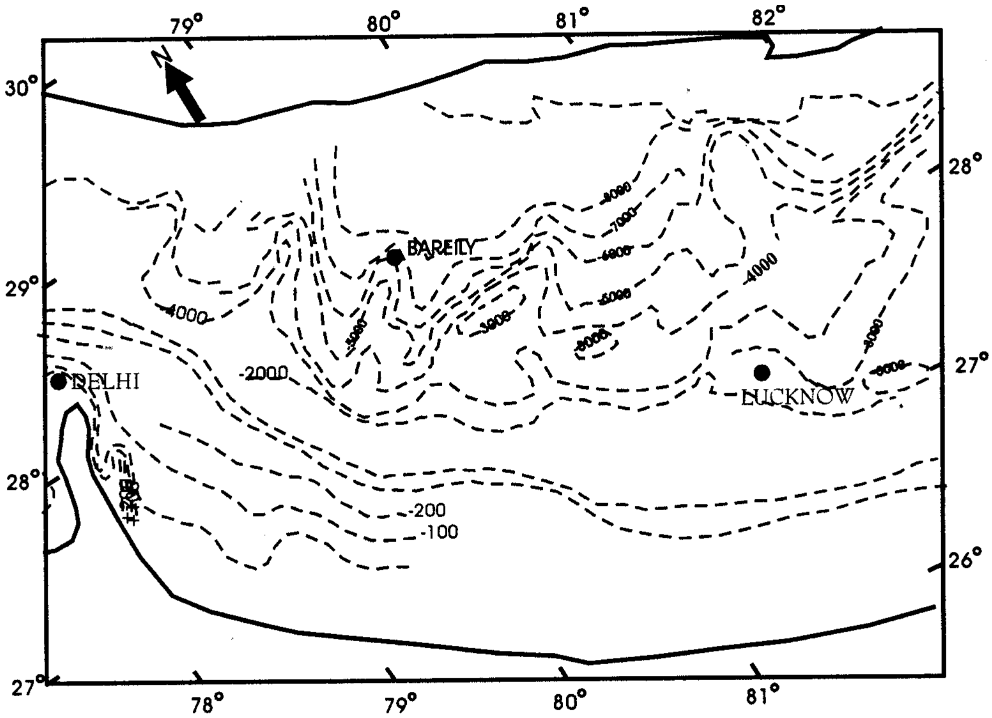

Figure 6. Basement depth contour map (in metres) of the Upper Gangetic plains. Modified from Eremenko and Negi[35].

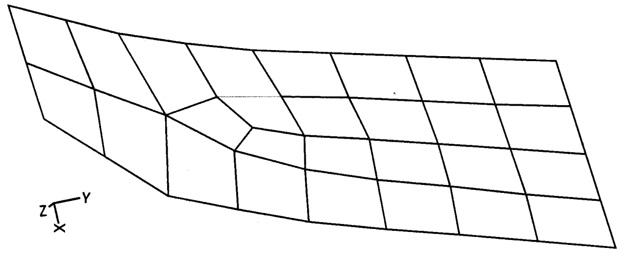

Figure 7. Top surface showing finite element mesh.

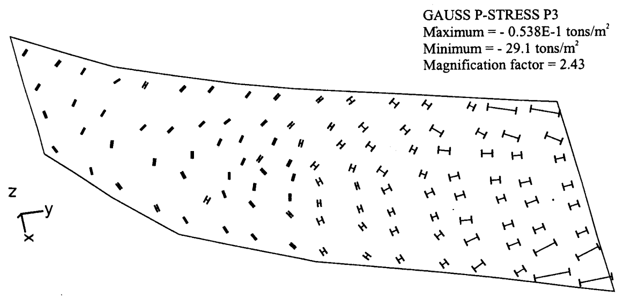

Figure 8. Vector stress diagram showing principal compressive stress for eastward movement.

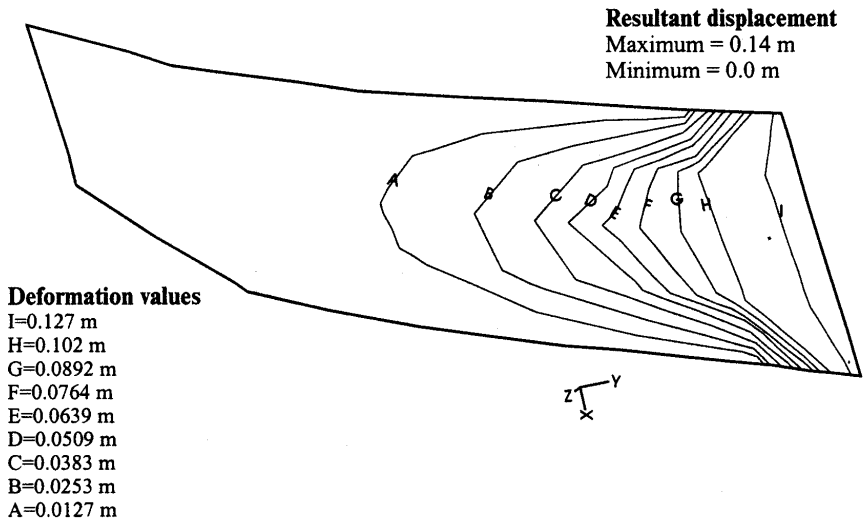

Figure 9. Deformation contours for eastward movement.

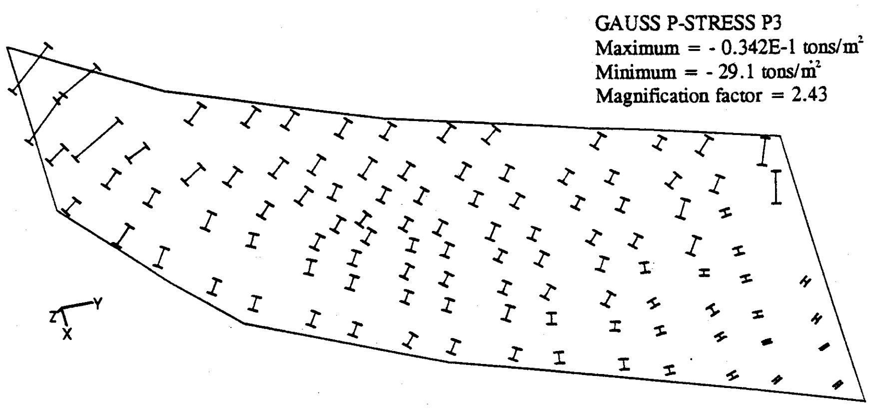

Figure 10. Vector stress diagram showing principal compressive stress for north-eastward movement.

Results

The vector diagram (Figure 8) for eastward movement shows that the eastern side is subjected to maximum compressive stress, which decreases to the west. The deformation contours also show that the deformation is maximum at the eastern side and it gradually decreases to the west (Figure 9). The pattern of deformation is defined by U-shaped curves with convexity to the west and U's become shallower to the east.

In the north-eastward movement experiment, the vector diagram (Figure 10) shows the maximum principal

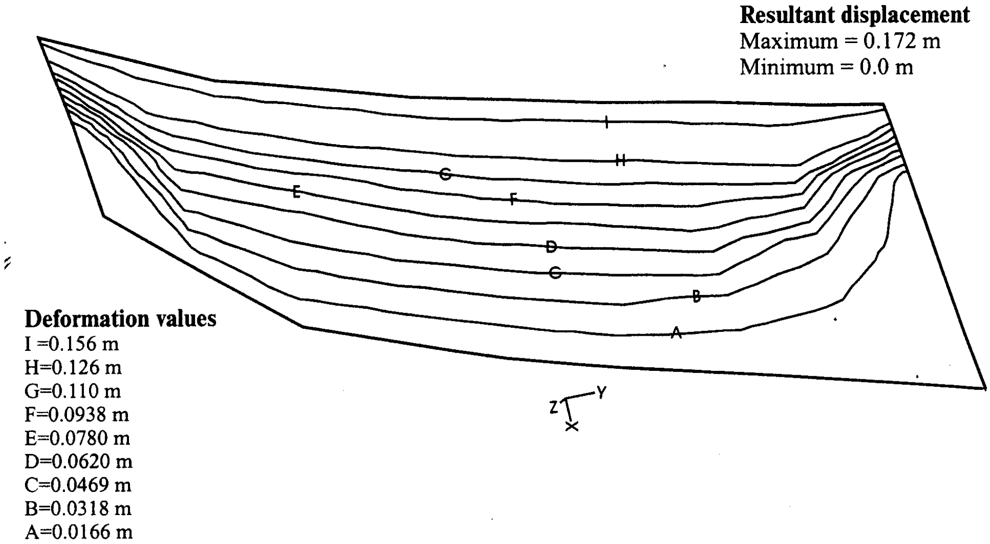

Figure 11. Deformation contours for north-eastward movement.

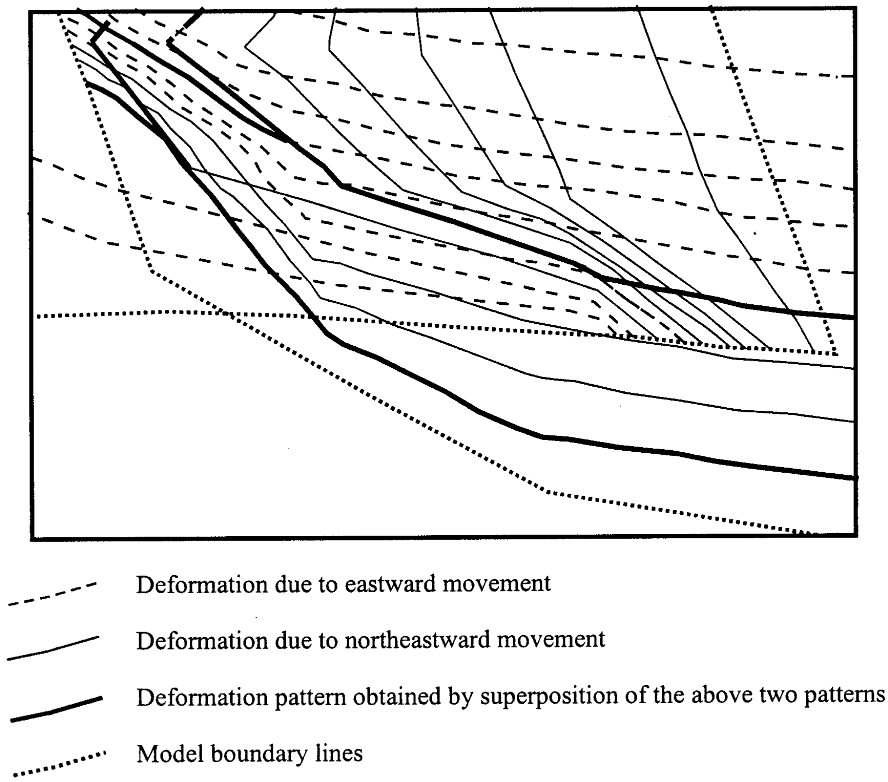

Figure 12. Development of fault patterns in V-shapes in the north and general convexity to the south-west by superposition of deformation patterns obtained by eastward and north-eastward movements.

compressive stress in the southern side and minimum in the northern side. The deformation contours (Figure 11) show corresponding deformation distribution. The deformation contours are subparallel to western/southern boundary of the model and change in direction of contours is of the order of 133°.

Discussion

Dating of tectonic events

A new hypothesis for inferring activity of tectonic blocks was used by Mohindra *et al.*[16], Srivastava *et al.*[17]

and Kumar *et al*.[18]. Because of high rate of sedimentation and sub-humid/humid climate, if a tectonic block is at a level lower than the adjoining streams, it is a region of sedimentation. If it uplifted above the level of floods then it is region of pedogenesis. However, if the block is still further uplifted, it is subjected to erosion and leads to formation of badlands. In a similar way, if a block tilts, the river flowing above it moves in the direction of downtilt, leaving behind freshly-deposited sediments, on which pedogenesis starts. If tilting takes place in number of steps, then the sequence of soils, from more to less developed soil, is expected from uptilt to downtilt direction. Using these ideas the following conclusions can be drawn about neotectonic activity in the area.

1. The Lower Ganga–Yamuna, Ganga–Ramganga and Upper Ganga–Yamuna blocks were uplifted during at about 8.5 ka, 5 ka and 2.5 ka, respectively.

2. The Ganga–Ramganga has tilted westward with significant activities at about 2.0 and 1 ka as soils are younging westwards.

3. In the last hundred years, minor tectonic activities have affected the river sinuosities and width of flood plains, as mentioned earlier.

Modelling of stress pattern

In the north-eastward movement model, deformation contours are essentially parallel to the south-western boundary, i.e. the extension of the Aravallis under the plains and boundary of the plains with the peninsula. This pattern will explain the development of the Yamuna faults and Solani and Ganga Faults, which show a change in direction of the same magnitude (138°). The eastward movement model requires development of U-shaped faults with convexity to the west. In fact, the Balawali and Ganga set of faults do form a U as expected. The superposition of the two deformation patterns obtained by finite element modelling (Figure 12) produces Vs with southward pointing edges (Figure 4 *a*). Intersection of the Solani and Ganga Faults forms a V pointing southward. This pattern is repeated twice further east by the Ramganga–Deoha–Ganga Faults and Ghagra I–III fault systems (Srivastava *et al.*[17]; Figure 4 *b*). Thus the pattern of occurrences of faults in the whole of the Upper Gangetic plains, i.e. the region between the Yamuna and Rapti rivers has probably resulted due to compression from the south-west and west and convexity of the major fault systems, i.e. Yamuna, Ganga and Ghaghra systems to the south-west is controlled by the southern boundary of the Indo-Gangetic plains with the peninsula and subsurface Aravalli Ridge in the west.

It is realized that a more accurate model, e.g. movement along N55°E as envisaged by Srivastava *et al.*[17] instead of north-east movement will provide better fit between the observed and modelled patterns. Also, as the present area represents a compressional regime, the possibility of the Yamuna and Ganga Faults being thrust/reverse type cannot be ruled out and this needs to be probed further.

Conclusions

A soil chronoassociation with five members, QGN1 to QGN5, with ages of < 500 years, > 500 years, 2.5 ka, ~ 5 ka and ~ 8.5 ka, respectively has been recognized from the study area.

Four tectonic blocks, i.e. Piedmont, Upper Ganga–Yamuna, Lower Ganga–Yamuna and Ganga–Ramganga Blocks are deciphered. The Lower Ganga–Yamuna Block has been further divided into three sub-blocks, Modinagar, Khurja and Etah sub-blocks.

Significant uplift of Lower Ganga–Yamuna, Ganga–Ramganga and Upper Ganga–Yamuna blocks took place at about ~8.5 ka, ~ 5 ka and 2.5 ka, respectively.

Westward tilting of the Ganga–Ramganga block took place at about 1 ka leading to shifting of the Ganga river in the same direction.

Other smaller movements observed during the recent past area: (i) Both the Upper Ganga–Yamuna Block and Modinagar sub-block have tilted to the east, leading to the shifting of the Yamuna eastward; (ii) Khurja sub-block has tilted very slightly to the west resulting in tightening of Yamuna river meanders and a decrease in width of the GnFP.

Finite element modelling of the stress pattern in the area suggests that fault patterns in the study have probably resulted due to compression from both the west and the south-west directions.

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