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BASEMENT REACTIVATION AND ITS RELATION TO NEOTECTONIC ACTIVITY IN AND AROUND ALLAHABAD, GANGA PLAIN

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ABSTRACT

The study of lineament pattern based on IRS-IA sub-scene (P24-R50) and Landsat (P143-R42) data combined with the drainage analysis and field observations, two prominent sets of lineament (NE-SW and NNW-SSE), besides less prominent E-W and N-S trending lineaments of tectonic origin have been observed in parts of Allahabad area. Pervasive and penetrative sub-vertical joint sets parallel to the macroscopic linear structures along with collapse structures possibly of neotectonic origin are also noted in the basement rock exposed to the SSW of Allahabad. The development of various meso- and macroscopic deformed structures, presence of collapse structure in the basement strata and the near orthogonal channel shift of axial rivers provide evidence of basement reactivation in parts of Allahabad area, Ganga plain in space and time.

Introduction

The existence of a strong compressional stress field in the Himalayas, continued down flexing of the Indian lithosphere, and their influence on the evolution of Ganga plain cause neotectonic activity in the Gangetic plains. Delineation of the neotectonic structures and zones of basement reactivation are important in the context of on going crustal movements and readjustments, environmental planning, disaster prevention, and to predict the future geomorphic changes. The area between Main Boundary Thrust and the Main Frontal Thrust has been observed to be tectonically active based on

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earthquake records, landslide and recent geomorphological changes (Sahoo *et al.*, 2000). Holocene tectonic movements at 8.5, ~5 and ~2.5 ka in parts of western Gangetic plains are suggested (Parkash *et al.*, 2000). Sinha *et al.* (2002) have shown that the course of Ganga River in and around Kanpur is tectonically controlled and the fluvial sedimentation is also influenced by basement reactivation and neotectonic activity. One of the important characteristics of the Ganga plain is the block tectonics. The basement structures are normally observed in the overlying sedimentary cover (Fuloria, 1996). The basement reactivation in the southern part of the Ganga plain is related to the Indian Shield tectonics whereas the Himalayan orogeny controls the northern part (Singh, 1996a). Mahadevan (1994) has suggested that the E-W trending tectonic control of deposition of Himalayan sediments in parts of Hamirpur-Kanpur-Unnao area (Singh and Bajpai, 1989) may not represent an older basement reactivated lineament and may be related to Neogene tectonics. Precambrian crust in Central Indian Shield has also undergone basement reactivation at the time of Killari earthquake (Rajendran *et al.*, 1996). Recent studies have indicated that there are a number of prominent E-W trending lineaments observed in parts of Bundelkhand Massif parallel to the E-W trending crustal-scale shear zone ("Bundelkhand Tectonic Zone"; Pati, 1999) observed around 25° 15' latitude and a number of earthquakes are reported along this zone in recent years. Such structures are known to get reactivated from time to time and never die (Sibson, 1975; Cox *et al.*, 1990). The Ganga plain is one of the most thickly populated areas in terms of human population and fertile soil horizons in the world and a comprehensive evaluation of possible zones of basement reactivation is highly desired.

The present study focuses on parts of Ganga plain around Allahabad area to bring forth evidence pertaining to basement reactivation and its role in the development of neotectonic structures based on remote sensing data, drainage analysis and field observations.

Ganga plain and Basement Reactivation

Singh (1996a) has suggested a three-fold geomorphic classification of Ganga plain (Fig. 1), which is a modification of four-fold classification earlier, proposed by Pathak (1982). The Piedmont Plain (PP) is about 20-50 km wide, located adjacent to the Himalayan Mountain Belt, comprises either Bhabar or Terai, or both (Singh, 1996a, 1996b). There are two important neotectonic features of this zone. The E-W trending Himalayan Frontal Fault and the two conjugate strike slip faults (NNE-SSW and NW-SE), those offset the Siwalik rocks also control the major drainage pattern in the area. Central Alluvial Plain (CAP), with maximum areal coverage, occupies the area between piedmont zone and axial river. The drainage shows a general SE trend and towards southern margin they exhibit a W to E flow direction. The lineament trends (based on the drainage data after Singh, 1996a) vary from a dominant NW-SE to WNW-ESE and W-E in the southern part. Marginal Alluvial Plain (MAP) is the southernmost part of Ganga plain with a northerly sloping surface located south of the axial river where basement control is very significant. The neotectonic activity in this zone is manifested by the basement reactivation in the form of NE-SW trending lineaments as a response to Himalayan tectonics (Singh, 1996a).

The importance of basement reactivation was emphasized very early by Hills (1946, 1947) to explain many present-day geomorphologic features associated with faults traversing the Australian landmass and he empirically showed that most of the present tectonic trends are observed in the basement lying parallel to the older trends with long tectonic history. It is well known that the thickness of Vindhyan Supergroup of rocks increases towards south and that of Indo-Gangetic Alluvium towards north with the Bundelkhand craton representing a basement arch. Basement reactivations during and after the evolution of Vindhyan Basin are well documented with evidence (Chakraborty and Bhattacharyya, 1996). According to them, the

Fig. 1. Three-fold division of Ganga plain (Singh, 1996; modified after Pathak, 1982) shows the boundaries between Piedmont Zone, Central Alluvial Plain (CAP) and Marginal Alluvial Plain (MAP). The star (*) shown below "Allahabad" indicates the study area.

Vindhyan crust is still undergoing flexural subsidence due to the thrust loading in the Himalayas by the accumulation of the Siwaliks and the Gangetic alluvium despite the presence of several faults on the crust indicating the rigidity of subcrustal lithosphere. The structural and tectonic sketch map (Fuloria, 1996) prepared with the help of limited geological and geophysical data shows the area of present study to lie in the tectonic block (Rae Bareli-Faizabad Buried Ridge) with NE-SW trending oppositely dipping two major faults.

Geological Setting

The area under study uniquely displays the juxtaposition of the Vindhyan Supergroup of rocks (Dhandraul Quartzite of Kaimur Group) and portions of CAP and MAP from S to N in a span of about 3 to 25 km (Fig. 1). The major part of the area is covered by alluvial deposit. There are two prominent terraces (T_1 and T_2; Fig. 2), other than present day river course (T_0). Large tract of area is occupied by present-day channel islands. Old channel islands are also discernible. Paleochannels, ox-bow lakes and meander-scars are also observed. The area is mostly covered with mud and sand. The Dhandraul quartzite is exposed with or without a lateritic or soil cover to the SSW of Allahabad. The subsurface geology is mainly based on the deep boreholes carried out by the Central Ground Water Board (Pandey, 2005). Mud and sand occur as alternating sequence up to 180 m below the ground level. Shale is encountered at 114 and 193 m in the sub-surface sections. Limestone is observed at 252 m but the dominant sub-surface rock type is sandstone. Sandstone is encountered at a depth of 188 and 278 m in two boreholes, respectively. The exploratory boreholes suggest that the basement is encountered at shallow depth close to Yamuna River to the west of Sangam. Shale, sandstone and limestone units do not show lateral continuity along their strike. This possibly is due to fault-induced basement reactivation.

Methodology

Rothery and Drury (1984) have shown that aerial photographs and satellite imagery are useful reconnaissance tools for the mapping of neotectonic structures in the local as well as regional scale. In the present study mainly geological (field checks), geomorphic (study of fault-generated landforms, morphometric indices and drainage pattern) and remote sensing techniques are applied.

The area lies between latitude 25° 07' 50" and 25° 36'01" and longitude 81°31'05" and 82°22'43" The lineament analysis was made on a floating IRS-1A LISS II FCC imagery (17 October, 1988; Bands 2, 3, and 4; Scale: 1:125,000) and ETM + (LANDSAT-7) data (Fig. 3; U.S. Geological Survey: Scene date: 2000/11/20, Landsat (Sensor: ETM+) Scene, WRS-(2) P143-R42, Level, Orthorectified; Sioux Falls, South Dakota: USGS). The interpretation of lineament was made on the basis of tonal, textural, vegetation, soil, relief and drainage pattern. The neotectonic structures were delineated based on the parameters like, sudden change in river course, preferred orientation of various orders of streams, nick points and distorted meanders, displacement of river courses, presence of asymmetrical terraces and escarpments. The drainage pattern was also studied in parts of toposheet no. 63G/15 (1:50,000) and selected field checks have also been made.

Drainage Characteristics in Allahabad area

The drainage pattern characteristics have been studied using the Survey of India toposheet no. 63G/15 (1:50,000) and path-row based IRS-1A imagery. The drainage pattern in parts of Allahabad district shows a subdendritic to dendritic pattern and streams up to 5th order. The 1st order drainage shows predominantly NE-SW trend whereas the 2nd order drainage shows bimodal orientation. The dominant trend is NNW-SSE and the less dominate NE-SW trend is also observed. Two prominent drainage basins have been observed to N and SE of Allahabad City. These lower order drainage basins show opposite flow directions indicating a broad, linear, E-W trending topographic high in the central part of Allahabad City. It might have been produced due to the upliftment of a horst-like block. Fracture density measurements have been carried out in a grid pattern and basin-wise assuming the drainage pattern to be the surface expressions of sub-surface tectonic structures. Such studies are well known in other areas, Mahi Valley, Gujarat (Raj *et al.*, 1999) and Ganga Plains (Singh *et al.*, 1996). The fracture density was found to be non-uniform and the major lineament (based on drainage) are observed to show NE-SW, NW-SE, and E-W trends. These orientations are similar to the fracture pattern seen in the Peninsular shield. The drainage characteristics of the three rivers in the area (Ganga, Yamuna, and Tons) are different from one another in many aspects. The Ganga River shows maximum channel width followed by Yamuna and Tons in parts of area under present study (Fig. 2). It is also important to note that the channel width of Ganga River is highly variable. Yamuna and Tons Rivers have nearly constant channel width. It is very clear that the bounding fault between Peninsular Shield and Marginal Alluvial Plain controls the Yamuna River course in the area under study. Upliftment of the northern margin of Vindhyan plateau is well known (Singh and Bajpai, 1989) and is considered to extend all along the southern margin of the Gangetic plain (Valdiya, 1984). Peninsular rivers (Chambal, Betwa, Ken and Tons) show a more or less similar stream trend (NE-SW) and their flow direction is towards NE. The Ganga and Yamuna show a general WNW-ESE trend in the regional scale in the CAP but the Yamuna River follows a NE-SW trend similar to Peninsular rivers to the SW of Allahabad (Fig. 2). This clearly suggests that the older lineaments do have surface expressions in the Marginal Alluvial Plain contrary to the views expressed by Mahadevan (1994).

The effect of neotectonic activity is very conspicuous in case of Ganga River course observed in parts of Allahabad district and adjoining areas. The river course shows dextral shift in an en echelon manner for a distance of about 6.25 to 7.5 km. These directions of shifts are parallel to the 2^{nd} order stream trend (dominant) observed in the drainage basin developed in different parts of Allahabad City. Ganga River takes an abrupt southward turn by about 90° to meet Yamuna River at Sangam (Fig. 2). The channel width of Ganga River shows widening to the north of Karchana forming braid bars. The change of channel width of Ganga River is likely controlled by gradient of slope of the ground surface, which in turn is controlled by block tectonics. The terraces of Ganga River are also asymmetric (Fig. 2) in nature suggesting possible neotectonic control. During the course of this study, a number of palaeochannels have been

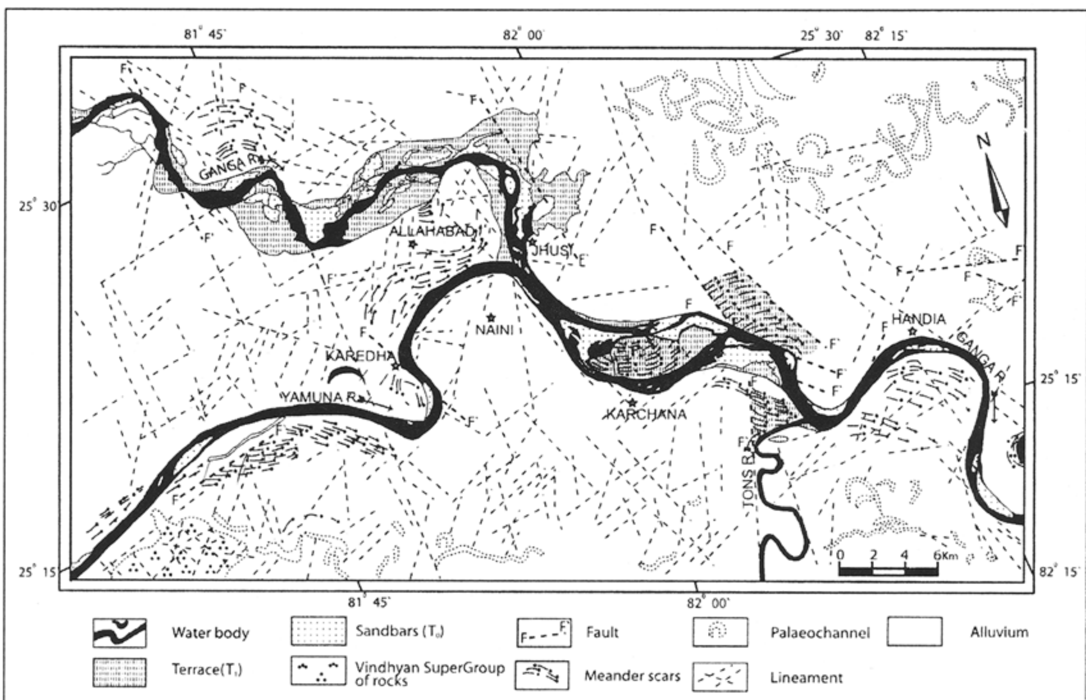


Fig. 2. Morphotectonic map of Allahabad district and adjoining areas is based on IRS-1A LISS II FCC imagery (1:125,000) and limited field checks.

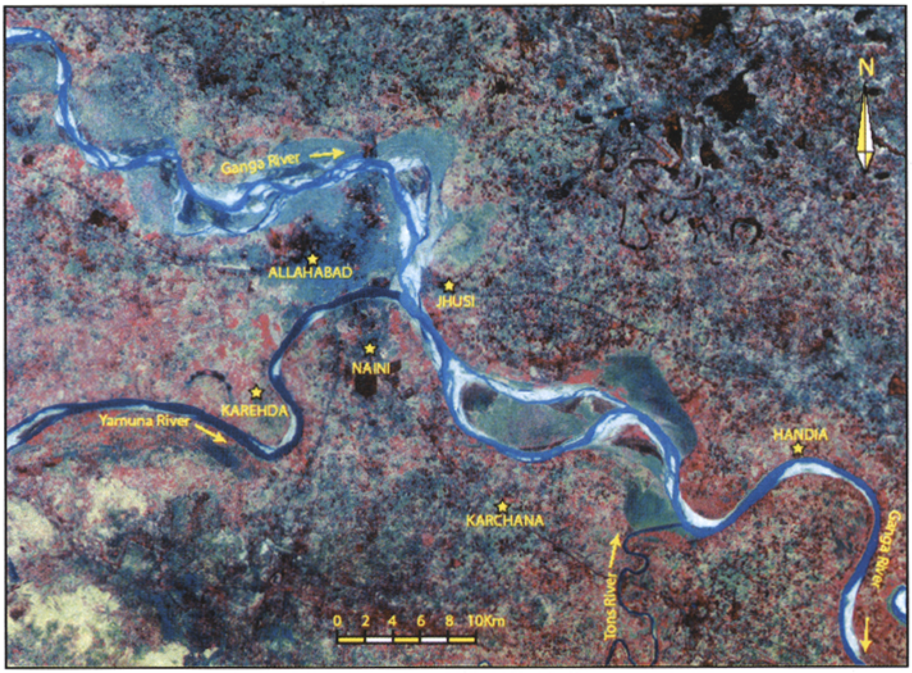
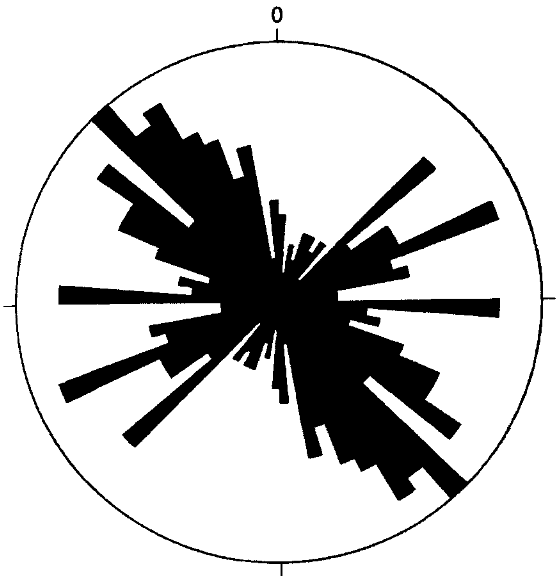


Fig. 3. LANDSAT-7 image of the study area showing abrupt truncation of Ganga and Yamuna Rivers' course by about 90° to the NW and SW of Allahabad, respectively.

mapped to the E, NE, and S of Allahabad and in most cases they are found to terminate against the lineaments. Similar findings have been reported earlier to the south of Allahabad (Gautam, 1990) and such terminations were also attributed to block faulting.

Lineament Analysis

Lineament analysis was carried out on IRS-1A imagery (17 October, 1988) on 1:125,000 scale and based on LANDSAT-7 (ETM +) data. The lineaments of tectonic origin were identified based on criteria discussed earlier. A total of 308 lineaments of varying lengths (~1 km to about 16 km) and orientations have been observed. In order to study the fracture density and domain-wise lineament concentrations, the lineament map (Fig. 2) was divided into 1.6×1.6 km^2 grids on the ground (i.e. 2×2 cm^2 on the map except for the edges and corners). The number of lineaments observed to the south of Yamuna River (Marginal Alluvial Plain) is more compared to those found to its north. This may be due to presence of Vindhyan Supergroup of rocks at shallow level south of Yamuna River and hence the basement fractures are more pronounced on the alluvium cover. The incidence of lineaments, however, is heterogeneous in the regional scale possibly due to variable thickness of the alluvium cover. Similarly, the fracture density values were also found to be heterogeneous on the regional scale. In general, the NNE-SSW trending lineaments are longer in length compared to NE-SW trending lineaments. Despite a little scatter, a bimodal distribution of lineament trend (Fig. 4) similar to the overall drainage pattern is observed in and around Allahabad. The 1st order drainage follows the older lineament trend (NNE-SSW to NE-SW) similar to the tectonic-controlled fluid and magmatic activity observed in the basement rock (Bundelkhand craton).



It is interesting to note that in parts of Allahabad district and the adjoining areas, the NNW-SSE trending lineaments, which are responsible for dextral en echelon shifts of Ganga River course observed to the NW of Allahabad City (Fig. 2), have not shown similar affect on the Yamuna River. Meander scars do show shift of Yamuna River towards SE. The reason for a north westerly sinistral shift of Yamuna River course observed in and around Karehda is not fully understood as yet. Though the meander scars around this location do indicate lateral movement of the river course.

Field Observations and Basement Structures

The basement rock comprising dominantly quartzites are exposed to the SSW of Allahabad (Fig. 2) and in the borehole sections (Pandey, 2005). A number of sub-vertical and sub-horizontal joint sets are observed. The joint surfaces are smooth and planar. These structures show sympathetic relationship with lineaments (Fig. 5) in Shankargarh area. Field observations in this area have revealed the presence of four distinct sub-parallel regional lineaments having average orientation of 320° and numerous sympathetic pervasive and penetrative sub-vertical joint sets (Fig. 6). The sub-vertical joints cut across the bedding at high angle and are very closely spaced. Bedding parallel joints are widely

Fig. 5. One of the four large-scale linear structures observed in parts of Shankargarh area having a preferred orientation and possibly controlled by basement fault.

spaced. This trend (320°) is parallel to the orientation of some of the regional mafic dykes observed in parts of Bundelkhand craton. According to Mahadevan (1994), the Ganga plain tectonics is not solely dependent on primitive lineaments as they are inactive and have no surface expression. The effect of neotectonism in the form of slumping, collapse structure (Fig. 7) and faulting in the marginal part of MAP and CAP close to Allahabad are very distinct. These structures cut across the bedding plane and propagate downward in a vein form. The top soil part is observed to cave in suggesting it to be a possible neotectonic activity.

Fig. 6. Closely spaced, penetrative and pervasive sub-vertical joint sets are observed parallel to the regional lineament and they cut across the bedding.

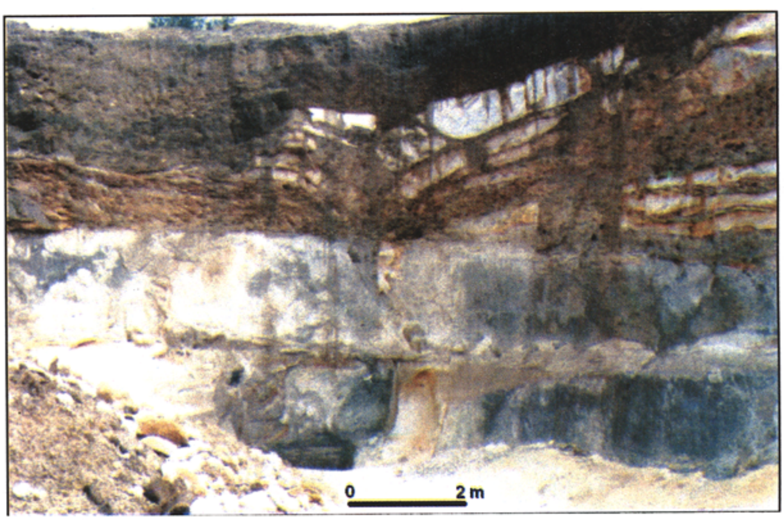


Fig. 7. Collapse structure at high angle to the bedding has resulted possibly due to neotectonic activity and presently capped by the alluvium cover.

Conclusion

The analyses of remote sensing data, drainage pattern and regional structures in the field suggest a strong relationship between basement reactivation and neotectonism of one of the most important domains of Ganga plain. The change in river course of Ganga by about 90° is shown to follow possible diagonal slip faults due to block tectonics. The lineaments identified on the satellite image are observed in the field as pervasive and penetrative macroscopic structures having closely spaced sympathetic joints with a preferred orientation. The presence of collapse structure observed on the basement rock and abrupt truncation of subsurface lithology seen in borehole data strongly indicate the role of basement reactivation for the development of neotectonic structures in parts of Ganga plain around Allahabad. It is well known that the Vindhyan crust is still undergoing flexural movement and the stressing of the continental crust leads to basement reactivation along the pre-existing weak planes. The present study shows evidence of basement reactivation due to stress conditions of Ganga plain foreland basin along palaeotectonic surfaces.

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