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Analysis of Tectonically controlled Valley Floor morphology of the Central Segment of Sabarmati River Basin: An Integral approach using satellite images and GIS Techniques

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ABSTRACT
Present paper deals with the integrated study of satellite and field investigation in the central segment of Sabarmati River basin that covers ~ 20,000 km^2 area along Cambay fault system. The valley floor morphology within the central segment of the Sabarmati River basin is controlled by several NNW-SSE, NW-SE, and NE-SW trending faults of Cambay basin. The sequential reactivation of these faults gives rise to morphological changes in the river system, leading to incision and widening of valley floor, favorable sites for deposition of Quaternary sediments. The consequence of sequential reactivation and deposition of sediments is reflected in the form of tectonic geomorphology in the area. Several geomorphic markers, such as paleochannels, wind gap, uplifted strath terraces, incised ravine surfaces, compressed meandering, and offset of drainage pattern associated with tectonic activity have been identified in the region.

Key words: Sabarmati River, Morphotectonics, Neotectonics, GIS, Geomorphology

INTRODUCTION

Morphotectonic studies can be defined as the study of different types of landforms produced by tectonic processes, or application of geomorphology to solve tectonics problems (Keller and Pinter, 1986). The tectonic landforms analysis has been done using high-resolution Landsat 8 optical images and CARTOSAT digital elevation models (DEM). In tectonically active regions, evolution of landforms depend upon the interactions between surface processes and tectonic deformation. (Kothyari et al., 2016; Graveleau et al., 2015). The detailed geomorphological and morphotectonic interpretation of drainage system can provide the information about the neotectonic activity in the area (Prakash et al., 2016). The Sabarmati River basin is controlled by rocky Aravallis to the north and the Gulf of Khambhat (GOK) in the south (Merh and Chamyal, 1997; Raj, 2012). The river flows across the southwest inclined topographic slope and crosses the alluvial plains in the central portion of the basin and finally disappears into the GOK, covering approximately 20,000 km^{2}area. In the central portion, the river flows parallel to the peri cratonic Cambay basin (Biswas, 1987). It is mostly occupied by Gujarat alluvium plains (Figure 1). Further, based on satellite data investigation Sareen et al., (1993) and Zeuner (1950) identified several NE-SW to NNE-SSW oriented linear features controlling the hydrological network. These studies revealed that the Quaternary landforms within the Gujarat alluvial plain are controlled by active tectonic activity (Chamyal et al., 2003; Jain et al., 2004). In the present study, ~90 km long stretch of Sabarmati River basin has been investigated to evaluate tectonic activity in the central portion of the basin. In the present study, we have used high-resolution satellite imageries to identify tectonic signatures from the central portion of Sabarmati basin. In addition to tectonic signatures major tectonic boundaries have also been demarcated.

Methodology

The methodology involves the visual and digital analysis of the satellite remote sensing data as well as field work for ground truth (Joshi et al., 2013). The database was generated using Landsat 8 ETM FCC data. Digital elevation model (DEM) was generated using the Shuttle Radar Topography Mission (SRTM) data downloaded from CIAT SRTM website (http://srtm.csi.cgiar.org) and CARTOSAT-1 data downloaded from Bhuvan website (http://bhuvan.nrsc.gov.in). Various thematic layers comprising river channel with water, bank line of the river, floodplain, fluvial terraces, sandbars/channel bars, point bars, palaeo-meanders/cut-off meander loops, paleochannels, and ox-bow lakes have been generated using onscreen analysis of satellite data in GIS platform. These layers were compiled to form a fluvial geomorphological map (Figure 11). Ground truth data collection was carried out in pre-monsoon season during April 2016. The ground control points and the field photographs were collected at certain places. For detailed geomorphic analysis, the entire study area has been divided into three major zones; zone of compressed meandering represented by zone-1, ravine surfaces marked as zone-2, and the upper hilly regions marked as zone-3.

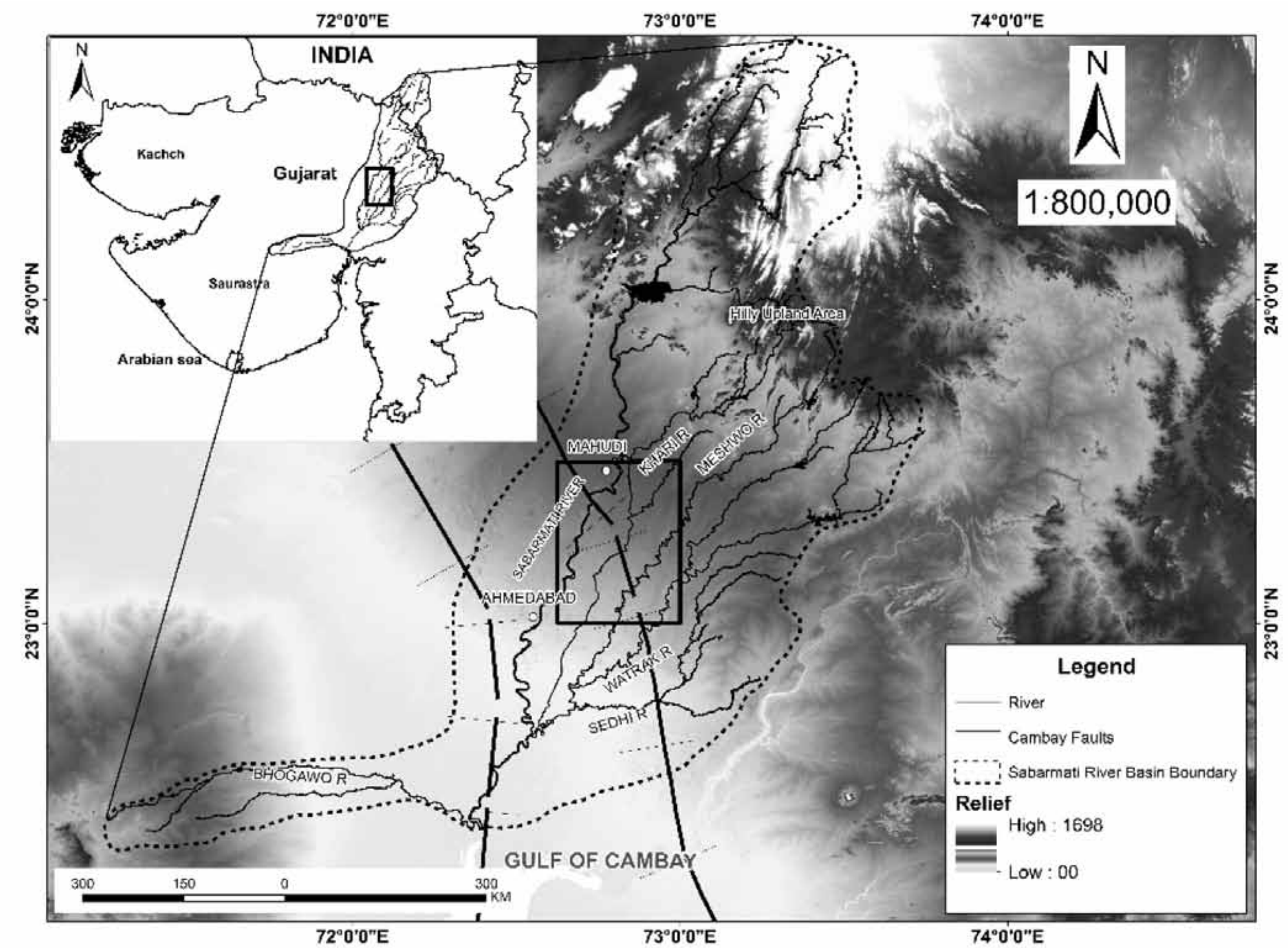

Figure 1. Location and drainage map of Sabarmati River basin (Note: the study area is highlighted by a black rectangle).

Observations

Based on tonal and textural variation we identified different levels of fluvial terraces and scroll plains near Mahudi (23°30′18.62″N latitude and 72°47′52.74″E longitude) (Figure 2a). The incision of first order drainage pattern (ravine surfaces) is clearly visible in DEM data (Figure 2a). Several traces of NE-SW, NW-SE, and N-S oriented faults have been identified using the satellite data with the help of DEM observation. It is inferred that the leading side of river terraces are truncated by faults (Figures 2 b and c). A trace of paleo river course has also been identified near Mahudi using DEM analysis (Figure 3).

Near Mahudi (23°30′18.62″N latitude and 72°47′52.74″E longitude) approximately 40 m thick two levels of starth terraces are well preserved at the west bank of River (Figure 2c). The T1 terrace is around 29 m thick, whereas the T2 terrace is ~11m thick and resting over the two thick conglomeratic bedrock (Figure 2d). The elevation difference of each terrace has been estimated from Cartosat DEM data. The lower fluvial sequence is formed by hard and compact fine to medium sand. In T2 terrace the stabilized dunes are found on the top of the fluvial sequence. The upper sequence comprises 7.5m of grayish yellow fine sand to medium sand and silty clay with an erosion contact. It is succeeded by the 2 m thick Aeolian deposit. The presence of an archaeological site on the top level of terrace indicates that the site was occupied by humans around 1600 AD (Tandon et al., 1999). Due to subsidence of land with the impact of tectonic activity forced the humans to settle down at this place. The previous study shows that the aggradation of oldest terraces T1 was started around 55ka (Srivastava et al., 2001) and continued till 12 ka. The incision pattern and presence of conglomerate bed indicate that these terraces are uplifted after deposition of the T2 surface befor 12ka (Srivastava et al., 2001). A Paleochannel and N-S trending fault is observed near Prantij (23° 24′ 52″ N 70° 50′ 53″ E) with the help of Cartosat ortho and DEM data (Figure 3). The presence of cutoff meander events is a key component in the complex dynamics of meandering rivers (Camporeale et al.,

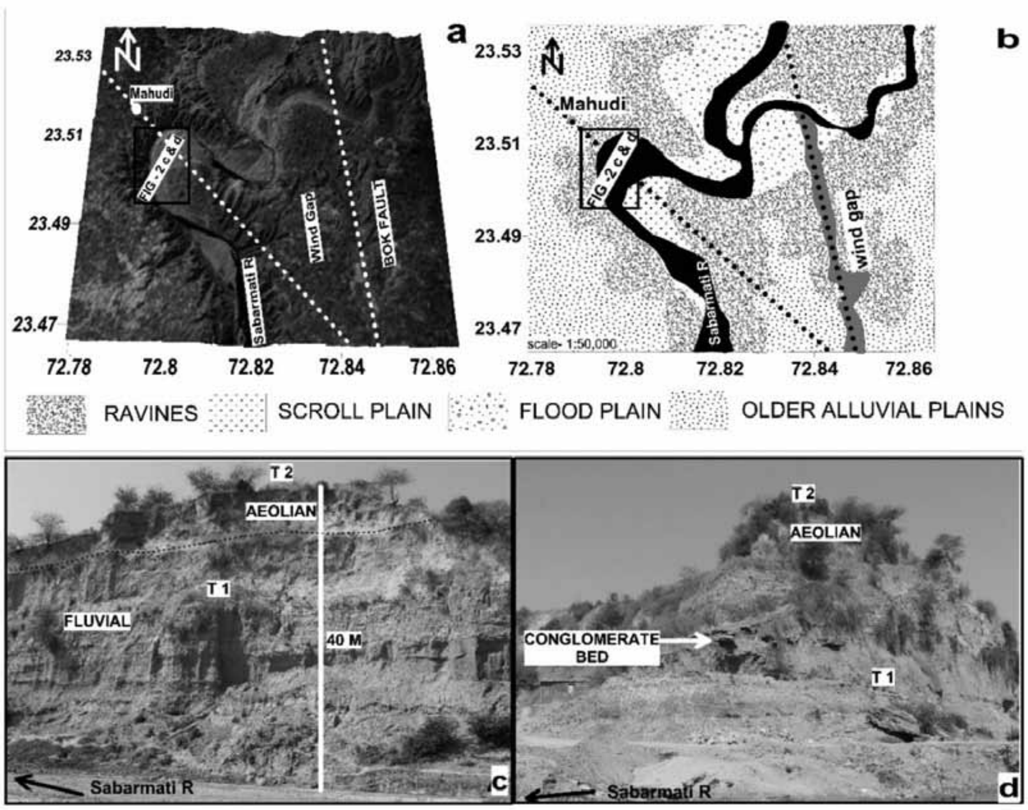

Figure 2. (a) Landsat image superimposed on DEM, (b) Geomorphic map of Mahudi area (c) River Section Near Mahudi showing two major divisions of formation (Aeolian and Fluvial) with two levels of terraces. (d) section found in the same area showing Displacement and Exposure of Conglomerate Bed.

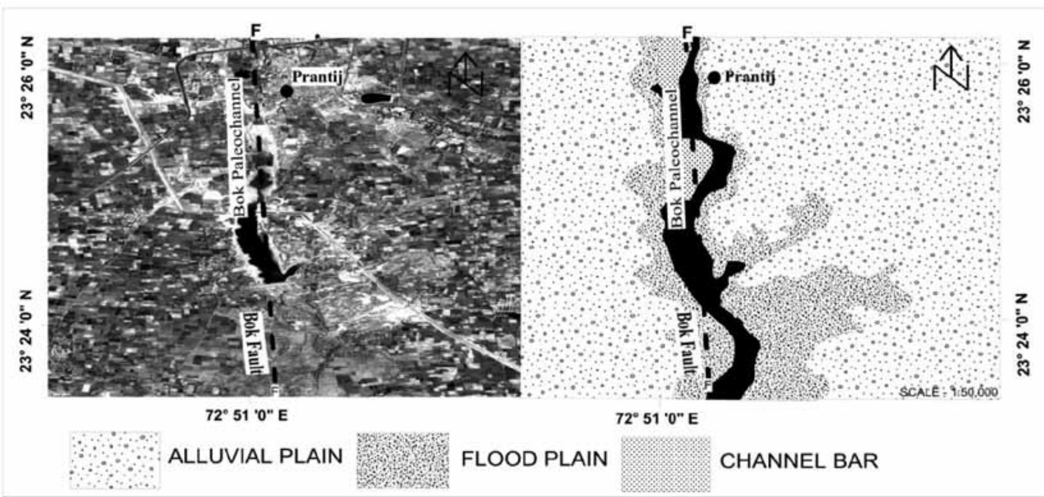

Figure 3. Cartosat Satellite data and Geomorphic Map of Bok Paleochannel with Bok Fault near Prantij.

2008). Such a cutoff meander is observed at Checkhlapagi village (23°19′14.10″N 72°50′56.09″E) along the faults trending NW-SE. it is also inferred that the N-S oriented Bok Fault is left laterally displaced near Chekhlapagi along NW-SE fault (Figures 4 a and b).

Field Evidences

A large amount of evidence of geomorphic expressions associated with tectonic activity has been documented within the Sabarmati river basin. These geomorphic

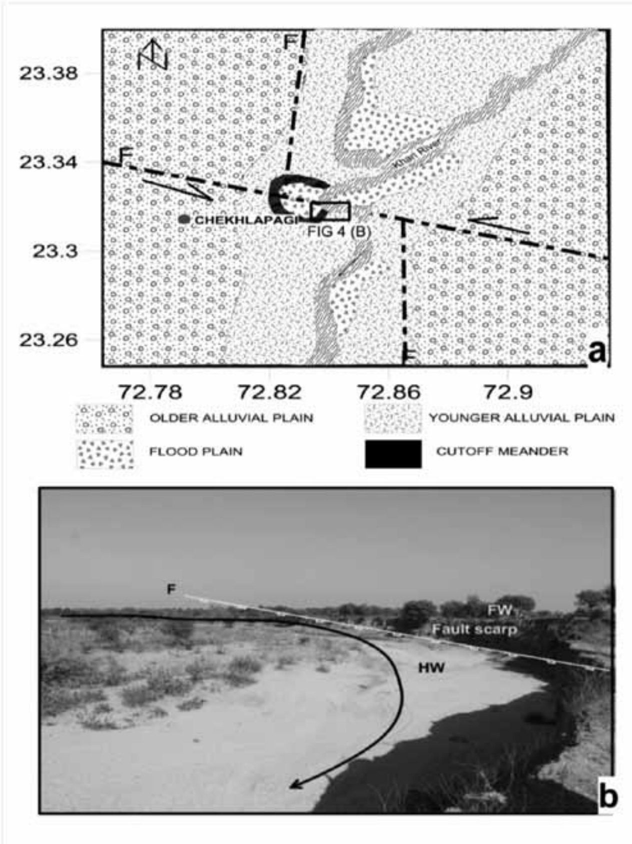

Figure 4. (a) Geomorphic map showing Major Geomorphic Features, lineaments near Chekhlapagi Village (b) Field photo of fault scarp and incised terraces near Chekhlapagi Village.

Figure 5. Two levels 22m high fluvial terraces near Oran Village.

expressions are the development of river terraces, incision of the channel, offset by river channel, development of deep gullies and ravine surfaces, uplifted scroll plains, compressed meandering, and fault scarp. River terraces and incised ravine surfaces are the most remarkable geomorphic expressions. They are associated with tectonic activity. Maurya et al., (2000) suggested that the ravines, drainage asymmetry, alleys valleys, and entrenched meanders are indicative of Holocene tectonic uplift.

Fluvial Terraces

At a place Oran (Lat: 23°24′16.3″N, Long: 72°47′25.″E) 22m thick two river levels of Strath terraces are well preserved (Figure 5). The T1 terrace is around 32 m thick. T1 terrace is composed of the 9m thick basal conglomerate. T2 terrace is preserved by the fluvial sequence (10m) and the Aeolian Deposit (3m).The fluvial sequence comprises fine to medium sand. The Aeolian deposit comprises

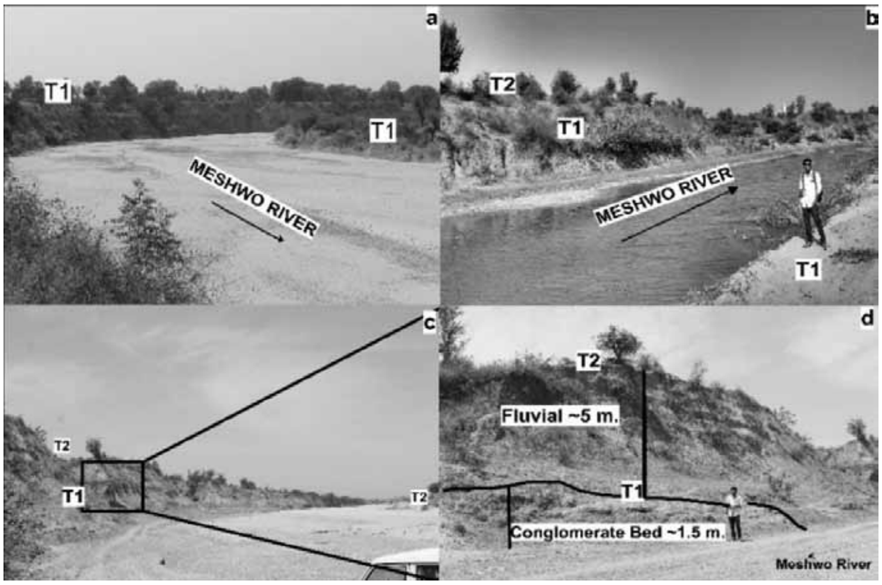

Figure 6. Different Types of Fluvial Terraces and their Field Evidence showing unpaired terraces (a) and (b): Two levels of unpaired terraces In Meshwo River near Krishnanagar, The most remarkable feature is ponding of river. (c) and (d): Two level of Terraces Rest upon conglomerate near Pimplaj village.

stabilized dunes. Near Krishnanagar (23° 4′ 34″ N latitude and 72° 50′ 1″ E longitude) two levels of unpaired terraces are well preserved along Meshwa River (Figures 6 a and b). These terraces are developed within the contraction band with NNW-SSE and NE-SW oriented faults. The river Meshwo has incised within the contraction zone. Near Pimplaj village (23° 14′ 26″ N 72° 57′ 35″ E) unpaired fluvial terraces are present. A prominent offset of Meshwo joining streams is also seen (Figures 6c and d). One can also see the offset of the stream along the fault and development of Ravines and gullies towards the upthrown block. Here compression of meandering is caused by relative motion along the fault , as the river crosses fault segments that became incised. The fault is oriented towards NW-SE. Here two-levels of surface terraces are found that can be described as T1 and T2. These terraces are resting over ~2 m thick conglomerate unit.

Wine Glass Valley

Wine glass valleys are conventionally associated with head ward erosion towards the up-thrown block of a normal oblique fault (Graveleau et al., 2015). In the present study, the wine glass Valley is associated with an NNW-SSE oriented fault near Mahudi. The tectonic uplift along this fault has not only developed wine glass Valley but several other geomorphic expressions, which are also observed along the surface trace of the fault. Fault scarps may be modified by head ward erosion. The trunk Stream of Sabarmati River flowing from hanging wall of the fault , incised and formed a deeply- V-shaped valley within the fault zone (Wine glass structure) (Figures 7 a and b).

Near Mahudi Presence of Scroll plains are observed (Figure 7 c). There are three generations of scroll plains. The scroll plain 1 is the oldest and the last one, the scroll plain3, is the youngest. (Srivastava et al., 2001). The presence of three scroll plains suggests the tectonically active nature of Sabarmati river basin. The presence of ingrown meander morphology and vertical offset, which distinct each scroll plain, suggests tectonically active nature. It represents the distinct tectonic events that are responsible for the formation of the scroll plains. As such, it can be said that the river had passed through two major tectonic activity events.

Offsets in Drainage

The offset of drainage pattern is one of the common geomorphic expressions of tectonically active areas. In the present study, several offsets have been documented along the NNW-SSE and NW-SE oriented faults. A prominent 3 km long offset of Sabarmati River has been observed along a NNW-SSE oriented fault, passing through the Mahudi. Another offset is found near the Oran village. At this place the offset of the river is around 2.80 km. Similar offsets with same trends are observed in Khari and Meshwo Rivers at 1.4 and 2.5km, respectively. Figure 8 depicts the satellite view of offset pattern observed along the Sabarmati river basin.

Ravine Surfaces

Ravines are first order geomorphic expressions of active movement. Within the Sabarmati river basin, the ravine surfaces are mainly associated with intrabasinal Cambay

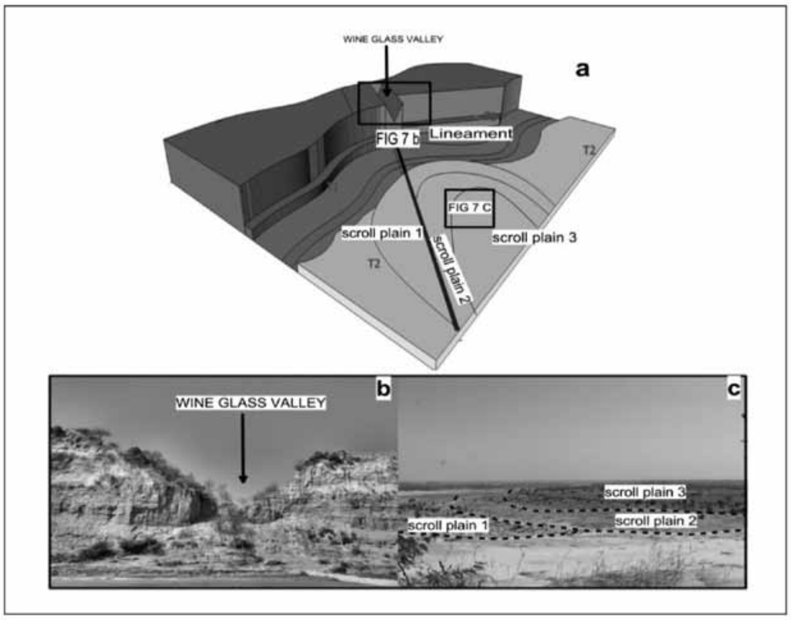

Figure 7. (a) Schematic block model of Mahudi area shows incision of fluvial terraces and development of wineglass Valley and Scroll plains toward the uplifted block (b) field photograph shows wineglass valley near Mahudi(c) 3 Level of scroll plains in Sabarmati River near Mahudi.

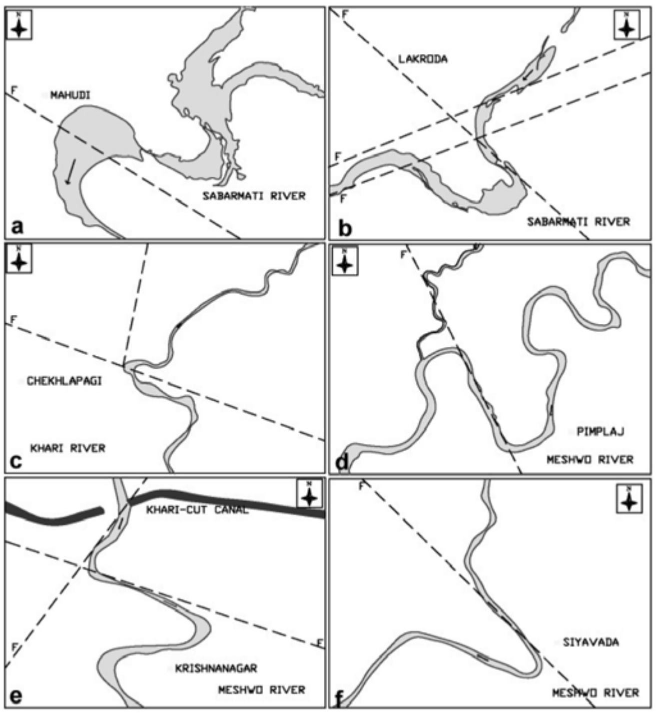

Figure 8. Offset in Major Drainage Pattern (a) and (b) Sabarmati River showing offsets and Lineaments, (c) Khari River showing offset and Lineament (d, e, and f) and Meshwo River Showing offsets and Lineaments.

faults and subordinate climatic effect. These ravine surfaces are oriented along NW-SE direction, as illustrated in Figure 9. In the present study area, these ravines are developed along the first order streams. Development of ravines and associated incision in this region is correlated with tectonic movement along these faults. Ravines are formed by the action of the stream that erodes the land. The directional analysis of ravine orientations shows that the ravine trends are related to neotectonic activity along older structural trends during Quaternary. In the central portion

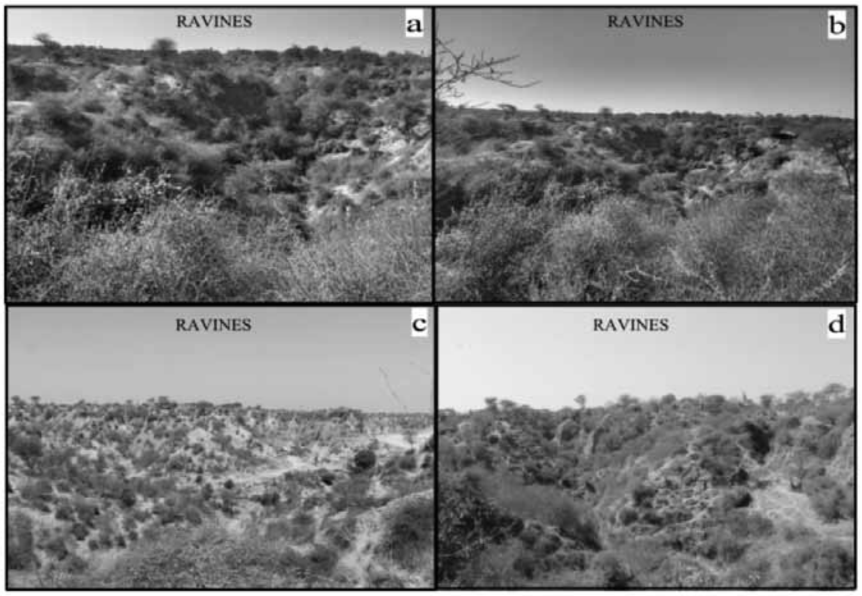

Figure 9. (a-b) Development of Ravine surfaces near Mahudi village. (c-d) Development of Ravine surfaces near Oran village.

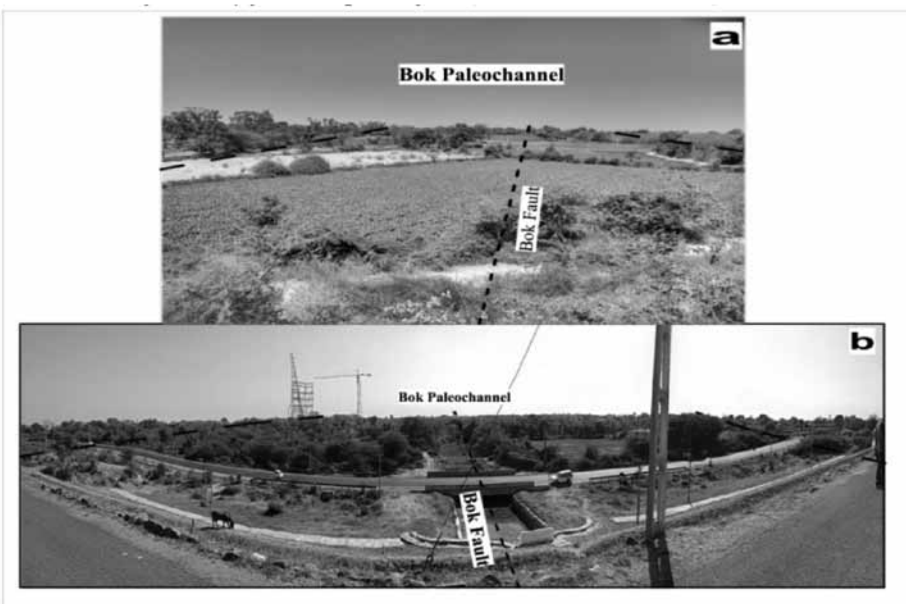

Figure 10. (a)Close view of Paleochannel. (b) Birds eye view of paleochannel near Prantij. (Note: The Bok fault passes from the paleochannel)

of Sabarmati river basin these ravine surfaces are incised to an extent of 10 to 80 m. The central zone of the study area can be termed as a zone of the incision. The presence of faults and associated incision along trunk streams of Sabarmati basin further confirm their association with tectonic activity during the formation of ravines.

Paleochannel

Paleochannel is a vanished course of past river system (Pettijohn, 1975). The occurrence of paleochannel provides evidence of channel movements that have taken place in Gujarat alluvial plains through time (Raj et al., 2014). In the present study, approximately 20 km long N-S oriented paleochannel of Hathmati River is documented. The channel morphology, sediment characteristics and linkage with present day river indicate that in the geologic past the channel was occupied by Hathmati River. The river gradually shifted towards west due to vertical movement of the Bok fault. Two uplifted blocks were identified towards the footwall of N-S oriented Bok fault and NW-SE trending Mahudi Fault. The Relative Motion along these two faults

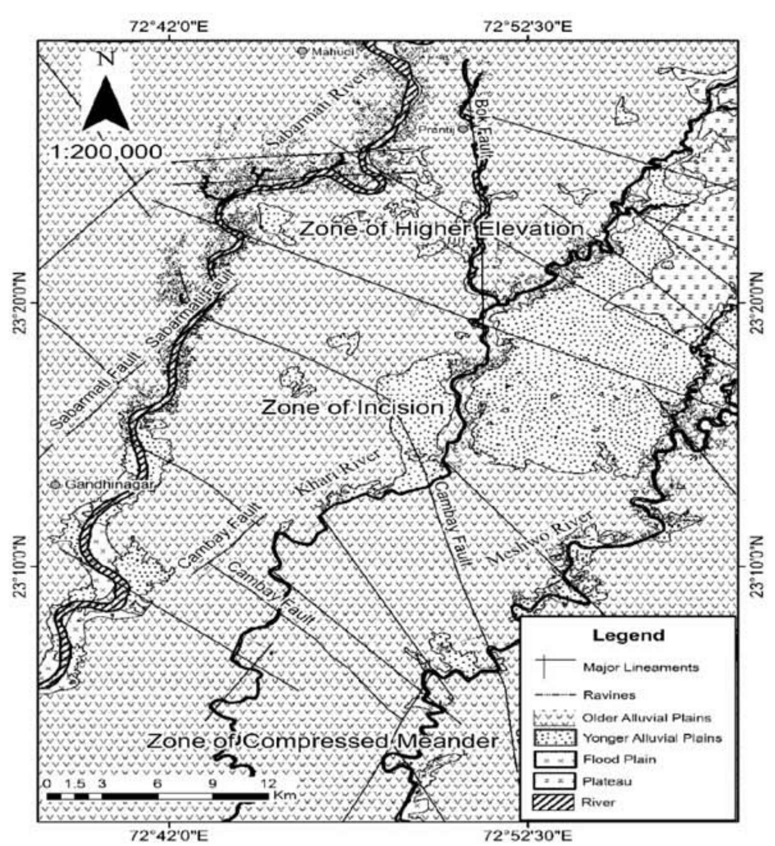

Figure 11. Geomorphological Map of study area (showing 3 zones and Major Geomorphic features with Major Lineaments present in the area)

resulted in uplift of the ground .This in turn caused lateral migration and incision of river channel giving rise to present day paleochannel (Figure 10).

DISCUSSION AND CONCLUSION

Seismotectonically the Sabarmati-Cambay basin is one of the major seismically active parts of western peninsular India (Pancholi, 2017 (*in press*)). The basin has witnessed occurrence of several micro to moderate earthquakes in the recent past. About 625 earthquakes in Cambay Rift region have been recorded by Gujarat state seismic network from mid-2006 through 2012.Their magnitude ranged from~1 to 4.4. A Larger number of located earthquakes since 2008 may be due to improved delectability, with the establishment more number of surveillance network. Annually, on an average 10-20 shocks of M 2-2.9 and 2-3 shocks of M $\geq$ 3 are being recorded (Pancholi, 2017). The entire length of the basin from north to south and entire width from west to east seem to be active.

The tectonic signatures along Sabarmati River, Gujarat, India have been examined in the central portion of the basin using satellite data and detailed field check. The morpho stratigraphy of the basin suggests that the upper fluvial sequences are overlying Aeolian sand (Srivastava et al., 2001). The optical chronology of fluvial sequences suggests that these were deposited between 55 and 12 ka during the Oxygen Isotope Stage-3 (Srivastava et al., 2001).

The incised valleys and ravine surfaces suggest that the river reached present stage after 12 ka. Previous studies show that the river adjustment in the central portion of Sabarmati river basin is caused by several phases of tectonic pulses between 12 ka and 3 ka. The presence of scroll plains and abundant paleochannels in the area are witness to Holocene tectonic movement along faults (Srivastava et al., 2001).

Based on Geomorphic development ,it is inferred that the zone of Incision is one of the most active segments of the study area compared to the zone of Higher Elevation and the zone of Compressed Meanders (Figure 11) .The landform development in the central segment of the area is controlled by NNW-SSE, NW-SE, and NE-SW trending faults. Geomorphic developments such as uplifted strath terraces, incised ravine surfaces, wind gap, paleochannels, offset of drainage pattern, compressed meandering are linked with the tectonic movement along NNW-SSE, NW-SE, and NE-SW trending faults. Based on stream offset, several new faults have been identified. The presence of these geomorphic features together suggests tectonically active nature of the terrain. The luminous Chronology of the sediments found in Mahudi area (Srivastava et al., 2001), suggests that Sabarmati River aligned to its present course as the result of tectonic activity in the region. The timing of incision and uplift is bracketed between 12 and 3ka. Evidence of tectonic activity during the Mid-Holocene is indicated by the preservation of three scroll plains (Srivastava et al., 2001). The Geomorphic mapping of landforms in the central segment of Sabarmati river basin will be useful for future earthquake hazard assessment and town mitigation planning.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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