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FIELD GUIDE

INPOST - 04

LATE QUATERNARY CONTINENTAL SEQUENCES IN THE SEMIARID ALLUVIAL PLAINS OF GUJARAT, WESTERN INDIA







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INQUA INDIA 2027

Field Guide Book

INPOST-04

Late Quaternary Continental Sequences in the SemiArid Alluvial Plains of Gujarat, Western India

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Abstract

The semi-arid alluvial plains in the state of Gujarat astride the Tropic of Cancer form an important part of the drylands of western India bordering the Thar Desert in the western part of the Indian subcontinent. The climatic conditions are controlled by SW monsoon, physiography and the Thar Desert. The drainage of Mainland Gujarat originates in the eastern highlands and debouch into the Gulf of Cambay. The southwest to west flowing Sabarmati, Mahi and the Narmada are the major rivers draining the alluvial plains of Mainland Gujarat. The distinct sedimentary facies, aggradation and incision phases evident in the near complete Late Pleistocene sediment sequences exposed along river valleys, showcase the climatic imprints along with interactions between the marine, fluvial and aeolian sedimentation. Geoarchaeological significance is reflected in several sites of Indus valley civilization that allow linking of climate-culture aspects.

The exposed sequence comprises pedogenised fine clayey silt of marine origin at the base that is correlated with the last interglacial high at ~125 ka B.P. (MIS 5e). This is overlain by fluvial sequence comprising layers of cross-stratified gravels (MIS-4), silty sand horizons with bedded calcrete, pedogenically modified silty sands with uppermost pedogenically modified horizon showing reddening (red soil) that has been used as inter basinal stratigraphic marker (MIS-3). The sediments above red soil comprise the upper fluvial sequence which is overlain by aeolian sand that has been correlated with the arid phase of the Last Glacial Maximum (MIS-2). Available data shows that aeolian sedimentation in the region began around 26 ka B.P. and continued episodically until around 6 ka B.P. (MIS-1), suggesting a northward propagation in environmental condition for aeolian sedimentation in response to deglaciation related strengthening of SW Indian monsoon. The Mid to Late Holocene sediments occur as elevated unpaired valley fill terraces, comprising tidal estuarine mud and sand and fine to medium sand of mixed environment in the estuarine mouths and fluvial sands and silts in the upstream reach. The proposed field excursion aims to showcase the climatic and tectonic history of the Late Quaternary alluvial basin located at the southern margin of Thar Desert in Gujarat state in western India.

Preamble

Over the past three decades, the urgency of human-induced climate change has shifted scientific focus toward the Earth's past to better anticipate its future. Quaternary science has thus emerged as a vital interdisciplinary field, centered on the delicate balance between landscape development and human sustenance. By examining the complex environmental shifts preserved in the stratigraphic record, we can decode how earth's surface processes respond to the prevailing drivers of climate change and tectonic activity. This field excursion is designed to demonstrate the critical importance of fundamental geological approaches, specifically the field-based geomorphic analysis and surficial deposit mapping integrated with modern analytical techniques. The umbrella question here is to reconstruct the Late Quaternary climatic and tectonic history of the Gujarat Alluvial Plain.

The alluvial plains of Mainland Gujarat occupy a unique geological position, overlying the N-S trending Cambay rift at the western continental margin of the Indian plate. While plate tectonics and neotectonism remain the primary drivers of this landscape, its tropical location has made it highly sensitive to Quaternary climatic fluctuations. Here, the sedimentary archives provide a rare, near complete continental record dating back to approximately 125 ka B.P., offering profound insights into the interplay between fluvial, marine, aeolian, and tectonic processes.

Participants will observe spectacular monsoon-fed river systems characterized by gorge-like valleys and vertical cliff banks reaching 30–50 meters. These landscapes are marked by deep ravines, entrenched meanders, and slope-deviatory river courses that serve as imprints of tectonic forcing. Simultaneously, the distinct sedimentary facies and alternating phases of aggradation and incision reveal the rhythmic pulse of the palaeomonsoon.

Highlights of the field transects:

- Enormous sediment archives for Late Quaternary climate reconstruction.
- Sites for interactions between the marine, fluvial and aeolian sedimentation- all manifested.
- Impressive geomorphic markers of active tectonics especially along the Narmada-Son Fault (NSF) zone.
- Sites of Indus valley civilization allowing linkage to climate-culture aspects.

Regional Geology

2.1 Introduction

Physiographically, the Gujarat State is divisible into three well-defined areas viz. Mainland Gujarat, Saurashtra and Kachchh peninsula (Fig. 1). The three divisions correspond well with the three distinct tectonic provinces of Western India (Fig. 2). The geological set up of Gujarat is the result of complex interaction between tectonism and sea level changes during the Cenozoic. The basic framework was formed due to sequential fragmentation of the western continental margin of the Indian plate

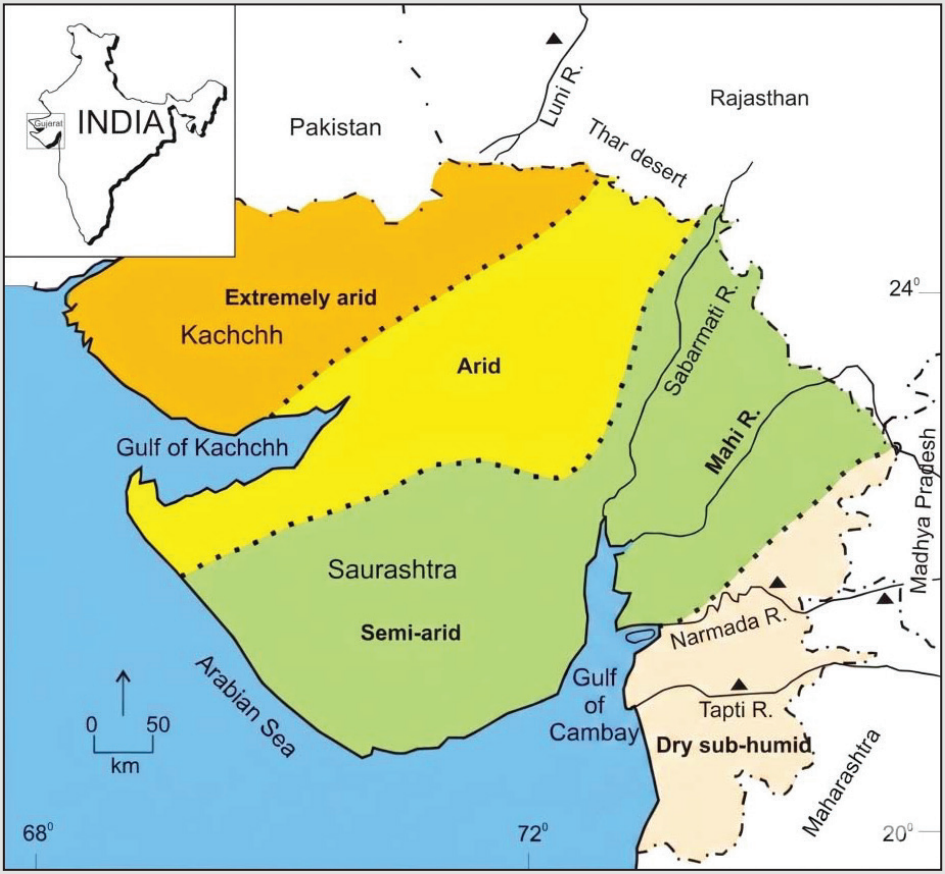


Fig. 1 Map showing the major physiographic divisions and climate zones of Gujarat

While a major part of Tertiary sediments in these basins is of marine origin, the Quaternary sedimentation has been largely fluvial (Merh, 1993).

2.2 The Gujarat Alluvial Plain

The Mainland Gujarat is divisible into four broad geomorphic zones (Fig. 3): the eastern upland zone, the shallow buried pediment zone, the alluvial zone and the coastal zone (Maurya et al., 2000). The flat alluvial plain bordered by the Aravalli and Trappean highlands to the east occupies a major part of the Mainland Gujarat. The subsurface cross section clearly brings out the influence of the tectonic framework of the Cambay and Narmada basins along with their various tectonic blocks on the Quaternary sediments. The basin therefore, comprised series of horsts and grabens, which were the direct manifestations of the various Tertiary structural blocks. These tectonic basins were periodically subjected to uplifts and subsidence relative to each other, while overall the basin was subsiding. The plain shows a gentle slope towards SW.

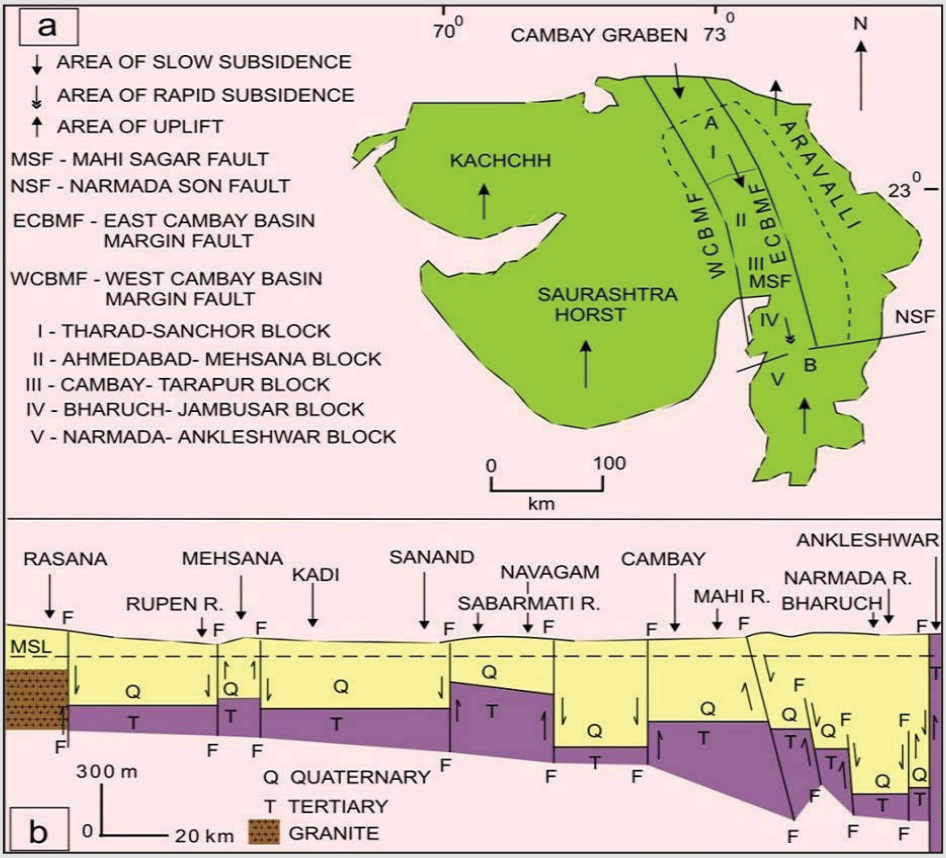


Fig. 2 (a) Map of Gujarat showing the nature of tectonic movements during Quaternary. (b) N-S cross- section across the Gujarat alluvial plain showing the variable thickness of Quaternary sediments (after Maurya et al., 1995).

The fluvial systems of alluvial plain of mainland Gujarat show a strong structural control on drainage architecture (Fig. 4) and the landscape of the area has evolved due to neotectonism and palaeo-environmental changes (Maurya et al., 2000; Chamyal et al., 2003). The drainage of Mainland Gujarat originates in the eastern highlands and debouches into the Gulf of Cambay. The Sabarmati, Mahi and the Narmada are the major rivers draining the alluvial plains of Mainland Gujarat (Fig. 4). All the rivers of the alluvial plains are characterised by gorge like valleys evidenced by the presence of 30-50 m high vertical cliffy banks, deep ravines, presence of tributaries on one bank only, deeply entrenched meanders, and the slope deviatory approach of several rivers. All these features suggest an obvious influence of tectonism.

The landscape and drainage configuration show dominant control of tectonic elements as revealed by lineament analysis (Maurya et al. 2000). The lineaments correspond to the three major structural trends, NE-SW, ENE-WSW and NNW-SSE which parallel the Aravalli, Satpura and Dharwar regional trends respectively (Fig. 5). The Dharwar trend is found to dominate in the northern and central part,

Fig. 2 (a) Map of Gujarat showing the nature of tectonic movements during Quaternary. (b) N-S cross- section across the Gujarat alluvial plain showing the variable thickness of Quaternary sediments (after Maurya et al., 1995).

while the Aravalli trend is present as the second major trend. The Satpura trend dominates the southern part. The N-S and NNW-SSE lineaments seem to reflect the basin configuration. Drainage courses of the area follow NE-SW and NNE-SSW lineaments.

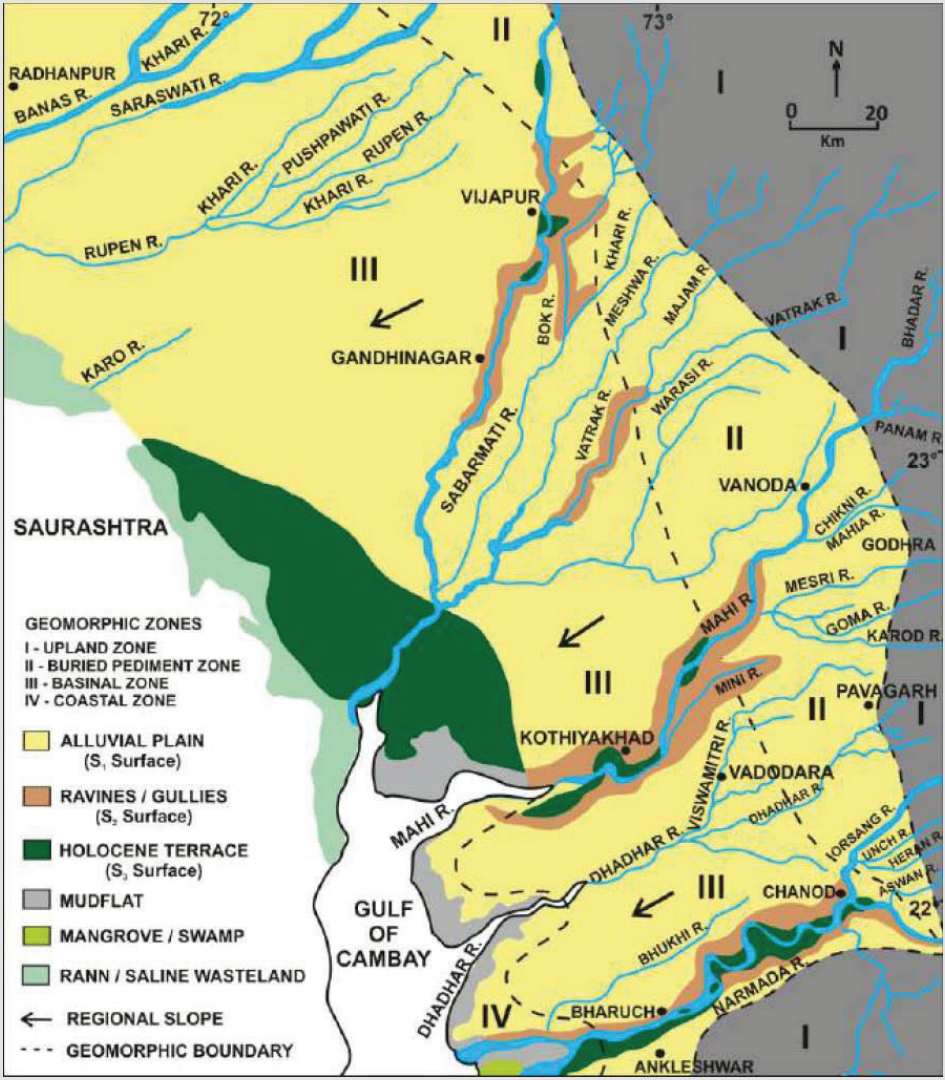


Fig. 3 Geomorphic map of the Gujarat Alluvial Plains showing various zones, geomorphic surfaces and related landforms (Maurya et al., 2000).

The two dominant trends are the NNW-SSE and ENE-WSW direction (Fig. 5) correlates with the subsurface intrabasinal horsts and grabens in the northern alluvial plains. The ENE-WSW to E-W trends suggest the subsurface continuation of the Aravallis. The area south of Mehsana up to Sabarmati river is devoid of basement highs which diverts the streams to flow towards the south as evidenced by the Sabarmati river. South of Sabarmati River, a NE-SW to NNE-SSW subsidiary trend is also seen in addition to the dominant basin trend. The eastern margin fault is represented by a series of subparallel en-echelon lineaments trending in N-S and NNW-SSE directions (Fig. 5). The lineament density on the eastern margin is higher compared to the western margin. The NE-SW lineament trend is replaced by the ENE-WSW trend near the Narmada river suggesting an obvious influence of the Narmada-Son Fault (Fig. 4). South of the Mahi river a major lineament trending NNE-SSW controls the extent of ravines south of the Mahi river and the course of the Vishwamitri river. An E-W trending lineament along the Mahi estuary marks the Mahisagar Fault in the subsurface.

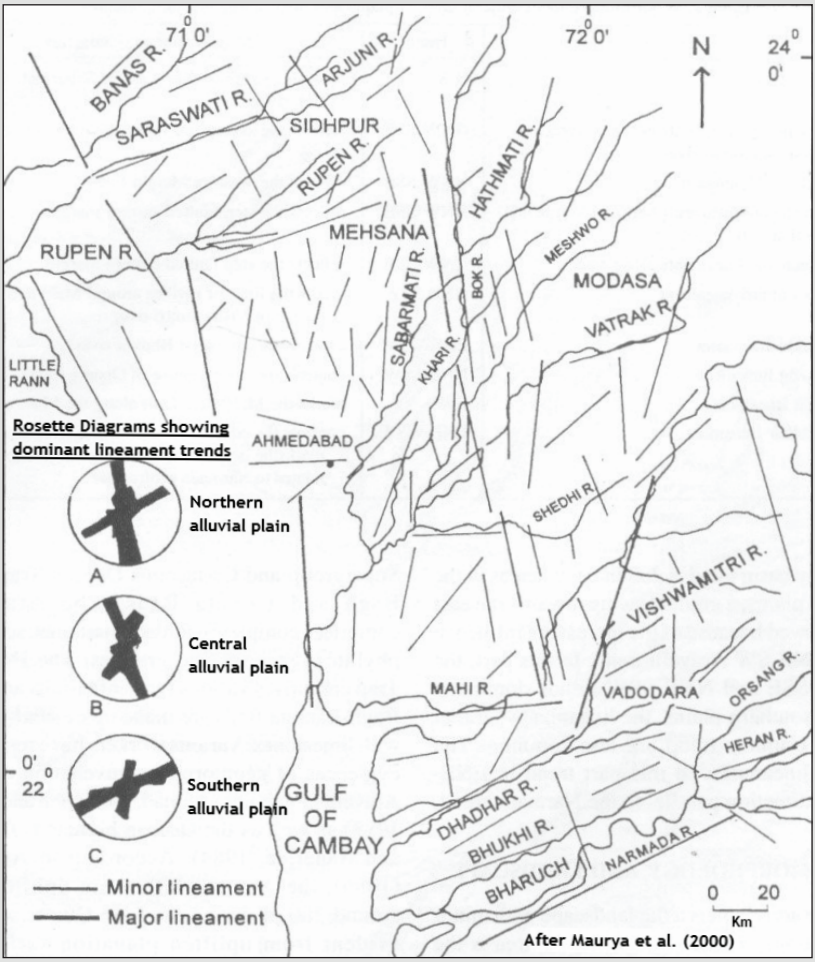


Fig. 4 Lineament map of the Gujarat Alluvial Plains (Inset –Rosettes showing dominant trends in (A) northern, (B) central and (C) southern alluvial plains (after Maurya et al., 2000).

The lineament rosettes for the northern, central and southern alluvial plains show a change from N-S in the northern plains to ENE-WSW trend in the southern plains (Fig. 5 A, B, C). In the northern plains, the N-S Cambay basin trend is dominant whereas in the central plains, a gradual swing towards the east is observed because of the increasing influence of the NE-SW Aravalli trend. In this part, the NNW-SSE and NNE-SSW trends dominate. In the southern plains, the lineaments parallel to the Cambay trend are less common. The major lineaments in this part trend in ENE-WSW direction parallel to the Narmada trend. The drainage configuration of the rivers of alluvial plains (Fig. 4) shows excellent correlation with the subsurface structural highs and faults (Maurya et al., 2000). In the southern plains, the lineaments parallel to the Cambay trend are less common. The major lineaments in this part trend in ENE-WSW direction parallel to the Narmada trend.

The drainage configuration of the rivers of alluvial plains (Fig. 6) shows excellent correlation several areas which are devoid of drainage viz. to the west of the Sabarmati river, between the lower courses of Sabarmati and Mahi rivers, and the lower course of Mahi and Dhadhar rivers, to the west of the lower course of Orsang River and to the south of Narmada River (Fig. 6) correspond well with the subsurface structural highs (Maurya et al., 2000). Several anticlines are present to the south of Narmada causing a northward shift of the course of the Narmada River (Fig. 6) (Maurya et al., 2000; Chamyal et al., 2002). The courses of the Sabarmati, Mahi and Orsang Rivers do not follow the SW regional slope of the plains (Fig. 6). Maurya et al. (2000) have indicated that the N-S to NNE-SSW courses of the Sabarmati, Mahi and the Orsang rivers appear to have captured the E-W to ENE-WSW courses of their tributaries which follow the regional slope of the plains. The Sabarmati has captured the course of Vatrak, the Mahi has captured the course of the Mini, Mesri and Goma rivers and the Orsang has captured the course of the E-W flowing Heran and Unch rivers (Fig. 6). Maurya et al., (2000) have envisaged a phase of drainage realignment during which the large-scale river capturing took place by the structurally controlled major rivers whose courses were determined by the subsurface structural features and the tendency of some rivers to flow along or parallel to basin axis. However, an axial drainage consistent with the basin axis is absent in the Gujarat alluvial plains.

The geomorphology around the various river valleys of Mainland Gujarat show mainly three distinct geomorphic surfaces (Maurya et al., 2000) – the alluvial plain (S1), the ravine surface (S2) comprising Late Pleistocene sediments and the Mid-Late Holocene valley fill terrace (S3). The sediments comprising these surfaces have great bearing on the evolutionary history of Mainland Gujarat during Late Pleistocene and Holocene.

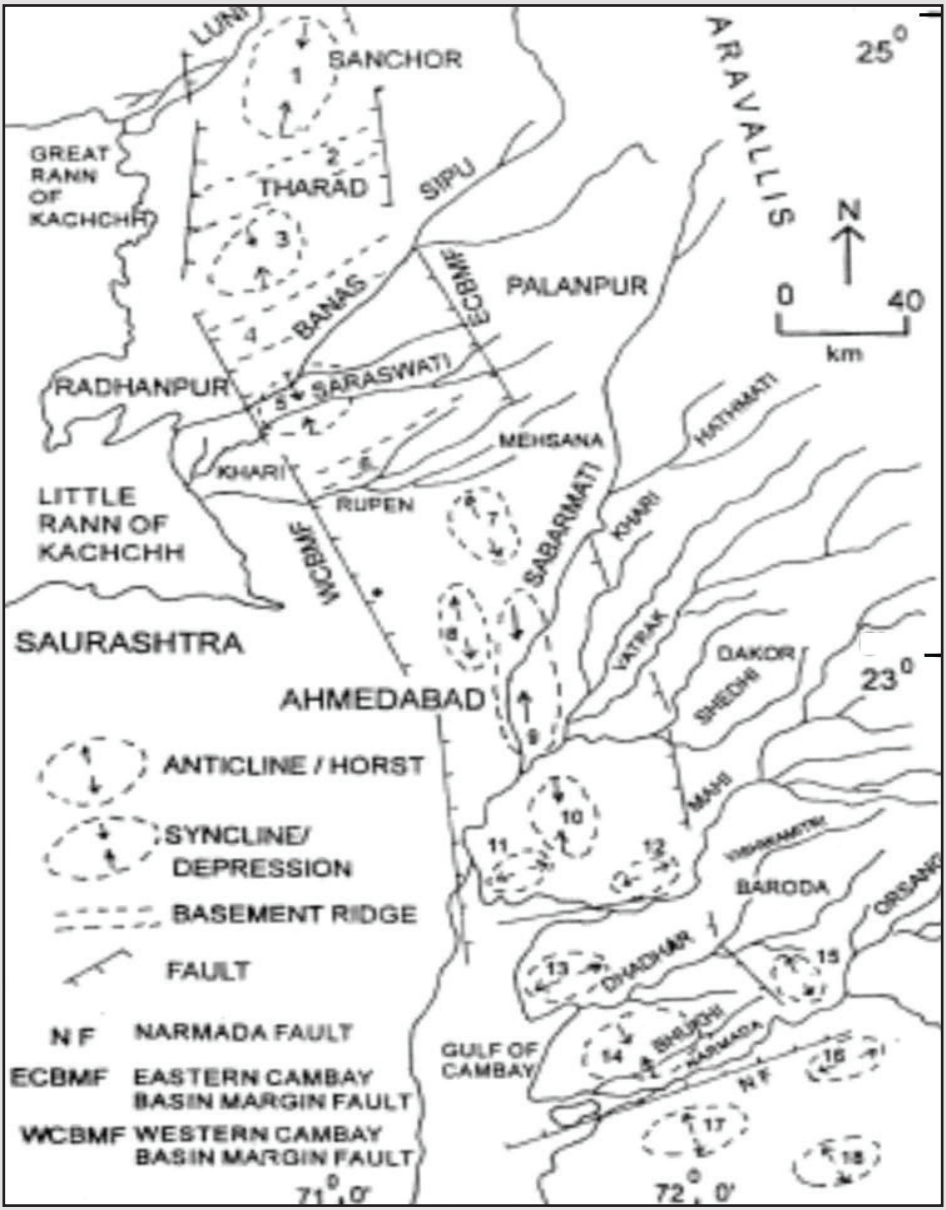


Fig. 5 Drainage map of Gujarat alluvial plain showing control of subsurface structural features (after Maurya et al. 2000). 1-Sanchor depression, 2-Tharad ridge, 3-Paiyak depression, 4-Diyodar depression, 5-Patan depression, 6-Unhawa ridge, 7-Mehsana horst, 8-Kalol high, 9-Gandhinagar basin, 10-Tarapur depression, 11-Cambay high, 12-Kathana anticline, 13-Dhadhar anticline, 14-Broach syncline, 15-Atali anticline, 16Jhagadia anticline, 17-Ankleshwar anticline, 18-Talodra anticline.

2.3 Regional stratigraphy of exposed Quaternary sediments

The exposed succession begins with the fine clayey silt that becomes fluvio-marine silty clay in areas proximal to the coast (Fig. 6). This is overlain by cross-stratified gravel. A silty sand horizon with bedded calcrete overlies the gravel. This is overlain either by gritty sand or assorted gravels. Upward in the sequence lie the pedogenically modified silty sands. The uppermost pedogenically modified horizon shows reddening (red soil) that has been used as inter basinal stratigraphic marker. With exception of a few localities where the red soil is overlain by cross-stratified gravel, in majority of the cases weak to moderate pedogenically modified silty sand horizon overlies the red soil (Fig. 6). This horizon grades either into a fluvio-aeolian sand or fining upward channel sand. The sequence above red soil has been designated as the upper fluvial sequence (Srivastava et al., 2001). This is overlain by aeolian sand that constitutes the top most litho-unit in the region.

Presence of fluvio-aeolian sediments suggests that the transition from fluvial to aeolian phase was gradual. After around 25 ka, the fluvial regime begins to dwindle as indicated by the fining upward channel sand. The establishment of aeolian sedimentation followed this. Since the controlling factors for aeolian sedimentation are the wind vector and the moisture/vegetation cover, it can be suggested that aeolian activity began with the weakening of southwest monsoon around LGM (~ 20 ka). The aeolian sedimentation terminated after LGM in the dry sub-humid Orsang basin whereas it continued till around 11 ka in the semi-arid Mahi basin. Further north in the Sabarmati basin aeolian sedimentation continued till 5 ka (Juyal et al., 2003). This shows a northward propagation in environmental condition for aeolian sedimentation and suggests a moisture-vegetation control on aeolian dynamics (Juyal et al., 2003).

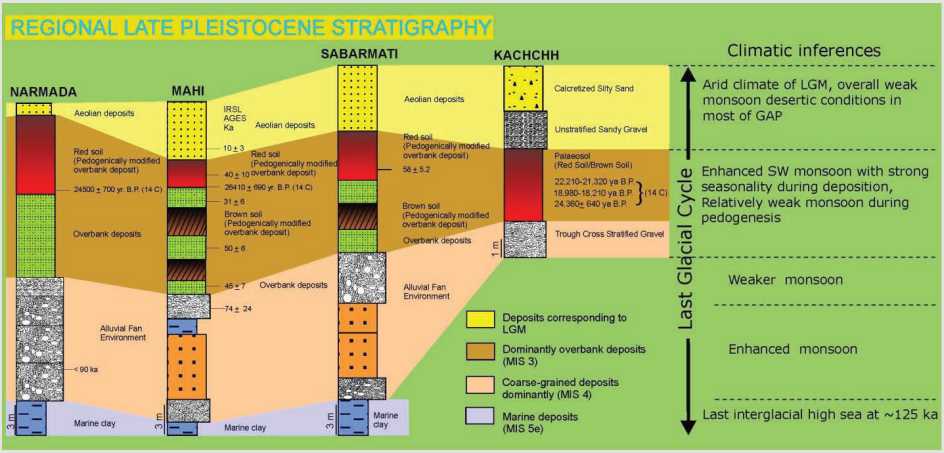


Fig.6. Physical stratigraphy of the exposed Late Pleistocene sediments (S1 and S2 surfaces) in the lower Narmada valley and the adjacent Mahi, Sabarmati valleys in mainland Gujarat and rivers of southern mainland Kachchh. Note the correlatability of the major climatically aggradational phases. Dates are after Juyal et al., (2000), Tandon et al., (1997) and Allchin et al., (1978). (Lithologs based on Chamyal et al., 2002; Maurya et al., 2000; 2003).

Flora, Fauna And Climate

The climatic conditions over the Gujarat Alluvial Plain are mainly influenced by SW monsoon, physiography and the adjacent Thar Desert. This region, astride the Tropic of Cancer falls in the sub tropical climatic zone located between 35o and 45oC isotherms and experiences moderate rainfall. The climate is dominantly semi-arid, but the northernmost part in has an arid climate, while the southernmost part experiences a sub-humid climate.There are mainly three seasons viz Monsoon (middle of June to October), Winter (November to February) and Summer (March to June). Winter is mild, pleasant and dry in the state. The average daytime temperatures is around 29°C (84°F) and night temperature is about 12°C (54°F), with sunny days and clear nights. Summer is extremely hot and dry when day temperatures usually rises to 45°C (120°F), while night temperature reaches about 30°C (86°F). In the weeks leading to the arrival of the southwest monsoon rains by mid-June, the high temperature gets associated with high humidity, making the condition very oppressive. As the rains arrive the temperature drops to below 35°C. Rainy season continues till the end of September, and often causes flood in many areas. The rest of the months receive almost no rainfall. During February, the month for the INQUA field, the weather is at its peak for fieldwork—cool, dry, and stable.

The variations in the rainfall, altitude, soil etc has lead to a great diversity in the flora and fauna of the alluvial plains. The dry deciduous forests and expansive agricultural lands are home to a variety of indigenous vegetation species such as Tectona grandis, Dalbergia latifolia, Adina cordifolia, Gmehna arborea, Grewia Tiliaefolia, Acacia catechu and Aracia nilotica to name a few. The exotic species include Eucalyptus tereticornis,Casuarina equisetifolia and Prosopis juliflora. Mangifera indica, Zizyphus mauritiana, Feronia limonia, Phyllanthus embica are the main fruit trees. The common crops are tobacco, cotton, and groundnuts along with rice, wheat, jowar, bajra, maize, tur, and gram.

The major domestic animals are cow, buffalo, horse, camel, sheep, goat and donkey. The wild animals found in the region are Panther, Wolf, Jackal, Fox, Chital, Nilgai, Langur, Mongoose, Squirrel, Porcupine, Rat etc. The reptiles include Crocodile, Python, Vipers, Monitor-Lizard, Chamelion etc. The common bird species are crow, sparrow, parakeet, myna, robin, bulbul, fly catcher, dove, egret, saras crane, duck, owl, vulture etc. Several migratory birds from Siberia, Central Asia and Europe also flock the wetlands in winter.

Literature Review

The evolution of the Late Quaternary continental landscape in mainland Gujarat has been a focal point of geological research for over five decades, with studies primarily utilizing fluvial and lacustrine archives to disentangle the complex interplay between tectonics, sea-level fluctuations, and climate. Through extensive field documentation and sediment analyses including textural parameters, palynology, geochemical characterization, and chronology, researchers have generated vital proxy datasets spanning the Late Pleistocene to Holocene. These investigations have focused on exposed sediment successions along major river basins in the southern Cambay Basin, such as the Narmada, Orsang, Dhadhar, Mahi, Sabarmati and Banas rivers. Early foundational work by Merh and Chamyal (1997) identified the Cambay Basin as a primary depocenter and established the basic lithostratigraphy of the Gujarat Alluvial Plains. Subsequent significant outcomes included the demarcation of the Pleistocene-Holocene boundary, the identification of palaeosols as climatic markers for Marine Isotope Stages (MIS) 5 or 3, and the documentation of a transition from fluvial-dominated to aeolian-dominated deposition during the Last Glacial Maximum (LGM) (Juyal et al., 2000; 2006).

The dynamic coupling between climate-driven erosion and tectonics using fluvial sequences and landforms remained the central research theme as the alluvial plains, fringed by the Cambay rift and situated within the Indian Summer Monsoon (ISM) trajectory are governed by these shifting variables (Maurya et al., 2000; Chamyal et al., 2002; 2003; 2007; Jain et al., 2004; Raj, 2004; Raj and Yadav, 2009;

Raj et al., 2015; 2021; Bhattacharya et al., 2017; Sridhar et al., 2018; 2022a). Investigations have revealed that the form and dimensions of present-day rivers are very different as compared to their Pleistocene counterparts (Sridhar et al., 1994; Gupta et al., 1999; Chamyal et al., 2003). Broad correlations show that river incision especially in western India was associated with wetter phases of the Holocene Climatic Optimum and Late Holocene whereas aggradation occurred during the drier MIS-4, Last Glacial Maximum (LGM) and mid-Holocene (Kale et al., 2003; Juyal et al., 2006; Sridhar et al., 2013). In summary, during the Late Pleistocene, the region transitioned from a marginal marine environment to an extensive fluvial phase before aeolian sedimentation began. The alluvial stratigraphy reflects a fluctuating fluvial regime between 120 ka and 30 ka, moving between meandering and braided systems, followed by an aeolian-dominated landscape from 30 ka to 11 ka. The modern fluvial regime emerged after 20 ka; incision began during the low sea stand and intensified with the onset of the SW monsoon between 14 ka and 11 ka, followed by a period of quiescence until 8 ka. Specifically in the Sabarmati basin, a second phase of dune accretion occurred between 9 ka and 5 ka, while valley-fill terraces formed under fluctuating monsoon conditions from 5 ka to 2 ka. The global climatic events such as the Holocene Climatic Optimum, Medieval Warm Period and the Little Ice Age have also been recorded in the fluvial and lacustrine archives across the river basins (Kusumgar et al., 1998; Prasad et al., 2014; Raj et al., 2009; 2015; 2021; Sridhar et al., 2015; 2020).

While the highly incised banks of these rivers generally prevent channel shifting or avulsions on a decadal scale, historical evidence shows significant stream capture and course realignment triggered by early Holocene tectonic upheaval and climate change (Maurya et

al., 2000; Raj 2004; Juyal et al. 2006). These processes of avulsion and river capture result in confluence migrations that produce interfingering deposits between mainstream and tributary channels (Sridhar et al., 2022b).

Parallel research in the Narmada-Son Fault (NSF) zone indicates that this area has remained tectonically active throughout the Cenozoic, characterized by low to moderate modern seismic activity (Gupta et al., 1972; Biswas, 1987; Chamyal et al., 2002; 2022; Mulchandani et al., 2007; Joshi et al., 2013a, b). This region is currently under a compressive stress regime, evidenced by the reverse nature of the NSF and sympathetic faults resulting from the inversion of the Narmada basin (Agarwal, 1986; Roy, 1990). The area south of the NSF underwent inversion in the Late Pliocene due to a thinner crust, while the northern section inverted during the early Holocene (Chamyal et al., 2002).

In more recent times, palaeohydrological studies relating to flood magnitude, occurrence of extreme events and its relation to the southwest monsoon variability over various time scales have also been taken up in these river basins (Sridhar, 2007; Sridhar and Chamyal, 2018; Sridhar et al.,2014; 2016; 2026). A clustering of high magnitude events at climatic transitions and arid periods during Mid–Late Holocene has been observed (Chamyal and Sridhar, 2021).

Despite the wealth of published data on stratigraphic and neotectonic markers, reconstructing a high-resolution climatic and tectonic history remains difficult due to limited temporal resolution and uncertainties in proxy data interpretation. Future research must bridge these gaps. Moreover, most exposed sections only reach back to approximately 125 ka, leaving the older Quaternary history buried and poorly understood. It is essential to further substantiate lithostratigraphic correlations with chronological reconstructions since fluvial systems respond differently to same forcing. Whether the river incision and aggradation are driven by monsoon intensification, tectonic uplift, sea-level changes, or the confounding effects of historical human-induced erosion and deforestation remains a crucial issue for future research.

Field Transects

Location: Gujarat Alluvial Plains, Mainland Gujarat, western India

Dates: 5th February to 7th February 2027

Starting and ending point at Vadodara.

Trip starts daily from Vadodara at 8:00 am and ends at 7:30pm in Vadodara.

The field excursion will be carried out in SUVs and all spots to be visited are accessible by road. However the participants will be required to walk down and along the river valleys to access the sections. The detailed route plan is as shown in Fig. 7 and described as below:

Component	Place from-to	Sites to be visited	Stay
Arrival from Delhi to Vadodara on 4th Feb 2027 General briefing and discussion in the evening			Vadodara
Day 1 **5th Feb 2027**	Field visit to understand Landscape evolution and Late Quaternary sequences of Mahi River Basin and Geoheritage site visit at Lothal	Spot 1 Rayka Spot 2 Dabka Spot 3 Kothiyakhad Spot 4 Lothal	Vadodara
Day 2 **6th Feb 2027**	Field visit for Late Quaternary alluvial fan sedimentation in the lower Narmada River Basin	Spot 5 Chandod Spot 6 Gamod Spot 7 Tilakwada Spot 8 Hanfeshwar	Vadodara
Day 3 **7th Feb 2027**	Field visit to understand the Tectonic geomorphology of the Narmada-Son Fault (NSF) zone	Spot 9 Tejpur Spot 10 Juna Ghanta Spot 11 Jitnagar Spot 12 Gora colony	Vadodara
Departure from Vadodara on 8th Feb 2027			

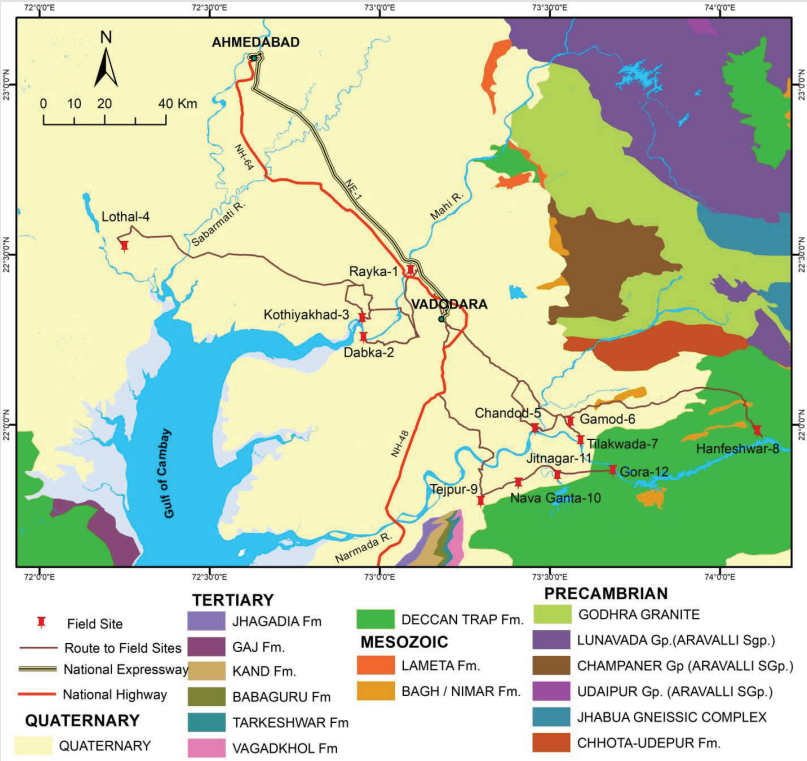


Fig.7 Map showing the generalized geology, major cities, field sites to be visited and route to the field sites.

Description Of Locations

6.1 Day 1: Landscape evolution and Late Quaternary sequences of Mahi river basin

6.1.1 The Mahi River Basin

The Mahi river basin is the third largest in Gujarat (32000 km2) after the Rivers Narmada and Tapi. The Mahi River emerges from the Aravalli mountains and flows along the eastern flank of the Cambay graben, which is an intracratonic rift graben (Biswas, 1987). It then crosses the alluvial plains of Gujarat before debauching into the Gulf of Cambay. The East Cambay Basin Margin Fault (ECBMF) cuts across the Mahi River, as indicated by a change in orientation of the river (Maurya et al. 1997). Several N–S and NNW–SSE trending fractures that developed parallel to the ECBMF have strongly influenced the drainage pattern of this river. Thus, whenever the river approaches a lineament it deviates from its NE–SW path and takes a NNE–SSW course. Subsurface data indicate the presence of pre-existing step faults parallel to the ECBMF that acted as the depocenter for Late Pleistocene sedimentation (Maurya et al. 1995). The Mahi basin lies in a horst segment and has over 300 m of Quaternary sediments overlying the Tertiary rocks (Maurya et al. 1995). The geomorphic features of the Mahi basin indicate a complex interplay of tectonism and base level changes in its evolution (Maurya et al. 1997). Two distinct geomorphic zones are identified based on the morphological characteristics. The first zone, identified as rocky upland zone, is characterized by high, steep rocky mountains with deep and narrow fluvial valleys and steep longitudinal profiles. The zone has been rejuvenated during Quaternary (Sen and Sen, 1983; Ahmad, 1986). The second zone is the alluvial zone, the area of the Pleistocene –Holocene alluvial deposits. The landscape of this zone is characterized by wide valleys. The development of extensive badlands in this zone suggests active denudational processes attributed to Holocene tectonic uplift (Rachna Raj et al. 1999). The Mahi River has carved out a conspicuous entrenched meandering course across this zone. All the geomorphic features in the Mahi iver form two distinct surfaces, an older (S1) and a younger (S2) have been identified in various geomorphic zones. The pre-Holocene surface (S1) is paired, highly eroded and extensively dissected surface, comprising sand silt and gravel mainly of fluvial and aeolian origin. The younger Holocene surface (S2) occurs as unpaired elevated terraces, comprising two lithofacies- tidal estuarine mud and sand and fine to medium sand of mixed environment. The two phases of tectonic uplift and fluctuating sea-levels have helped in shaping the landscape of lower Mahi valley.

The sequence commences with the deposition of marine clay (Rachna Raj et al. 1998), shows evidence of intense pedogenesis (Khadkikar et al. 1998) and is overlain by a planar cross-stratified gravel (Gravel-1). This is succeeded by a sandy layer with mud drapes and bedded calcretes. Trough cross bedded gravel (Gravel-2) overlies this, which in turn is overlain by two to three pedogenised horizons, the upper most being red in color (red soil). The red soil is overlain by medium to fine-grained fluvial sand that becomes fluvio-aeolian in character in the upper part. The aeolian sand sheet finally blankets the succession. At Rayka, the aeolian sand sheet directly overlies the red soil however, recent investigations carried out in the lower reaches of the Mahi basin indicated that a renewed phase of fluvial aggradation followed after the development of red soil. This event has been designated as the upper fluvial sequence (Srivastava et al. 2001, Juyal et al., 2006) which gradually merges upwards into the aeolian sediments.

Proximity of the Mahi basin to the Gulf of Cambay and presence of marine clays at the base of the exposed sections suggests an eustatic control on sedimentation. The overlying fluvial aggradation was consequent to base level changes following marine regression. During this phase, river could erode and transport sediments from poorly vegetated catchment (Graf 1988). Presence of basalt and carbonate concretions in Gravel-1 indicates poorly vegetated source (proximal catchment). The silty sand with bedded calcretes overlying Gravel-1 suggest cohesive banks and persistent flow (sinuous stream) with periods of dryness resulting in the formation of bedded calcretes (McCarthy and Metcalf 1990). Dominance of poorly sorted clasts of calcrete, quartzite and basalt in Gravel-2 indicates substantial flow intensities. Rolled carbonate nodules further indicate the ability of flow to erode pre-existing alluvial carbonate under frequent channel migration. The textural evidences suggest the existence of ephemeral fluvial system during the deposition of Gravel-2. Fine sand, silt and clay that have been pedogenised dominate the overlying sediments. These form laterally extensive sand sheets. Higher concentration of silt indicates that deposition occurred away from the main channel on the flood plain by the meandering stream (Juyal et al. 2000). Presence of pedogenic horizons suggests periods of alluviation followed by prolong periods of pedogenesis. Out of the three horizons the upper most is red in colour, whereas the lower two are grey in colour. Generally, the red soils develop on better drained sites reflecting higher elevation and/ or more permeable parent material, whereas the grey flood plain soils are formed in poorly drained areas with less permeable material (Kraus 1997).

Following the development of red soil, climate temporarily reverted back to drier conditions as indicated by the overlying trough cross-stratified sandy gravel. However, this event was short lived and localized. Discrete occurrence of planar and cross-stratified gravel dominated by poorly sorted clasts of basalt, quartzite and calcrete at Dodka, Jaspur and Sultanpur suggest sudden increase in sediment supply. This could happen in arid and semi-arid environment where episodic storm surge events are common during which rivers are capable of eroding and transporting sediments from poorly vegetated catchment (Graf 1988). This gives rise to braided channel system having typically large width to depth ratio in which the number of individual channels can vary from 1 to more than 20 (Thornes 1994). In a rare event the riverbed is completely occupied, however in a given time the distributary channels carry water and are known for frequent migration of channels that lead to bank erosion. However, in view of its limited extent, it can be suggested that the event was short lived and local in nature.

A persistent fluvial regime reappears in the basin with the deposition of fine silty sand usually overlying the red soil. Distinct fluvial signatures are preserved in the form of current/ripple laminations and mud balls suggesting prevalence of low energy meandering river system. The deposits are typical of flood plain fine facies of Miall (1996) representing the sedimentation in a flood plain regime (Willis and Behrensmeyer 1994). These sediments are at times associated with the bedded calcrete at places like Jaspur and Dahewan. Bedded calcrete formation is usually related to the ground water fluctuations in a riverine playa environment (Goudie 1983), thus suggesting its deposition proximal to a channel. It has been further suggested that flood plains are

most conducive locations for the development of bedded calcretes where ground water remains close to the surface in semi-arid areas, thus a high evaporation is ensured leading to its development (McCarthy and Metcalf, 1990). Therefore, a vertical aggradation of this facies that varies in thickness ranging from 2-10 m suggests that the deposition was facilitated under a persistent flow regime under well-defined channel (e.g. meandering course) with periodic over spilling of silty sand on to the adjacent floodplains. Evidence of moderate pedogenesis associated with these sediments suggests phases of non-deposition when the channel responsible for the flood plain aggradation migrated laterally. Such channel migration occurs under changing water budget (both increasing and decreasing). In either situation, river tends to abandon the old course and occupies the new one. This led to the exposure of the flood plain sediments for sub-aerial weathering a process responsible for the development of flood plain soils (Kraus and Aslan 1993). It is evident that the sediments above the red soil were deposited under improved moisture availability. The overlying aeolian sand shows gradational contact with the underlying fluvial horizon. This indicates initiation of drier climatic condition, which could be associated with enhanced wind activity in the region.

6.1.2 Spot – 1 Rayka Section

The Rayka section is located on the eastern flank (left bank) of the river Mahi, 20 km NW of Baroda and exposes a ~40 m high alluvial cliff'. The section has been considered as a type section and documents a sequence of the paleoclimatic variation over the past ~125 ka (Fig. 8). The exposed succession shows two distinct phases of fluvial aggradation. The earliest is located between Gravel-1 and Gravel-2 in the form of sandy calcareous (62% sand) unit. This is followed by the second phase,

which is represented by a sandy silt (59% sand) unit intercalated with palaeosols lying above gravel-2. The stratigraphic succession of the deposit commences with a clay containing shallow marine microfauna which is overlain by planar cross-stratified gravel-1. The clay has yielded fairly rich assemblage of foraminiferids comprising benthic foraminiferids (Rachna Raj et al. 1998) like Pararotalia sp., Brizalina spp., Nonion spp., Cibicides spp., Florilus spp., Ammonia spp., and three species of planktonic foraminiferids viz., Turborotalia sp., Globigerina bulloides (Parker, Jones and Brady) and Globigerinoides ruber (d'Orbigny). On the basis of the foraminiferids, it has been concluded that the formation was deposited in an estuarine to marginal marine environments having low salinity due to influx of fresh water during Late Pleistocene. The marine clay is yellowish brown (10 YR 5/4) to brown (7.5 YR 5/4) in colour and is highly pedogenised and the exposed thickness of the unit ranges from 0.5-3 m which extends to a depth of 25 m below mean sea level at Rayka (Murthy 1975). The unit shows intense fracturing which intersects giving rise to subangular cohesive blocky aggregates, continuous concave upward planes appear which have been interpreted as pseudo-anticlines (Fig.9). Calcium carbonate is dispersed irregularly throughout the clays, both the form of nodules and tubes (Fig. 8). The clay mineral assemblage (Malik et al., 1999) is dominated by a very high percentage of smectite (montmorillonite), with suubordinate quantities of illite and Kaolinite. Presence of shallow marine foraminifera in the clays suggests that they were deposited during a high-sea strand corresponding to a fluvial climate.

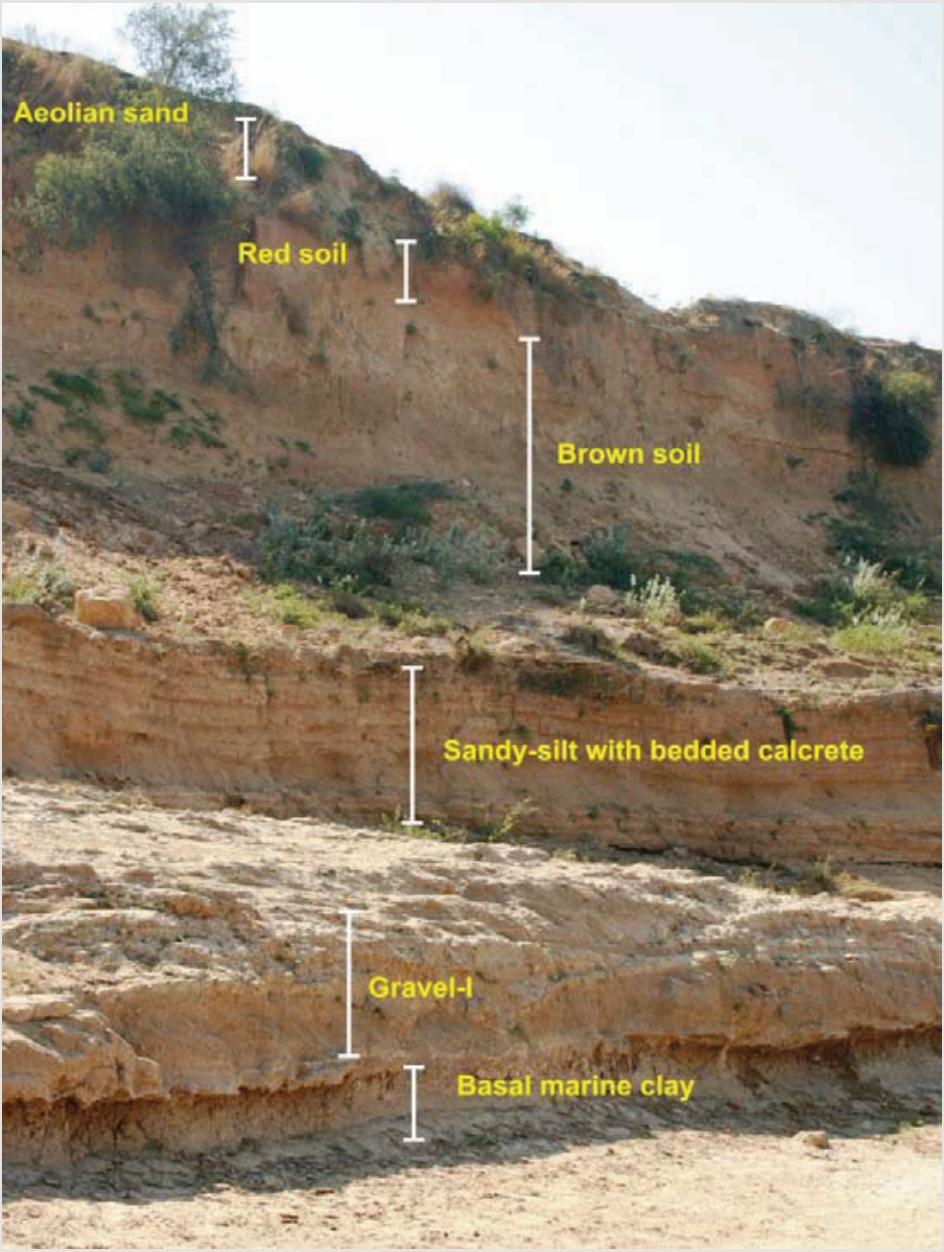


Fig.8. Sediment Succession at Rayka



Fig.9. Vertisol showing pseudo-anticline and other vertic characters at Rayka

The cross-bedded gravel that overlies the marine clay with an erosional contact indicates initiation of fluvial activity. Well-developed 2-3 m thick planar- cross stratification in the gravels, comprised of basalt fragments and carbonate nodules, indicate proximal source. Planar cross-stratification (1 m) is commonly associated with ephemeral flow and is often formed by an advancing channel bar. The presence of associated clay drapes indicates the recessions of the flood peaks during which clay particles settle out. Thus, suggests that gravel-1 was deposited during the peak flood events when large volumes of wash load and bed load were eroded from poorly vegetated slopes.

This unit is overlain by laminated sandy silt with and carbonate occurring both as discrete bands and irregular nodules. Nearly 50 such layers are recorded which occur at regular intervals. The composite thickness of these laterally traceable layers varies between 3-5 m. No significant pedogenesis has been found to be associated with these layers which could be due to syn-depositional tectonism as indicated by soft-sediment deformation structures (Maurya et al. 1997; Jain et al. 1998). Textural characteristics and consistency in the appearance of the individual layers which are invariably separated by the calcium carbonate bands indicate a calm water environment in the flood basin area. The individual layers are suggestive of repeated flood events along a possibly sinuous stream during a humid climate when banks with strongly cohesive and sediment availability restricted substantial vegetation in the catchment. In between episodes of overbank sedimentation there were probably periods of aridity facilitating calcium carbonate precipitation.

The soft sediment deformational structures confined within fine grained silty sand show fold structures of intraformational character. These in some cases extend up to 15 m. The geometric shapes of these folds vary from wide open folds to flexures to monoclines. The calcrete bands show well developed plunging folds, where the fold axis tends towards south with a plunge of 10-150. The wave length of the fold varies from 1.5 to 2 m with an amplitude of 0.5 m. The monocline shows an apparent steepening towards west, suggesting that the downfaulted block lie to the west. The smaller closely spaced minor faults within the strata are significant indicators of syn-depositional tectonism. In another study by Jain et al (1998) at Rayka, four NW striking faults were mapped, having throws ranging from 1 to over 3 m. They have related growth folds in synchronous sediment units. They showed that a slump sheet moved tens of meters towards northeastward down the 0.70 dip slope of one tilt block during displacement on its bounding faults.

The silty sand horizon is overlain by a highly mottled and pedogenised mud. This shows well developed vertisolic characters such as desiccation cracks, drab halos and calcium carbonate root casts. The deposit is typical of a flood plain and seems to have been deposited during the final phase of flood events in isolated flood pools. Intensive fracturing, reflecting pedogenic activity has given rise to sub angular aggregates described as peds. Peds form through repeated expansion and shrinkage of clays coupled with root activity of plants. Striations formed due to preferential orientation of clay minerals are found on the ped faces. Calcium carbonate nodules and tubes occur throughout. Vertical fissures form in response to extreme drying events when the soil starts cracking. Greenish grey drab haloes consist of a white carbonate rich core enveloped by greenish grey clays gradually merging with host clays.

The vertisol is overlain by a 1-2 m thick gravel-2 with trough cross- stratification. It occurs as isolated bodies dominated by poorly sorted clasts of calcrete, quartzite and basalt. A wedge-like geometry is seen where stratification planes of the gravel extend into the adjacent sand unit to form a large trough. The lower bounding surface is erosive with respect to the underlying mottled clays. The foresets show normal grading and dip of 140 - 250 due SW to SSW in the northern sections and SSE, SSW and W in the southern sections (Malik et al., 1999). Trough cross-stratification is usually formed by the downstream migration of trains of sinuous crested mega dunes in a deep channel profile. These troughs show a decreasing amplitude towards the top suggesting declining flow. Such poorly sorted relatively large clasts (~10 cm) are indicative of enhancement in the flow intensity due to the change in the stream gradient. The trough axes of the foresets are indicative of the channel orientation with high angle of plane beds (160-180) suggesting their deposition as point bars. Rolled carbonate nodules indicate the ability of the flow to erode the stable surface in the upper alluvial plain. The lithofacies are a product of sedimentation under a high flow regime in developing channel bars (Miall, 1978, 1985; Todd and Went, 1991). Overall, the evidence suggests the existence of an ephemeral fluvial system.

Gravel-2 is overlain by thick (~10 m) alluvium comprising fine sand, silt and clay which is intercalated with three weathered horizons identified as palaeosols. These deposits form laterally extensive sheets of silty sands with pedogenic calcium carbonate nodules dispersed in sub-parallel layers. Higher silt content indicates their deposition away from the main channel as a floodplain deposit by stream that has a consistent flow path. The presence of palaeosols indicates the episodic nature of deposition with each phase of alluviation followed by a period of pedogenesis. These possibly were caused either by channel avulsion in association with continued aggradation after the deposition of Gravel-2, or they reflect episodes of climatically induced flow regime changes. The temporary hiatuses corresponding to the peodogenesis could be due to waning flow or channel avulsion. The three palaeosols show well developed thick B horizons and the complete absence of the A horizons. Each soil is somewhat different in colour. The lower and middle palaeosols are yellowish brown to grey in colour (10YR 5/4 and 10YR 7/4). Small submillimeter diameter buried root-channels lined by carbon are seen. These soils generally are less calcified as compared to the overlying red (rubified) soil. Carbonate nodules occurring within the soil profile are orthic and irregular in morphology and are on an average 1-2 cm in size. The granulometric analysis shows mean average grain size ranging between 3.33 and 3.96 Ø. It comprises average percentages of 48% to 62% of sand, 28% to 36% of silt and 8% to 16% of clay and is moderately well sorted. The clay mineral assemblage shows high concentration of montmorillonite with subordinate amount of kaolinite and illite. On the basis of granulometric analysis these soils can be categorized as sandy laom. The brown coloured horizons which show higher concentration of clay as compared to the overlying rubified soil, suggests clay illuviation and soil formation evidenced by the presence of root channels, development of aggregates (peds) and minor calcareous nodules. These features indicate that the soil is moderately developed. The presence of montomorillonite along with subordinate kaolinite and illite suggests a provenance similar to the red soil. The relatively higher content of kaolinite indicates a wetter climatic phase with a precipitation >900 mm (Weaver, 1989). This clay mineral forms in high leaching conditions. However, the presence of calcretes nodules (though less profuse) in these profiles is attributed to subsequent drier time spans.

The upper soil, which has been used as a stratigraphic marker in the Mahi basin, is yellowish red in colour (5YR 5/6). The granulometric analysis of this lithofacies shows mean average grain size ranging between 3.34 to 3.75 Ø. The sediments are composed of 54% to 74% of sand, 20% to 28% silt and 6% to 18% clay and are moderately well sorted. The clay mineral assemblage is dominated by smectite (montmorillonite) with subordinate amount of illite and kaolinite. Hematite is observed in trace amounts. On the basis of granulometric analysis this soil may be categorized as sandy loam. The undulatory nature of the upper contact suggests a subdued palaeotopography. Pedogenesis is indicated by clay concentration in the soil profile. The higher concentration of smectite (montmorillonite) along with subordinate amount of illite, kaolinite and hematite (in trace amounts) suggests that the clay minerals were derived from sediments containing ferromagnesian minerals, along with potash and sodic feldspars and micas (Weaver, 1989). This is also supported by the presence of basalt granules in the host sediments, the weathering of which led to the above mentioned newformed clays mainly smectite (montmorillonite). Presence of hematite in trace amounts may be because of lack of crystallinity of this mineral that was responsible for the coloration of the soil horizon (Pye, 1983). The carbonate nodules accumulated at the base of the soil profile forming a distinct zone, showing sharp boundaries not connected to each other.

These characters obviously point to the nodules as being pedogenic calcretes, and their concentration in the lower portions of the unit typically suggests that these are related to the weathering profile. The palaeoprecipitation values calculated using the equation given by Retallack et al. (1995) gives values of around 2000 mm for a depth of 350 cm. But as such values are unlikely for calcic soil it is suggested that the red sol is actually a pedo-complex (cumulative soil) and spans a considerable period of time.

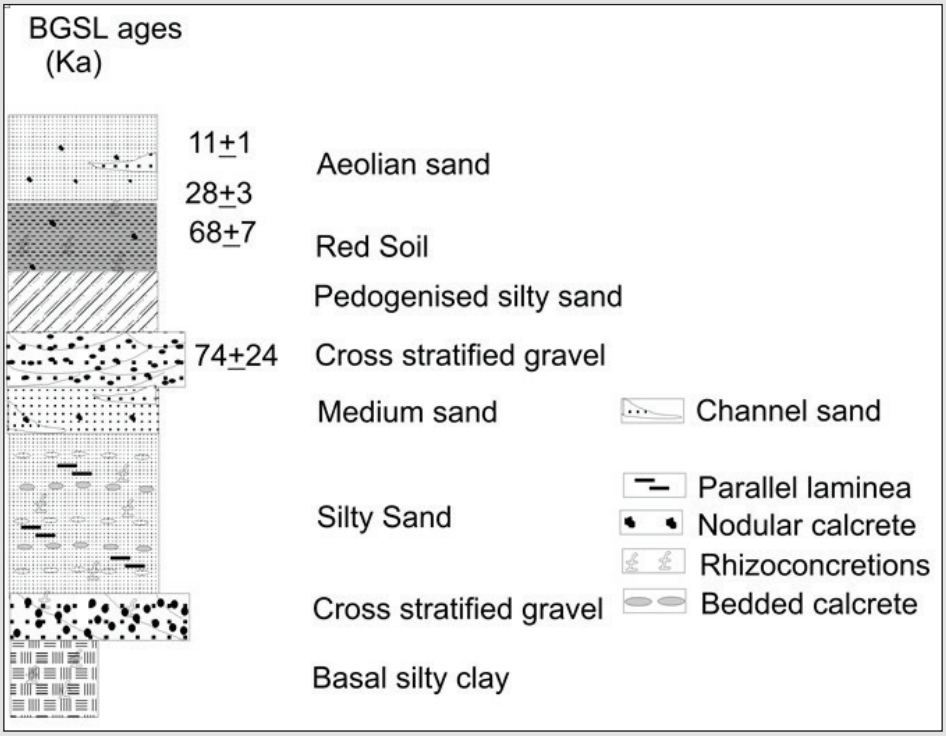


Fig.10. Lithostratigraphic succession at Rayka with BGSL ages (after Juyal et al., 2000)

The uppermost alluvial units are capped by fine aeolian sand and silt perhaps indicating the onset of aridity in the region, alternatively, aeolian sand accretion can also take place in areas proximal to channels. In the latter case, such aeolian sand accretions are known as source bordering dunes.

Juyal et al. (2000) provided the chronology for the exposed Late Quaternary sequence at Rayka that is considered to be the type locality in the Mahi basin (Fig. 10). The basal marine clay was assigned the Marine Isotopic Stage-5 (MIS-5). Gravel-1 and 2 were deposited between the MIS-5 and 74 ka and the silty sand with intercalated pedogenised horizons were bracketed between 74 ka and 40 ka. However, recent chronometric data based on Quartz extract on red soil at Jaspur show that the sequence overlying red soil could have developed between 68 and 50 ka.

Thus, the earlier age of 40±10 ka on red soil obtained on feldspar mineral at Rayka (Juyal et al. 2000) probably suggests an age underestimation due to fading, a phenomenon associated with feldspar dating (Huntley and Lamothe, 2001). Since luminescence dating gives the sediment deposition ages, hence it can be inferred that red soil development postdates 68 ka (age of red soil sediment) and pre-date 50 ka (age of the overlying fluvial sand) and probably representthe Marine Isotopic Stage-4. The overlying fluvial and fluvio-aeolian sediments (Upper fluvial sequence) are bracketed between 50±8 and 34±3 ka (MIS-3). Presence of bedded calcretes in the upper fluvial sequence dated to MIS-3 indicates that fluvial activity was not monotonous but punctuated by fluctuating hydraulic discharge. Towards the upper part, dominance of very fine sand indicates that there was a subordinate aeolian component getting admixed with the weak fluvial regime. Finally, the drier conditions set in as indicated by the initiation of aeolian sedimentation around 30 ka.

6.1.3 Spot – 2 Dabka Section

At this section 15 m cliff is exposed on the left bank of the river of which the basal 2m succession is covered by the scree material. The exposed succession shows well developed 3 m thick medium to fine silty-sand horizon of red palaeosol. The horizon is yellowish red (5YR 4/6) and is calcretised. The base of the horizon shows high concentration of calcrete nodule ranging in size from 1.5 mm to 2.5 mm in diameter. The sediment size becomes coarser towards the top along with the decreasing concentration of the calcrete nodules. In the upper part the sediments are mainly silty-sand and show well developed pedogenic features like buried rootlets, rhizoconcretions and burrows that are dark brownish-black in colour. This is overlain by 5-6 m thick horizontally stratified silt horizon with sub-horizontal calcrete layers. The "loess-like" silts, which are 3 m thick, overlies this and the succession is capped by 1 m thick dunal sands.



Fig.11a A view of late Quaternary cliff sections exposed along the estuarine zone in the Lower Mahi River Basin

6.1.4 Spot – 3 Kothiyakhad section

This section is located in the estuarine zone of Mahi basin. The S2 surface at Kothiyakhad occurs as 3-6 m high, flat terrace and has been mapped all along the lower Mahi basin as an unpaired terrace whose cliffy sections are cleaned by recent erosion. Two major units identified in the successions are: 1) dark greyish brown clay with organic content and 2) greyish silty sand. These occur in alternation with an erosional contact and the base is unexposed. The clay units have yielded a good population of foraminiferids, whereas the silty-sand units have preserved fresh water ostracods. Radiocarbon dating of four organic rich clay horizons at Kothiyakhad has provided dates of 3660±90, 3320±90, 2850±90 and 1760±80 yrs B.P. (Kusumgar et al. 1998). However, since the base of this sequence is not exposed, it is obvious that the actual deposition of the terrace sediments commenced prior to 3660±90 B.P (Fig.12a). Radiocarbon dating of shells in the basal gravelly layer of a comparable fluvial terrace overlying basement rocks at Vanoda in the pediment zone of the Mahi River has provided date of 6400±120 yr B.P. This suggests that the deposition of Holocene valley fill terraces was initiated within the river channels as the Holocene sea reached post-glacial high on the west coast at around 6000 B.P. (Hashimi et al., 1995). A total of 25 genera of foraminiferids were identified from the mud units of Kothiyakhad. Out of these 23 are benthic comprising of Brizalina, Bulimina, Bolivina, Biloculina, Lagena, Triloculina, Pseudobulimina, Hopkinsina, Sagrina, Ammonia, Cibicides, Discorbis , Discorbinella, Florilus, Hastegerina, Melonis, Nonion, Nonionella, Pyrgo, Pyrgoella, Pararotalia, Parafissurina, Rosalina and few other Rotaliid. The two planktonic forms identified are Globigerinoides sacculifer (Brady), Globigerina bulloides (Parker, Jones and Brady), Globigerinoides ruber (d'Orbigny). The silty-sand units have yielded 3 genera of ostracods namely Condona, Darwinula and Ilyocypris. Considering the morphology of benthic forms the 23 genera of foraminiferids were classified in two groups (Kusumgar et al., 1998); Angular asymmetrical and rounded symmetrical morpho-groups.

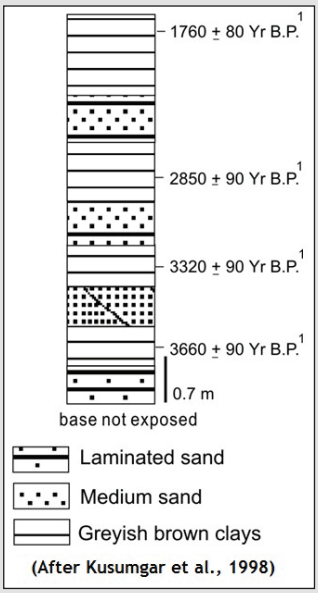


Fig.12 a. Litholog at Kothiyakhad showing radiocarbon dates.

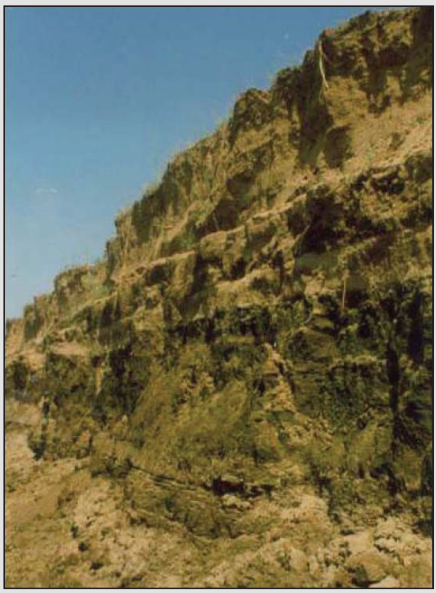


Fig.12 b. View of the Kothiyakhad section.

In addition to above, seismically induced structures have also been observed in the Holocene terrace sediments at Kothiyakhad (Maurya et al. 1998, 2000). These include-contorted laminations, load structures, convolutions and small scale folds, syn-sedimentary microfaults. Convolutions have been formed by tight folding of the beds leading almost to the formation of pseudonodules. Downward penetrating 'sand dyke like features' of fine sand into the underlying clay horizons due to seismic loading is also observed (Fig. 12b). The underlying horizons show effects of downward dragging indicating that the dyke was forcibly intruded. Occurrence of load structures adjacent to these dykes and absence of any significant sediment cover suggest the role of seismic loading in the formation of these structures.

Soft-sediment deformational structures are important indicators of past seismic activity (Allen, 1975). The deformation took place due to liquefaction, which occurs during shaking of the sediments near the sediment-water interface resulting in sagging or crumpling of sediments. Radiocarbon dating of organic rich clay horizons (Kusumgar et al., 1998) from the Kothiyakhad section in the lower Mahi valley suggests that the deformation occurred during a Late Holocene seismic event which took place between 3320+90 and 2850+90 yrs. B.P. The Holocene tectonism thus played a major role in the evolution of the Gujarat alluvial plains.

6.1.5 Spot-4 Lothal

The testimony to the Late Holocene climate and sea-level fluctuations is seen in the Geo-heritage site at Lothal in the Sabarmati River Basin. From a geological perspective, the site is a testament to the Holocene evolution of the Gujarat coastline. The surrounding landscape is characterized by vast, low lying alluvial plains and salt wastes, reflecting a history of marine transgressions and heavy sediment deposition from the major river systems. A recent study by Gupta et al., 2024 has identified the palaeochannels running alongside Lothal as River Sabarmati, one of the four major rivers flowing into the Gulf of Cambay.



Fig. 13. The Brick-walled Dockyard at Lothal



Fig. 14. The Pot Furnace at Lothal

Lothal, one of the southernmost sites of Indus Valley Civilization, was a vital and thriving trade centre in ancient times and a port during the Bronze Age Harappan period (2600 BCE to 1900 BCE), with its trade of beads, gems and valuable ornaments reaching the far corners of West Asia and Africa (Possehl, 1976). Lothal is renowned for its well-preserved brick-walled dockyard (Fig.13), warehouse and bead making techniques (Fig. 14). The most striking feature is the massive fired-brick basin, identified as the world's earliest known artificial dockyard.

The engineering of this structure demonstrates an advanced understanding of hydrography and tidal hydraulics. The Harappans utilized the high tidal range of the Gulf of Khambhat to sluice ships into the basin, accounting for the heavy siltation rates that still characterize the region today. The ancient inhabitants managed the local clay-rich soils (black cotton soil) to create durable, water-resistant building materials. However, it is reported that after the great flood of c. 2000 BCE, the prosperity of the Harappans started declining slowly, and by c. 1800 BCE, Lothal became a defunct port (Rao, 1979). The gradual tectonic shifting of river courses likely choked the dock with silt and isolated the city from its vital maritime link, leading to its eventual abandonment. Today, the site serves as a critical case study in how environmental changes and sedimentology dictate the rise and fall of coastal civilizations.



Fig.15. Geomorphic map of the lower Narmada valley (Chamyal et al., 2002)

6.2 Day- 2 Late Quaternary alluvial fan sedimentation in the lower Narmada river basin 6.2.1 The Lower Narmada River Basin

The Narmada River, the largest river of peninsular India, flows along the ENE-WSW trending Narmada-Son Fault (NSF), a well-known seismotectonic feature (Biswas, 1987). A major part of the course of the Narmada River falls within the rocky area comprising Late Cretaceous – Eocene basaltic lava flows belonging to the Deccan Trap Formation. The river follows a constricted course in this reach characterised by waterfalls, rapids, scablands and gorges (Rajaguru et al., 1995). The true alluvial reach of the Narmada is encountered in its lower part within the state of Gujarat. This reach is about 90 km in length and forms the southern margin of the N-S extending Gujarat alluvial plains. A significant feature of the lower Narmada valley is the deposition of a huge thickness of Tertiary and Quaternary sediments in a fault controlled basin. To the south of the ENE-WSW trending Narmada–Son Fault (NSF), the Tertiary rocks and basaltic flows of Deccan Trap Formation occur on the surface, while to the north they lie in the subsurface and are overlain by Quaternary sediments. However, the overlying Quaternary sediments having a maximum thickness of ~800 m (Maurya et al., 1995) still remain unclassified. Drill data from some of the deepest wells in the basin have revealed occurrence of Deccan Trap at depths of ~6000 m followed by an Archaean basement (Roy, 1990).

The Tertiary sediments, outcropping to the south of the NSF, represent the full sequence from Eocene to Pliocene overlying the Deccan Trap and show extensive deformation in the form of several ENE-WSW trending anticlinal highs and ENE-WSW and E-W trending reverse faults. Neotectonic studies along the NSF have been singularly lacking, however some studies dealing mainly with the channel form, fluvial processes and hydrological aspects have been restricted to the middle and upper reaches of the Narmada River (Kale et al., 1994; Rajaguru et al., 1995; Gupta et al., 1999).

6.2.2 Geomorphology

Geomorphologically, the lower Narmada valley is divisible into four broad geomorphic zones (Fig. 15) - the upland zone consists dominantly of basaltic flows and patches of Cretaceous sandstones of Bagh Formation, a low highland consisting of Tertiary rocks, vast expanse of alluvial zone, which correspond with the basin part and a narrow coastal zone comprising mud flats. Topographic profiles and field studies in the upland area reveal a highly-rugged topography evidenced by steep escarpments bounding the mesa tops and deep narrow gorges along the course of various streams. Since the area consists mostly of southerly dipping basaltic flows, the ridges and the associated intramontane valleys trend in ENE-WSW direction. The low highlands to the west of the basaltic uplands comprising Tertiary rocks, exhibit a hummocky topography in conformity with the anticlinal folds and faults. The straight ENE-WSW trending mountain front scarps along the northern edge of the basaltic uplands and the low Tertiary highland mark the NSF beyond which lies the alluvial basin fill. The study area shows a large variety of geomorphic features like deep ravines, uplifted terraces, abandoned cliffs (palaeobanks), incised cliffy banks and entrenched meanders. The alluvial plain between the ENE-WSW trending mountain front scarps and the Narmada river exhibit a gentle slope towards north while the alluvial plain in the north of Narmada River show a gentle WSW slope.

6.2.3 Geomorphic Surfaces

Four major geomorphic surfaces have been mapped in the lower Narmada valley (Fig. 15) - the alluvial plain (S1), the extremely dissected ravine surface (S2), a gravelly fan surface (S3) and the flat topped valley fill terrace (S4). The almost flat but gently sloping alluvial plain which occupies a major part of the area, has been designated as the S1 surface. This surface is extremely dissected in the vicinity of the river valley and exhibits gullies as deep as 20-30 m. We term this extensively gullied ravine surface as S2 to distinguish it from the undissected alluvial plain and the fundamental importance of the extensive dissection in the geomorphic evolution of the area. The S3 surface is a gravelly surface comprising a series of alluvial fans deposited along the mountain front scarps of the NSF near Rajpipla. This fan surface is bounded by a NW-SE trending fault passing through the river Narmada on its eastern side and by a NNW-SSE trending fault passing through the Karjan river, a tributary of the Narmada on its western side. The S4 surface is a wide flat topped terrace surface of 5-12 m height, which occupy a deeply incised fluvial valley. The terraces show no evidence of ravine erosion and abut against the abandoned cliffs (palaeobank) of S1 and S2 surfaces.

The Narmada River in its lower reaches presents a geomorphic set up that is at considerable variance with that in the middle and upper reaches described by Rajaguru et al. (1995) and Gupta et al. (1999). The river emerges from the trappean uplands after crossing the NSF near

Garudeshwar and follows a NW oriented fault controlled course upto Tilakwada. Further, the river flows in a general WSW direction. The river in this reach shows large meanders with wavelengths of 5-8 km. The Orsang, Aswan, Men and Bhuki are the major rivers joining the Narmada from the north. The Karjan River which drains a major part of the trappean uplands in the lower Narmada valley meets the Narmada from the south. The other tributary, the Madhumati River drains the western fringe of the trappean upland. Between the Karjan and Madhumati rivers there are several north flowing small streams meeting the Narmada. The streams draining the low highlands consisting of Tertiary rocks join the Narmada in the estuarine part. These streams follow courses that are in conformity with the structural features seen in the Tertiary rocks.

The present drainage of the lower Narmada valley consists of incising rivers evidenced by 40-50 m high alluvial cliffs and deeply entrenched meanders. Even the smallest streams, particularly those joining from the south, are found to have incised by 20-25 m. Presence of deep gullies (ravines), uplifted Holocene terraces, entrenched meanders and palaeobanks which comprise abandoned alluvial cliffs 15-30 m high away from the present channel are suggestive of neotectonic activity in the area. The Narmada River exhibits characteristics of underfit streams which are characterized by narrow channel inside a wide belt of terraces (Drury, 1970). Even the largest seasonal floods do not overtop the cliffy banks (Gupta et al., 1999). Presently, the Narmada River has a tendency to shift towards north (Agarwal, 1986). However, no traces of palaeochannels are found beyond the channel belt marked by a series of palaeobanks. The meanders continue to grow towards north conforming with the northward shift of the river. Close examination of the palaeobanks with the present channel confirms that the Narmada River has preferentially shifted towards north. This is clearly evident by the palaeobank in the lower reach where the straight palaeobank coincides with the NSF. This suggests that the Narmada has shifted away from the NSF due to neotectonic activity along this fault.

6.2.4 Late Quaternary Sediments

Sediments comprising the various geomorphic surfaces have been studied with a view to delineate the morphostratigraphic relationships between the various geomorphic surfaces and to understand the overall landscape evolution of the lower Narmada valley (Chamyal et al., 2002; Bhandari et al., 2005; Joshi et al, 2013).

S1 and S2 surfaces

The sediments that comprise these surfaces (S1 and S2) are exposed along the 40–45-m high incised cliffs along the lower Narmada valley. The sediment succession comprises a basal clay overlain by alluvial fan facies and the alluvial plain facies dominated by overbank sediments. The alluvial fan took place in response to neotectonic activity along the NSF (Chamyal et al., 1997; 2002).

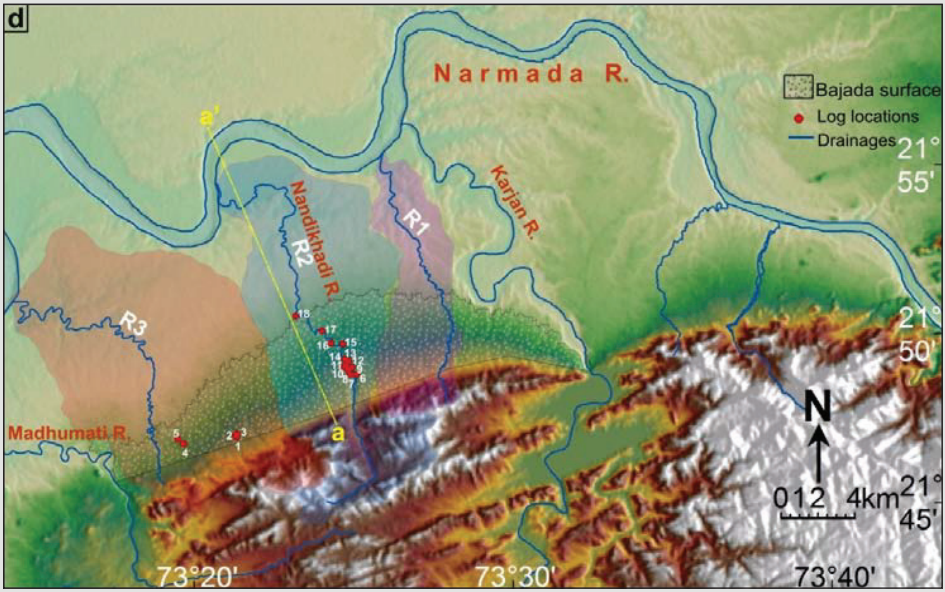


Fig. 16 DEM of lower Narmada basin showing the physiographic and tectonic setting of bajada fan, and drainage basin of feeder channels.

The alluvial fan facies – The alluvial fan sediments overlie the basal clays with an erosional contact evidenced by several scour and fill structures. The Narmada–Son Fault, with a known history of tectonic activity during Tertiary and Quaternary, provided the essential geomorphic and tectonic setting for the deposition of sediments in an alluvial fan environment. The alluvial fan has been recognised by the fan shape of the deposits occurring adjacent to a tectonically active mountain front (NSF) and is characterised by coarse-grained sediments. Proximal parts of the fans are dominated by coarse gravel. Massive to crudely stratified, clastsupported and matrix-supported gravels are dominant in the middle sections. Gh and Gms, however, occur throughout the fan but show increased complexity of facies and decreasing abundance down the fan. Planar and trough cross-stratified gravels are intercalated with Gms, Gh and Gc as thin beds. Individual beds of Gc, Gms and Gh are > 5 m thick. Gp and Gt vary from 2–5 m in thickness. Irregular erosional bases and channel fills are common. Fine to coarse pebbly sands make up about 50% in the distal fan sections. The most abundant lithofacies types point to debris flow, sheet flow and stream channel as the dominant aggrading processes, which are considered intergradational in most alluvial fan sequences. The clasts are unbedded (massive) and clast- to matrix-supported gravels (Gc and Gms) and horizontally stratified gravels are commonly imbricated (Gh). Thin waning flows of interbeds of sand and clay are also common alluvial fan lithofacies. Other diagnostic features of this alluvial fan are that they display considerable vertical and lateral variability of lithofacies. This is attributed to transport distance from source area to basin, the highly irregular, flashy and often catastrophic nature of the discharge, which is typical of all alluvial fans and the consequent highly variable stream power and sediment discharge that occurs during active fan sedimentation. The clasts are dominantly basaltic, which suggests trappean basaltic uplands as the provenance for these fan deposits.

An alluvial bajada has been recognized along a part of the Narmada-Son Fault (NSF) (Fig. 16) and confined by the Karjan River on the eastern side and by the Madhumati River on western side (Joshi et al. 2013). The bajada sequence exposed along the incised cliffs of various north flowing parallel streams has been studied in their proximal, medial and distal part. The sediments are characterized on the basis of grain size, fabric, sedimentary structures, bed geometry and sorting, and lithologs prepared from the mapped cliff sections. Detailed study of sedimentary characteristics, lithofacies analysis and facies associations indicate that sediments are mainly of three types – sediments that were deposited by debris flows and sediment gravity flows, and as extensive bar deposits. Three major aggradational sequences are recognized. Each sequence is composed of coarsening-upward sequence of proximal facies overlain by fining-upward sequence of distal facies. Coarsening upward sequence record periods of tectonic activity related to uplift along the NSF and fan progradation, whereas fining-upward sequence results from tectonic quiescence periods. The presence of rhizocretions, calcium carbonate nodules and calcite sheets within the basal debris flow and sediment gravity flow indicate semi-arid climate, whereas the formation of pedoginized paleosol indicate relatively wetter climate prevailing in the study area. Tectonic activity along the NSF has played dominant role by controlling the geometry and volume of bajada sediments (Joshi et al. 2013). Climate is found to be responsible for compositional and temporal distribution of bajada sediments. OSL dating suggests that the bajada sediments were deposited during the later part of Late Pleistocene. The incision of the sediments is attributed to uplift due to inversion of the lower Narmada basin during the early Holocene.

The alluvial plain facies – The alluvial plain sediments are found to overlie the alluvial fan sediments. These sediments are found to be dominated by overbank fines with channel fill and crevasse splay deposits. These belong to the fluvial architectural element, sandy bedforms (SB) of Miall (1985) and typically occur as lens, sheet, channel fill and crevasse splay forms. The sediments show development of very weak pedogenesis. However, most of them fall well short of being categorised as typical palaeosols. Massive sand sheets (Sm) constitute a major part of the alluvial plain facies and comprise laterally extensive sheets of fine to medium sands having a maximum thickness of 5 m. These are devoid of any internal stratification and lack lateral accretion surfaces suggesting that these are essentially developed due to vertical accretion. Thick sand sheets are generally attributed to have formed by meandering rivers during large floods when flood plains adjacent to the channel get submerged (Miall, 1985). Additional evidence is provided by weak pedogenesis of the top of sand sheets. However, an exact one to one correspondence is not common. This indicates frequent shifting of the channel belt and rapid sedimentation. Horizontally stratified sand (Sh) is next dominant lithofacies comprising laterally extensive and horizontally stratified fine to medium sands. This facies along with Sm shows fining upward trends. At places, laminated silts/sands (Fsc) occur as channel fills, which are identified by their concave up channel floor. The dominance of sandy bedforms suggest deposition by sand-dominated river systems (Allen, 1978; Miall, 1977). Overbank deposits show sheet-like geometry reflecting vertical aggradation (Miall, 1985). The alluvial plain sediment successions show a 3–6-m thick deeply pedogenised brownish red to reddish brown buried soil which is laterally consistent. The parent material for the soil is fluvial overbank fine sand and silt. The soil shows fracturing in the form of blocky aggregates. The pedogenesis is also indicated by the presence of copious amounts of calcrete throughout the soil horizon. The red colour of the soil is attributed to the prescence of coatings of ferric oxides around the grains during post depositional pedogenic processes (Merh and Chamyal, 1997). The morphological characteristic of the soil is comparable to those in the nearby Mahi and Sabarmati valleys.

6.2.5 Palaeoenvironmental Implications

The exposed sediments of the lower Narmada valley indicate two distinct phases of changes in the fluvial regime. One is the multidistributary channel system that deposited the alluvial fan sediments (Chamyal et al., 1997, 2002), followed by the deposition of finer alluvial plain sequence, described in this paper, by a large river in an alluvial plain setting. The reasons for the sudden change of multidistributary river system to a more integrated single channel river system, are not clear. The observed sedimentary characteristics of the alluvial plain sequence discussed above indicate a low sinuosity, single channel large river that was hyperavulsive. On a conservative estimate, the avulsions may have taken place on a scale of hundreds of years. The river was characterised by a ~8-15 m deep channel that was ~70-80 m wide even during low discharge levels. Present day large rivers show similar characteristics (e.g. Brahmputra, Coleman, 1969) in which the sediments show large-scale bedforms while the river migrates at a high rate. Presently, the Narmada has a large drainage basin most of which lies in the humid region further east of the Gujarat alluvial plain. This accounts for the high discharge levels of the Narmada river which is next only to those of the Brahmaputra and the Ganges (Coleman, 1969).

The phase of alluviation up to the palaeosol appears to be synchronous regionally and globally. Studies in adjacent Mahi, Orsang (Juyal et al., 2000; in press) and Sabarmati basins (Tandon et al., 1997) point towards the existence of largely semiarid climate and ephemeral river systems in Gujarat alluvial plains during most of the Late Pleistocene. The present study on the alluvial plain sedimentation in lower Narmada valley, however, indicates deposition by a large river which was supported by a climate significantly wetter than present. Though a general correlatability of the depositional phases during Late Pleistocene is obvious (Chamyal et al., 2002), the large-scale sedimentary bedforms of the type described here are not observed in the Mahi and Sabarmati basins. The exposed sediments and the modern discharge levels of the Narmada River, therefore, present a contrasting picture as far as Gujarat alluvial plain is concerned.

The Narmada River in the Late Pleistocene has been inferred to be a mobile meandering river which carried large quantities of sand (Gupta et al., 1999) with periods of large floods (Kale et al., 2003). Studies on Holocene palaeoflood deposits in central India (Kale, 1999; Kale et al., 1994; 2003; Ely et al., 1996) have revealed a strong correlation between periods of extreme discharges and stronger monsoons. We, therefore, infer that the alluvial plain sediments of the lower Narmada valley suggest humid climate in the large catchment area located further to the east. Additional evidence for a large catchment of the Narmada River during Late Pleistocene is provided by the dominance of subrounded clasts in the alluvial fan sediments (Chamyal et al., 1997) which underlie the alluvial plain sediments. The subrounded clasts (a deviation from the normal angular clast composition of alluvial fans) has been attributed to longer distance of transport before they were deposited in alluvial fan environment in the lower Narmada valley. This suggests that the Narmada River has maintained a large catchment at least during the last 100 ka. The alluvial plain sequence of the lower Narmada valley suggests discharges higher than the present-day Narmada River in the upper part of the Late Pleistocene. The palaeosol occurring towards the top of the sequence however correlates with the regional phase of intense pedogenic activity in the Gujarat alluvial plain before the Last Glacial Maximum. The overlying stratified sands and silts reflect a significant weakening of fluvial regime during the arid phase of the Last Glacial Maximum, though the river still remained perennial, again mainly because of the large catchment area of the drainage basin.

Overall, the 50-25 ka period is a period of widespread fluvial aggradation in India as seen from the studies on alluvial sequences in Gujarat alluvial plain (Tandon et al., 1997; Juyal et al., 2000; Maurya et al., 2000), Maharashtra upland rivers (Kale and Rajaguru, 1987), Central Narmada (Badam et al., 1986; Gupta et al., 1999; Kale et al., 2003), Son and Belan valleys (Williams and Clarke, 1984) and the Indo Gangetic plain (Singh, 1996). Well dated global fluvial sediment records from Guadalope basin in Spain (Fuller et al., 1998), the entire Mediterranean region (Macklin et al., 2002), Thames River (Maddy et al., 2001), Mississippi River (Autin, 1996; Blum et al., 2000), and Australia (Nanson et al., 1992; Kershaw and Nanson, 1993) also suggest enhanced fluvial aggradation under humid climate during the 50-30 ka time period. There is thus a strong reason to believe that the deposition of alluvial plain sediments below the palaeosol and showing large scale bedforms in the lower Narmada valley took place by a large river that operated in conditions humidier than present in response to global climatic perturbations. The humid climate together with a large catchment area contributed to the high discharges leading to the formation of large scale sedimentary structures in these sediments.

6.2.6 Spot-5 Chandod section

The 35 m thick sediment succession exposed at Chandod has been considered as the basis for the reconstruction of physical stratigraphy (Bhandari et al., 2005) (Fig.17 and 18). Fluvial deposits of 35 m thickness are exposed at Chandod. The base of the section is characterized by a 3 m thick planar cross stratified gravel (size ranging from 10-15 cm) and the matrix holding the gravels is of sandy origin. These are overlain by 2 m thick planar cross stratified sand which is overlain by planar cross stratified gravels having a thickness of 4 m. overbank fine sands and silts and shows typical fracturing in the form of blocky aggregates.

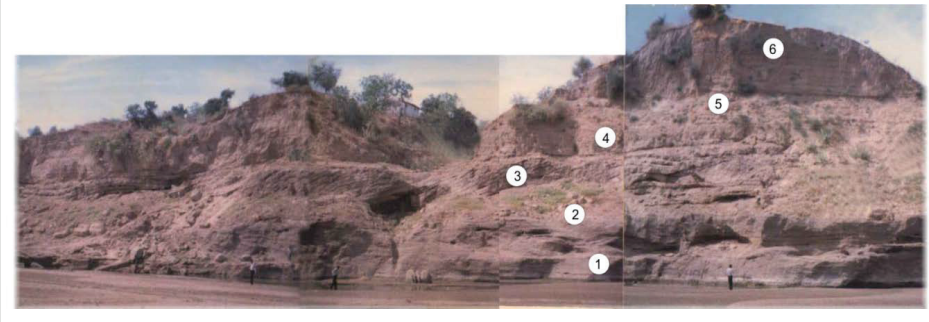


Fig. 17. Photomosaic showing part of the laterally extensive cliff exposure at Chandod. All units show erosional bases. 1) distal alluvial fan facies, 2) large channel fill sands, 3) giant epsilon cross bedded strata, 4) horizontally stratified overbank strata, 5) palaeosol, 6) thinly stratified sands and silts (after Bhandari et al. 2005).

There is copious amount of calcretes throughout the horizon. The soil shows typical reddish brown colouration. Overlying this is 6 m thick deposits of massive sand which shows no internal stratification.

At Chandod channel fills are observed at two stratigraphic levels, which are separated by the epsilon cross stratified facies (Fig. 17 and 18). The older channel fill overlies the gravel deposits which belong to the distal alluvial fan facies with a deeply scoured base. The channel fill shows a gentler concave geometry and is filled by vertically accreted fine to

medium sands. Overall, the structure indicates a westward oriented channel that was ~ 70 m wide and about 4 m deep. Each channel fill sheet is about 1 m thick and the channel axis, decreasing to 0.3 m at the margins. Internally the sands show fine horizontal laminations and a complete absence of lateral accretion feature. This suggests filling up of channel primarily through vertical accretion in an almost standing body of water. This happens normally in chute cutoffs where deposition takes place in the remaining body of standing water after the channel is abandoned. The channel margins show low dip of 15-200. This suggests that the channel was not produced due to incision. The stratigraphically younger channel fill at Chandod indicates a much deeper and larger channel although only about 30% of the total structure is observed, the rest having been eroded away by the present river. The channel fill is exposed at the southern extremity of the ~ 400 m long outcrop. This channel fill occurs above the epsilon cross bedded strata. The margin has a steep dip of about 300. Extrapolation of the channel margin suggests a ~ 80-90 m wide and ~ 10 m deep channel. The channel trough is filled by sand sheet with concave up geometry which shows internal stratification. Laterally sediments of this channel fill are found to grade into stratified overbank sands. Epsilon cross strata is also observed at Chandod ranging in thickness from 10-15 m. It terminates against the overlying thick bedded overbank facies. Laterally, the epsilon bed transits into horizontal strata and further away, merges with overbank deposits. The deposition of this facies is attributed to lateral migration of very deep (15-20 m) sand bed river channels. Similar large scale epsilon cross bedded strata have been attributed to deposition in deep water (Jackson, 1978).

6.2.7 Spot-6 Gamod section

Along the banks of the river Aswan the 15 m thick succession (Fig. 19a) of Gms facies is characterized by convex upward surfaces (Fig. 19b). A major bounding surface separates two vertically stacked packages, each containing four cycles of the Gms facies. At the base of the succession a sandsheet deposit (Sm facies) separates the underlying sheet of the Gms facies from the eight cycles of debris-flows. The dominant clast size is 10 cm. Deviation from this size occurs in the form of ~16 cm tabular blocky clasts. No St and Gp facies are observed at this locality.

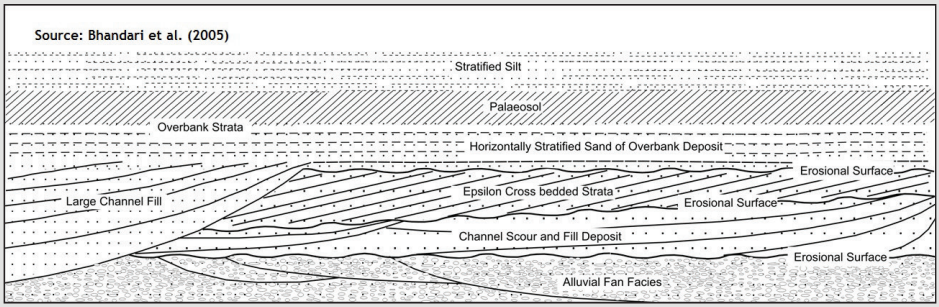


Fig. 18. Sketch showing the vertical relationship between the sediments exposed in the >400 m long cliff exposure at Chandod (after Bhandari et al. 2005).

6.2.8 Spot-7 Tilakwada section

The sediments of alluvial fan 1 are best exposed at Tilakwada (Chamyal et al. 1997). The Tilakwada section illustrates the various characteristics of facies development, both spatially and temporally. The alluvial fan 1 deposit (Fig. 20 and 21) occurs all along the cliffy banks of Narmada around Tilakwada. At places basal matrix supported gravel is quite thick (6.5 m). The size of the clasts range from 25-35 cm and are dominantly basaltic. The top of the sediment succession at Tilakwada is represented by a massive sand of about 2.5 m thickness showing no internal stratification.

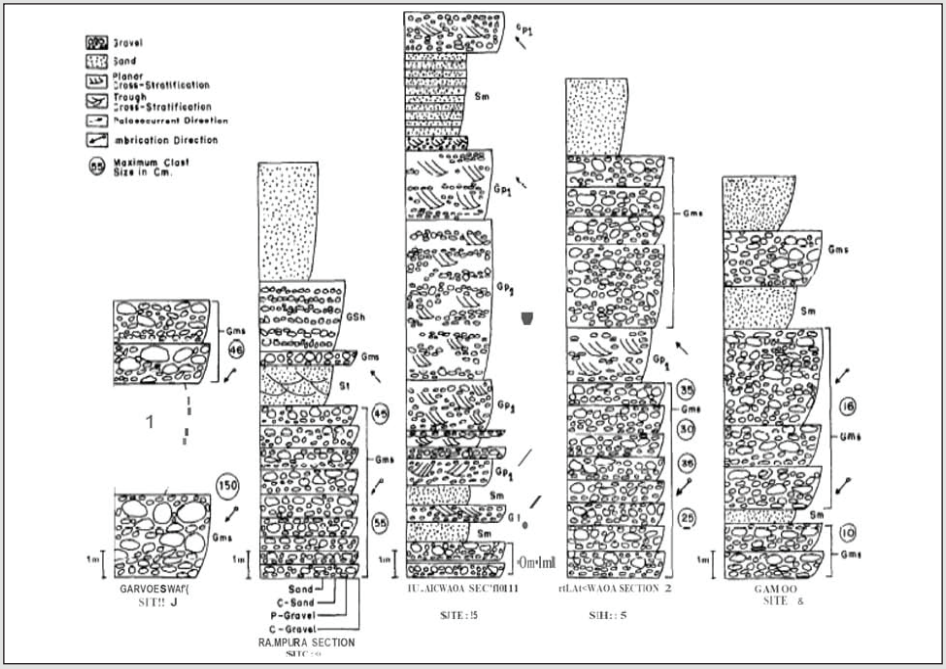


Fig.19b. Lithologs of alluvial fan succession on the right bank of Narmada River at Tilakwada, Gamod and nearby sites (after Chamyal et al., 1997). The red dot indicates an age of <90 ka from the sand lens.



Fig. 20. View of right bank cliff at Tilakwada comprising sediments of alluvial fan 1.

The 30 m thick bank scarps expose a succession of a ubiquitous packet of Gms facies. The facies is within present at the base of all exposures in the area (Fig. 20). These gravels have lobate geometries, contained which are lenses of the Gp facies. The clasts have thin white veneers of calcite, which has also cemented the gravel. The clasts are basaltic and some show remnants of pre-depositional spheroidal weathering. Nesting of clasts is present. The Gp1 facies occurs intercalated between Gms gravels, and progressively becomes more prominent towards the top of the section. The alluvial architecture, when traced over long exposures using panoramic photographs, reveals the major contribution of the Gms facies The oldest exposed sediments at Tilakwada are made up of thick (2 m) matrix supported gravels. The gravels have a maximum size of 30 cm and are bounded together by sandy matrix. These are overlain by a lens of massive sand. This horizon was dated by Blue Green Stimulated Luminescence (BGSL) technique at PRL, Ahmedabad and is found to be <90 ka in age. The sand is internally unstratified and is about 0.75 m thick. The massive sands are overlain by a planar cross-stratified gravel bed having a maximum thickness of about 5m. The planar cross-stratified gravels alternate with massive sand horizons and are at places as thick as 9 m. The alluvial architecture was constructed by both confined and unconfined flows. Of the primary depositional processes that directly contributed to aggradation of the fan, viscous debris-flows played a major role, with a minor contribution by sheet-floods. Debris-flow deposits (Gms facies) make up over 70% of the alluvial architecture. Debris-flows aggraded the fan at both proximal and distal ends. The maximum clast size progressively decreases down-fan, in agreement with the expected fall in flood velocity. Evidence of intervening quiescent periods between fan aggradation events is present in the form of large-scale planar cross-stratified gravel (Gpt) and trough cross-stratified sand (St) facies. Braided rivers with longitudinal gravel bars dominated the surface of the fan during these phases. A major deviation from the norm is observed in the clast roundness of the debris flow deposits. Most of alluvial-fan deposits are recognized by their angular to

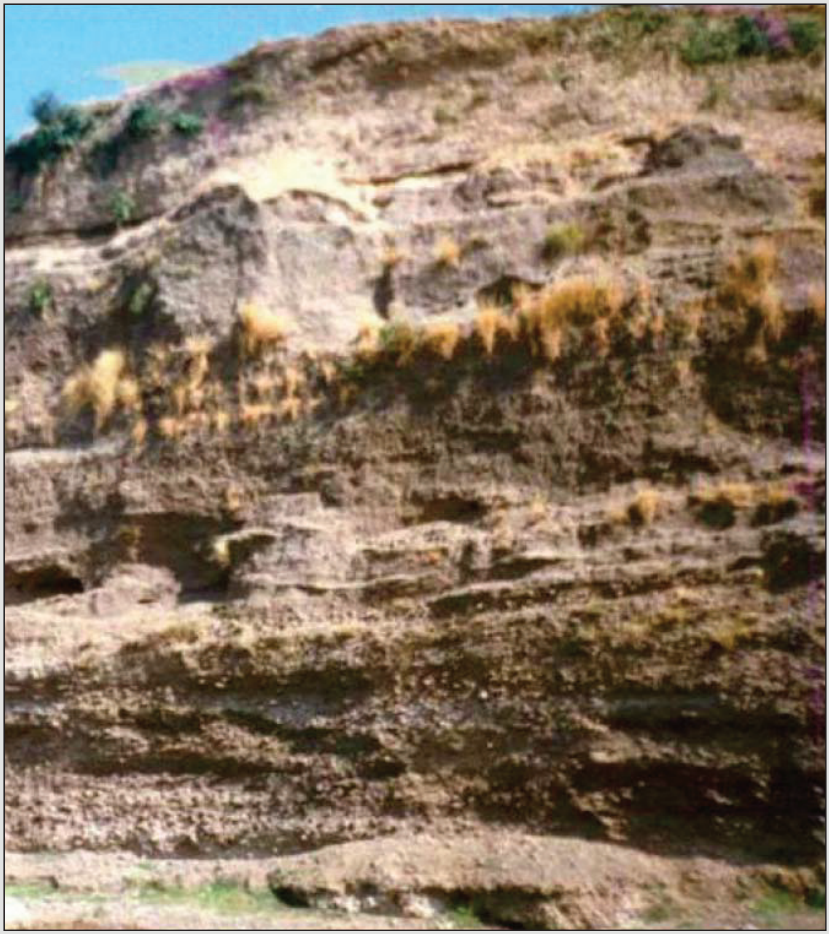


Fig.21. Incised cliff section showing the sediment succession of alluvial fan 1 at Tilakwada

sub-angular nature. Angularity of clasts has been stressed and the only exception accommodated is a conglomeratic provenance. In the present case it is suggested that the greatly elongated catchment area upstream of Nawagam (fan apex) as a determinant.

Rounding of clasts took place when the angular fragments were transported as bed load along the lengthy course of the Narmada (feeder channel), to be temporarily arrested as channel bars upstream of the fan apex, Hemispheroidal, discoidal clasts also attest to such a mechanism. The flat base suggests that these clasts rested on a stream bed while the exposed surface of the clast was modified to its present shape by the stream flow. These subrounded clasts were then eroded from the bars, remobilized and entrained in viscous debris-flows during flash floods.

6.2.9 Spot-8 Kadipani- Hanfeshwar

The thick fluvial sequences, dominated by coarse sediments, are exposed along the Banganga (BG) River, a small, northern tributary of the Narmada River within the Dhadgaon gorge (Fig. 22(A)).

Mahuabari site

A 4.5 m section (Fig. 22 (B), site a in inset) is exposed along the upper reach of the Banganga River (21o 59′ 36″ N - 74o 5′ 48.3″ E). The sediment sequence can be divided into two major facies. The basal 200 cm comprises Gcm, with occasional inversely graded gravel (Gci) showing good sorting within individual layers. The average gravel size ranges between 5 to 7 cm but large clasts up to 40 cm are also seen. The larger clasts are sub angular to occasionally angular whereas the smaller clasts are largely sub rounded.

Vertical variation in the clast size is observed occasionally (Fig. 22(B) a (I)), imbrication is rare but weak horizontal beddings are evident (Fig. 22(B) a (II)). The clasts comprise cobbles and pebbles of basalt and sandstone available in the immediate catchment and contact between the units is gradational. The matrix supported gravel (Gmm) units are about 0.2 to 0.6 m thick and occur at the top of the sequence overlying the Gcm or Gh-Sh facies.

Ambabari site

At Ambabari (Fig. 22(B), site b in inset), a 10.5 m section (Fig. 22(B)b) (21o 58′ 39.11″ N - 74o 7′ 33.28″ E) was studied. The basal 2.20 m comprises alternate layers of coarse and fine gravel, sub angular to sub-rounded and poorly sorted with a thin capping of fine sand (Fig. 22(B)b). This is overlain by 80 cm thick Gcm and 30 cm of a coarse sand unit with a sharp conformable contact. Overlying these horizons is 80 cm of poorly sorted gravel and a 1 m thick Gcm with a thin sand cap. A 30 cm unit of cross stratified sand (Sp) rests above this (Fig. 22(B)b (III)) and shows an erosional contact with the underlying Gcm. This is overlain by 80 cm of coarse sand and a 1.2 m thick fine sand unit. Overlying this is the coarse facies including matrix supported, clast supported and sandy gravel with a thin layer of topsoil (Fig. 4b (IV)).

At the end of a small gorge ~35 m section is exposed (21o 59′ 9.6″ N - 74o 6′ 16.1″ E). The sequences are laterally extensive and the horizontally bedded gravel and sand couplets dominate the facies assemblage (Fig. 22). The Gh-Sh facies overlie the basal coarse unit and in turn is overlain by matrix supported gravel unit (Gmm). The individual beds vary in thickness from < 1cm to 20 cm. Pebbles and cobbles are seen as isolated pebbles within the finer facies. The clasts are sub angular to sub rounded with the maximum size being around 10-12 cm and show occasional imbrication whereas ripple cross laminations are observed in the sand layers. The beds do not show any grading, normal or inverse and appear as vertical stacked sequences showing repetition in deposition. Within the lower 2 m of the section, three distinct facies are seen, starting with 1.5 m interbedded Gh-Sh, followed by 30 cm clast

supported gravel and 20 cm graded gravel. Minor break in the deposition within the sequence is observed in the form of thin alcretized layers.

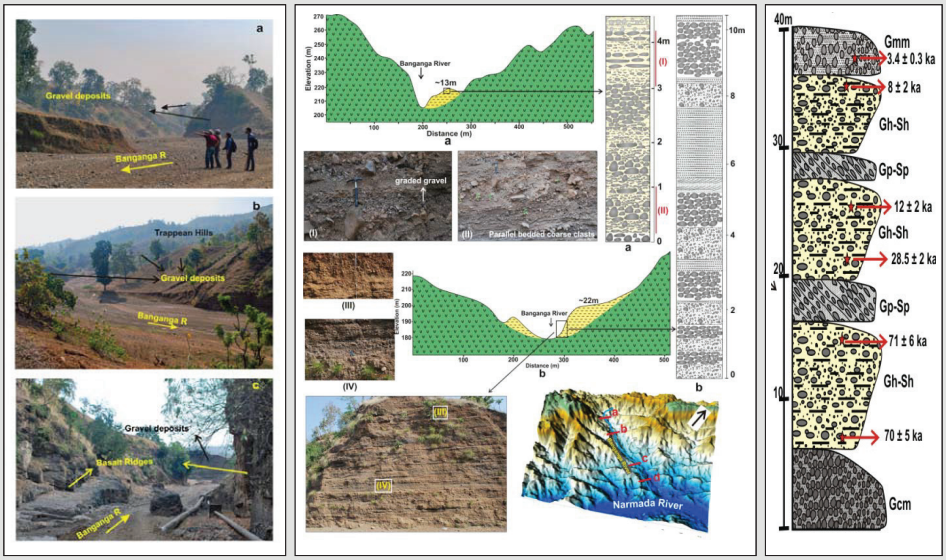


Fig. 22. (A) The late Quaternary sequences exposed along the Banganga tributary. (B) Lithologs, cross sections and photographs showing different lithofacies at various sites in the Banganga River. The inset DEM shows the sites of lithologs and corresponding cross profiles. a. Cross profile at site 'a' (Mahuabari) in the upper part of the Banganga valley showing the late Quaternary valley fill deposits and the corresponding litholog. The photograph (I) shows grading in gravel occasionally observed in the sequence and (II) shows the weak horizontally bedded clast supported coarse gravel. b. Cross profile at site 'b' (Ambabari) and the litholog. The photograph (III) is a close view of the matrix supported gravel (Gmm) and (IV) shows the lenses of cross stratified gravel and coarse sand (Gp and Sp). (C) Composite lithostratigraphic succession based on the exposed lithofacies at various sites along the Banganga River with OSL chronology. (Sridhar et al., 2022)

It is evident from the stratigraphic and sedimentological characteristics, and chronology of the sediment record in the Banganga valley, that the BG infill sediments represent the aggradation events in the DG gorge during the late Quaternary (Fig. 22(C)). It is also evident that the aggradation in the gorge occurred in at least two episodes ~70 ka and ~ 28 ka with an intervening period of evacuation (~ 50-30 ka).

The predominance of multi-storeyed horizontally stratified gravel-sand units in the BG sequence indicates deposition as sheet bars in bed-load dominated river (Smith, 1970; Hein and Walker, 1977; Rust and Koster, 1984; Miall, 1996). These BG facies are channel-bar (GB) and channel-fill (CH) sediments (coarse gravel) deposited by flows with higher sediment-to-discharge ratio unlike the typical over-bank deposits, found in the lower alluvial reaches. The estimated values of bed shear stress, power per unit area and flow velocities based on maximum clast sizes in the BG facies are similar to the present-day

values for the Narmada River (Kale, 2003) but much lower than the present-day maximum flood flows with very high shear stresses between 300 and 3000 Nm-2 and stream power between 2600 and 12 800 Wm-2 (Rajaguru et al., 1995). This suggests that the flow competence and power in the Banganga River during the Late Quaternary were not unusually high. Moreover, it is unlikely that the Banganga River with a small catchment (30 sq km) can generate such a large volume of coarse sediments. Consequently,

it appears that the sediments in the Banganga valley were deposited as tributary infill by the bed-load dominated Narmada River during high sediment supply and transport-limited conditions between ~70 ka and ~12 ka in the DG gorge. The occurrence of similar, thick sequences of coarse sediments in the Narmada alluvial fan downstream, provides further links with the valley-fill and incision episodes in the DG gorge.

The episodes of aggradation at ~ 70 ka and ~28 ka in the DG Gorge were in response to the tectonically induced steepening of the channel gradient in the upstream whereas the incision of the DG gorge and deposition of the NR fan downstream was facilitated by climatically induced decrease in the sediment supply- discharge ratio in addition to the tectonic slope. The phases of aggradation in the bed rock and alluvial reaches of the river however, seem to be non-synchronous. The tectonically steepened channel gradient facilitated the mobilisation of the coarse sediments in the gorge while the role of southwest monsoon may have been limited. The final evacuation of the gorge and the incision in the Banganga basin occurred in response to the tectonic uplift and high river discharge during the early Holocene. The tectonic activity related to the Narmada- Son Fault has played a pivotal role in determining the nature of fluvial activity in the Narmada River basin during the Late Quaternary.

6.3 Day 3: Tectonic geomorphology of the Narmada-Son Fault (NSF) zone

6.3.1 The Narmada-Son Fault

The Narmada–Son Fault (NSF) divides the Indian plate into two halves and has a long tectonic history dating back to the Archaean times (Ravi Shankar, 1991). The NSF trends in ENE-WSW direction and is laterally traceable for more than 1000 kilometres. It demarcates the Peninsular India into two geologically distinct provinces- the Vindhyan-Bundelkhand province to the north and the Deccan province to the south. Ravi Shankar (1991) regards the Narmada –Son Fault as a part of the composite tectonically controlled zone in the middle of the Indian plate and termed it as the SONATA zone (abbreviated form of Son-Narmada-Tapti Lineament zone). The Narmada and Tapti Rivers all throughout their course follow these tectonic trends. Other synonyms used in literature to describe this zone include – Narmada-Son Lineament (Choubey, 1971), Central Indian Shear - CIS (Jain et al., 1995) and Central Indian Tectonic Zone - CITZ (Radhakrishna and Ramakrishnan, 1988; Acharyya and Roy, 2000). Geophysical studies in the central part of this zone reveal this to be a zone of intense deep-seated faulting (Reddy et al., 1995). The zone witnessed large-scale tectonothermal events associated with large granitic intrusions around 2.5-2.2 Ga and 1.5-0.9 Ga (Acharyya and Roy, 2000). It was again reactivated during the Deccan volcanic eruption during Late Cretaceous-Palaeocene (Agarwal et al., 1995). Profuse occurrence of E-W trending dykes suggest that the zone formed the main center of eruptive activity (Bhattacharji et al., 1996). The entire zone is presently characterized by high gravity anomalies, high temperature gradient and heat flow and anomalous geothermal regime (Ravi Shankar, 1991) suggesting that the zone is thermo-mechanically and seismically vulnerable in the framework of contemporary tectonism (Bhattacharji et al., 1996).

The westward extension of this zone into the lower Narmada valley exhibits a less complex structural setting. Data on the NSF in this part is mainly the result of extensive geophysical surveys for commercial exploitation of petroleum reserves in the subsurface. In the lower Narmada basin, it is expressed as a single deep seated fault (NSF) confirmed by the Deep Seismic Sounding studies (Kaila et al., 1981). Seismic reflection studies have firmly established that the NSF is a normal fault in the subsurface and becomes markedly reverse near the surface (Roy, 1990). Reactivation of the fault in Late Cretaceous led to the formation of a depositional basin in which marine Bagh beds were deposited (Biswas, 1987). The NSF remained tectonically active since then with continuous subsidence of the northern block, designated as the Broach block, which accommodated 6-7 km thick Cenozoic sediments (Biswas, 1987). The total displacement along the NSF exceeds one kilometer within the Cenozoic section (Roy, 1990). However, the movements along this fault have not been unidirectional throughout. The general tendency of the basin to subside have been punctuated by phases of structural and tectonic inversion (Roy, 1990). The N-S directed compressive stresses during the Early Quaternary, folded the Tertiary sediments into a broad syncline, the Broach syncline, in the rapidly subsiding northern block (Roy, 1990). The Broach syncline extends from the NSF to the Mahi River in the north. The E-W trending axis of this syncline lies to the north of the Narmada River. Corresponding anticlinal structures are found in the Tertiary rocks exposed in the southern upthrown block. Historical and instrumental records indicate that the compressive stresses still continue to accumulate along the NSF due to continued northward movement of the Indian plate. This is evidenced by the fault solution studies of the earthquakes at Broach (23rd March, 1970) and Jabalpur (22nd May, 1997) which suggest a thrusting movement (Gupta et al., 1972; 1997; Chandra, 1977; Acharyya et al., 1998). However, the underlying cause of the seismicity in the NSF zone is not yet understood (Quittmeyer and Jacob, 1979).

6.3.2 Offset Along NSF

The S1 surface shows an anomalous NNW slope between the Narmada River and the NSF. The difference in the elevations of the Late Pleistocene sediments comprising this surface on either side of the NSF in the Narmada and Karjan valleys suggest an offset of about 35 m. The sediments of S1 surface occur at elevations up to 100 m across the NSF as seen near Gora in Narmada valley and Jitnagar in Karjan valley in the Narmada and Karjan valleys, respectively. At these places, these sediments occur well above the present high discharge levels and overlie the basalts, which also show vertical downcutting by the river. The S1 surface, generally attains elevations of 50–60 m along the Narmada River. NNW directed tilting of these sediments, observed in the area to the south of Narmada, provides additional evidence for differential uplift along the NSF. However, the Mid–Late Holocene sediments (S4 surface) do not show any observable offset along the NSF suggesting that the offsetting of the S1 surface took place during the Early Holocene phase of tectonic uplift. The displacement of the S1 surface points to a differential movement of about 35 m along the NSF during the Early Holocene.

The coalesced group of alluvial fans, 'bajada', is identified in this segment between the Karjan River and Madhumati River, and shows highest topographic elevation in comparison to the adjacent alluvial plain areas to the east of Karjan valley, to the west of Madhumati valley and the Narmada valley to the north. The altitude of the fan surface near the mountain front is 120 amsl and extends over ~24 km in length along the mountain front. The Nandikhadi River is a tributary of Narmada River that originates in the south from trappean uplands. It is the most important drainage basin of segment II as it shows significant evidence of active tectonics. The upland zone of Nandikhadi River is characterized by frequent occurrence of knick points, tight meanders and deeply incised channel. The height of the knick points range from 1 m to 16 m. The total fall of gradient related to knick points is of ~ 37 m which is in a very short distance of 1.5 km.

As the river course approaches towards loose Quaternary sediments, it shows incision of up to 40 m which decreases to 6-7 m in a very short distance of less than 3 km. In the vertical incised cliffs exposed along the river exhibits the sediments of bajada deposits. The detailed description of deposits along with lithologs is given below in the description of individual locations. In longitudinal section, the deposits appear to be wedge shaped. The bajada surface displays planoconcave-upward geometry created by the distally decreasing slope. The sediments are readily divisible into seven distinct sedimentary facies. In approximate order of abundance, the principal facies identified are- matrix supported gravel (Gmm), clast supported gravel (Gcm), massive silty sand (Sm), soil (P), trough cross-bedded gravel (Gt), horizontally stratified gravels (Gh) and massive brick red sand lithofacies (Ss). The OSL age of 25.1+1.8 ka BP obtained from the middle part of the bajada succession suggests that the sedimentation occurred during the later part of late Pleistocene. This correlates with the slow synsedimentary subsidence of the basin during the Late Pleistocene documented earlier (Chamyal et al., 2002). However, the Late Pleistocene sediments exposed along the incised cliffs of Narmada River are finer as they were deposited in alluvial plain environment (Bhandari et al., 2005). The bajada sediments are sedimentologically different but stratigraphically comparable with the sediments exposed along the Narmada River. We presume that in the downstream, the bajada sediments may show intertonguing relationship with the finer alluvial plain sediments deposited by Narmada River.

6.3.3 Spot-9 Tejpur- Madhumati river basin

The Madhumati River is one of the major tributaries of Narmada that joins it from the south. The river course has a total length of about 41 Km arising from the trappean region and traverses through the NSF and alluvial plain before joining the Narmada river. The Madhumati River drains western fringe of the trappean upland. The river emerges from the trappean upland near Umarkharda. The drainage of the trappean uplands and alluvial zone presents contrasting characteristics. The drainage pattern in the upper reaches of the basin has been identified as trellis where as the lower reaches of the basin has a dendritic pattern. The density of the tributaries in the upper reaches is more and the tributaries are straight whereas in the alluvial plain tight entrenched meandering can be observed. The drainage basin is elongated in NE SW direction. The course of the Madhumati River shows a strong control of the structural framework of the area. From Umarkharda to Dholi the river flows towards west along an almost E-W trending course. At Dholi, the river channel takes a right angle turn to flow towards north along a remarkably straight N-S oriented course up to Tejpur which lies to the north of the NSF. The straight nature of the river course and the right turn strongly points towards the existence of the N-S trending transverse fault (Fig.23). The geomorphic evidence of the NNW-SSE trending Madhumati fault is observed near Tejpur. The fault is represented by the displaced scarps of the NSF which indicates a dominantly strike slip movement along this transverse fault (Fig.23). The displaced basaltic ridge near Tejpur is locally known as the 'Khaseli Dungar' which literally means 'shifted hill' (Fig.23). This fault shows a right lateral offset of the NSF for about 1 km. The presence of the fault is evidenced by the straight channel of the Madhumati River and the formation of a large deeply incised and compressed meander in alluvium as it emerges from the uplands. The slicken sides exposed along the fault plane, in basaltic rocks on the left bank of the river, suggests oblique slip movement (Fig.23). The significance of this N-S trending fault on the geomorphic set up is well brought by the straight deeply incised course of the Madhumati river and the lateral shift in the fault scarps of the NSF. The incision in basaltic rocks observed in this reach of the river is of the order of 40 m.

A large entrenched meander is present near Tejpur where the incised cliffs up to 35 m high are present (Fig.24). Downstream of Tejpur, the river follows a general NW direction with several entrenched meanders in the alluvial zone (Fig.23). At Rajpardi, the river takes a northwesterly turn because of the influence of the Rajpardi fault.

In the alluvial zone of Madhumati river, the Late Quaternary fluvial deposits are characterized by a regular and cyclic sequence of sand and gravel. The clasts of the gravel bed consist of basalt derived from the upland. The clasts are poorly sorted and the matrix is mainly coarse to medium sand.

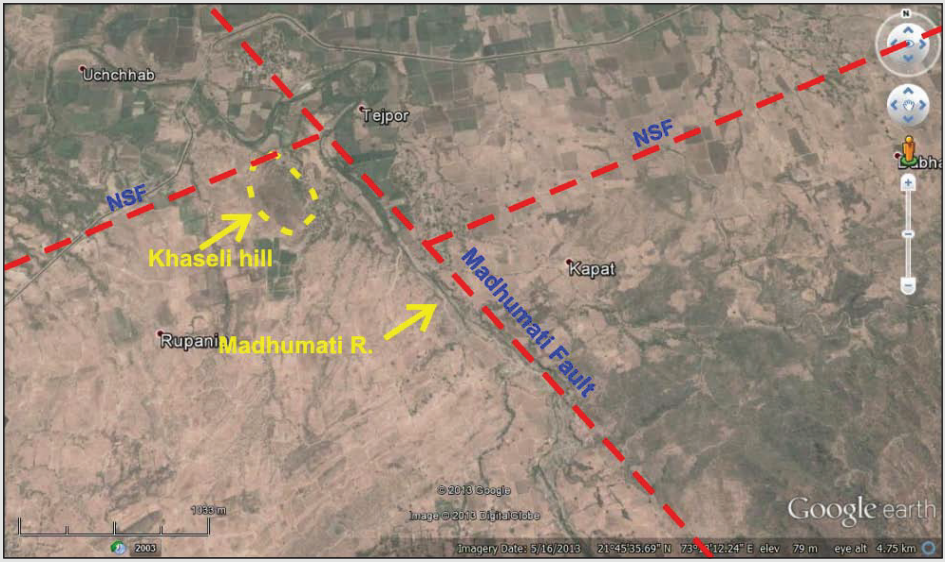


Fig. 23 Google earth image of NSF zone in the vicinity of Madhumati River. The various structural elements are marked. Note the straight course of Madhumati River which follows the NNW-SSE trending transverse fault and the compressed meander near Tejpur.

In the lower reaches these cyclic sequences of sand and gravel overlie the clay horizon. The best and highest exposed section from alluvial zone of the Madhumati river basin is located at Tejpur. Here the Quaternary sediments abruptly abut against the trappean rocks along the NSF. The average thickness of the section on the right bank is about 35 m. The oldest exposed sediment is a gravel, its thickness is about 1 m. This bed is succeeded by 5 m thick pedoginised sand which in turn is overlain by 2 m thick gravel, showing no stratification. This bed is succeeded by 5 m massive sand which in turn is overlain by 7 m horizontally stratified gravel embedded with cobbles, within this layer sand lenses of about 1 m thick are present. This bed is overlain by 3 m weakly pedogenised sandy silt which in turn is overlain by 3 m weakly stratified gravel. This bed is overlain by 3 m thick massive sand which in turn is succeeded by 4 m gravel. The sediments are capped by 1 m topsoil. The volcanic ash layer has been reported within the Quaternary alluvial succession (Fig. 24) which is correlated with Youngest Toba tuff (Raj, 2008). The ash is unconsolidated, well-sorted, homogenous and friable to the extent of getting to fine powdery material. The glass shards make up 90% of the ash although pumice fragments are also present. Accessory minerals include quartz, felspars, biotite and occasional zircon. The details of the micro-structures of glass shard and pumice shard have been

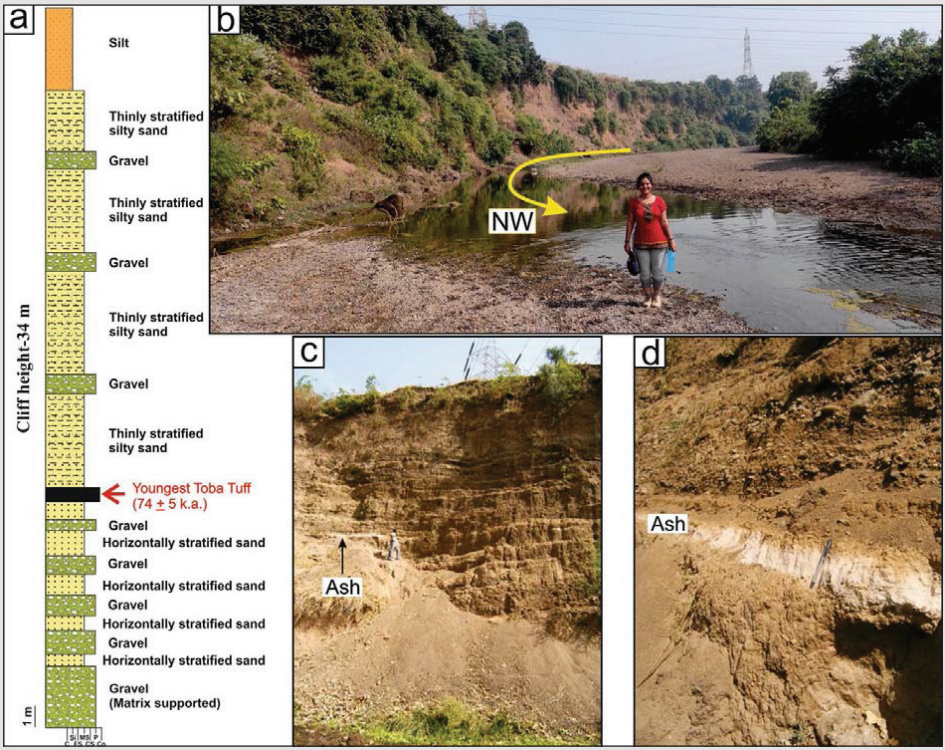


Fig. 24 a Litholog of the Tejpur section in Madhumati River showing the YTT ash layer (Redrawn after Raj 2008). b Upstream view of the deeply entrenched meander at Tejpur exposing Late Pleistocene bajada fan sediments. Litholog of the section is shown in a. Luminescence date of the ash is after Biswas et al. (2013). c View of the central part of the Tejpur section showing the YTT ash layer. d Close view of the ash layer (from Maurya et al., 2023)

brought out very clearly by the SEM studies. The shape of glass shards ranges from blocky, cuspate, flat or platy, triangular, tri-radiate or multi-junctional (Fig.25 a, b, c and d). Most of them show a typical bubble wall structure, which is indicative of a magmatic type of eruption.

The Toba volcanic event is one of the largest eruptions during the Quaternary (Schultz et al 2002). The Toba volcanic event is one of the largest eruptions during the Quaternary (Schultz et al 2002). This volcanic mega eruption (Rose and Chesner1987, 1990; Knight et al 1986; Acharyya and Basu1993) occurred in the Indonesian archipelago on northern Sumatra some 70,000 years ago during a major shift in global climatic conditions from interglacial marine isotopic stage (MIS) 5 to glacial MIS 4 (Ninkovich et al 1978). More than two orders of magnitude larger than any historical eruption, Toba has been estimated to produce at least 3000 km2 of dense rock equivalent rhyolite magma (7 × 1015) and more than 800 km3 of ash (Viseras and Fernandez 1995). It is estimated that at least 1% of the Earth was covered by more than 10 cm of ash known as Youngest Toba Tuff (YTT).

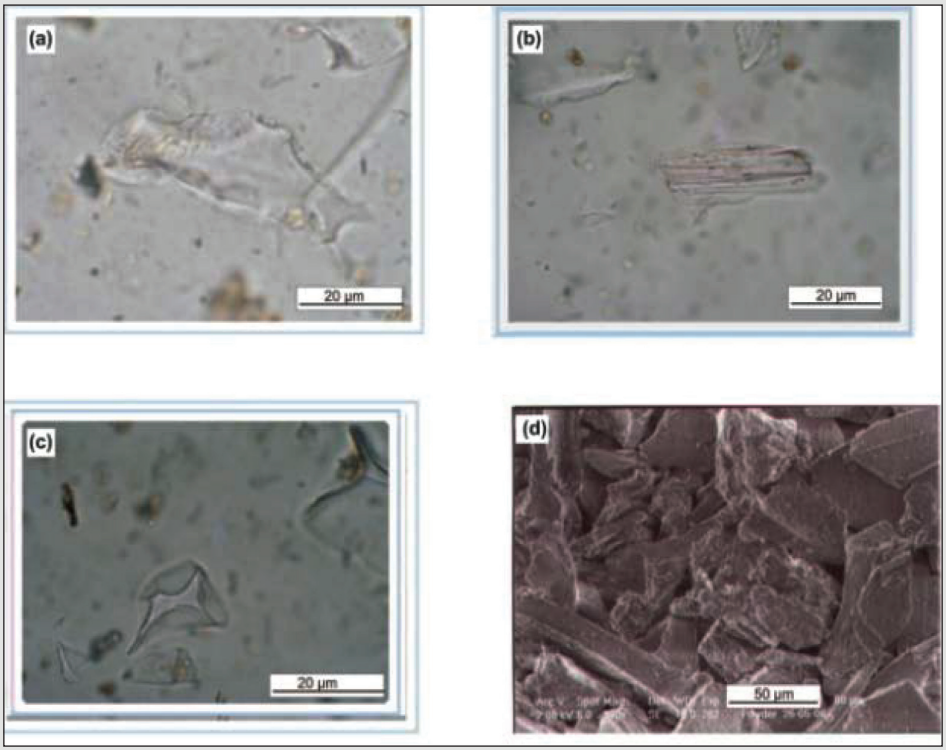


Fig.25 SEM photographs of: (a) Glass shard showing typical conchoidal fracture. (b) Light, porous pumice shard consisting of parallel vesicles seen as long stretched thin capillary tube. (c) Shard showing tri-radiate junction wall of three bubbles. (d) Glass shard of different size and shape showing smooth and conchoidal surface (after Raj, 2008).

The widespread tephra bed is reported from eastern and western parts of the Indian subcontinent (Acharyya and Basu 1993; Ninkovich et al 1978 and Chesner et al 1991) to the Arabian Sea (Schultz et al 1998), Indian Ocean (Pattan et al 1999) and also to the south China Sea (Buhring et al 2000 and Song et al 2000). The Toba event is believed to have a potential magnitude relevant to the global climate system (Singurdsson 1990) and has been held responsible for the shift to glacial climate (Chesner et al 1991; Rampino and Self 1992, 1993).

6.3.4 Spot-10 Juna-Ghanta and Nava Ghanta

The Nandikhadi River is a tributary of Narmada River that originates in the south from trappean uplands. It is the most important drainage basin as it shows significant evidence of active tectonics. The upland zone of Nandikhadi River is characterized by frequent occurrence of knick points, tight meanders and deeply incised channel (Fig. 26). The height of the knick points range from 1 m to 16 m. The total fall of gradient related to knick points is of ~ 37 m which is in a very short distance of 1.5 km.



Fig. 26 Geomorphic set up of Nandikhadi river basin (after Joshi et al., 2013a). (A) Sharp physiographic contrast along the NSF and the deeply incised Nandikhadi River channel (view looking south). The scarps expose south-dipping basaltic flows of the Deccan Trap Formation. Arrows indicate downstream direction of the river. (B) A ~10 m high waterfall along the Nandikhadi River near the upland zone. Note the upstream dipping basaltic flows. (C) Slickensided surface of the transverse Madhumati Fault in basalt at Tejpur, indicating oblique slip movement.

As the river course approaches towards loose Quaternary sediments, it shows incision of up to 40 m which decreases to 6-7 m in a very short distance of less than 3 km. In the vertical incised cliffs exposed along the river exhibits the sediments of bajada deposits (Fig. 27). The detailed description of deposits along with lithologs is given below in the description of individual locations. In longitudinal section, the deposits appear to be wedge shaped. The bajada surface displays planoconcave-upward geometry created by the distally decreasing slope. The sediments are readily divisible into seven distinct sedimentary facies. In approximate order of abundance, the principal facies identified are- matrix supported gravel (Gmm), clast supported gravel (Gcm), massive silty sand (Sm), soil (P), trough cross-bedded gravel (Gt), horizontally stratified gravels (Gh) and massive brick red sand lithofacies (Ss). The OSL age of 25.1±1.8 ka BP obtained from the middle part of the bajada succession suggests that the sedimentation occurred during the later part of Late Pleistocene. This correlates with the slow synsedimentary subsidence of the basin during the Late Pleistocene documented earlier (Chamyal et al., 2002). However, the Late Pleistocene sediments exposed along the incised cliffs of Narmada River are finer as they were deposited in alluvial plain environment (Bhandari et al., 2005). The bajada sediments are sedimentologically different but stratigraphically comparable with the sediments exposed along the Narmada River. We presume that in the downstream, the bajada sediments may show intertonguing relationship with the finer alluvial plain sediments deposited by Narmada River.

The Quaternary sediments occur at altitude of ~120 m amsl and represent the sediments of directly overlies the Deccan trap with abrupt contact (Fig. 28). It consists of subangular to subrounded clasts of Deccan basalt and range in size from pebble to boulder. There is a general absence of grading and is massive in nature which suggests that the clast supported gravels were deposited by low strength, pseudoplastic debris flows. The clast supported gravels overlain by massive silty sand (Sm) and horizontally stratified gravel deposits (Gh).

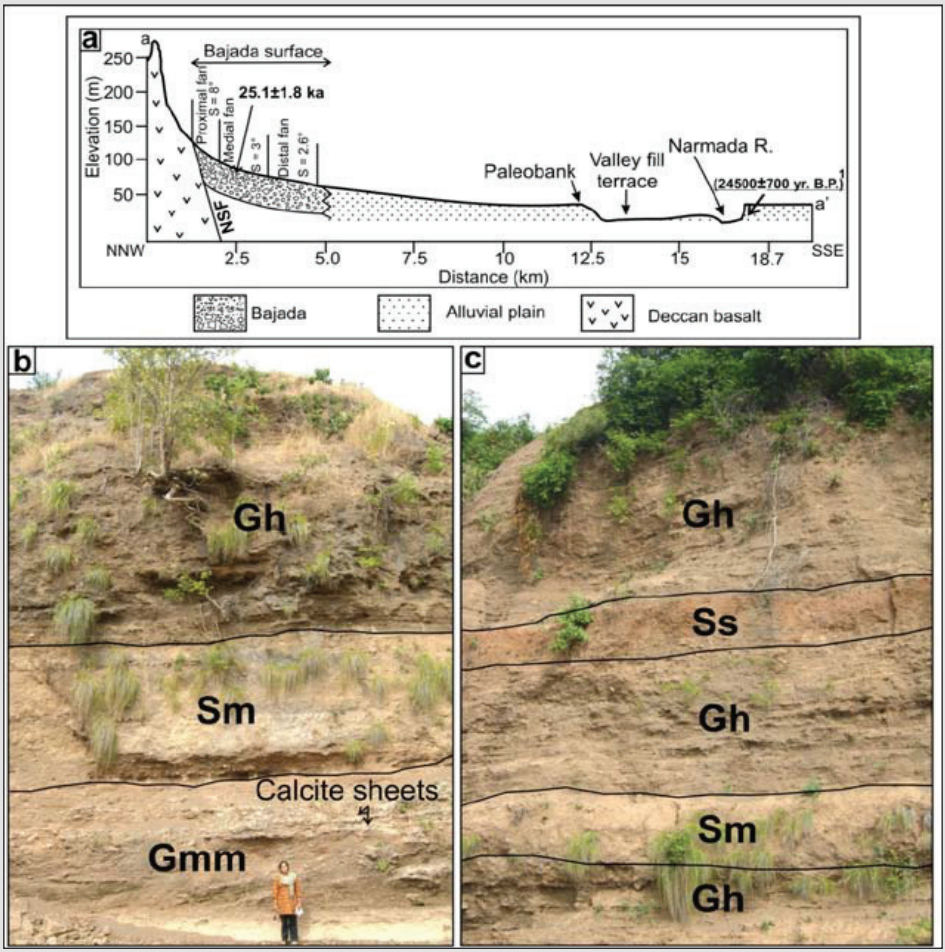


Fig.27 (a) Topographic cross profile of the bajada surface drawn from the DEM. Note the wedge shaped coarse proximal fan deposits. The succession starts with deposition of clast supported massive gravels (Gc) gravelly bajada sediments deposited in front of the mountain front. Three sectors of bajada surface and their slopes are also shown. (1- Allchin et al., 1978). (b) and (c) are the view of the cliff section exposing bajada sediments. Note the parallel horizontal calcite sheets formed in basal matrix supported gravel lithofacies.

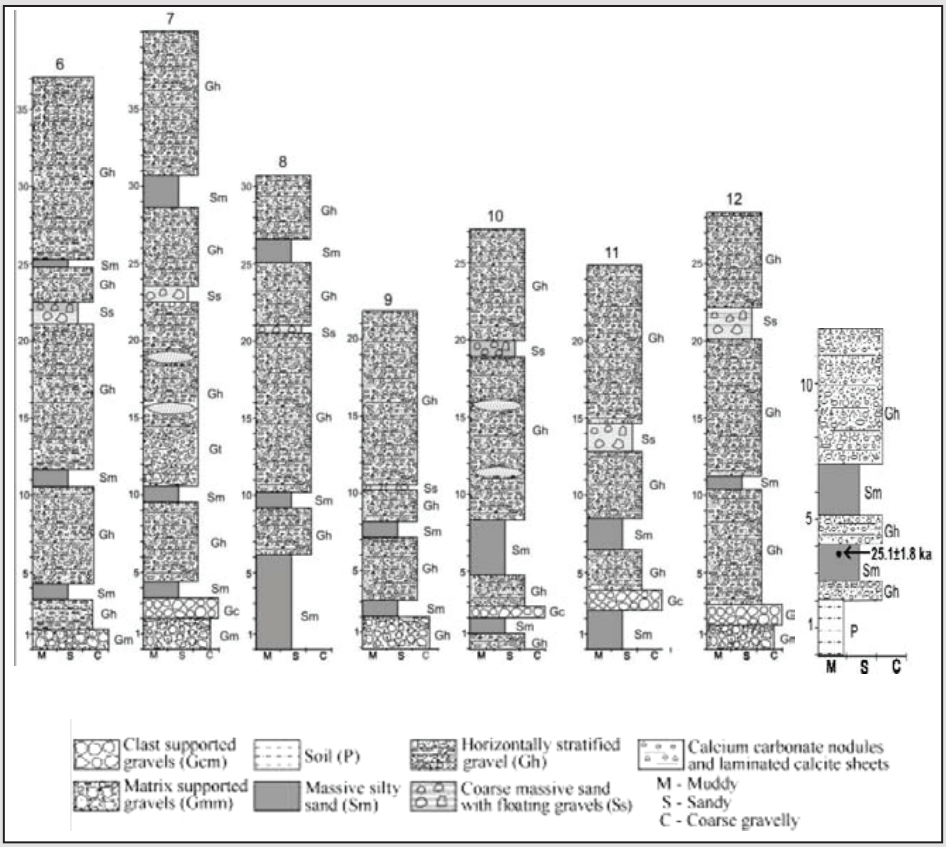


Fig. 28 Lithologs of Bajada sediments exposed at various locations (6-12) along the Nandikhadi River along with the chronology at the Nava Ghanta site (after Joshi et al., 2013).

At Nava Ghanta, the sediment succession represents distal part of the fan comprising of soil, horizontally stratified gravels and massive silty sand. OSL dating of sediments of lower silty sand deposit has been carried out which gave the date of 25.1±1.8 ka. The silty sand deposits are comparable to dissected ravine geomorphic surface S2. The sediments of S2 surface dated back to 24.5±0.7 ka (Allchin et al., 1978) deposited in a slowly subsiding basin during Late Pleistocene (Chamyal et al., 2002). Hence the silty sand deposits are correlatable with S2 surface, the deposition of sediments can be explained by tectonic uplift along the NSF generated tilted block structure in which coarse gravelly sediments deposited in the fault zone area and simultaneously fine sediments were deposited in the subsiding part.

6.3.5 Spot-11 Jitnagar

In the NSF zone of Karjan River near Jitnagar, the rocks are incised and exposed in the cliff sections. These rocks are various southward dipping basaltic flows that represent the part of the tilted block which is attributed to the tectonic movements along the NSF. The exposed section forms a raised fluvial terrace surface within the trappean mounds on the right bank of the river. The ~20 m thick sediments overlie the trappean rocks, which arealso incised by ~ 25 m (Fig. 29). The dominantly fine-grained sediments comprise mainly sand and silty sand deposits. Calcite sheets and nodules occur in the middle of the section. OSL dating of the upper silty sand layer yielded an age of 32.7 ± 3.9 ka B.P. (Fig. 29).

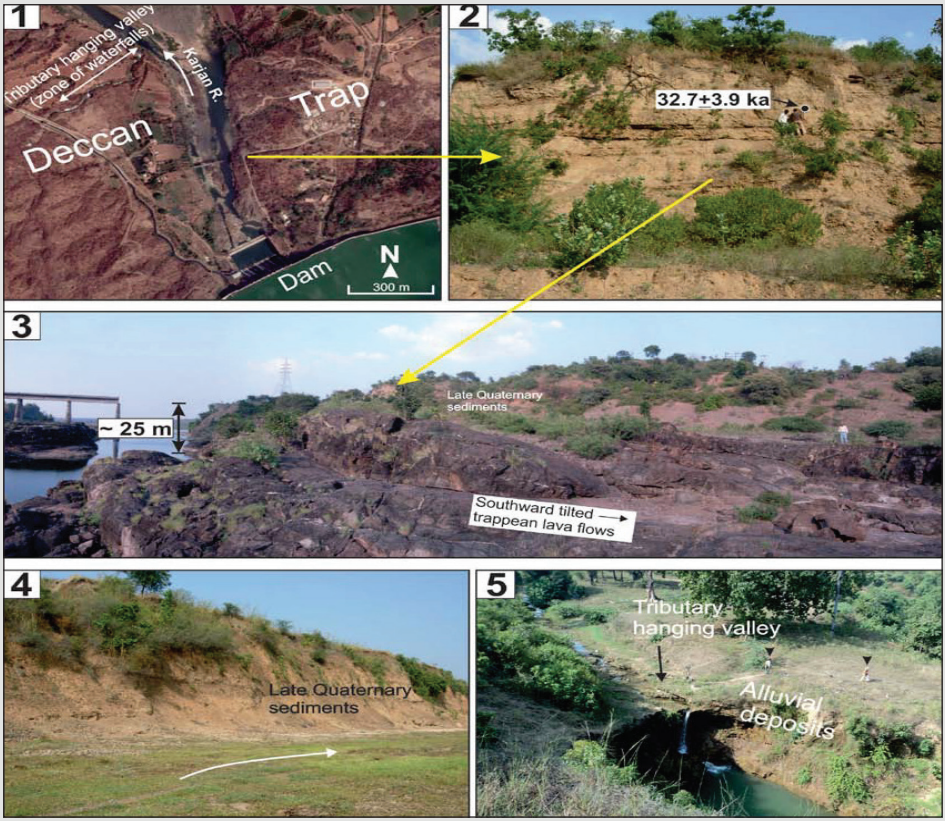


Fig. 29 Satellite image of the Karjan River channel in the NSF zone around Jitnagar. Note the rugged hilly topography developed over the Deccan Traps, bedrock channel and a fluvial hanging valley with multiple falls. Arrow shows the location of the sediment section shown in 28.2. 28.2 Late Quaternary fluvial sediments overlying Deccan Traps exposed in the cliff section on the right bank of the Karjan River. OSL date and location of sample is also shown. Note the general sandy silty nature of the sediments that contrasts with the present day channel which is full of pebbles, cobbles and boulders. 28.3 Downstream (northward) view of the Karjan River at same location. Note the ~ 25 m elevation from river level of the Late Quaternary sediment section shown in 28.2, overlying the incised and upstream (southward) dipping basaltic lava flows. 28.4 View of the ~ 25 m high incised cliff section located ~ 2 km downstream of the section shown in 28.2. The section is exposed along left bank of the Karjan River near Nani Limatwada showing Late Quaternary sediments comparable to the section in 28.2. The difference in elevation of the two sections suggests post-depositional faulting activity along the NSF. 28.5 View of 28.1 waterfall along a lower order tributary stream in Late Quaternary sediments on the left bank of Karjan River (Loc. Upstream of Nani Limatwada). (after Chamyal et al., 2022)

The fine grained nature of the sediments exposed at > 25 m above the river level and overlying bedrock is in complete contrast with thepresent channel bed which is full of coarse debris ranging from pebbles to gravels to boulders. Based on available regional Late Quaternary stratigraphy of the Narmada basin and NSF zone (Chamyal et al., 2002; Joshi et al., 2013b) and lithologic similarity, the sediments exposed at Jitnagar are correlatable with the sediments exposed in the cliff section,couple of kilometers downstream along the Karjan Riverat Nani Limatwada.

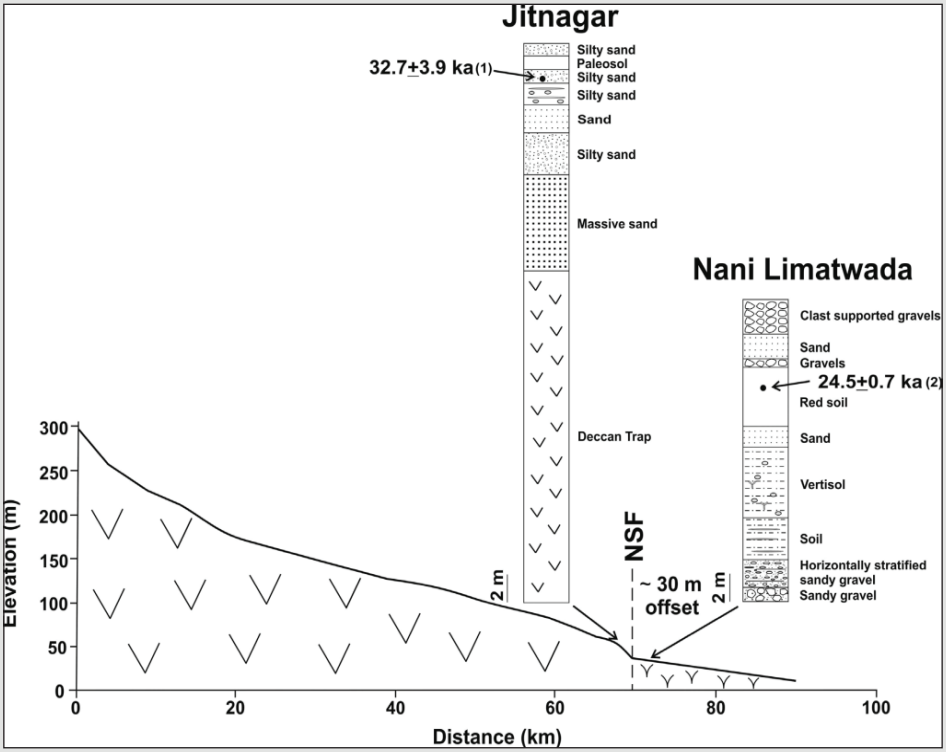


Fig. 30. Long profile of the Karjan River showing the locations and lithologs of exposed Quaternary sediments at Jitnagar and Nani Limatwada across the NSF. Elevation difference between the two sections suggest ~ 30 m offset along the NSF during Holocene.



Fig. 31. A photograph showing deformation in Bagh Formation (Late Cretaceous) in Narmada-Son 53 Fault zone at Gora Colony.

At Nani Limatwada village, ~ 20 m incised vertical cliffs are exposed (Fig. 29). The section here represents the deposits of Late Pleistocene sediments made up of sandy gravel, horizontally stratified gravel, vertisol (brown), and red soil (reddish-brown). Stratigraphically, the red soil is comparable to the Late Pleistocene red soils of Narmada, Mahi and Sabarmati (Merh and Chamyal, 1993; Maurya et al., 2000; Chamyal et al., 2002). However, there is a significant difference between the sediments' altitude at Jitnagar and Nani Limatwada (Fig. 30). This difference in the altitude suggests ~ 30 m displacement along the NSF, most of which occurred during the Holocene. The formation of waterfalls in tributary streams is attributed to this phase of tectonic uplift.

6.3.6 Spot-12 Gora Colony

Mesozoic rocks of Bagh formation are outcropped as inliers near Gora colony. The rocks are marine in nature deposited during the transgression and regression phases prevailing in the Cretaceous time. Here, the NSF is expressed by steep mountain front scarp in the rocks of Bagh formation and basaltic flows. This is related to the phase of tectonic upliftment occurred in the Late Cretaceous time during which the NSF reactivated as a reverse fault and made a tectonic contact between rocks of Bagh formation and traps. To the north of the scarpline basaltic rocks continue for a short distance and abuts against Quaternary sediments. The upliftment along the NSF has generated steep gradient in the alluvial plain to the north of scarpline. Also the influence of NSF is clearly visible in the development of 1st order drainage flowing almost parallel to the trend of NSF and meeting Narmada river at it left bank.

Heritage, Cuisines And Culture

The Gujarat Alluvial Plains are not only a geological archive but also a cradle of human civilization, where the landscape has directly shaped the culture, diet, and history of the region.

7.1. Geoheritage Sites

Six important geological sites from the Narmada-Son Fault (NSF) zone, the Lower Narmada Valley, and the Lower Mahi Valley in central Mainland Gujarat have been described by Maurya et al (2023) from geoheritage and geotourism point of view. Three geosites viz. Ghanta, Tejpur and Jitnagar are included from the NSF zone that comprise textbook examples of a fault controlled landscape and tectonically active fault zone. One of these geosites at Tejpur contains a layer of Youngest Toba Tuff (YTT) ash layer midway in the exposed river cliff section that represents the largest volcanic eruption during Quaternary time, which occurred at ~74 ka in Indonesia. Two geosites from the Lower Narmada Valley viz Tilakwada and Chandod are described that comprise one of the world's largest Late Pleistocene alluvial fan deposits and alluvial plain sediments with large-scale sedimentary bedforms indicating large size of the paleo-Narmada River compared to the present one. The geosite in Lower Mahi Valley viz Rayka comprises sediments representing the climatic changes during the last full glacial cycle, vertically stacked in one river section. All the described geosites are a part of the present field excursion. The sites are located close to and accessible from the world's tallest statue, the "Statue of Unity", which attracts millions of tourists.

7.2 UNESCO Heritage Sites

Gujarat holds a prominent place on the global heritage map, with sites that showcase both ancient urban planning and unique geological phenomena.

Dholavira (UNESCO World Heritage Site): Located in the Rann of Kachchh, this Harappan city is a masterpiece of water management and stone architecture. Geologically, it sits on the Khadir Bet, providing insights into the post-glacial sea-level fluctuations that once made this an island.

Champaner-Pavagadh Archaeological Park (UNESCO): This site blends Hindu and Islamic architecture against the backdrop of the Pavagadh Hill—a volcanic outlier of the Deccan Traps. The hill itself is a geoheritage landmark, representing the terminal phases of Cretaceous-Paleogene volcanism.

Rani ki Vav (UNESCO): Located in Patan on the banks of the Saraswati River, this 11th-century stepwell is an architectural marvel built into the alluvial deposits. It demonstrates the historical importance of groundwater management in the semi-arid plains.

Lothal: A vital Harappan port town nears the Gulf of Cambay. Its dockyard is one of the world's earliest examples of maritime engineering, designed to utilize the high tidal range of the gulf.

7.3. Archaeological Sites in the Vicinity

Beyond the famous landmarks, the river basins house numerous sites that trace the evolution of the "Human-Climate" relationship.

Langhnaj: A classic Mesolithic site in the Sabarmati valley. It is significant for the discovery of microlithic tools and human burials within the stabilized sand dunes, marking a period of transition during the Early Holocene.

Achhala and Kanewal: Located near the Mahi River, these sites have yielded evidence of prehistoric rock paintings and Chalcolithic settlements, often situated on the elevated "Bhur" (sandy) ridges to avoid seasonal flooding.

The Narmada Valley: Renowned for its Middle Palaeolithic tool assemblages and vertebrate fossils, including the Elephas namadicus, often found in the basal gravels of the river.

7.4. Culture and Traditions

The culture of the plains is deeply rooted in the agricultural cycles of the "Alluvial Heartland."

Fairs and Festivals: The Vautha Mela is a major animal trade fair held at the confluence of seven rivers (including the Sabarmati and Vatrak). It is a vibrant display of rural Gujarati life, where the river confluence is treated as sacred.

Craftsmanship: The region is famous for Patola weaving (Patan), Block Printing (Ahmedabad/Jetpur), and Beadwork. These crafts often use motifs inspired by the local flora and the geometric patterns found in historical architecture.

Vibrant Arts: Folk dances like Garba and Dandiya Raas are central to the identity of the plains, originally performed to celebrate the harvest and the goddess Amba.

7.5. Cuisines of the Alluvial Plains

The "Gujarati Thali" is a sophisticated balance of flavors, influenced by the semi-arid climate and the availability of diverse grains.

The Sweet-Salty Balance: Unique to this region, sugar or jaggery is added to most savory dishes (like Dal or Kadhi). Historically, this provided quick energy for those working in the heat of the plains. **Farsan (Snacks):** Items like Dhokla, Khandvi, and Patra are made predominantly from gram flour (Besan), reflecting the prominence of pulse cultivation in the alluvial soils.

Seasonal Delicacies:

Undhiyu: A winter specialty made of mixed vegetables and tubers, traditionally cooked upside down in earthenware pots (Matlu) buried in the ground.

Aamras: During the summer, the mangoes from the orchards of South Gujarat and the plains (like Kesar and Alphonso) become a staple.

Rotla and Shaak: In the more arid northern stretches of the plains, Bajra Rotla (pearl millet flatbread) served with garlic chutney and buttermilk is the traditional meal, suited for the rugged landscape. This intersection of geology and culture provides a holistic view of the region, showing how the tectonic stability and fertile silts of the basins have supported continuous human habitation for millennia.

Local conveniences

1) In case of **Medical Emergency** contact **Zydus Multispeciality Hospitals**
Old Padra Rd, nr. Akshar Chowk, Tandalja, Hira Nagar, Vadodara, Gujarat, 390020
Contact Number: India Toll Free: 1800 123 5433 Emergency: +91 78744 12345
International Mobile: +916357 094217

2) In case of **Safety/ Criminal Emergency/ Theft** contact **Sayajiganj Police Station** Main Road, Sayajiganj, 390005, Baroda Contact Number: 0265-2362400/ 2361479 or Dial -101

3) **Shopping:** Indigenous clothes, apparels and handicraft items are available at the Alkapuri Market and Navabazar in the city.

Conclusions

The salient conclusions of the field excursion are as under:

1. The exposed sediments in the various river valleys date back to Late Pleistocene and were deposited during the last glacial (Maurya et al., 2000; Juyal et al. 2000). The sedimentation commenced with the deposition of marine basal clays during the last interglacial high sea at~125 ka BP.

2. Regression of the sea led to the initiation of fluvial sedimentation. Continuation of tectonic phase is evident by the occurrence of tectonically formed soft-sediment deformation structures in the fluvial sediments between gravel-I and gravel-II in Mahi basin pointing to slow synsedimentary subsidence between ~125 ka to 65 ka along the step faulted eastern margin of the Cambay rift graben (Maurya et al. 1997a).

3. Two episodes of fluvial aggradation are observed. The first possibly corresponds to Oxygen Isotope Substage 5 (extrapolated age-estimate) and the second is dated to 50–30 ka. These events reflect a more humid environment and are seen in both regional and global contexts (Juyal et al. 2000). The red soil in the region formed during the period 40-25 ka and is a good chronostratigraphical marker horizon.

4. The Late Pleistocene sedimentation ceased with the burial of fluvial sediments under a thick cover of aeolian sediments during the last glacial (Merh and Chamyal, 1997). A consistent blanket of these aeolian sediments all over the area suggests widespread aridity which coincided with the expansion of the Thar desert into the Gujarat alluvial plains during this period (Allchin et al. 1978).

5. The present landscape of the area is the result of tectonic uplift during Holocene. The structurally controlled drainage, presence of tributaries on one bank only, preferential development of cliffs and ravines and deeply entrenched meanders are manifestations of tectonic uplift of the area during this period.

6. The incision of Late Pleistocene sequence took place during Early Holocene (10 to 6 ka) when the sea was rising very rapidly (Chappel and Shackleton, 1986; Hashimi et al. 1995). This suggests that Gujarat alluvial plains experienced tectonic uplift during Early Holocene which resulted in the formation of extensive ravines, steep incised cliffs along the river valleys and exhumation of the Late Pleistocene sediments. Another evidence for tectonic uplift of the area is provided by the marine basal clays deposited during the last interglacial high sea which now occur at heights of 20-45 m above msl in the various river sections.

7. This was followed by the Middle to Late Holocene aggradation which commenced at 6400±120 yr B.P. and continued upto 1760±80 yr B.P. Tectonic instability during this aggradation phase is evidenced by the seismically induced deformation structures within these sediments in Mahi and Orsang valleys. The Mid-Late Holocene transgression was within the incised river channels only (except the lower part of Sabarmati). The incision of the lower terrace can be attributed to another phase of tectonic uplift that continues even today as evidenced by the low magnitude seismic activity recorded during the last few hundred years.

8. The Holocene climate change and tectonism is thus responsible for the evolution of the present landscape of Gujarat alluvial plains whereas Pleistocene tectonism is responsible for the accommodation of a huge thickness of the Quaternary sediments.

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Annexure

Field Excursion Guidelines: Do's and Don'ts

To ensure the safety of all participants and to promote responsible scientific field practices, all participants are requested to adhere to the following guidelines throughout the field excursions.

Keep a valid passport (for international participants) or a government-issued photo ID (for Indian participants) with you at all times during the field excursion.

Do's	Don'ts
1. Follow the instructions of the excursion leaders, coordinators, and local authorities at all times.	1. Do not collect rocks, fossils, archaeological artefacts, biological specimens, or any other materials without prior authorization.
2. Remain with the group and inform the excursion leader before leaving the designated route.	2. Do not damage, deface, or remove material from geological outcrops, caves, monuments, heritage structures, or other natural features.
3. Wear appropriate field attire, including sturdy closed-toe footwear, full-length trousers, a hat or cap, and weather-appropriate clothing.	3. Do not wander alone or separate from the excursion group without informing the field leaders.
4. Carry sufficient drinking water, personal medications, sunscreen, insect repellent, and other essential field supplies.	4. Do not climb unstable slopes, cliffs, rock formations, or enter hazardous areas unless specifically instructed or supervised.
5. Keep a valid photo identification and your excursion registration details with you during travel.	5. Do not swim or enter rivers, lakes, lagoons, or coastal waters unless expressly authorized by the excursion leaders.
6. Respect local customs, religious sites, cultural heritage, and private property.	6. Do not consume alcohol, recreational drugs, or engage in unsafe or irresponsible behaviour during the excursion.
7. Follow the Leave No Trace principles by carrying back all waste and helping to keep field sites clean.	7. Do not operate drones or other restricted equipment without obtaining the necessary permissions.
8. Use designated trails and approved observation areas to minimise environmental disturbance.	

9. Observe geological, ecological, archaeological, and cultural features carefully without causing any damage.

10. Record field observations systematically and collect samples only with prior permission from the excursion leaders and the relevant authorities.

11. Exercise caution near cliffs, riverbanks, caves, unstable slopes, road cuts, and other potentially hazardous terrain.

12. Respect wildlife by maintaining a safe distance from animals, birds, reptiles, insects, and their habitats.

13. Immediately report any illness, injury, emergency, or hazardous situation to the excursion organizers.

14. Be prepared for changing weather conditions and comply with all safety advisories issued by the excursion leaders.

8. Do not photograph restricted installations, sensitive locations, or local residents without prior permission.

9. Do not create excessive noise or disturb local communities, religious activities, wildlife, or natural habitats.

10. Do not leave valuables unattended or rely solely on mobile phone connectivity in remote areas.

11. Do not undertake any activity that may compromise your safety, the safety of fellow participants, or the conservation of the area's geological, ecological, archaeological, or cultural heritage.

Disclaimer

Participation in the field excursions is entirely at the participant's own risk. While the Organising Committee and excursion leaders will make every reasonable effort to ensure participant safety and provide appropriate guidance, they shall not be held responsible for any personal injury, illness, loss of personal belongings, property damage, delays, or unforeseen incidents arising during travel or field activities. Participants are expected to act responsibly, follow all instructions issued by the excursion leaders, and comply with applicable local laws and regulations throughout the excursion.













Scan for
Field Guide Book

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