DISCUSSION

Rivers are extremely sensitive to tectonic and environmental changes and are ideally suited for investigating the interaction between these two geological factors. This is well evidenced in regions having a long history of tectonic movements and sea level changes. Fluvial systems of Mainland Gujarat show a strong structural control on the drainage architecture and the landscape of the area (Pant and Juyal, 1993; Raj et al. 1998b, 1999a, b; Maurya et al. 1995, 2000; Juyal et al. 2000; Chamyal et al. 2002, 2003). The climatic conditions over the region are mainly influenced by the southwest monsoon and the topography. The spatial distribution of rainfall is uneven, allowing distinct categorisation of the state into sub-humid, semi-arid, arid and extremely arid zones (Fig. 1.2). The lower Narmada basin forms the transition zone between the subhumid south Gujarat and the semiarid northern part. The sedimentary records exposed in the Sabarmati, Mahi and Narmada basins (Fig. 8.1) are crucial for understanding the Late Quaternary geomorphic evolution of the region (Maurya et al. 2000; Chamyal et al. 2002). It has been suggested that these sediments are stratigraphically correlatable (Merh and Chamyal, 1997; Chamyal et al. 2002).

The peninsular India has been undergoing high compressive stresses due to the sea floor spreading in the Indian Ocean and locking up of the Indian plate with the Eurasian plate in the north (Subramanya, 1996). A significant part of these compressive stresses are being accumulated along the NSF in the central part of the Indian plate which is responsible for the moderate to high intensity seismic activity being experienced in the region (Gupta et al. 1972; 1997; Acharyya et al. 1998). Attempts on proper evaluation of seismic risk have been hampered by lack of data on

neotectonic activity along the NSF. This is probably the first study, which provides insight into the neotectonic movements along this fault.

The lower Narmada basin which has been the site of prolific sedimentation during the Cenozoic (Biswas, 1987) is ideally suited for such a study. The present study has revealed that the NSF has been neotectonically active throughout the Late Quaternary and has played a significant role in the geomorphic evolution of lower Narmada basin. The study has also revealed a complex
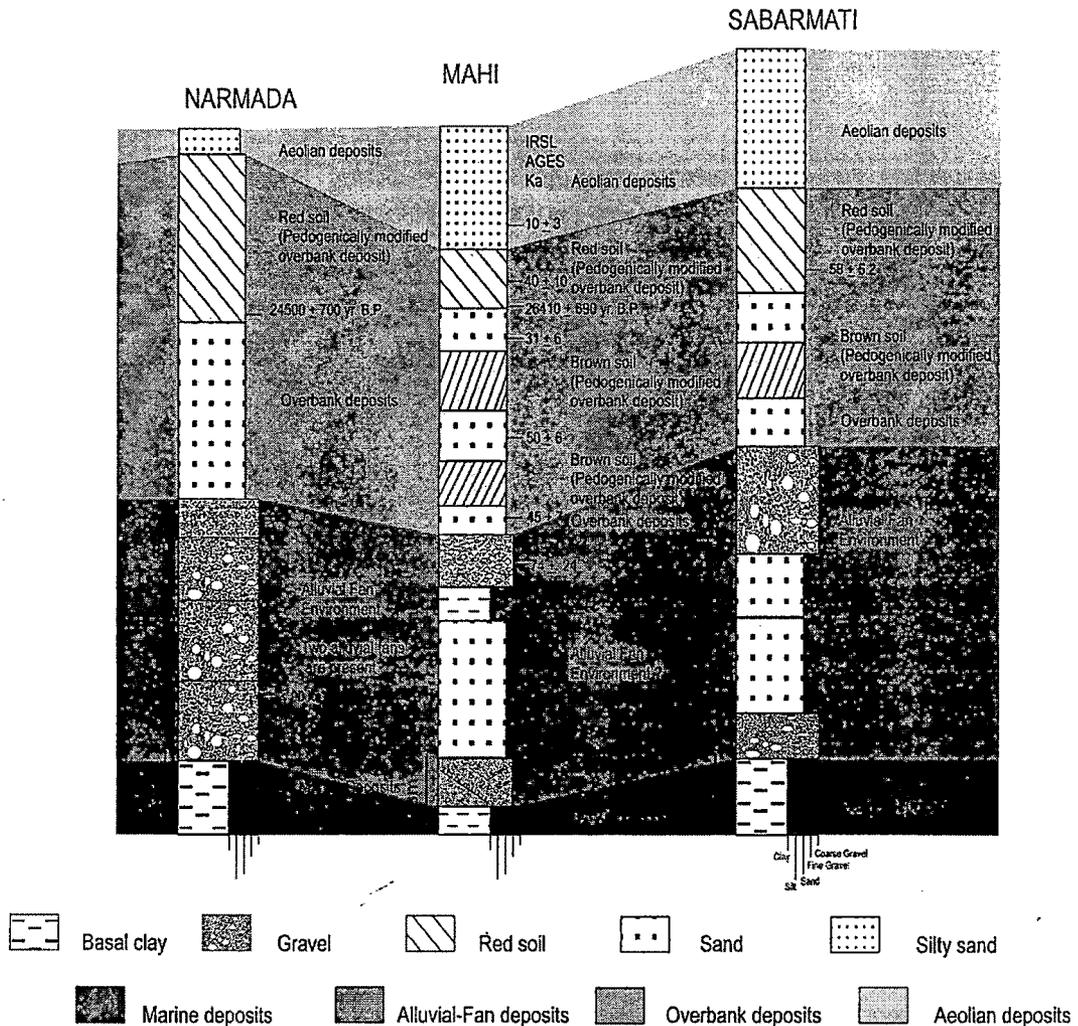

Fig. 8.1. Physical stratigraphy of the exposed Late Pleistocene sediments (S_1 and S_2 surfaces) in the lower Narmada valley and the adjacent Mahi and Sabarmati valleys (after Chamyal et al. 2002). Note the correlatibility of major aggradational phases. Dates are after Chamyal et al. (2002), Juyal et al. (2000), Tandon et al. (1997) and Allchin et al. (1978)

history of tectonic movements along the Narmada-Son Fault during Quaternary. The study is based on a variety of data including detailed geomorphic mapping, vertical and lateral mapping of

Quaternary sediments exposed in incised valley sections, neotectonic and deformational features, composite landform assemblage and their morphostratigraphic relationships. Using these, the role of tectonics in the evolution of present landscape of the lower Narmada valley has been inferred.

The Narmada River is the largest river of peninsular India which flows along the ENE-WSW trending Narmada-Son Fault (NSF), a well-known seismotectonic feature (Biswas, 1987) transecting through the central part of the northward drifting Indian plate (Fig. 2.2). 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 (Fig. 1.1B, 2.2). The true alluvial reach of the Narmada is encountered in its lower part within the state of Gujarat where more than 800 m thick Quaternary sediments are reported overlying hydrocarbon bearing Tertiary sediments (Maurya et al. 1995). This reach is about 90 km in length and forms the southern margin of the N-S extending Gujarat alluvial plains (Fig. 1.1).

The upland region of the lower Narmada basin comprises southward dipping basaltic flows of the Deccan Volcanic Group (DVG) delimited to the north by the Narmada-Son Fault. Several evidences point to neotectonic activity due to movement along the NSF. The entire area indicates a strong control of the ENE-WSW and NNW-SSE (Fig. 6.1) trending lineaments on the geomorphology and drainage architecture. The ENE-WSW trending ridges with southern slopes and north facing escarpments including the Narmada-Son Fault (NSF) and ENE-WSW trending narrow intramontane valleys evidence the dominant control of ENE-WSW trend. Three tilt blocks have been delineated within a major tilt block formed due to differential uplifts along the NSF and two other sympathetic faults (Fig. 3.5). A gradual decrease in the ruggedness of the topography towards south, preferential locations of river ponding (Figs. 3.15, 3.16), gorges (Fig. 3.14) and increased fluvial incision suggest continued southward tilting of the fault blocks due to differential uplift along ENE-WSW trending faults. The alluvial zone to the north of the Narmada Son Fault is made up of Late Pleistocene to Holocene sediments and indicates two phases of river incision in the Karjan river basin, which are attributed to uplifts during Early and Late Holocene. Morphometric analyses (Figs. 6.3, 6.4, 6.5, 6.6, 6.7 and 6.8) of parameters sensitive to tectonics substantiate the field observations on active tectonics. The field evidence from the upland and alluvial zone and the morphometric analyses point to differential uplift of the Karjan basin along ENE-WSW trending faults during Holocene.

Data on Early and Middle Pleistocene tectonic and environmental changes in western India are completely lacking. The only area where evidence of such changes could be preserved is in the subsurface sediments of Mainland Gujarat. The lower Narmada basin has been the site of thick Quaternary sedimentation due to rapid to slow synsedimentary subsidence in a thrusting environment. The synclinal folds in the northern subsided block and corresponding anticlinal folds to the south of NSF indicate the existence of compressive stresses during this period which

were responsible for the transformation of the E-W Narmada-Son Fault into a reverse fault (Fig. 2.6 B) at the onset of Quaternary (Roy, 1990). Rapid but unequal subsidence of the basin gave rise to a ~800 m thickness of sediments (Fig. 2.7), which now lie in the subsurface. 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 (Agarwal, 1986) (Fig. 2.6A). The folding and faulting of Tertiary rocks to the south of the Narmada River are the manifestations of tectonic activity during the Early and Middle Pleistocene. The cover of Late Pleistocene to Holocene sediments over the Tertiary rocks to the south of NSF suggests that the episode of intense folding and reverse faulting was confined to the Lower and Middle Pleistocene.

The present landscape of the alluvial plain in the lower Narmada basin is characterised by four distinct geomorphic surfaces (Fig. 3.3) termed as S_1 (alluvial plain), S_2 (ravine/gullied surface), S_3 (Early Holocene fan surface) and S_4 (Mid-Late Holocene valley fill terrace surface). The sediments forming the S_1 and S_2 surface date back to Late Pleistocene. The Late Pleistocene sediments are exposed along the cliff sections of the various rivers of Lower Narmada basin. The sedimentation commenced with the deposition of the marine basal clays during the last interglacial high sea at ~125 ka which is presumed to be about +7 m as revealed by the studies on the adjacent Mahi river basin (Raj et al. 1998b) and Saurashtra coast (Pant and Juyal, 1993). The bluish mottled clays uniformly forming the base of the exposed Quaternary successions in Mainland Gujarat represent marine deposits of this high sea level (Raj et al. 1998b). These deposits are encountered in the Sabarmati and the Mahi valleys also. Infrared stimulated luminescence dates in Mahi basin suggests that these basal clays belong to the last interglacial high sea level (Juyal et al. 2000) when the sea rose by +7 m on the west coast of India (Pant and Juyal, 1993). Global sea level curves indicate that the sea was about + 7 m above the present mean sea level during this period. Regression of this sea led to the initiation of fluvial sedimentation. The fluvial sediments indicate deposition in two fluvial macroenvironments– the alluvial fan environment and the alluvial plain environment. The alluvial fan deposits overlie the marine clays followed by the alluvial plain sediments in a slowly subsiding basin.

The presence of alluvial fan facies in the sediment record is generally taken as direct evidence of a tectonic activity (Steel et al. 1977; Heward, 1978). Optimal conditions for fan development are created in regions undergoing extension (Blair and Bilodeau, 1988). Extensional basin settings are especially conducive for long term fan development leading to deposition of fan sequences hundreds of meters thick where as long term development of fans is hindered in compressive tectonic regimes owing to greater strong component of lateral tectonic deformation

(Blair and McPherson, 1994). The transformation of the Narmada-Son Fault from a normal fault in Tertiary to reverse fault in Quaternary is implicit in the seismic studies of the area (Roy, 1990). Additional evidence for prevalence of compressive stress regime in the Lower Narmada basin is provided by numerous reverse faults (Fig. 2.6) in the Neogene sediments exposed immediately to the south of Narmada-Son Fault (Agarwal, 1986). These evidences suggest that both the fans, fan 1 and 2 were formed in a compressive tectonic environment. This could be the reason for the fact that the maximum thickness of the fan sequences is about 70-80 m only of which about 35 m is exposed. This compares well with the observation of Blair and McPherson (1994) that fan development is hindered in compressive tectonic settings. The existence of compressive stress regime affected the fan morphology due to which both fans show a rather elongated fan shape resulting in alluvial fans of unusual axial lengths (Chamyal et al. 1997). The alluvial fan sediments are overlain by a thick sequence of alluvial plain facies which indicate termination of fan sedimentation and initiation of riverine sedimentation by a more integrated drainage system.

The Late Pleistocene alluvial plain sequence overlying the alluvial fan sediments (Chamyal et al. 2002) reveal fluvial characteristics that are at variance with the present day channel characteristics of the Narmada River. The alluvial plain sequence in the lower Narmada valley is dominated by the overbank sediments and comprise large channel fills, horizontally stratified sands, massive sand sheets, crevasse splay and backswamp deposits. However, the overall dominance of sands and silts suggests, in general, a sand bed river meandering through a wide alluvial plain.

The large channel fills are a significant component of the alluvial plain sediments in the lower Narmada valley. These occur as large sediment bodies of broad concave-up geometry with gently sloping channel margins. This is in contrast to the U shaped channel fills with steep channel margins which indicate incision of the underlying deposits before aggradation takes place (Hopkins, 1985). The channel fills are filled with sand sheets with internal laminations, which are thickest along the trough axis. These may have been filled by deposition in standing body of water remaining after the channel was abandoned. Such filling of channels in modern settings has been demonstrated by Meckel (1972). The nature of the fill is determined by the rapidity of channel abandonment (Hopkins, 1985). A sand filled channel indicates progressive abandonment by diversion of flow through a favoured distributary (Hopkins, 1985).

The channel fills indicate a large river having roughly 70-80 m width and ~8-15 m depth during periods of low discharge. This is much larger in comparison to the 30-40 m width and ~5 m deep channel of the present day Narmada River during lean seasons. The large scale stratification and thicker bedding of the epsilon cross strata indicate deposition due to lateral migration of very deep (15-20 m) sand bed river channels. The large channel fill structures occur in isolation and are associated with overbank sediments. Occurrence of large channel fills,

adjacent overbank strata and absence of laterally adjacent channel fills indicate mainly a large single channel river. The channel troughs indicate consistently west oriented channels. No large scale variance in palaeocurrent directions derived from other independent parameters from the outcrops is seen. This is indicative of a channel with relatively low sinuosity and frequent occurrence of chute cutoffs (Bridge et al. 2000).

Two generations of channel fills are present in the lower Narmada valley. The one occurring at Kanjetha (Fig. 5.8) underlies the epsilon cross bedded strata. A similar large channel fill with a broader concave-up shape occurs below the epsilon cross bedded strata. The partially exposed channel fill structure at Chandod overlies the epsilon cross bedded strata (Fig. 5.9). Vertical superposition of channel fills indicates high deposition rates accompanied by high channel migration rates. Since no significant variation in the fluvial regime is visible that may suggest distinct climate change, the frequent shifts of the river channel across the alluvial plain can be attributed to autocyclic factors.

Overbank sediments result from deposition due to overtopping of the banks during river floods or avulsions. A large amount of work has been done on the sedimentation processes in overbank regions by Allen (1965), Elliott (1974), Smith (1983), Bridge (1984), Farrell (1987), Sinha and Friend (1999). Miall (1985) assigned overbank deposits to a single architectural element however, overbank sequences have been shown to have complex and varied architecture (Behrensmeyer, 1987; Bown and Kraus, 1987; Kraus and Aslan, 1993; Smith 1990, 1993). A common characteristic of overbank deposits is the presence of horizontal stratification (Willis and Behrensmeyer, 1994) ranging from thinly stratified to thickly stratified. Overbank deposits with well preserved stratification can result from relatively rapid deposition. Rapid deposition and high rate of channel shifting can lead to absence of palaeosols in overbank sequences which seems to be the case in the lower Narmada valley given the conditions of a slowly subsiding basin (Chamyal et al. 2002) and the dominance of overbank strata in the sediment succession. During increased aggradation rate avulsion frequency is also high (Bridge et al. 2000). Flooding processes were repetitive under the conditions of overall aggradation of the floodplain, a phenomena commonly associated with avulsion (Rhee et al. 1993). The crevasse splay deposits occur in close association with the overbank sediments, which suggests that the crevasse deposits were formed far away from the trunk channel (Rhee et al. 1993). Channel shifts (avulsions) can be gradual or abrupt. Rapid abandonment takes when a new channel is formed in a catastrophic flood event, whereas gradual abandonment takes place when successive high water stages result in enlargement of a crevasse finally causing river diversion (Hopkins, 1985; Rhee et al. 1993). The channel abandonment may have taken place by both means in the lower Narmada valley during the Late Pleistocene.

The thick palaeosol marks a phase of pedogenesis of the overbank sediments. Chronologic data on this regionally recorded pedogenic phase indicates that it is pre-LGM (Allchin et al. 1978; Tandon et al. 1997; Juyal et al. 2000; in press). The overlying thinly stratified sands and silts therefore appear to have been deposited during the arid phase of the Last Glacial Maximum. These multibed sediments were deposited by vertical accretion during successive floods in broad shallow channels, which may have remained stable for relatively longer time. The sheet like nature of the deposits and the lack of erosional downcutting indicate that these were formed by vertical accretion on a broad poorly channelised alluvial plain. These deposits therefore mark significant reduction in fluvial activity due to considerably depleted water supply which is directly related to the onset of aridity. Continued sedimentation indicates that the river retained a large catchment during the arid phase. Lack of root structures and dessication cracks also suggest that the flow was perennial.

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 by a large river in an alluvial plain setting. 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 (eg. 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 basin, 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.

Late Pleistocene fluvial sediments exposed in the 15-20 m high cliffs in upper and middle reaches of the Narmada River (Gupta et al. 1999; Ely et al. 1996; Kale et al. 2003) have been studied mainly for their rich mammalian fauna and archaeological artefacts (Badam et al. 1986; Biswas, 1997; Mishra and Rajaguru, 2001). The sediments comprise massive silts, cross bedded sands and layers of gravels and boulders (Gupta et al. 1999) though no stratigraphic or sedimentologic details are available on them as yet. A recent study (Kale et al. 2003) has described an imbricated boulder bed (average clast size 35 cm) in a section located on an abandoned channel of the Narmada River near Bhedaghat, which has been dated to 25,160±550 yrs B. P. based on radiocarbon dating of shells found in this horizon. The boulder bed has been attributed to an extraordinary flood or series of great floods (Kale et al. 2003) which suggests existence of humid climate in the upper reaches of the Narmada River during Late Pleistocene. The rich mammalian fauna found in the Late Pleistocene deposits in central and upper Narmada basin has also led to the conclusion that the Central India was a mosaic of dense forests, park savannas and water bodies (Badam et al. 1986) during this period.

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. It can therefore be inferred that the alluvial plain sediments of the lower Narmada basin 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 (Fig. 4.30). 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 basin. 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 basin suggest 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.

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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. Palaeoclimatic studies of the Thar desert and its margins (Andrews et al. 1998; Kar et al. 2001), loess deposits in China (Maher and Thompson, 1995), marine sediment cores from Arabian Sea near Oman (Clemens et al. 1991) provide evidence for strong monsoon and enhanced precipitation levels during this time. 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.

A period of tectonic uplift followed during the Early Holocene in the entire Mainland Gujarat region, resulted in the formation of gorge-like, deeply incised river valleys, extensive ravines, entrenched meanders and the exhumation of the Late Pleistocene sediments (Maurya et al. 2000). The Late Pleistocene sediments were exposed by incision accompanied by extensive gully erosion triggered by tectonic uplift during Early Holocene. Extensive ravine formation and 30-40 m incised cliffs of Late Pleistocene sediments point to a significant post-depositional interval of gully erosion with contemporaneous incision. Evidences suggest that the ravine erosion post-dates aeolian sedimentation of Late Pleistocene. This means that the formation of a fluvial incised valley is not related to the lowering of sea level. Fluvial incision and ravine erosion during low sea level around the last glacial maximum would have led to a very randomised distribution of aeolian sediments within the gullies which is not the case even in the Mahi and Sabarmati basins which have a more complete aeolian record (Tandon et al. 1997; Juyal et al. 2000; Maurya et al. 2000).

The aeolian sediments occur as capping over the underlying fluvial sediments and is clearly observed in the incised cliff sections as well as in the ravines. Absence of ravine erosion in the Mid-Late Holocene terrace sediments is an important geomorphic evidence which helps to constrain this interval of extreme erosional activity. These geomorphic evidences indicate that the incision and ravine formation in Late Pleistocene sediments occurred during Early Holocene (~10 to 6 ka) which is a period of rapid sea level rise (Chappell and Shackleton, 1986; Hashimi et al. 1995). This suggests tectonic uplift of lower Narmada basin during Early Holocene which

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resulted in the formation of extensive ravines and a deeply incised fluvial valley. On   a

preliminary basis, an uplift of about 40 m can be inferred from the 40-45 m high incised cliffs of Late Pleistocene sediments. This estimate may be on the conservative side as the base of the incised valley is not exposed. Rao et al. (1996) showed subsidence of the continental shelf on the west coast of India by about 40 m during Early Holocene while the continental margin was uplifted (Whiting et al. 1994). The subsidence of the ocean floor is in response to the deformation and uplift of the peninsular India during Holocene due to the continuing northward movement of the Indian plate (Subramanya, 1996).

Differential uplift along the NSF is evidenced by the occurrence of Late Pleistocene sediments at elevations upto 100 m across the NSF as seen near Gora and Jitnagar in the Narmada and Karjan valleys respectively. At these places, sediments occur well above the present high discharge levels and overlie the basalts which also show vertical downcutting by the river. The Late Pleistocene sediments generally attain elevations of 30-50 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. The displaced Late Pleistocene sediments across NSF in the Narmada River indicate a displacement of about 35 m along the NSF during Early Holocene.

Many of the incised fluvial valleys have been attributed to a low sea level (Allen and Posamentier, 1993; Darymple et al. 1992). The vertical incision is not related to the lowering of sea level during the extreme arid climate of the last glacial maximum. It has been suggested that in non-glaciated areas, valley erosion takes place under wet conditions and not in arid conditions (Huntington, 1907; Jones et al. 1999). Studies in central and upper parts of the Narmada basin have also indicated that the present channel of Narmada with high cliffy banks was formed possibly during the Early Holocene wet phase (Rajaguru et al. 1995; Gupta et al. 1999). The abandoned cliffs (paleobanks) (Fig. 3.19) consisting of Late Pleistocene sediments indicate a much wider channel and less sinuous channel belt of the Narmada River during this interval. Even the largest seasonal floods are not enough to fill the entire valley at the present day (Gupta et al. 1999). Currently, the river occupies the northern margin of the Early Holocene channel belt and is clearly more sinuous. The palaeohydrological analysis of the lower Narmada basin has shown that the Early Holocene discharge of the river was about 3.76 times more than the present confirming the globally recorded higher precipitation levels during Early Holocene.

The tectonic uplift of the lower Narmada valley during Early Holocene marks the structural inversion of an earlier subsiding basin. Such inversions of the basin have been common in the Tertiary times and are well recorded in the sediments of this age (Roy, 1990). In the Luni basin Holocene sediments provide an important constraint on the age (~5 ka BP) of incision (Jain et al. 1999). Srivastava et al. (2001) have placed the adjustment of the Sabarmati along a N-S

transect around 12 ka BP and the incision is bracketed between 12 and 4-5 ka BP. Earlier Maurya et al.(1997a) emphasised that the maximum incision along the Mainland Gujarat Rivers was during the Early Holocene.

The difference in the elevations of the Late Pleistocene sediments on either sides of the NSF in the Narmada and Karjan valleys point to a differential movement of about 35 m during Early Holocene. Differential uplift along NSF is also evidenced by the NNW tilting of the Late Pleistocene sequence, anomalous topographic slope in the same direction and incised cliffs up to 20-30 m in the streams that flow along this slope in the area between NSF and the Narmada River.

The S_1 and S_2 surfaces are overlain by the sediments of S_3 surface. In the Lower Narmada basin, around Rajpipla, a major tectonic uplift along the Narmada Son Fault (NSF) probably caused a sudden change in gradient, resulting in the accumulation of S_3 surface where the particles are derived from steep drainage basins in the subsiding basin with an alluvial fan environment. Uplift of adjacent areas along the NSF and the other two faults trending NNW-SSE and NW-SE have controlled the fan stratigraphy in terms of both accommodation of space and sediment supply (cf. Gordon and Heller, 1993).

Tectonics and climate appear to be the two main factors responsible for the erosional and depositional processes that built the architecture of Early Holocene fans around Rajpipla. Accumulation of fan successions in tectonically subsiding blocks during periods of humid climate is common (Nilsen, 1982; Harvey, 1988; Dorn et al. 1987). According to the stratigraphic framework provided by Merh and Chamyal (1997) and Juyal et al. (2000), the alluvial sediments underlying the fan deposits are of Late Pleistocene age (~125 ka to ~10 ka) which indicate that fan aggradation took place in Early Holocene. High precipitation levels are witnessed all over the globe during this period (Yan and Petit-Maire, 1994). The SW Indian monsoon also restrengthened during this time-span after the arid phase of the Late Pleistocene (Singh, 1998). The fans around Rajpipla are characterised by a wide range of grain sizes of immature sediments deposited by different fluvial processes and by a general absence of soil profiles. These characteristics, according to Evans (1991), point to humid tropical fan features. An overall humid climate with precipitation levels higher than present together with tectonic activity along the various faults including the NSF is, therefore, inferred for the formation of alluvial fans around Rajpipla during the Early Holocene.

The role of tectonic activity in the erosion of these fans is brought out by the development of numerous streams and ravines/gullies. The change from active fan aggradation, indicated by debris flow accumulation, to the present state of erosion, evidenced by gullying and incised channel enlargement is attributed to a change from tectonic subsidence of the fan block to the Late Holocene uplift (Maurya et al. 2000). This resulted in the formation of the present-day

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incised channels and gullies over the alluvial fan surface which has provided sites for the study of the various fan facies.

The S_4 surface is a wide flat topped terrace surface of 5-12 m height, which occupy a deeply incised fluvial valley comprising Late Pleistocene sediments. These terraces comprise tidal estuarine sediments in the lower reaches and fluvial sediments in the upper reaches (Maurya et al. 2000). The palynological studies of this surface at Baruch have indicated shallow estuarine environment. The terraces show no evidence of ravine erosion and incised cliffs along the river and abut against the abandoned cliffs (palaeobank) of Late Pleistocene sediments. The tidal estuarine terrace sequence is dominated by tidal muds indicating their deposition in tide dominated estuarine conditions. Similar facies is found in the present estuary which is also tide dominated (Nigam, 1984) suggesting similar tidal estuarine environment during the deposition of these sediments. Moreover, the tripartite (coarse-fine-coarse) facies assemblage characteristic of wave dominated estuaries (Darymple et al. 1992) is also not found in the sediments. In tide dominated estuaries, the muddy sediments accumulate primarily in the tidal flats and sand marshes while sands are deposited in the tidal channels that run along the length of the estuary (Woodroffe et al. 1989; Darymple et al. 1990). The geomorphic setting suggests that these sediments were deposited as aggrading transgressive tidal estuarine facies transforming the fluvial incised valley into an estuary during the Middle Holocene high sea. Radiocarbon dating of the comparable terraces found in the lower Mahi valley have indicated that these terraces represent the aggradation phase of Mid-Late Holocene which lasted from 6400 ± 120 yr B. P. to 1760 ± 80 yr B. P. (Kusumgar et al. 1998; Maurya et al. 2000).

Studies from tide dominated estuaries are less as compared to wave dominated estuaries (Darymple et al. 1992), however, the estuarine valley fill complex of the Narmada river broadly conforms to the available models of tide dominated estuaries (Wright et al. 1973; Harris 1988; Woodroffe et al. 1989; Darymple et al. 1990). Comparison of the present estuary with the one indicated by the palaeobank against which the terraces abut, reveals that the present mouth of the Narmada River has roughly retained the original funnel shape of the estuary formed during the Mid-Late Holocene. However, the size of the estuary is now considerably reduced. The several islands in the present estuarine reach are interpreted to have been deposited as mid-channel bars in this zone. The causes of such channel patterns in tide dominated estuaries are not known (Darymple et al. 1992).

Upstream of the tidal estuarine terraces, comparable fluvial terraces occur right upto the upland zone with identical geomorphic setting. These terraces mainly consist of horizontally stratified fluvial silty sands (Sh). The lateral accretion surfaces are completely absent indicating aggradation of the incised valley through vertical accretion when the lower reaches of river was undergoing tidal estuarine sedimentation. However, the change from fluvial to tidal facies is not

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sharply defined and appears to be transitional. The occurrence of Holocene terraces is significant as it provides geomorphic evidence to effectively constrain the phase of extensive ravine erosion and fluvial incision of the Late Pleistocene sediments indicating that this phase took place during Early Holocene.

Thus, the Mid-Late Holocene valley complex is the product of a high sea level induced deposition in a deeply incised fluvial valley. A significant slowing down of tectonic uplift facilitated the encroachment of the sea into the valley and creation of a depositional wedge which extended upto the foot hills. The 5-12 m exposed thickness of the valley fill sediments reveal tide dominated estuarine deposition in the lower reaches and fluvial deposition upstream of the tidal reach. The width of the present estuarine reach of the Narmada is much smaller but morphologically similar to the one in which the terraces were deposited. Studies on valley fill terraces in the nearby Mahi valley which have identical sediment composition indicate uninterrupted sedimentation from 6400 ± 120 to 1760 ± 80 yr B.P. (Kusumgar et al. 1998; Maurya et al. 2000). Seismically induced deformation from these terraces in Mahi and Orsang valleys (Maurya et al. 1998; 2000) suggest that the region remained tectonically unstable during this interval.

The sea remained at approximately the same levels until around 2 ka BP as revealed by the radiometric dates on the marine terraces in the Mahi estuary (Kusumgar et al. 1998) and the coral reefs in Saurashtra (Juyal et al. 1995). No evidence of the regression of the Holocene high sea is recorded on the West Coast of India. The Mid-to-Late Holocene terraces in Mainland Gujarat also do not show regressive deposits. Since, there is no evidence of regression of the Holocene high sea (Chappell and Shackleton, 1986; Hashimi et al. 1995), the occurrence of terrace surface much above the present highest tide levels can be attributed to post depositional uplift of lower Narmada valley due to continuing differential uplift along the NSF. Thus the occurrence of uplifted terraces of the alluvial plains along with the raised coral reefs in Saurashtra, raised mud flats in Saurashtra and south Gujarat, the drying up of Ranns of Kachchh, Okha Rann and the Nal region can be attributed to tectonic uplift of entire Gujarat after 2 ka BP (Chamyal et al. 2003). Historical and instrumental records indicate that the compressive stresses produced by the northward movement of the Indian plate, still continue to accumulate along the NSF. This is evidenced by the fault solution studies of the earthquakes at Broach (23rd March, 1970) and Jabalpur (22nd May, 1997) which suggest thrusting movement with a strike slip component (Gupta et al., 1972; Chandra, 1977; Acharyya et al. 1998).

Geomorphic history of the lower Narmada basin delineated in the present study indicates that the various surfaces evolved during Late Pleistocene-Holocene primarily due to vertical tectonic movements along the ENE-WSW trending NSF in a compressive environment. Two major phases of tectonic activity along the NSF are recorded. The first phase includes the Late

Pleistocene when slow synsedimentary subsidence of the basin took place along the NSF which allowed for uninterrupted sedimentation except for brief periods of pedogenesis of basal clays and the overbank sediments. Available chronological data and correlation with adjacent river basin indicate that the fluvial sediments belong to aggradation phases corresponding to marine isotopic stages (MIS) 5 and 3 (Juyal et al. 2000). Synsedimentary subsidence of the basin in compressive tectonic setting is evidenced by the hindered alluvial fan sedimentation, thick overbank sediments and associated sediment deformation. The second phase includes the Holocene, which is marked by basin inversion due to differential uplift along the NSF. Inversion of basin after a prolonged period of subsidence is common (Ziegler, 1983). The period of inversion is usually a period of net erosion (Mather, 1993). Two phases of uplift during Holocene have been recognised. The first of these occurred during Early Holocene which formed extensive ravines and a deeply incised fluvial valley. The second during Late Holocene to Recent, which uplifted the Mid-Late Holocene sediments forming terraces.

Tectonic activity of significant magnitude during Early Holocene has been reported from the sea level studies of the west coast and the Himalaya located at the trailing and leading edges of the Indian plate respectively. In Himalaya, termination of lacustrine sedimentation has been attributed to tectonic activity during Early Holocene (Kotlia et al. 2000). This suggests a major tectonic phase in the tectonic history of the Indian plate evidences of which are also found along the NSF in the central part of the Indian plate. This suggests a renewed phase of extreme compression of the Indian plate, which led to tectonic inversion along the NSF in lower Narmada valley. Significant increase in compressive stresses accumulating on an intracrustal fault like the NSF can transform a previously subsiding basin into an uplifting one. Since the NSF has been characterised by compressive stress regime throughout Quaternary, variations in the degree of compression, which can in turn be interpreted in terms of varying rates of plate movement, alone are responsible for the Late Pleistocene subsidence and Holocene tectonic inversion in the lower Narmada basin. Studies from other parts of the NSF are needed to confirm the continuity of these movements along the length of the fault.