

**LATE QUATERNARY SEDIMENTATION, NEOTECTONICS AND
PALAEOENVIRONMENT OF THE LOWER NARMADA BASIN,
WESTERN INDIA**

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SUMMARY

The Narmada River, the third biggest river of India and the largest river of peninsular India originates from the Maikala ranges at Amarkanthak in Madhya Pradesh however, the present study is confined to the lower reaches of the Narmada basin in Gujarat only. The Narmada River flows along the ENE-WSW trending Narmada-Son Fault (NSF). A major part of the course of the Narmada River falls within the rocky area. 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 overlie the Tertiary sediments. This reach is about 90 km in length and forms the southern margin of the N-S extending Gujarat alluvial plains (GAP).

The fluvial depositional history combined with tectonics and environmental studies helps in understanding the landscape evolution of the fluvial systems. The main purpose of this study was to delineate the Late Quaternary tectonic movements along the Narmada Son Fault (NSF), a seismically active tectonic element in the Indian plate and the environmental changes. Therefore, emphasis was laid on applications of detailed geomorphic, stratigraphic and sedimentological approaches to understand the Late Quaternary geology and resulting landscape in the lower Narmada basin. 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 and palaeoenvironments have been used to decipher the hidden secrets in the evolution of the lower Narmada basin.

The present drainage of the lower Narmada basin is incisive as evidenced by 30-40 m high alluvial cliffs and deeply entrenched meanders. Presence of deep gullies (ravines), uplifted terraces, entrenched meanders and palaeobanks, 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 characterised by narrow channel inside a wide belt of terraces. 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. It has also revealed a complex history of tectonic movements along the Narmada-Son Fault during Quaternary.

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. The entire area indicates a strong control of the ENE-WSW and NNW-SSE 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. A gradual decrease in the ruggedness of the topography towards south, preferential locations of river ponding, gorges 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, a tributary river basin of lower Narmada basin which, are attributed to uplifts during Early and Late Holocene. Morphometric analyses 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.

The lower Narmada basin has been the site of thick Quaternary sedimentation due to rapid to slow syndimentary 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 at the onset of Quaternary. Rapid but unequal subsidence of the basin gave rise to a ~800 m thickness of sediments, 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. 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. 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 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 S₁ and S₂ 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. The overlying 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. Optimal conditions for fan development are created in regions undergoing extension. In the lower Narmada basin 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. 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 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 basin is dominated by the overbank sediments and comprise large channel fills, horizontally stratified sands, massive sand sheets, crevasse splay and backswamp deposits. The large channel fills are a significant component of the alluvial plain sediments in the lower Narmada basin. These occur as large sediment bodies of broad concave-up geometry with gently sloping channel margins. 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. 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.

Overbank sediments result from deposition due to overtopping of the banks during river floods or avulsions. 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 basin given the conditions of a slowly subsiding basin and the dominance of overbank strata in the sediment

succession. Flooding processes were repetitive under the conditions of overall aggradation of the floodplain, a phenomena commonly associated with avulsion. 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. 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. The channel abandonment may have taken place by both means in the lower Narmada basin 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. 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 basin indicate two distinct phases of changes in the fluvial regime. One is the multidistributary channel system that deposited the alluvial fan sediments, 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. The river was characterised by a ~8-15 m deep channel that was ~70-80 m wide even during low discharge levels. The present study on the alluvial plain sedimentation in lower Narmada basin, 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, 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 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, Maharashtra upland rivers, Central Narmada, Son and Belan valleys and the Indo-Gangetic plain. 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 basin 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.

The Narmada River in the Late Pleistocene has been inferred to be a mobile meandering river which carried large quantities of sand with periods of large floods. Studies on Holocene palaeoflood deposits in central India 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 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 basin. This suggests that the Narmada River has maintained a large catchment at least during the last 100 ka.

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 sediment. 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. Evidence 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.

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. This suggests tectonic uplift of lower Narmada basin during Early Holocene which 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. The subsidence of the continental shelf on the west coast of India by about 40 m during Early Holocene while the continental margin was uplifted. 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. 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. 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. 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. The abandoned cliffs (paleobanks) 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. 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 basin 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.

The difference in the elevations of the Late Pleistocene sediments on either sides of the NSF in the Narmada and Karjan basins 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.

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 S₃ 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.

Tectonics and climate appear to be the two main factors responsible for the erosional and depositional processes that built the architecture of Rajpipla fans. Accumulation of fan successions in tectonically subsiding blocks during periods of humid climate is common. According to the stratigraphic framework 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. The SW Indian monsoon also restrengthened during this time-span after the arid phase of the Late Pleistocene. 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, 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 S₄ surface is a wide flat topped terrace comprising tidal estuarine sediments in the lower reaches and fluvial sediments in the upper reaches. The palynological studies of this surface at Baruch have indicated shallow estuarine environment. The tidal estuarine terrace sequence is dominated by tidal muds indicating their deposition in tide dominated estuarine conditions. The geomorphic setting suggests that these sediments in the lower Narmada basin 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.

Comparison of the present Narmada 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.

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. 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. The post depositional uplift of lower Narmada basin is 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.

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. 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. 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. The period of inversion is usually a period of net erosion. 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 and the second during Late Holocene to Recent.

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. 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 basin. 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.