CHAPTER - IX

CONCLUDING DISCUSSION

The Gujarat alluvial plains reveal an interesting evolutionary history which has considerable significance as far as the Quaternary tectonic history of western India is concerned. The exposed sediments ranging in age from Middle Pleistocene (~240 ka) to recent, suggest a complex interplay of tectonism, paleoclimate and sea level changes in the deposition of the sediments and evolution of landscape.

Previous workers have dwelt at length on the effects of palaeoclimate and varying depositional environments during the deposition of these sediments. Archaeologic studies provided the chronologic controls of the exposed sediments.

Regional studies wherein the Gujarat alluvial plains have been considered as a single geologic unit rather than dividing it into several drainage basins, are very few. However, all these studies have been unable to explain several geomorphic and drainage anomalies of the area. The main reason for this drawback of earlier studies has been the lack of appreciation of the control exercised by Quaternary tectonism in the evolutionary process of these plains.

The present study has been able to establish the significant role of tectonism and identify the various Quaternary tectonic events which have helped in the evolution of present landscape of the alluvial plains. In the process, the various geomorphic and drainage anomalies have been explained for the first time. A comprehensive field approach has been used in carrying out the entire study.

The study area shows a variety of geomorphic features that have very subtle reflections in the topography. Geomorphologically, the area is divisible into several zones - the uplands, the pediment zone, the basinal zone, and the coastal zone. The eastern part of the plains is basically a shallow buried pediment zone. Here the Quaternary sediments directly overlie the basement rocks. On the northwestern side the plains are abruptly truncated by the Ranns of Kachchh. The region of north Gujarat particularly north of Banas river is characterised by the presence of stabilised dunes. The topography in this part corresponds more to the dunal topography of the desert area than the flat terrain of the alluvial plain. The frequency of these dunes decreases towards the south, but are never observed to disappear completely. These dunes occur as raised mounds of varying dimensions giving rise to a gently rolling topography in an otherwise flat monotonous terrain.

The area around the river valleys is more interesting. Remarkable similarity of the geomorphic features in all the major river valleys is observed indicating an identical evolutionary history of all the rivers. The ravines in and around the river valleys are the most striking aspect of the landscape of the study area. The consistent presence of imposing alluvial cliffs rising upto 50 m, entrenched meanders, anomalous braids, and funnel shaped mouths are significant geomorphic evidences of tectonism encountered in all the rivers of the area. Preferential development of cliffs and ravines and presence of tributaries only on one bank has also been observed.

A low elevated terrace is observed in all the river valleys. Investigations on these terraces have revealed it to be a Mid-Late Holocene terrace which is marine in the estuarine zones and fluvial in the upper reaches. The discovery of these terraces has been a major finding of this study which has for the first time explained the Late Pleistocene-Holocene evolution of the Gujarat plains.

The coastal segment of the study area shows a larger variety of geomorphic features. The coastline is rather straight and is marked by the unusually broad estuarine mouths of the Mahi, Dhadhar and the Narmada rivers. Extensive mudflats are developed in and around these estuaries. The alluvial plains and the alluvial cliffs along the river extend right upto the coast. The plains rise abruptly above the mudflats.

All the geomorphic features in the various river valleys of Gujarat alluvial plains form three distinct geomorphic surfaces -the alluvial plain (S_1), the ravinal surface(S_2) and the younger terrace (S_3).

The S_1 surface constitutes a major part of the study area. It is a flat , undulating at places, surface which typically corresponds to the morphology of alluvial plains. This surface is extensively used for agriculture. However, this surface has been considerably modified by the aeolian activity during the last glacial maximum. Clear evidences of this aridity are observed all over this surface in the form of aeolian deposits. The dunes which are now stabilised occur as isolated mounds, dune fields giving rise to hummocky topography. The entire S_1 surface as such is covered by a blanket of aeolian deposits. Stratigraphically, the S_1 surface is comparable to the S_2 surface.

The S_2 surface comprises the ravine affected older sequence and is the most extensively devoted geomorphic unit in the area. This surface is characterised by deeply cut ravines suggestive of a badland topography. In some cases the dissection in these ravines reaches upto 15 m. The surface is well developed all along the three major river valleys. This surface is confined by the S_1 surface on one side and the river channel on the other. Along the river channel it is marked by steep cliffs of 15 to 45m. The older surface rising upto 40m from the river level, is paired, highly eroded and extensively dissected surface. The sediments that make this surface date back to Middle Pleistocene. These sediments comprise semi-consolidated cross-stratified gravels, sands and silts, and multiple palaeosol horizons. A very prominent horizon of this older sequence is a reddish buried soil in the upper part of the sequence, which has been used for inter-basinal as well as intra-basinal correlations. Radiocarbon dates of pedogenic calcretes from this horizon indicate an age of 22600 yr B.P. This is overlain by aeolian sediments of last glacial age.

The youngest surface S_3 has developed within the river channel. This forms a series of discontinuous elevated surfaces which terminate abruptly against the older (Pleistocene) ravine affected sequence. Morphologically, this surface corresponds to the morphology of a fluvial terrace and is preserved on the convex side of the present day meander bends. Interestingly these terraces are found in the river channel right upto the foothills. These terraces have great significance with respect to their genesis and evolution of the plains during Late Holocene.

The pre-Holocene morphology of the alluvial plains is rather difficult to visualize because the Terminal Pleistocene-Holocene changes have considerably modified the previous geomorphology leading to the formation of three distinct geomorphic surfaces all over the plains. Complex interplay of tectonism and sea level changes during Holocene are responsible for the morphostratigraphic evolution of the Gujarat alluvial plains (Table 9.1).

The deposition of Quaternary sediments commenced with the formation of the Quaternary basin due to activation of basement faults. These faults were essentially the Cambay basin faults which were formed during the rifting of the western continental margin. The Cambay basin was the site of marine sedimentation during Tertiary which was accompanied by subsidence. The formation of the Quaternary

Table : 9.1 : Morphostratigraphy of Gujarat Alluvial Plain.

Geomorphic Surface	Lithology	Event	Tectonics/sea-level	Age
S_3 Surface	Tidal-estuarine muds and sands in the downstream and fluvial silts and sands in the upstream Complete absence of pedogenesis and calcretisation	Incision of the terrace and formation of present day meanders.	Uplift of the area	Late Holocene to Recent
		Deposition of tidal estuarine sediments near the mouth and fluvial sediments in the upstream.	High sea level	Middle to Late Holocene
S_1 and S2 Surface	Fluvio-marine, fluvial and aeolian clays, sands and silts with cross stratified gravels and multiple layer of palaeosols in the upper part. Pedogenised layers charecterised by extensive development of calcretes.	Erosion of the pleistocene sequence giving rise to incised cliffy banks, entrenched meanders and ravine erosion.	Uplift of the area	Early Holocene
		Deposition of sediments above gravel-II ending with aeolian sediments. Intermittent phases of pedogenesis and formation of a wide pediment zone.	Tectonically stable conditions.	~100 Ka to Terminal Pleistocene
		Deposition of sediments from Gravel-I and Gravel-II.	Syn-sedimentary subsidence along the step faults parallel to basin bounding faults.	~200 Ka to ~100 Ka
		Deposition of bluish mottled clays followed by pedogenesis.	High sea level.	~240 Ka

basin is attributed to the continued subsidence of the Cambay and Narmada rift grabens. However, the marine sedimentation changed over to dominantly fluvial at the onset of Quaternary.

The Quaternary basin was thus an elongate structural graben formed due to continued Tertiary subsidence of the two rift grabens. The syn-sedimentary subsidence of the basin is testified by the huge thickness of the Lower Pleistocene sediments which are unexposed. The varying thickness of the sediments indicate that the subsidence of the basin was unequal. The southern part of the basin to the south of Mahi river subsided at a much faster rate than the northern part. The thickness of the Quaternary sediments is ~300 m in the northern part whereas it is greater than 800 m in the southern part. The subsidence of the basin ensured that the Lower Pleistocene sedimentation was confined within the basin. The Lower Pleistocene subsidence constitutes the first tectonic event (T_1) during Quaternary (Table 9.2). In the absence of lithologic data on the Lower Pleistocene sediments, it is not possible to analyse the influence of this phase of subsidence on the sedimentation pattern.

However, the subsurface studies in the southern Cambay basin led to the identification of Quaternary folds and faults. This is attributed to a Quaternary tectonic event. The present study indicates that this deformational event took place in the Lower Pleistocene. The fold features indicate the existence of compressive stresses in this part of the basin. The E-W Narmada fault was transformed into a reverse fault in Lower Pleistocene due to these compressive stresses.

Table 9.2 : Quaternary tectonic events and resulting geological changes in the evolution of Gujarat alluvial plains.

Tectonic event	Uplift/ Subsidence	Effects	Evidences
T_4 (Late Holocene to Recent)	Uplift	Incision of the Holocene terrace, formation of present day meanders.	Uplifted Holocene terraces, seismically induced soft-sediment deformation structures, present day seismicity.
T_3 (Early Holocene)	Uplift	Incision of Pleistocene succession, formation of entrenched meanders, severe ravine erosion.	30-50 m high vertical cliffs of Pleistocene sediments, extensive ravine erosion in pleistocene sediments, formation of new drainage and development of badland topography.
T_2 (~200 Ka - ~100 Ka)	Subsidence	Syn-sedimentary subsidence of the basin along the step faults parallel to the basin bounding faults leading to variation in the thickness across the faults.	Soft sediment deformation structure between Gravel-I and Gravel-II.
T_1 (Early Pleistocene to ~240 Ka)	Subsidence	Unequal subsidence of the Quaternary basin along basinal faults as a result of continuation of the subsidence of Cambay basin. Subsidence more in the southern part than in the northern part. Presence of compressive stresses in southern part leading to formation of folds and reverse faulting along the Narmada faults.	Huge and varying thickness of Quaternary sediments, subsurface faults and folds.

The exposed sediment column is remarkably correlatable all over the Gujarat alluvial plains. The sediments dating back to Middle Pleistocene (~240 Ka) are ideally exposed in the precipitous cliffs of the three major river valleys- the Narmada, the Mahi and the Sabarmati. The presence of the rubified soil horizon is conspicous in all the basins. Multiple layers of palaeosols and the wide shallow pediment suggest that the by and large tectonically stable conditions prevailed during the deposition of these sediments. However, the occurrence of soft-sediment deformation structures below gravel-II point to a tectonic event (T_2) of slow synsedimentary subsidence of the basin (Table 9.2). This subsidence phase perhaps represent the last dying phases of the major subsidence phase during Lower Pleistocene.

The absence of soft-sediment deformation structures in the Sabarmati valley is interesting. However, this conforms well with the subsurface thickness data which indicates that the southern part of the basin subsided more than the northern part indicating that the subsiding movement ceased a little earlier in the northern part. Occurrence of two to three regionally correlatable gravel beds in a sediment column dominated by fine grained sediments and several buried soils, indicate rejuvenation of the source area. The exposed sediments are universally capped by aeolian sediments deposited during the last glacial maximum which comprise two distinct units- the lower loessic silts and the upper stabilised dune sands.

A regionally extensive Holocene aggradation phase has been identified for the first time in the Gujarat alluvial plains during this study. This aggradation phase is represented by a series of low elevated valley-fill terraces in the various river valleys.

Even the small insigfnicant streams have preserved the evidences of this aggradation phase suggesting the regional nature of this phase. These terraces are preserved on convex banks of the present day meanders of the various rivers indicating their deposition as channel bars. The height of the terrace varies from 1 to 6m from the river level. The surface shows no sign of ravine erosion and is used for agriculture. These surfaces are encountered all along the river valleys right upto the mouth of the rivers.

The low incised cliffs ranging in height from 1- 6m show the sediment nature that makes these terraces. The entire thickness of the valley fills complex can be grouped in two lithofacies-tidal estuarine mud facies and medium to coarse sand, and fine to medium fluvial sand facies. The sedimentary facies of these terrace sediments is essentially similar in all the major river basins. The tidal estuarine facies comprise cross-stratified to rippled sand with abundant mud laminae, mud flasers and layers of estuarine mud. The present day estuaries show a similar sedimentary facies and this facies thus can safely be interpreted as having been deposited in a tidal estuarine environment. The tidal estuarine facies is confined to the lower reaches and broadly matches with the present day tidal limits within the river channels.

The fine to medium fluvial sand facies is found in the terraces in the middle and upper reaches of the rivers. This facies comprises fine fluvial silty sands which are well sorted and exhibit parallel horizontal bedding with occasional cross bedding. The facies distribution thus suggest that during middle Holocene aggradation phase, marine deposition took place in the estuarine zones and fluvial deposition in the upstream parts.

The discovery of valley-fill terraces has an important bearing on the landscape evolution of the Gujarat alluvial plains during Terminal Pleistocene-Holocene. The fact that these deposits occupy the incised valley consisting of Pleistocene deposits suggests that these terraces have been deposited during the Middle Holocene high sea level. The ravine erosion and the river incision therefore pre-dates the deposition of these terraces and could be regarded as of early Holocene age. The rise of sea level during the Middle Holocene led to the choking of the river channel resulting in the initiation of a new cycle of sedimentation within the active channel. The sediments were deposited as bars attached to the channel. The deposition never extended beyond the channel as the channel itself was confined by the steep incised cliffs.

The alluvial cliffs extend right upto the coast indicating that the extension of the Pleistocene fluvial deposits is well beyond the present day coastline. The ravine erosion has effected even the youngest horizons of the older sequences, suggesting that the ravine erosion post-dates aeolian sedimentation. The ravine erosion was accompanied by fluvial incision within the main channel. The heights of the cliffs of the older sequences are directly proportional to the incision that occurred during the early Holocene. This incision is of the order of at least 35-40 m corresponding to the average height of the cliffs. The incision seem to have taken place in a relatively short period of time and is not related to the fall in sea level. During this period, on the west coast, the sea rose very rapidly from 14,500 yr B.P. to 7,000 yr B.P. intervened by a still stand from 12,500 to 10,000 yr B.P. This suggests that Gujarat alluvial plains experienced tectonic uplift during early Holocene. The uplift of the area during Early Holocene (T_3) resulted in the formation of extensive ravines and steep cliffs along the river valley (Table 9.2). The uplift took place along the pre-existing Cambay basin faults.

The phase of ravine erosion and river incision ceased as sea level reached the post-glacial maximum during the Middle Holocene leading to the formation of a depositional wedge which extended upstream. The rise of sea level led to aggradation within the channel with deposits ranging from non-marine(fluvial), through estuarine (tidal) to open marine. The sediment fill of the Holocene terraces therefore seems to be quite complex. The rise of base level combined with landward migrating tide-limit and its associated grain size barrier effect impedes transport of fluvial material downstream from the landward migrating bayline . This resulted in the accumulation of transgressive tidal-estuarine sand and mud deposits onlapping the fluvial channel. However, the depositional wedge mentioned above extended well beyond the bayline as evidenced by the fluvial terraces in the upstream parts as well. This means that the rise in sea level led to the deposition of tidal sediments within the bayline and beyond it fluvial sedimentation was initiated.

It should be mentioned here that the transgression was within the river channel only (except the lower part of Sabarmati) and even the highest tides could not reach the top of ravinal surface. This is indicated by the younger surface made up of tidal-estuarine deposits that are incised and abut against the older sequence. Consequently the sediments supplied to the valley from the upstream during the Holocene were deposited as aggrading transgressive-tidal facies that overlapped the lowstand channels as the various river valleys were transformed from a fluvial incised valley into an estuary. The Holocene sea trangressed over a wide depressed in the lower reaches of the Sabarmati.

The younger terrace shows a maximum incision of 6m. Since the sea level is presumed to have remained at the same level with minor fluctuations, the incision of the lower terrace can be attributed to another phase of tectonic uplift (T_4) that perhaps continues even today (Table 9.2). Radiocarbon dates of these terraces indicate an age of 3660$\pm$90, 3320$\pm$90, 2850$\pm$90 and 1760$\pm$80 yr B.P. Tectonic instability during this period is well evidenced by the seismically induced soft deformation structures in the Holocene terraces at Kothiyakhad in the Mahi valley and in Orsang valley. These structures were formed during a seismic event which took place between 3320$\pm$90 and 2850$\pm$90 yr B. P. Continued tectonic instability of the area is evidenced by the earthquakes recorded during the last few hundred years attributed to the continued instability of the Cambay basin.

The foregoing discussion indicates that the Quaternary tectonic activity in Gujarat alluvial plains can be categorised into four tectonic episodes. The first tectonic episode (T1) took place in Lower Pleistocene, T2 from ~200 ka to ~120 ka, T3 in Early Holocene and T4 from Late Holocene to Recent. The first two witnessed subsidence of the basin while the last two during the Holocene were of tectonic uplift.

The present study indicates that the Holocene tectonism is responsible for the evolution of the landscape of Gujarat alluvial plains whereas Pleistocene tectonism is responsible for the accumulation of a huge thickness of the Quaternary sediments. The present study when viewed in conjunction with the existing lithostratigraphic and sedimentologic data provides a complete evolutionary history of the Gujarat alluvial plains during Quaternary.

The Quaternary tectonic history of the Gujarat alluvial plains worked out during this study compares well with the neotectonic studies carried out in adjacent areas. The Holocene phases of tectonism are correlatable to the neotectonic activity reported from the western continental shelf. Recent studies on Saurashtra coast have shown that evidences of sea level are masked by the Holocene uplift of the landmass.