CHAPTER - VII

SEDIMENTATION AND TECTONICS

The Gujarat alluvial plains extend from north Gujarat to the Narmada river in the south indicating confinement of Quaternary sedimentation in a N-S oriented linear basin. The presence of a wide pediment zone to the east suggest that maximum sedimentation took place in a narrow depression. The basinal zone of the alluvial plains correspond to the bounding faults of the Cambay basin suggesting that the site for Quaternary sedimentation was provided by the Tertiary Cambay graben. Within the Cambay basin, the Quaternary sediments overlie the Tertiary rocks.

The subsurface data indicates a highly variable Quaternary sediment cover within the basinal zone. The N-S cross-section across the alluvial plains shows an uneven Quaternary basement (Fig. 7.1) indicating deposition in several fault bound sub-basins. The Quaternary sediment thickness varies from 300 to 800 m. However, only the top 50 m form the exposed part while the rest is in the subsurface for which no data is available. Archaeologic, geologic and geochronological studies on the exposed sediments have established that these sediments date back to Middle Pleistocene. The huge thickness of the Lower Pleistocene sediments in the subsurface suggests synsedimentary subsidence of the basin during their deposition. More details on the Lower Pleistocene tectonics is given in the next chapter. In the present chapter, the exposed sediments are described and role of tectonism in their deposition is highlighted based on the structures observed in the sediments and geomorphic set up of the area.

The Quaternary sediments in the alluvial plains are exposed along the cliffy banks of the various rivers. Excellent exposures of these sediments varying from 30-50 m are found along the three major rivers viz. the Narmada, the Sabarmati and the Mahi. The various other smaller rivers expose the top part of the sediment succession depending upon the depth of incision. Considering the total thickness of the Quaternary sediments comprising the plains, the exposed sediment column constitutes less than one tenth of it. The exposed sediments have been classed as, the Pleistocene sequence and the Holocene sequence for descriptive purposes. The Pleistocene sequence have been studied by earlier workers for their lithostratigraphic

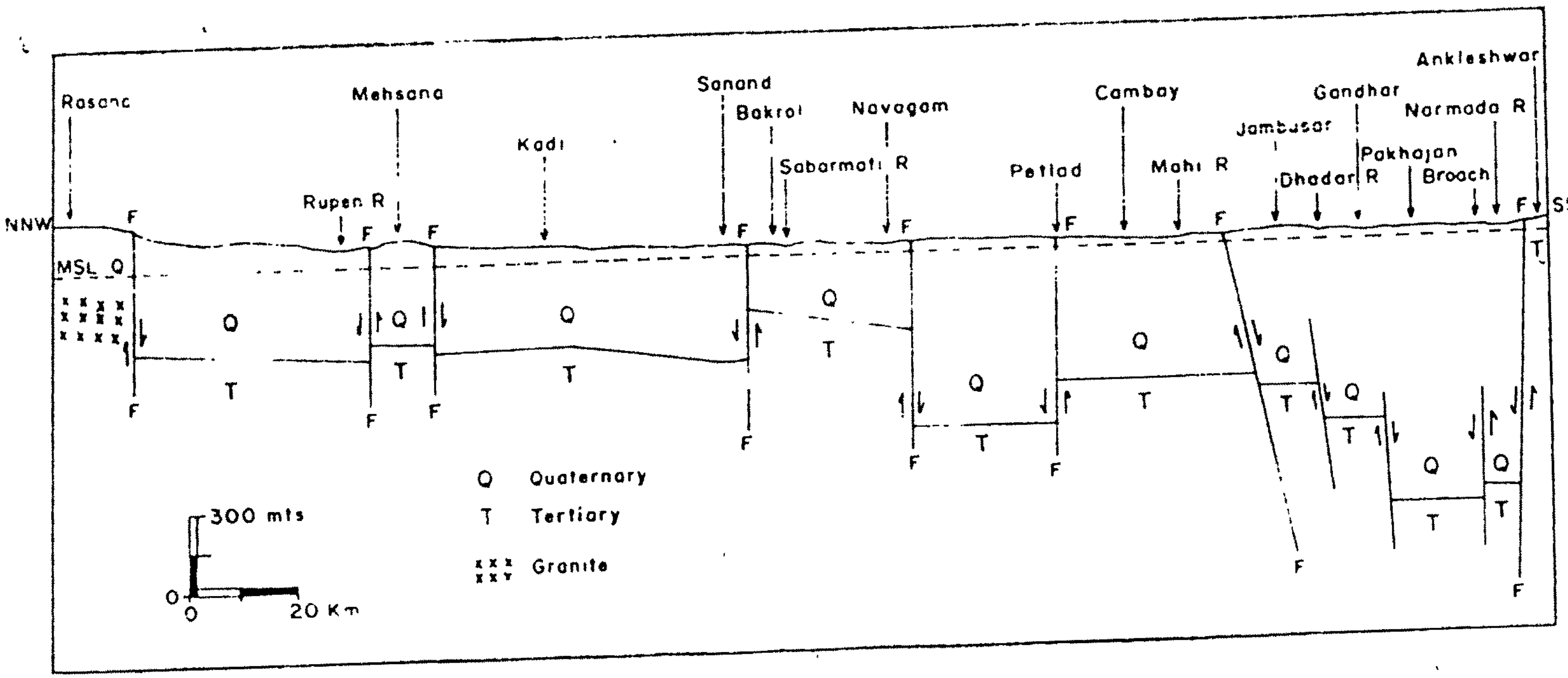

Fig. 7.1 N-S cross-section across Gujarat alluvial plains showing uneven Quaternary basement (based on thickness data from ONGC)

and palaeoclimatic significance as summarized in Chapter-II. The Holocene sediments have been investigated for the first time during this study.

THE PLEISTOCENE SEQUENCE

A very significant aspect of the sediments exposed in the various river valleys is the correlatability of these sediments (Chamyal and Merh, 1992). Further stratigraphic studies by Merh and Chamyal (1993), Chamyal (1995) and Chamyal and Merh (1997) established the contemporaneity of the sediments exposed in the various river valleys. They have subdivided the exposed sediments in Sabarmati, Mahi and Narmada river valleys into several formations (Fig. 7.2, 7.3, 7.4). The various stratigraphic studies have been based on the conspicuous rubified soil horizon. Pant and Chamyal (1990) were the first workers to make use of red soil in stratigraphic studies as marker horizon. The remarkable correlatability of the exposed sediments have far reaching implications in understanding the post-Middle Pleistocene evolutionary history of the Gujarat alluvial plains. The correlatability of the exposed sediments throughout the Gujarat alluvial plains suggests that::

1. All the three major river valleys have an identical evolutionary history since Middle Pleistocene.
2. Identical climatic and depositional conditions prevailed over the entire area since Middle Pleistocene.

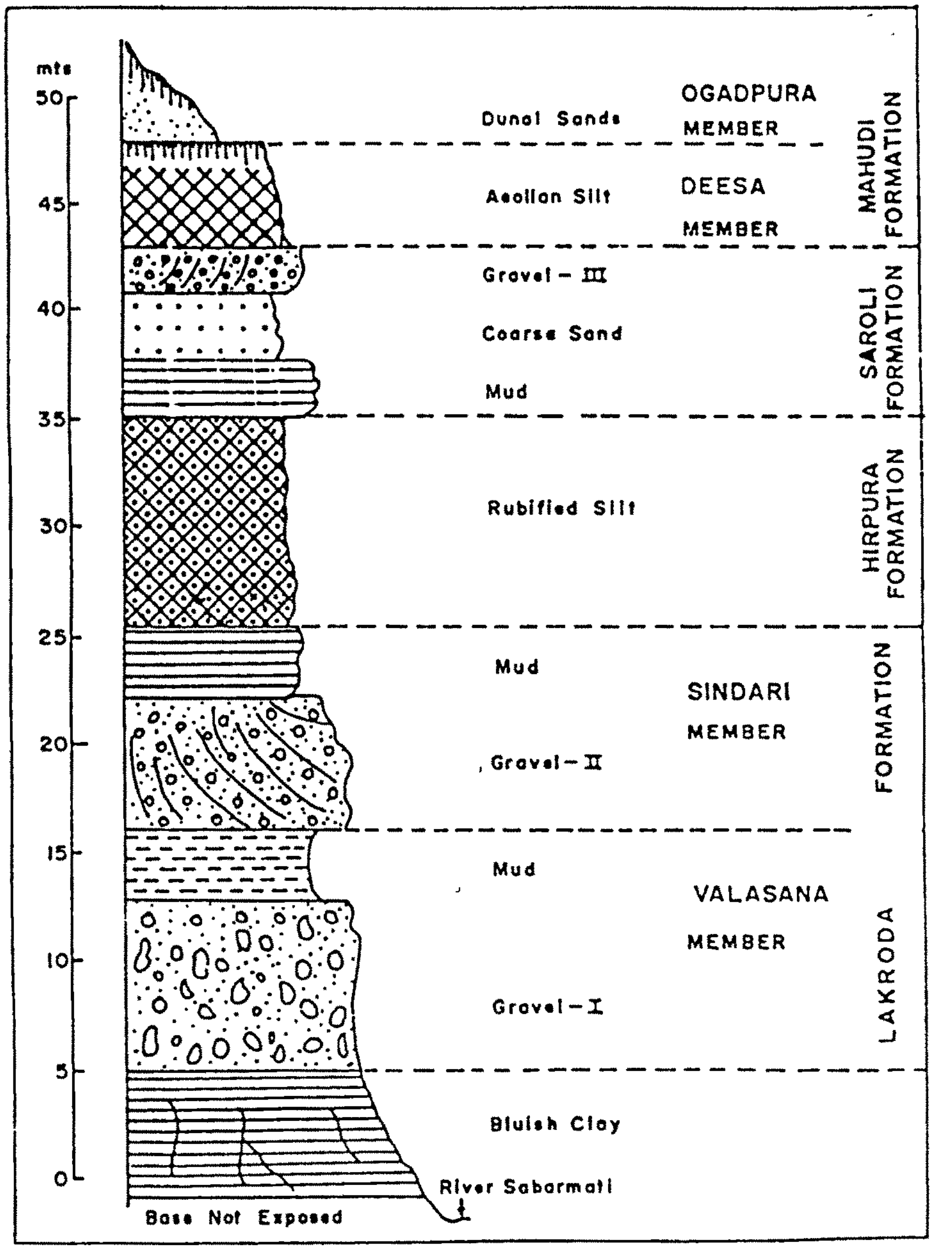

Fig. 7.2 Composite lithostratigraphy of exposed Quaternary sediments in Sabarmati and other rivers in north Gujarat (after Merh and Chamyal, 1997).

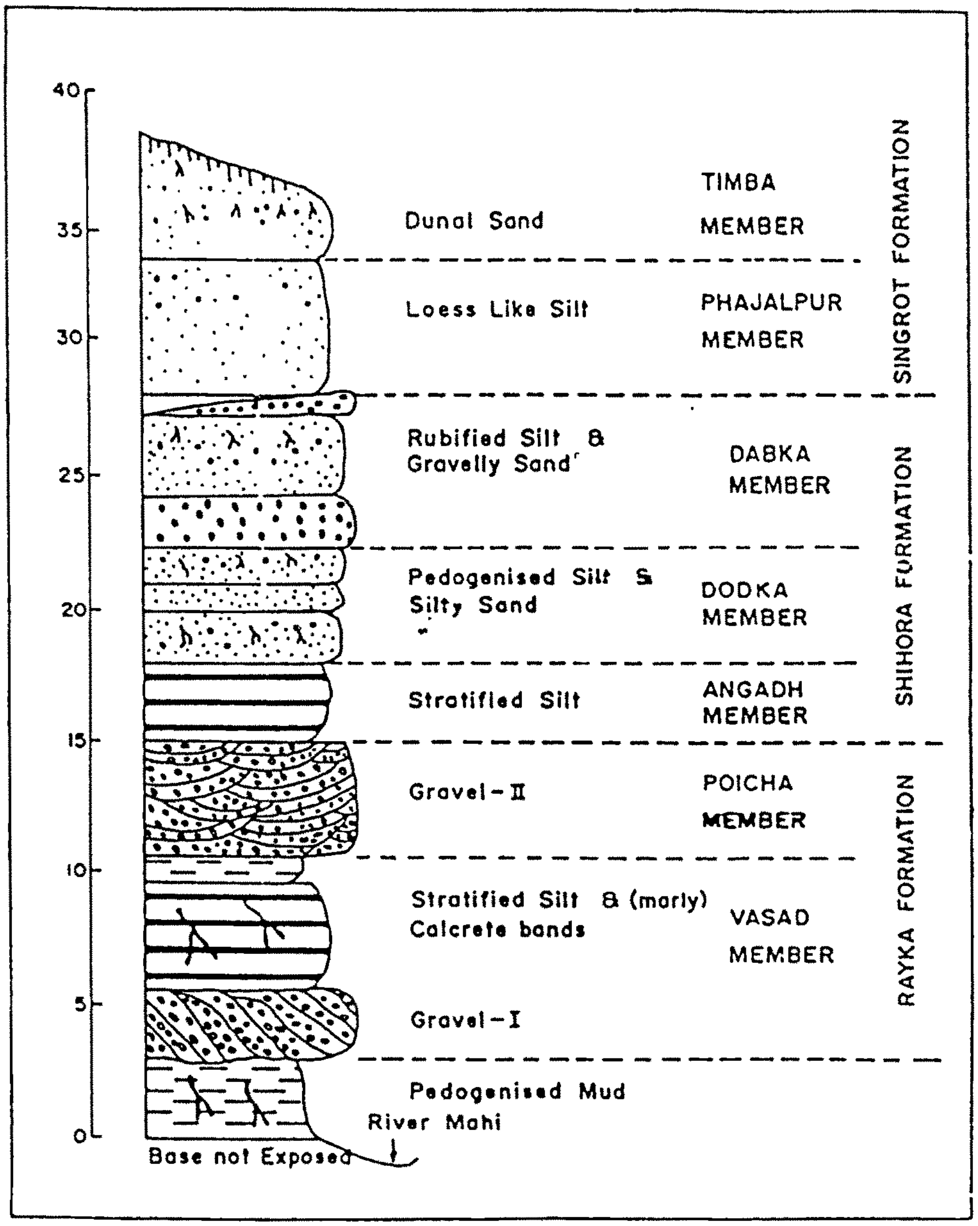

Fig. 7.3 Composite lithostratigraphy of exposed Quaternary sediments in Mahi river basin (after Merh and Chamyal, 1997).

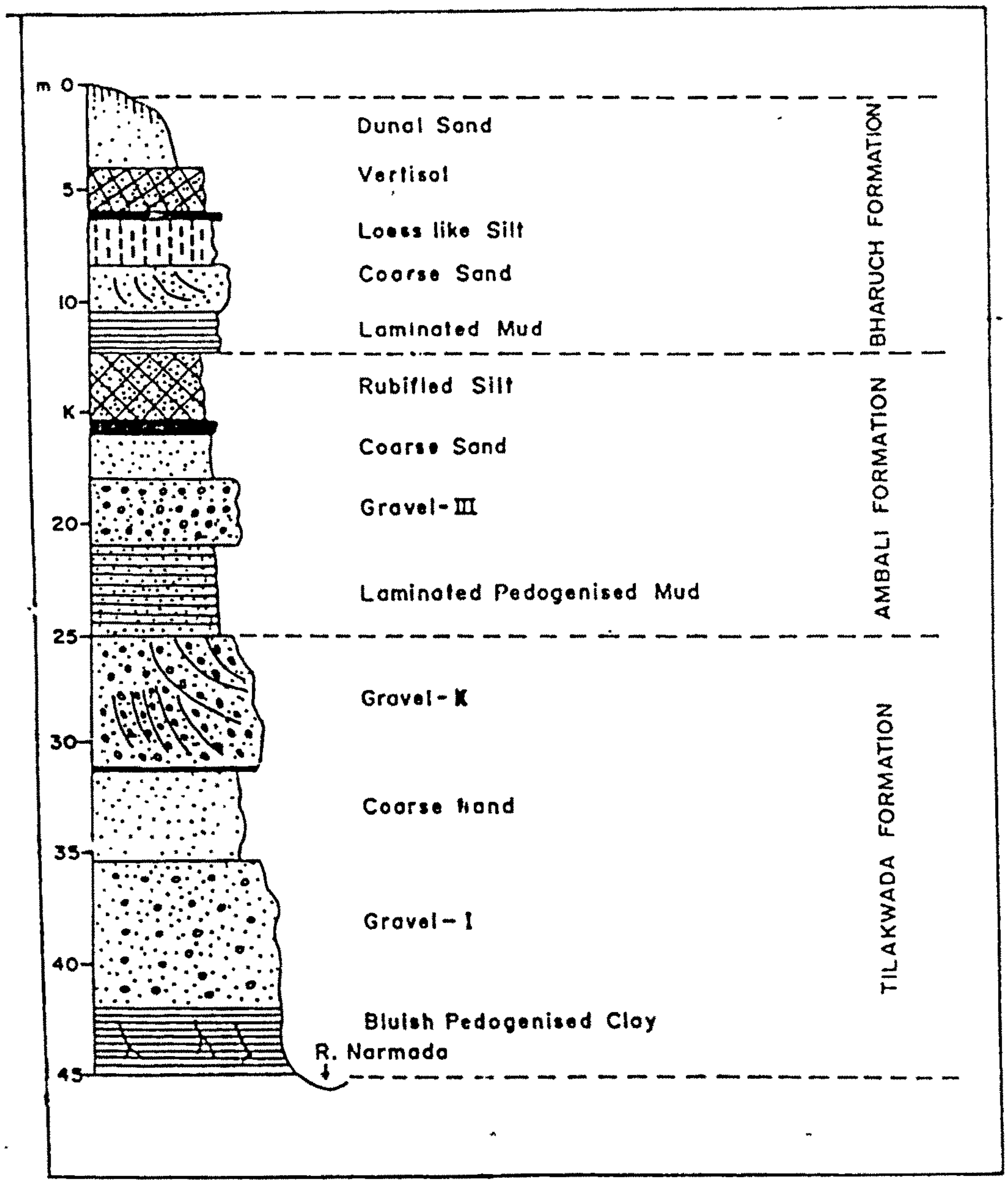

Fig. 7.4 Composite lithostratigraphy of exposed Quaternary sediments in Narmada valley (after Merh and Chamyal, 1997).

3. The entire basin remained as a single tectonic unit since Middle Pleistocene unlike Lower Pleistocene when the basin was divisible into several distinct fault bound sub basins.

The exposed sediments (Plate 7.1, 7.2, 7.3) reveal an interesting sedimentologic and paleoclimatic record during Late Quaternary. The largely non-marine sedimentary record suggest the prevalence of dominantly climatic controlled depositional conditions, with several intervening periods of non-deposition and pedogenesis. The exposed sediments comprise diverse lithofacies ranging from channel bar sediments to over bank deposits. Merh and Chamyal (1997) have given a detailed account of the various lithofacies exposed in the three major river basins of Gujarat plain. The different facies present in these river is given in Table 7.1. These lithofacies show considerable diversity from basin to basin revealing the individuality of each river in the matter of deposition (Merh and Chamyal, 1997). A broad similarity and correlatability of the exposed strata, major aggradation phases, sequence of climatic variations and changes in depositional environments is clearly discernible. The oldest exposed Quaternary deposit in the Gujarat plain is a highly pedogenised bluish mottled clay. The pedogenisation is indicated by the abundant presence of calcium carbonate nodules, rhizoliths, and well developed cracks. They show excellent preservation of hydroplastic slickensides on the cracked surfaces which have been formed due to alternate expansion and contraction during wet and dry phases. These clays have now been assigned the status of a separate formation

Plate 7.1 Photograph showing the nature of Pleistocene sediments exposed in Sabarmati valley (Loc. Oran).

Plate 7.2 Photograph showing the nature of Pleistocene sediments exposed in Mahi valley (Loc. Dabka).

Plate 7.3 Photograph showing the nature of Pleistocene sediments exposed in Narmada valley (Loc. Tilakwada).

Plate 7.4 Photograph showing gravelly deposits of lower Narmada alluvial fan (Loc. Tilakwada).

FACIES CODES	DESCRIPTION	NARMADA RIVER	MAHI RIVER	SABARMATI RIVER	INTERPRETATION
Gms	Massive inversely graded cobbly to bouldery gravels	Present	--	Present	Debris - flow deposits
Gm	Matrix supported crudely stratified gravels		Present	Present	Channel bar deposits, as longitudinal bar deposits
Gt	Trough cross-stratified gravels	–	Present	Present	Minor channel fills by low sinuosity channel
Gsh	Gravel-sand couplets, crudely stratified	Present	–	--	Sheet flow deposits
Gp_1	Planar cross-stratified gravel	Present	Present	–	Longitudinal gravel
Gp_2	Planar cross-stratified gravel with lensoidal geometries	Present	–	–	Rechannelized flows genetically related to debris- flow events
Gp	Planar to epsilon cross-stratified gravel	--	–	Present	Lateral accretion on the point bar
Gs	Sandy-gravel sheet lobes	–	Present	Present	Deposited at the channel margins
St	Trough cross-stratified gravel	Present	Present	–	Channel-fill elements of braided rivers
Shi	Horizontal to inclined stratified sand and silt assemblage	Present	Present	Present	Overbank deposits (under upper flow regimes)
Sm	Massive Sand sheets	Present	Present	Present	Sheet - flow deposits (buried by subsequent deposition after pedogenesis)
Fl	Fine sand and silt (interbeds)	–	Present	Present	Overbank waning flood deposits
Pc	Palaeosols, rhizoconcretions and calcrete nodules	–	Present	Present	Buried soils and precipitation of CaCo, solution along the cracks, channels

Table 7.1 Sedimentary facies exposed in the major rivers (after Merh and Chamyal, 1997).

named as the Mahi formation (Rachna and Chamyal, 1997). The formation is highly fractured (Khadkikar et al., 1996) and has preserved various field evidences that point to pedogenesis. Of prime importance are the vertical tubules filled with calcium carbonate and truncated at the top by gravels of Rayka formation. Calcium carbonate-impregnated vertical fissures accompanied by extensive development of drab haloes are also present (Retallack, 1990). The haloes form a downwardly bifurcating structure that indicates pedogenesis. The formation is studded with criss-crossing vertical burrows which are similar to those observed in present day tidal flat deposits (Reineck and Singh, 1980). The subsurface of data CGWB also shows the presence of bluish clay which continues to about 25 m below mean sea level north of Mahi river (Murthy, 1975). Merh (1992) categorically stated that the bluish clay deposits in Mainland Gujarat are the result of Middle Pleistocene transgression and are correlatable with the miliolites of Saurashtra.

The recent work of Rachna and Chamyal (1997) have provided the first unequivocal evidence for the marine origin of this deposit. They have reported several foraminiferids from the Mahi Formation exposed at Rayka in the Lower Mahi valley. At Rayka, it is made up of greenish-brown clays that ranges in thickness from 0.5-3 m. The base of these clays is not exposed and it occurs at an altitude of 20 m amsl. According to Murthy (1975) it continue, to a depth of 25m below the mean sea-level. The entire formation has yielded a fairly good assemblage of benthic foraminiferids (Rachna and Chamyal, 1997) comprising Pararotalia sp., Brizalina spp., *Nonion* spp., Cibicides spp., Florilus spp., Ammonia spp., three planktonic foraminiferids found are Turborotalia sp., Globogerina bulloides (Parker, Jones and Brady) and Globogerinoides ruber (d'Orbigny). However similar micropalaeontological studies on these deposits in other river valleys are essential before making generalizations on the level and extent of Middle Pleistocene transgression in Mainland Gujarat.

The overlying gravel-I deposit has an erosional contact with the clays. The gravel shows planar cross bedding and comprises clasts of calcrete and basalts. This gravel is overlain by finer fluvial sands and silts which are again overlain by another gravel horizon designated as gravel-II. The absence of a well developed soil profile between the two gravel horizons is very significant. This is very surprising in a sequence where the soil occurs as a rule rather than an exception. These horizons exhibits several soft-sediment deformation structures which indicate slow active tectonic movements during their deposition.

The overlying gravel-II shows large scale trough cross stratification and consists of clasts of calcrete and basalts. This gravel unit is overlain by finer fluvial sediments viz. sandy silts and silts. Several palaeosols occur over gravel-II. Khadkikar et al. (1996) have recorded three buried soils in the sediments overlying gravel-II at Rayka in the lower Mahi basin. This excludes the soil profiles developed in the aeolian sediments. Multiple palaesols are characteristic of long term tectonic stability. However, the presence of gravel horizons indicate rejuvenation of the source area.

A rubified soil marks the top of fluvial succession. This red soil horizon is remarkable for its consistent presence all over the Gujarat plain. It has been used as a marker horizon for interbasinal and intrabasinal correlations. However, it is yet to be correlated with a comparable soil horizon outside the Gujarat plain. The reddening appears to indicate a strong climatic control on the formation of this soil. Micromorphological studies have been carried out on the red soil of Sabarmati basin which have provided some insight into the textural characteristics and mineralogy (Sridhar and Chamyal, 1995; Sareen and Tandon, 1995). According to Sareen and Tandon (1995) the reddening is due to the pigmentation of grain margins. Reddening can take place in humid conditions (Krynine, 1949; Folk, 1976) as well as in oxidising conditions and also due to rapid decomposition of organic matter in semi-arid and arid environments (Walker, 1979). According to Pye (1983) presence of a source of iron and oxidising interstitial conditions can lead to reddening in both humid and arid regions. However, the presence of unaltered feldspars (Sridhar and Chamyal, 1995) rule out the presence of humid conditions. Further, the latitudinal position of the area and the abundant calcrete nodules suggest the prevalence of semiarid to arid conditions during the formation of red soil.

Pant and Chamyal (1990) have described it as an originally aeolian deposit subsequently reddened. However, the field evidences strongly suggest a fluvial mode of deposition for the red soil. Radiocarbon dates of the pedogenic carbonates from red soil at Dabka have yielded date of 23 ky (Hedge and Swtisur, 1973) for the soil formation. All over the Gujarat Plains the fluvial sequence is overlain by aeolian sediments. A loess like fine silt forms the lower part and dunal sands form the upper part of the aeolian sequence. Both are separated by a well developed brown soil. The dunal sands are stabilized as is evidenced by the soil formation over them. These aeolian deposits were deposited during the Terminal Pleistocene aridity which has been recorded all over the globe. The stabilised dunal sands provide a characteristic hummocky topography to the Gujarat plains.

Chamyal et al. (1997) have documented a Late Pleistocene alluvial fan in the Lower Narmada valley (Fig. 7.5). The rounded clasts is a major characteristic of this fan. Chamyal et al. (1997) have cited the elongated catchment area as the reason for rounded clast. The deposition of the fan sediments took place in a tectonic graben bounded by faults related to the Narmada fault system. Downstream of the fan sequence, the sediment succession is correlatable to the succession exposed in other river valleys of alluvial plains. The erosion of the fan leading to development of vertical cliffs of over 35 m exposing the fan sediments (Plate 7.4) is attributed to tectonism. The present study has revealed that the phase of erosion of the alluvial fan is related to the regional erosional phase discussed in the subsequent pages, which gave rise to the ravines and steep cliffy banks along the rivers of the alluvial plains.

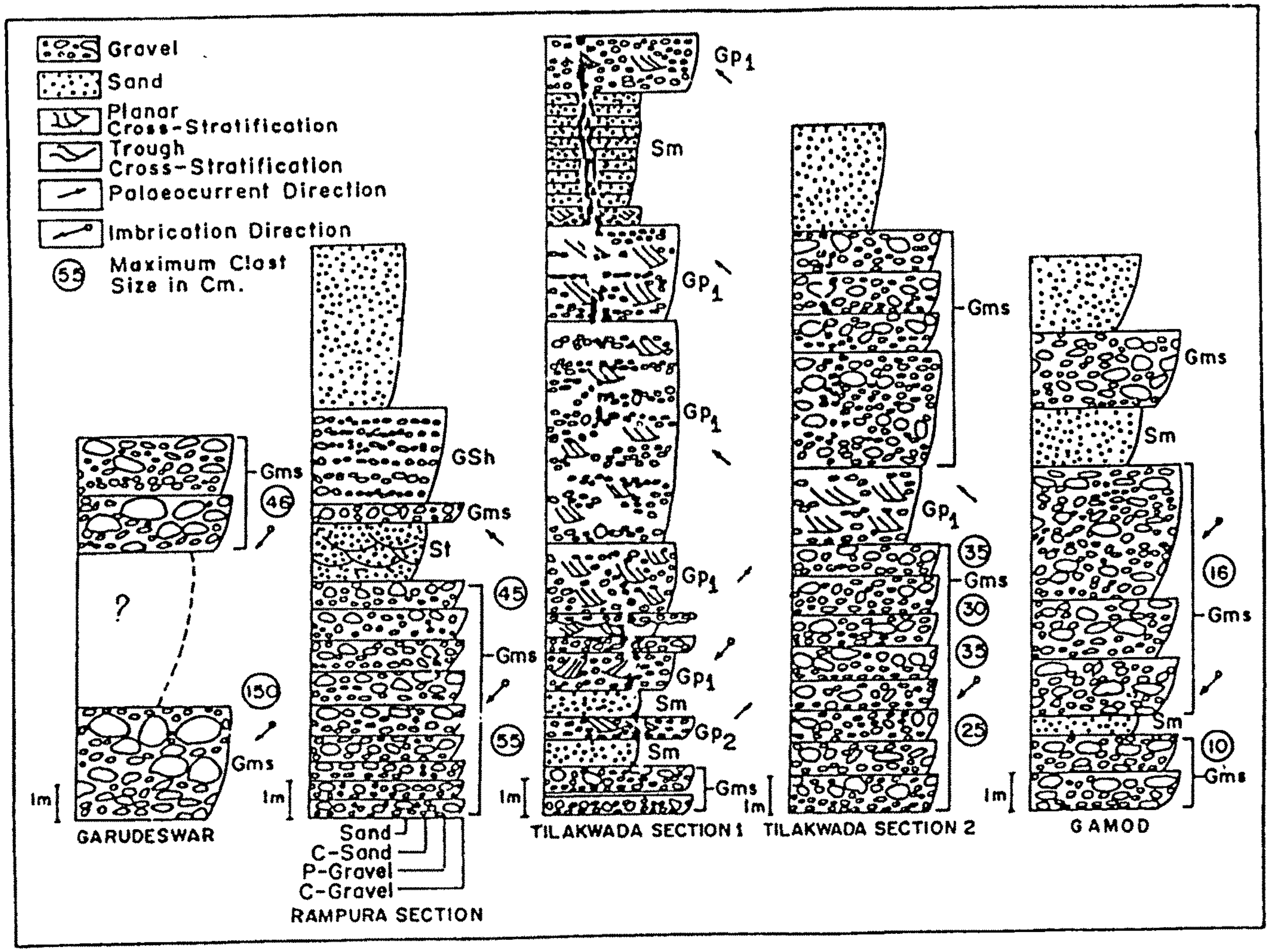

Fig. 7.5 Lithologs of exposed sediment successions of Lower Narmada alluvial fan (after Chamyal et al., 1997).

Lack of geochronological controls has been a major handicap in understanding the Quaternary geology of Gujarat plains. For a long time archaeologic studies formed the only basis for estimating the ages of the exposed sediments. The studies carried out by Zeuner (1950), Sankalia (1946) proved very useful in this regard. Based on archaeologic studies Pant and Chamyal, 1990; Chamyal and Merh, 1992, 1995; and Merh and Chamyal, 1993 proposed that the exposed sediments dated back to Middle Pleistocene. Tandon et al. (1996) provided TL dates for some of the horizons from the section exposed at Hirpura in Sabarmati valley (Table 2.2). However these dates do not help in clarifying certain ambiguities with regard to the lithostratigraphic studies. These ambiguities in the understanding of Late Quaternary history of Mainland Gujarat will remain until some type sections in all the major river valleys are satisfactorily dated. The global significance of the palaeoclimatic and palaeoenvironmental changes as revealed by the exposed sediments will be realised only when some important horizons are correlated globally and regionally atleast with the palaeoclimatic record from Saurashtra and Thar desert.

THE HOLOCENE SEQUENCE

The Holocene sediments are exposed in low incised cliffs of a low flat topped surface that typically corresponds to the morphology of a terrace. It occurs as a series of unpaired elevated surfaces along the river channel that terminate abruptly against the ravinal surface. 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 3 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 channels right upto the mouth of the river (Fig. 6.1). The Lower Mahi valley exposes some of the best sections of the terrace sediments. The Narmada and Sabarmati also preserve few incised sections of these terraces. However the base of the Holocene sequence is nowhere exposed.

At Kothiyakhad in the lower Mahi valley, a 3.6 m thick section shows a 0.3m thick horizontally laminated very fine silty- sand at the base, overlain by 0.5 m thick mud horizon (Fig. 7.6). The contact between the two is erosive and is marked by mud flasers. Overlying is a 0.95m thick horizontally laminated silty-sand horizon that shows well-developed herringbone structures with an average mean current direction 320^0 NW and 135^0 SE. This is overlain by 0.85m thick mud and in turn by 0.7m thick laminated silty-sand. The top of the succession is capped by 0.7 m thick mud. The section at Mujpur is exposed as a 6m high cliff. The exposed sediment succession shows intercalations of silty-sand and mud and is quite comparable to the one exposed at KothiyaKhad. However, the obvious dominance of mud-bearing horizons in the Kothiyakhad sequence as compared to the Mujpur succession could be attributed to the proximity to the estuary mouth.

The muddy units have yielded good populations of foraminiferids as compared to various silty-sand units and cross-bedded sandy units which are either barren or have yielded fresh water ostracod, sponge spicules (?) and pelecypod shells

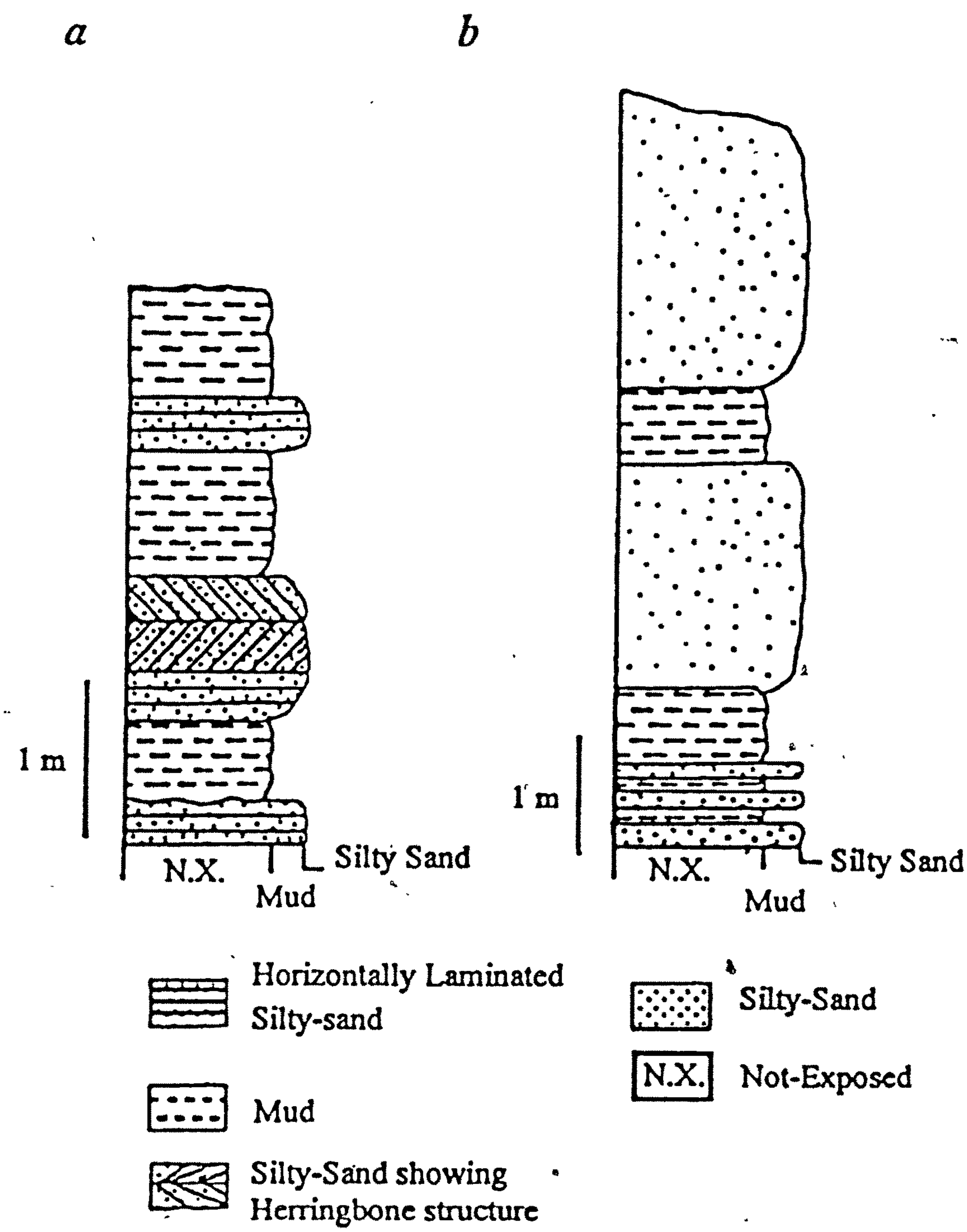

Fig. 7.6 Lithologs of marine Holocene valley fill terraces from lower Mahi valley (a- Kothiyakhad; b- Mujpur).

(Rachna and Chamyal, in press). A total of 25 genera of foraminiferids were identified from the mud units. Benthic forms identified are Brizalina sp., Bulimina sp., Bolivina sp., Biloculina sp., Lagena sp., Triloculina sp., Pseudobulimina sp., Hopkinsina sp., Sagrina sp., Ammonia sp., Cibicides sp. Discorbis sp., Discorbinella sp., Florilus sp. , Hastegerina sp., Melonis sp., Nonion sp., Nonionella sp., Pyrgo sp., Pararotalia sp., Parafissurina sp., Rosalina sp., and few other Rotaliid. Few planktonic forms identified are Globogerinoides sacculifera (Brady), Globogerina bulloides (Parker, Jones and Brady), Globogerinoides ruber (d'Orbigny). The incised sections of the Holocene terraces in the lower part of the Narmada and Sabarmati valleys is predominantly mud suggesting their deposition in an estuarine environment as tidal flat deposits.

The entire thickness of the valley fill complex can be grouped in two lithofacies- tidal estuarine muds and medium to coarse sand, and fine to medium fluvial sands (Plate 7.5, 7.6, 7.7). The tidal estuarine facies comprise cross-stratified to rippled sand with abundant mud laminae, mud flasers and layers of estuarine mud. The present day estuary shows a similar sedimentary facies and this facies thus can safely be interpreted as having been deposited in a tidal estuarine environment. The fine to medium fluvial sands are well sorted and exhibit parallel horizontal bedding and wave ripples, indicating a subdued tidal influence as compared to the underlying tidal estuarine sands and muds. Radiocarbon dating of four organic rich clay horizons (Fig. 7.7) have provided dates of 3660±90, 3320±90, 2850±90 and 1760±80 yrs B.P. (Kusumgar et al., 1997). However, since the base of this sequence is not exposed, it

Plate 7.5 Photograph showing the nature of sediments in a fluvial Holocene terrace in Sabarmati (Loc. Sanpad).

Plate 7.6 Photograph showing the nature of sediments in a marine Holocene terrace in Mahi valley (Loc. Sultanpura).

Plate 7.7 Photograph showing the nature of sediments in a fluvial Holocene terrace in Orsang valley (Loc. Anklawadi).

Plate 7.8 Photograph showing intraformational folds in calcretised silty sands below gravel-II in Mahi valley (Loc. Khorwad).

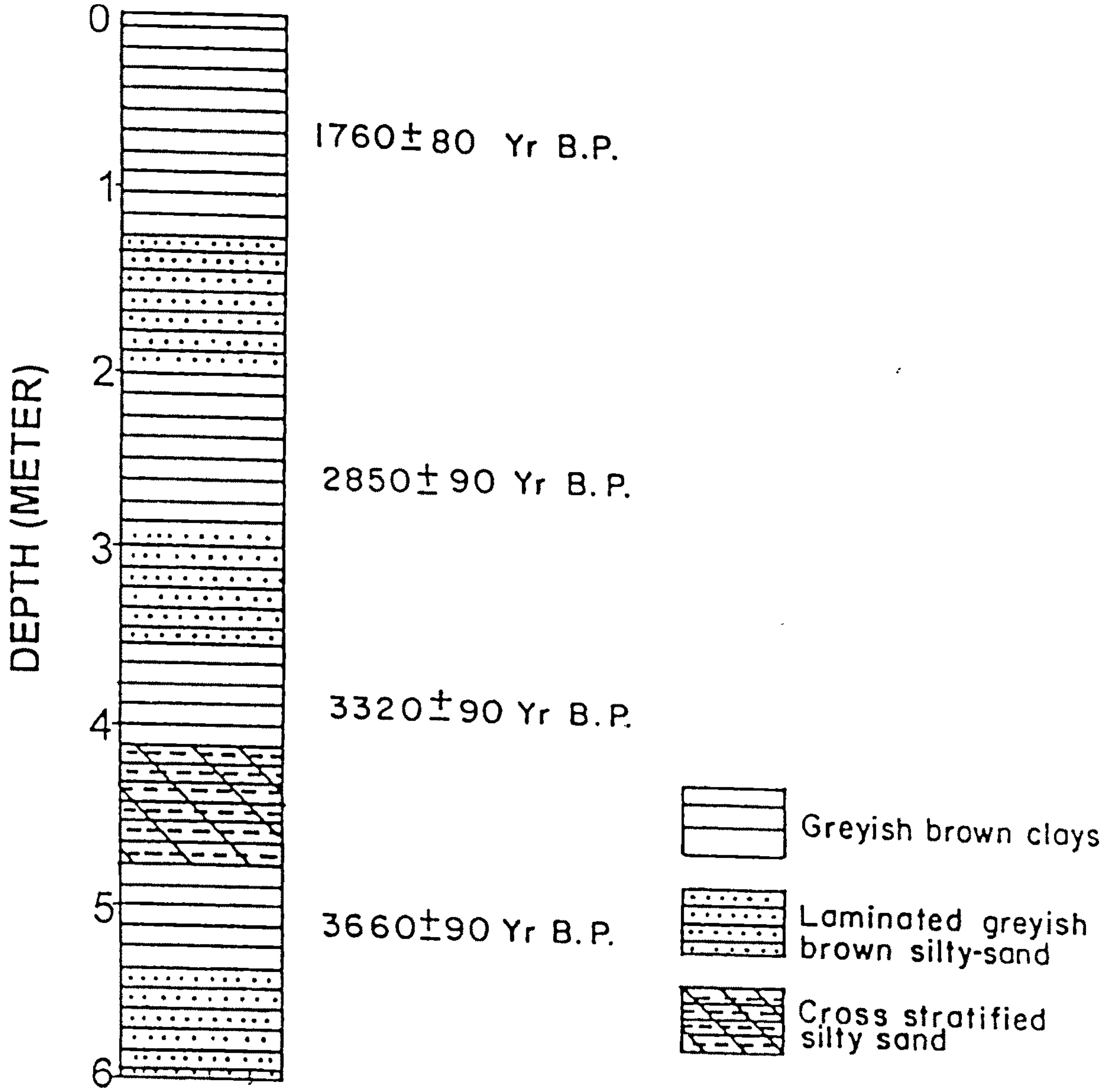

Fig. 7.7 Composite litholog of Holocene terraces from lower Mahi valley with radiocarbon dates (after Kusumgar et al., 1998).

is obvious that the deposition of the terrace sediments commençed before 3660±90 B.P. It can be assumed that Holocene aggradation phase 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).

The Holocene terraces have an important bearing on the evolutionary history of the Gujarat alluvial plains during the 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 safely regarded as of Early Holocene age. This erosional phase which gave rise to cliffy banks of the rivers and deep ravines was triggered by tectonic uplift of the area during this period. The rapidly rising sea level during Early Holocene (Hashimi et al., 1995) points to role of tectonic uplift in inducing this great erosional phase. 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. These incised cliffs occurring away from the present day channel represent the early Holocene palaeobank (Fig. 6.1). The incision of the terraces suggest a late Holocene to Recent episode of tectonic uplift which could be attributed to the continued instability of the Cambay Basin.

SOFT SEDIMENT DEFORMATION STRUCTURES

The soft sediment deformation is defined as the deformation of unlithified sedimentary strata caused either due to intergranular movements or intracrystalline deformation that dominates after lithification (Maltman, 1984). The soft sediment deformation structures are useful in interpreting the syn-depositional tectonism (Woodcock, 1976) and in deducing ancient tectonic activity (Allen and Banks, 1972). Allen and Banks (1972) linked the seismic shocks to sediment deformation and suggested that soft sediment deformation structures play an important role in deducing ancient tectonic activity. Deformation mechanism in sediments involve changes of stresses in particulate materials initiated by some external agent conveniently termed as 'triggers' (Owens, 1987), which may be activated due to several reasons ranging from stresses prevailing essentially in a sedimentary depositional environment to biological and purely under the influence of gravity or tectonic movements producing deformation structures of varying structural styles (Preston, 1987).

The lithostratigraphy of the exposed sediments is well established (Pant and Chamyal, 1990; Chamyal and Merh, 1992).The succession comprise fluvial gravels, silts and sands and several paleosols in the upper part. The horizon between gravel-I and gravel-II comprising alternate layers of sands and silts is characterised by development of some 50 bands of calcrete (Khadkikar et al., 1996) at Rayka in the Mahi basin which are also folded. The sediment column above the gravel-II comprises multiple layers of paleosols indicating tectonic stability during their deposition. However, the confinement of the deformational structures between the two gravel units point to a significant tectonic event of synsedimentary subsidence. The deformation structures are confined within the finer grained sediments between gravel-I and gravel-II. The structures are recorded from the sediments of Mahi and Narmada rivers. Significantly, these structures are absent in the Sabarmati valley. Based on the deformation mechanism and lithology, a general classification of the structures documented is given in Table 7.2. Genetically, these structures have been divided into biological, local, gravity and tectonically and seismically formed soft sediment deformation structures.

Syntectonic sedimentary folds

The fold structures in Lower Mahi, are of intraformational character. These in some cases extend upto 15 m and are limited to horizons comprising alternate beds of fluvial silts and sands between the two gravel horizons. Folding of silty beds is particularly prominent. At Rayka the geometric shapes of these folds varies from wide open folds to flexures to monoclines. The calcrete bands show well developed plunging folds within the finer grained sediments all along the Lower Mahi river basin (Plate 7.8, 7.9). The fold axis of these folds trend towards south with a plunge of 10-15^0. The wavelength of the folds varies from 1.5-2 m with an amplitude of 0.5 m. The monoclines show an apparent steepening towards west suggesting that the downfaulted blocks lie to the west. Absence of shear planes related to gravity sliding adjacent to or within the folds rule out the possibility of these structures being in any

Table - 7. 2: Classification of deformational structures in the Quaternary sediments of Gujarat Alluvial Plains

Lithology	Biological	Local	Gravity	Tectonic/ Seismic
Sand	Bioturbation	–	Slump structure, Slides, Pseudonodules.	Slumps and slides, discontinuities and faulting minor faults and isolated dislocations, syntectonic sedimentary folds,injected liquefied sand, load structures, sand dykes.
Silt	Burrow, collapse, bioturbation	–	Slump structure, Pseudonodules, Slides	Slump structures, slides, discontinuities, microfaulting, syn-tectonic sedimentary folds, slickenslides, contorted laminations, convolution, overturned folds, pseudonodules.
Clay	Burrows	desiccation cracks	Disrupted laminations	Disrupted laminations, discontinuities, micro-faulting, shear zones, slickenslides, seismically induced deformation.

Plate 7.9 Photograph showing intraformational folds in calcretised silty sands below gravel-II in Mahi valley (Loc. Rayka).

Plate 7.10 Photograph of a synsedimentary fault in Mahi valley. The fault dies out in the overlying horizons (Loc. Poicha).

way related to gravitationally produced slump folds. The formation of these folds was facilitated by the deposition of contrasting lithologies, coarser sands and finer silt sediments accumulating in a subsiding block. The folds gradually diminish in the downstream direction into undisturbed horizontal strata.

Faulting, Discontinuities and Slickensides

The smaller closely spaced minor faults within the strata are significant indicators of syndepositional tectonism . The geometry and orientation of these minor fault zones is controlled by the regional fault system. Such minor faults which die out in the overlying horizons have been observed at several locations in the Mahi (Plate 7.10) and Narmada valleys. These minor faults show a N-S trend corresponding to the major basement faults and exhibit a dominant vertical movement. Each minor fault, exhibit a small increment of slip, the total displacement being distributed on a number of fault planes, particularly in the sandy horizons. The cause for this according to Underhill and Woodcock (1987) is slip hardening of each fault after very small displacement causing the next slip increment to be taken up through undeformed sediments rather than on the original plane. Discontinuities in the sediment strata have been found to be linked with faulting. A few but ill preserved slickensides (Plate 7.11) in clays have also been documented in the Mahi valley which undoubtedly point to lateral movement. These striations are related to post depositional faulting. Hydroplastic slickenslides are observed in the clays underlying

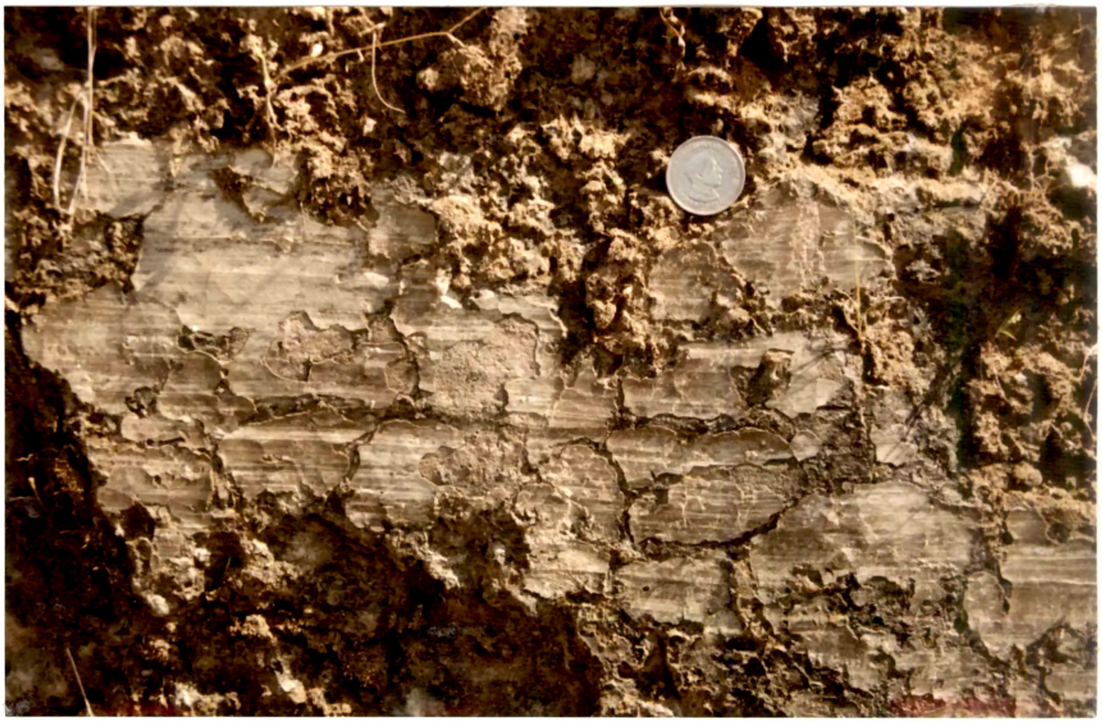

Plate 7.11 Photograph showing slicken-sided surface in Mahi valley (Loc. Kadana).

Plate 7.12 Phtograph showing slump structure in Mahi valley (Loc. Rayka).

the gravel-I. These have been formed because of the expansion and contraction of the clays due to alternate wetting and drying during pedogenesis.

Slumps and slides

Quite a few slump structures have also been observed concentrated adjacent to the fault zones suggesting an unambiguous linkage between the movement along these faults and resulting failure in sediments. The largest slump structure of synsedimentary nature is observed at Rayka in the lower Mahi valley (Plate 7.12). The shear plane of this slump also trends NNW-SSE. Another significant slump structure is observed at Bhimpura in the Narmada valley (Plate 7.13). The slump plane of this structure also oriented in N-S direction. The direction of slumping is towards west to southwest. Gravity is recognised as an important factor for producing slumps and slides. However, parallelism of the shear planes of the slumps indicate a tectonically induced gravity deformation in the sediments.

Pseudonodules, burrows and other structures

The term pseudonodule covers a structure consisting of a single laterally extensive row of uniformly sized sand masses giving an impression of a horizon of concretions (Allen, 1984). Pseudonodules alongwith ball and pillow structures are observed at a number of places in the Lower Mahi basin. According to Allen (1984) pseudonodules alongwith ball and pillow structures are not concretions in the true sense but are accepted as soft sediment deformation structures. Hubert et al. (1972)

Plate 7.13 Photograph showing slump structure in Narmada valley (Loc. Bhimpura).

regarded these structures as primarily due to the downslope movement of interbedded sand and mud. Other structures observed, though of less importance are dessiccation cracks and disrupted laminations in clays. Burrows are attributed to organic activity and are commonly observed in pedogenised horizons. Change in mineral composition in clays gave rise to the dessication cracks, the empty spaces are now occupied more often than not by veins of calcium carbonate.

Spontaneous occurrence of the soft sediment structures underline the influence exercised by tectonism on the deposition of these sediments. The various deformational structures in the sediments between gravel-I and gravel-II are indicative of syndepositional subsidence of the basin. Active normal faulting parallel to the ECBMF and differential subsidence of the blocks along these faults coinciding with the aggradational phase of the river which resulted in the formation of various kinds of deformational structures. The lower Mahi basin is characterised by a dominant N-S and NE-SW trending fractures (Pant and Chamyal, 1990). According to them a series of N-S trending step faults have developed parallel to the Cambay basin margin fault which controlled the sedimentation in the basin. The basalts in the basement east of East Cambay Basin Margin Fault also show step faulting in a SW direction (Bhandari et al., 1986) conforming with the SW paleocurrent directions (Pant and Chamyal, 1990). Similar step faulting on the eastern margin is observed in the Sabarmati valley also (Sridhar et al., 1997). Correlation of soft sediment deformation structures with the subsurface faults in Narmada basin is difficult in the absence of detailed subsurface data. However, the trends of the deformation structures follow the basement trends.

These structures indicate slow subsiding movements along these step faults during the deposition of the Quaternary sediments (Fig. 7.8, 7.9, 7.10, 7.11). The confinement of these structures between the two prominent gravel units point to a significant tectonic episode of synsedimentary subsidence which ceased after the deposition of gravel-II as indicated by frequent development of paleosols in the upper part of the exposed sequence. This phase of synsedimentary subsidence appear to be the last dying pulses of the great Lower Pleistocene subsidence of the Quaternary basin. Absence of these structures in the Sabarmati valley indicate that this tectonic episode did not occur in the northern part of the basin. However, this conforms with the lower thickness of the Quaternary sediment cover in this part indicating less subsidence than the southern part of the basin.

SEISMICALLY INDUCED SOFT SEDIMENT DEFORMATIONAL STRUCTURES

The seismically induced deformational structures from Mainland Gujarat are reported for the first time. These structures are observed in the sediments comprising the Holocene valley-fill terraces discovered during the course of this study. The deformation structures have been recorded from the incised cliffy sections of the Holocene terrace at Kothiyakhad and Mujpur that lie on fault induced meander of the Mahi river near Dabka (Pant and Chamyal,1990) and at Anklawadi in the Orsang valley. These structures include-injected liquefied sand, contorted laminations,

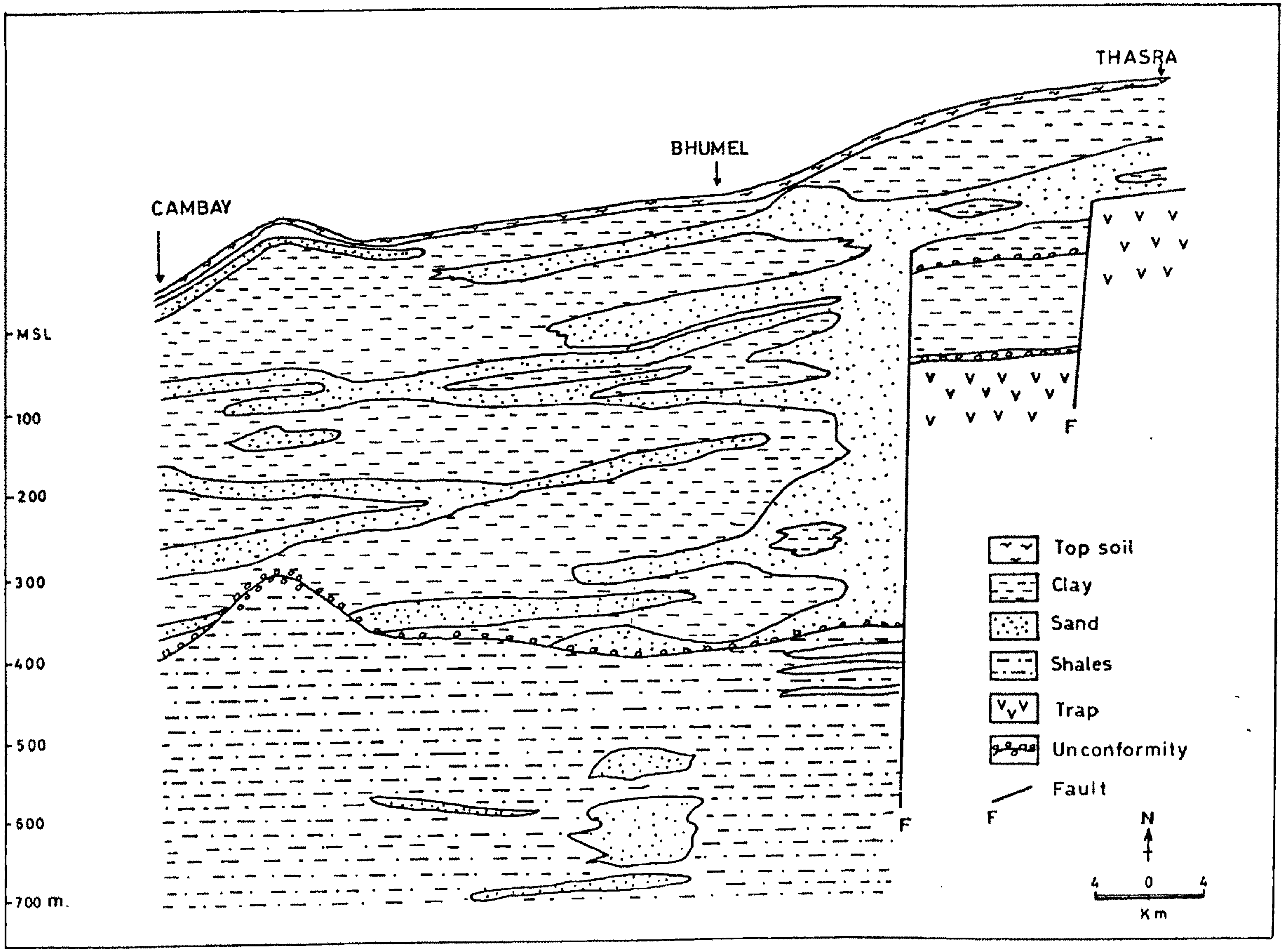

Fig. 7.8 Cross-section showing subsurface geological and structural features (after MRBC report).

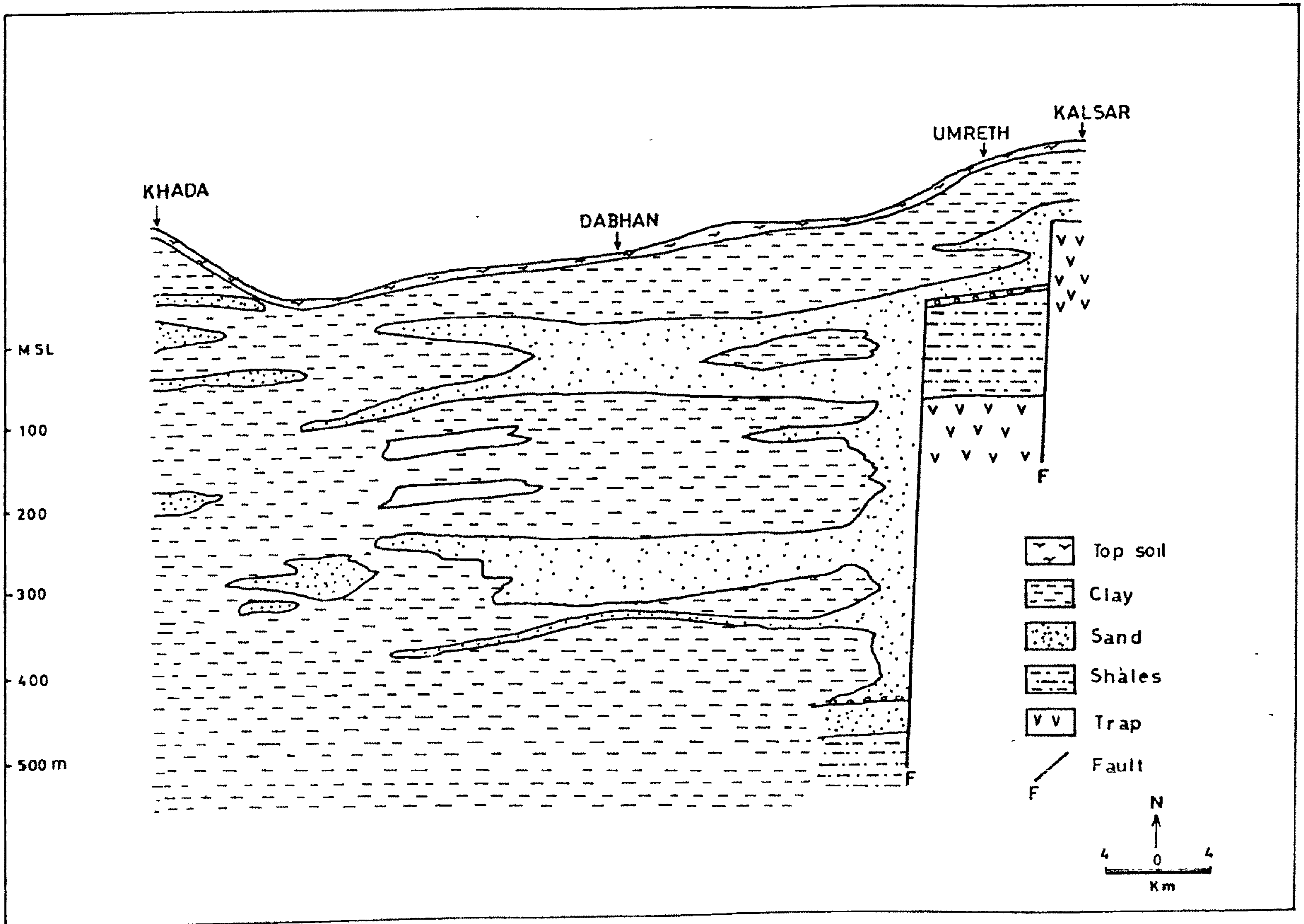

Fig. 7.9 Cross-section showing subsurface geological and structural features (after MRBC report).

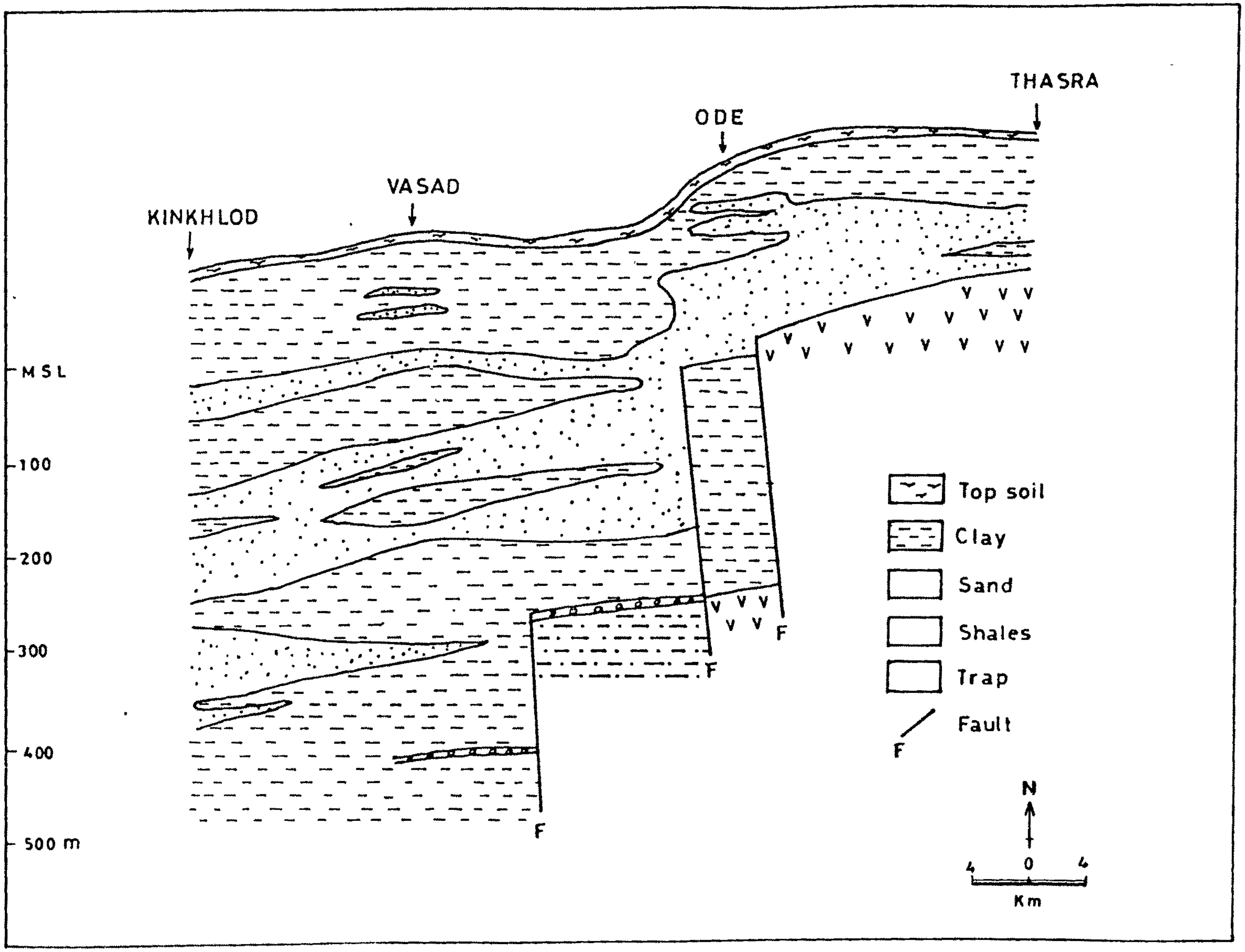

Fig. 7.10 Cross-section showing subsurface geological and structural features (after MRBC report).

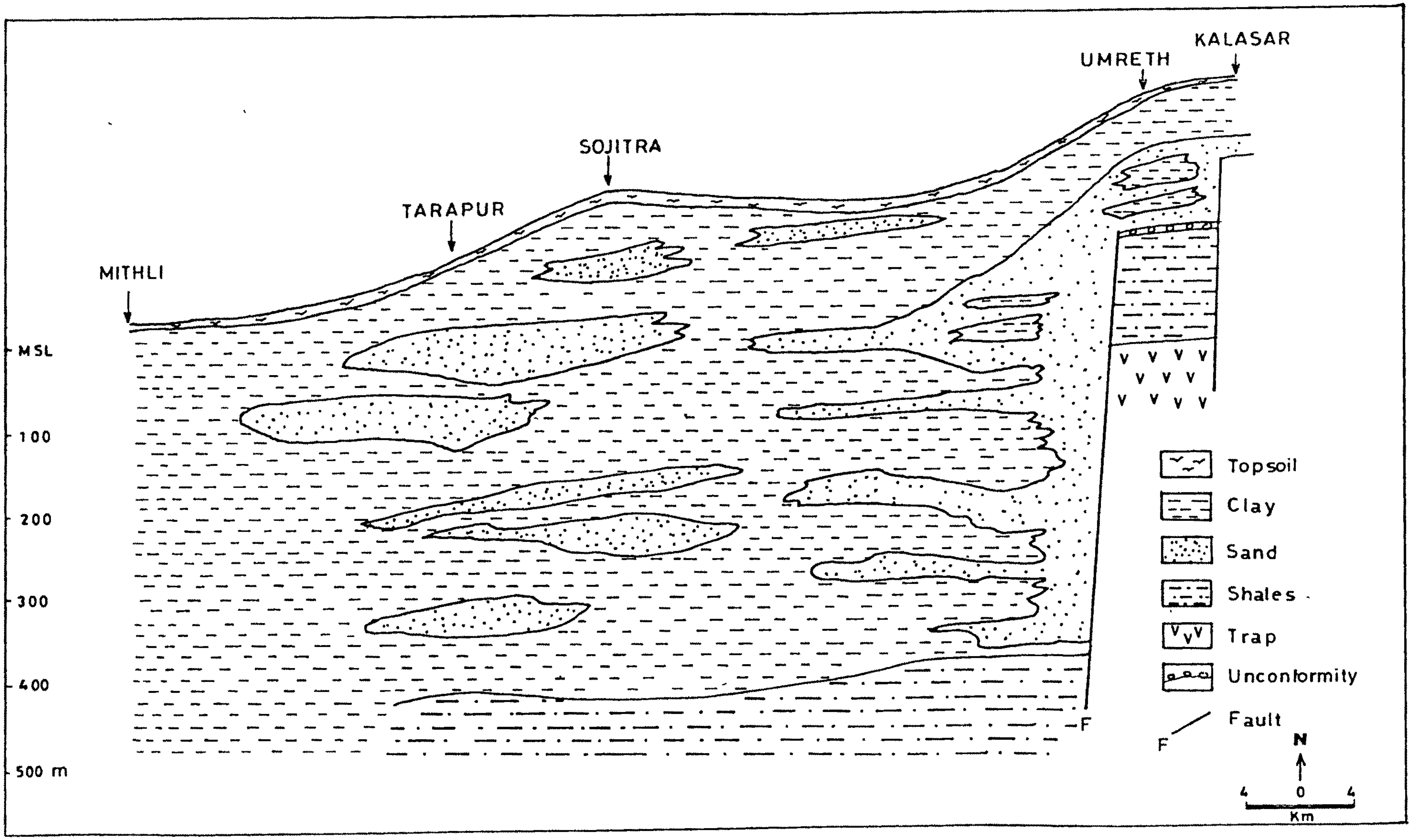

Fig. 7.11 Cross-section showing subsurface geological and structural features (after MRBC report).

overturned folding, load structures, convolutions and small scale folds, syn-sedimentary microfaults and pseudonodules.

The injected liquefied sand is seen to have penetrated subhorizontally into the underlying laminated silty clays (Plate 7.14). The forcible injection of the sand is evidenced by the deformed clay laminations which have been complexly folded and even overturned . The sand body itself is structureless and is irregular in shape. The uneven surface over the deformed horizon is filled up by a thin layer of tidal mud indicating the nearness of sediment-water interface during the period of deformation (Sims, 1975). The deformed horizon is overlain by undisturbed fine to medium sand showing cross- bedding, herringbone structures and ripples.

A silty clay horizon shows lamination which exhibits overturned folding (Plate 7.15). The tight folding appears to have taken place by sliding along a shear plane. This overturned fold was formed as the deforming layer ran into more resistant sediments leading to development of the shear plane and subsequent slipping of the laminations. Such tight folding of silty clay material is the result of liquefaction and shear stress generated by the passage of seismic waves (Mohindra and Bagati, 1996). Downward injection of fine sand into the underlying clay horizons due to seismic loading is also observed (Plate 7.16). These downward penetrating 'sand dyke' like features might have taken place initially along a mudcrack which widened due to the intrusion of fine sand (Plate 7.17). The underlying horizons show effects of downward dragging indicating that the dyke was forcibly intruded. Such dykes upto 0.5 m in length have been observed. Occurrence of load structures adjacent to these

Plate 7.14 Photograph showing forcibly injected liquefied sand resulting in the deformation of laminated fine silts,marine Holocene terrace in Mahi valley (Loc. Kothiyakhad).

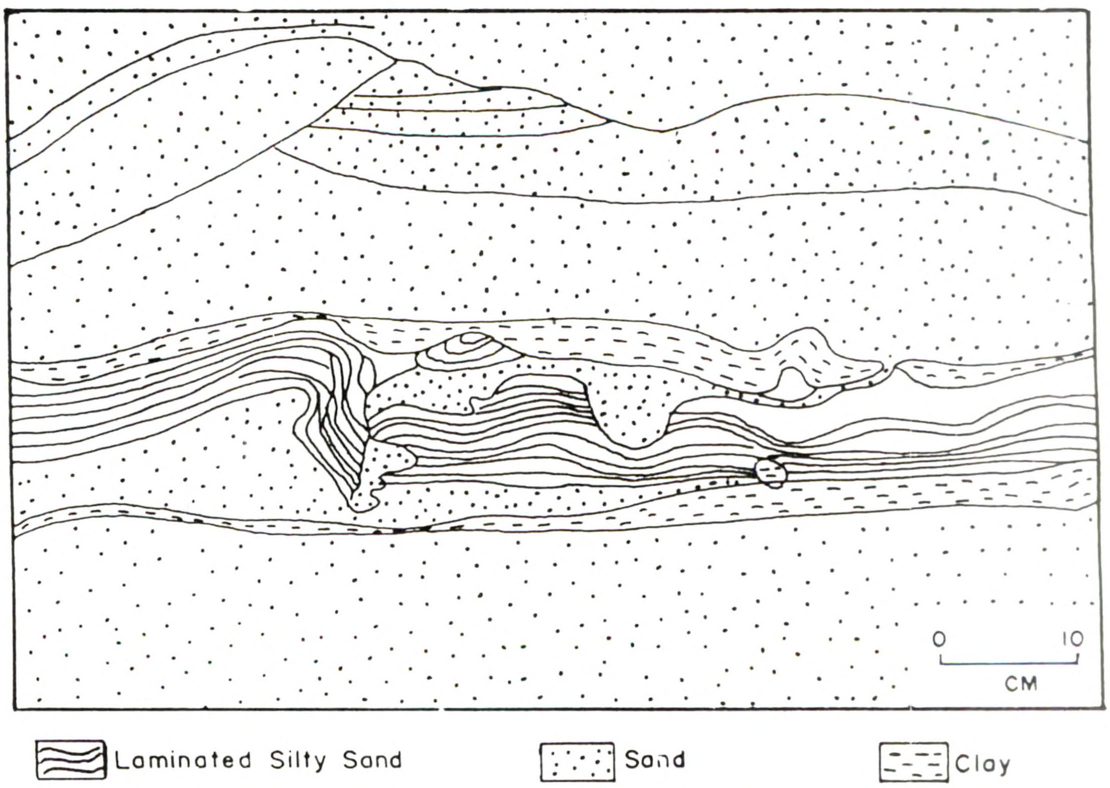

Plate 7.14A Tracing overlay of the above photograph. Note the thin layer of tidal clay filling up the microrelief produced due to deformation.

Plate 7.15 Photograph showing tight folding of the marine Holocene terrace sediments in Mahi valley (Loc. Mujpur).

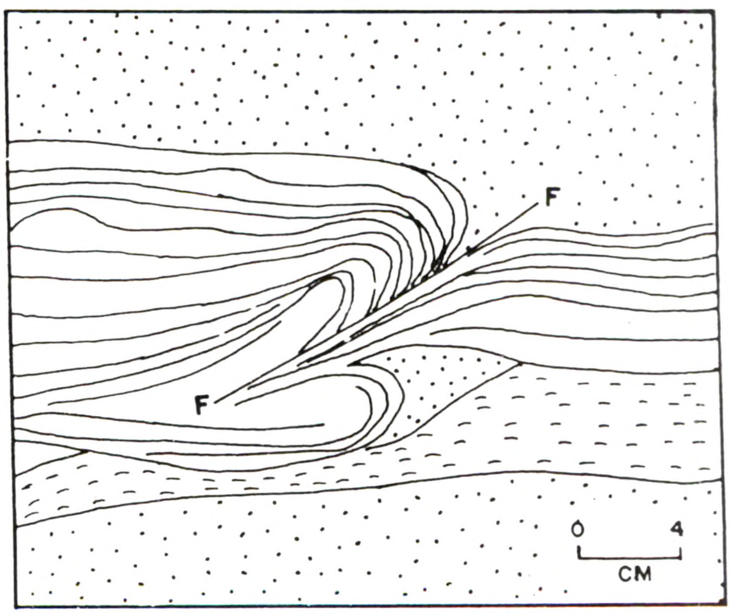

Plate 7.15A Tracing overlay of the above photograph. Note the shear plane. (Legend same as in plate 7.14A)

Plate 7.16 Downward injected sand dyke in a fluvial Holocene terrace in Orsang valley. Note the deformation of the sorrounding sediment layers and load structures (Loc. Anklawadi).

Plate 7.17 Downward penetrating sand dyke and the resulting buckling of adjacent sediment layers in Holocene terrace in Mahi valley (Loc. Kothiyakhad).

dykes ((Plate 7.18) and absence of any significant sediment cover suggest the role of seismic loading in the formation of these structures. The load structures are similar to those described by Sims(1975).

Convolutions in silty clay beds are prominent (Plate 7.19). The convolutions have been formed by tight folding of the beds leading almost to the formation of pseudonodules . The same horizon shows a series of anticlinal and synclinal folds of low amplitude. The clay layers involved in this folding show pinch and swell structures. The formation of these folds and contorted laminations is attributed to intense compressional stresses developed during an earthquake (Mohindra and Bagati, 1996). Randomly disseminated organic rich clays are observed in silty clays (Plate 7.20). The dissemination of organic rich clays is interpreted as having been formed due to seismic shaking of the over-saturated sediments and subsequent dewatering. Small scale microfaulting is also seen even as the laminations are ill preserved.

The deformational structures described above are intraformational in character and are overlain and underlain by undisturbed horizontal strata. The filling up of the microrelief at the top of the deformed layers by post deformation sedimentation followed by deposition of undisturbed strata suggest that the sediments were at or near the sediment-water interface during the time of deformation. 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 (Sims, 1975). The lack of unambiguous structures such as sand dykes and sediment plumes could

Plate 7.18 Photograph showing load structures formed due to seismic loading in a fluvial Holocene terrace in Orsang valley (Loc. Anklawadi).

Plate 7.19 Photograph showing tight convolutions in marine Holocene sediments in Mahi valley. Note the undeformed overlying and underlying horizons (Loc. Kothiyakhad).

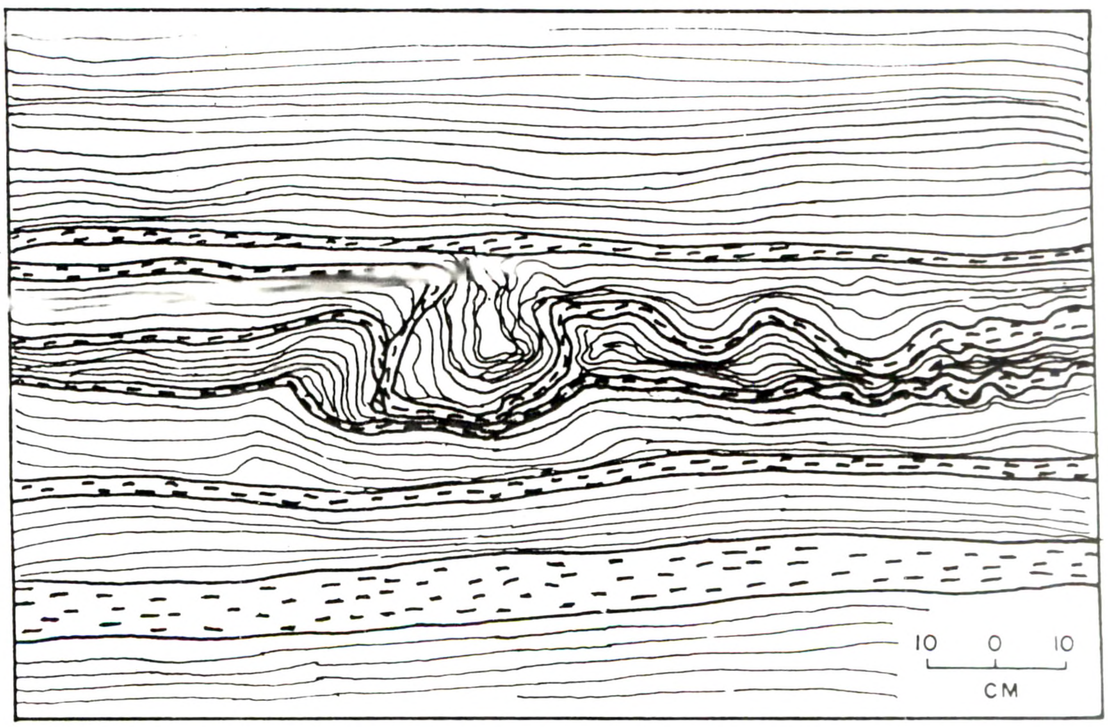

Plate 7.19A Tracing overlay of the above photogr aph showing the deformation. (Legend same as in plate 7.14A)

Plate 7.20 Photograph showing randomly disseminated organic matter due to seismic shaking of oversaturated sediments in Mahi valley (Loc. Mujpur).

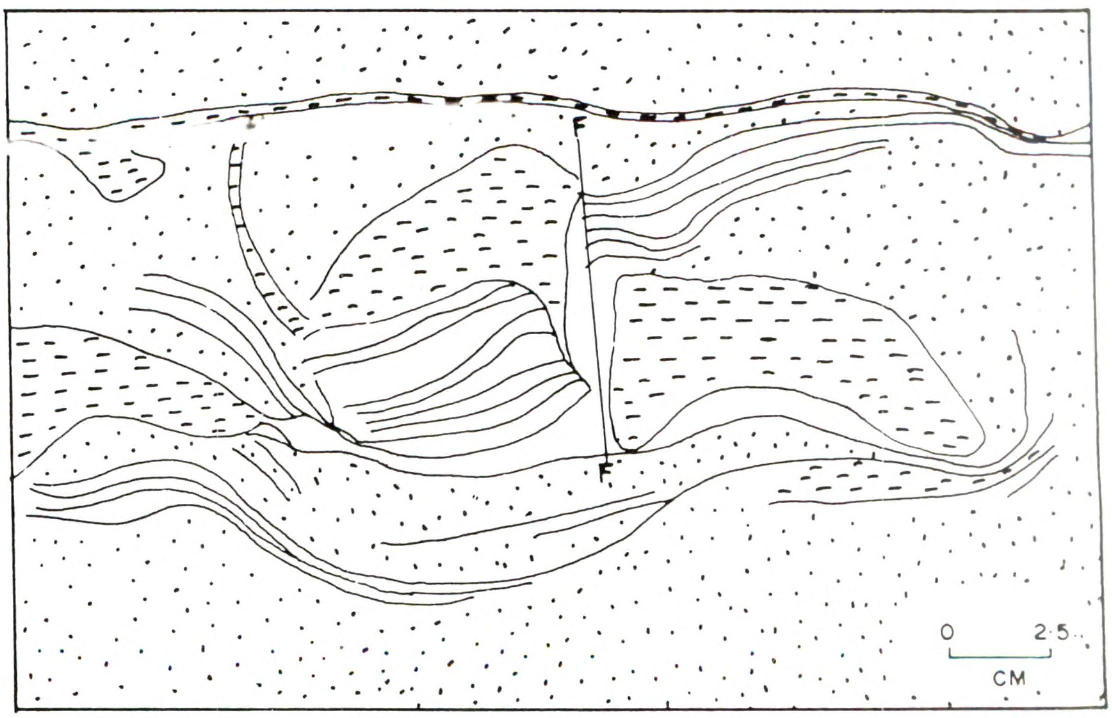

Plate 7.20A Tracing overlay of the above photograph showing synsedimentary microfault. (Legent same as in plate 7.14A)

be, as explained by Sims (1975), due to the fact that the sediments are dominantly fine grained clays that have very little or no liquefaction potential.

Soft-sediment deformational structures are important indicators of past seismic activity (Allen, 1975). No standard terminology exists for describing these structures (Lowe, 1975). The structures described above are similar to the earthquake induced structures of Sims (1973; 1975), Hempton and Dewey (1973) and to those experimentally generated by Kuenen (1958). These structures fulfill the criteria laid down by Sims (1975) for correlating such deformational structures with seismic events. The deformational structures described here are related to atleast one major seismic event. Radiocarbon dating of organic rich clay horizons (Fig. 7.7) 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. This tectonic episode which led to the upliftment of the Holocene terraces, perhaps continues even today as evidenced by earthquakes attributed to the continued instability of the Cambay basin (Biswas,1987,Maurya et al.,1995, Joshi et al., 1997).

The Gazetteer of Kheda district records two earthquakes that shook the area, one on 13th August, 1821 and the other on 20th July, 1935. Between 1860 and 1864 many seismic shocks were felt but did not cause any loss of life or property. The area also lies in the proximity of the Narmada geofracture which has witnessed major earthquakes in recent times (Gupta et al.,1972,1997). The devastating Bharuch earthquake occurred on 23rd March, 1970 which was followed by two more shocks on 26th March and 26th April, 1970. These earthquakes suggest the continuing instability of the Cambay basin during the recent geologic past and historic times (Table 7.3).

Table 7.3 : List of Epicentres of some important earthquake in and around Gujarat Alluvial plians.

S.No	Date	Epicentre °Lat	°Long	Magnitude	Remarks
1	1684	21.2	72.8	3.7	Surat.
2	13.8.1821	22.8	72.7	4.3	Kaira, lasted about a minute, said to be East and West.
3	27.5.1827	Near Barwani		-	A shock occurred in Narmada valley at the foot of the hill called Dumohapahari, a tremendous rumbling noise was heard. This was supposed to have been due to a landslip but was found not to be so. In the morning the hill was reported to have rent for about three fourths of a mile and engulfed trees of great size.
4	9.10.1842	Baroda		4.3	---
5	18.11.1863	22.0	75.0	5.0	A shock took place in Nimar in Barwani country walls fell at the later place . It was felt on the southern side of the Narmada river from Manpoor to Barwani, but not noticed to the south of Satpura range.
6	29.4.1864	23.0	72.7	5.0	Ahmedabad
7	27.7.1935	21.0	72.8	5.7	Dumas.
8	14.3.1938	21.6	75.0	6.25	Khandwah- Satpura range
9	Jan. 1967	22.0	75.0	5.0	Felt at Nisarpur and Ali-Rajpur in Dhar and Jhabua districts.
10	23.3.1970	21.7	73.0	5.4	Broach.
11	30.8.1970	21.6	72.7	3.5	Aliabet.