DISCUSSION

Quaternary was a period during which temperature and precipitation led to repeated change in the water balance of rivers. Stream channels, which were adjusted to carry the sediment loads fed to them during interglacials, underwent changes in form and function as a consequence of onset of cold conditions (Williams et al., 1998). These changes of river form and process are termed as river metamorphosis (Schumm, 1977) and such changes are well preserved in the fluvial records of southern margin of Thar desert suggesting fluctuating southwest monsoonal precipitation during their deposition.

The southwest monsoon is one of the major weather systems on earth. Marine and terrestrial evidence show that monsoon intensity varied through time. The continental records from western India, for example, the Thar Desert indicate that lake levels were controlled by the monsoonal precipitation (Bryson and Swain, 1981; Enzal et al., 1999). Furthermore dune-building activity in the region is intimately associated with the SW monsoonal winds (Chawla et al., 1992; Thomas et al., 1999). On longer time scales, evidence pertaining to southwest monsoon variation comes from marine sediments (Anderson and Prell, 1993; Rosteck et al., 1997). Marine evidence of strong monsoon is based on the concentration of

lithogenic grain size, carbon mass-accumulation rates and relative percentages of foraminifera or cocolthiophores. The variation is mainly due to the wind strength and not necessarily implies strong precipitation over the land (Bruns et al., 2001). Stable isotopic analysis of speleothem from Hoti cave in northern Oman by Burns et al. (2001), suggest that rapid speleothem growth occurred during enhanced southwest monsoon system dated to 6-10.5 ka, 78-82 ka (MIS-5a), 120-135 ka (MIS-5e), 180-200 ka (MIS-7) and 300-325 ka (MIS-9). However, the pluvial phase corresponding to MIS-3 was non existent in the speleothem record and according to Burns et al. (2001), the continental records of climate indicate MIS-3 as dry period.

The monsoon upwelling index from the Arabian Sea indicates strengthening of monsoon activity between 50 and 37 ka (Prell and Van Campo, 1986). Similarly a twin peak of upwelling productivity in the Indian Ocean suggests strengthening of summer monsoon between 50-30 ka (Clemens et al., 1991). In fact, the marine indicators of monsoon wind intensity during MIS-3 are often much higher than those during the early Holocene (Hermelin and Shimmield, 1995; Rosteck et al., 1997). Logically, it may be true that strong winds do not necessarily mean continental wetness. However, this study has shown that marine indicators of monsoon wind intensity reflect enhanced precipitation in western India during MIS-3.

Previous studies in the desert margins have indicated that the fluvial regime responded to the waning and waxing of southwest monsoon system and this can be used to reconstruct the past precipitation changes in the region (Tandon et al., 1997; Khadkikar et al., 1999; Juyal et al., 2000; Kar et al., 2001; Srivastava et al., 2001, Jain and Tandon, 2003). In the present study it has been found that the older fluvial record in the Orsang basin has indicated response of the fluvial system to the pluvial phases corresponding to MIS-5e and

MIS-5a. Similar evidence were found in the Mahi basin (Juyal et al., 2000). These evidences are in conformity with the observations made by Burns et al. (2001). In addition to this a pluvial phase that has been dated to 50-30 ka (MIS-3) was widespread in the basins of Sabarmati, Mahi and Orsang. MIS-3 being a wet period is also recorded in the Thar Desert (Jain et al., in press). This is further substantiated by stable isotope studies on pedogenic carbonates from the Thar Desert that indicate normal monsoon during MIS-3 (Andrews et al., 1998). Fluvial aggradation and pedogenesis between 59-39 ka in the Sabarmati basin have been reported by Tandon et al. (1997). The upper fluvial sequence in the Sabarmati basin is consistent with the widespread evidence of enhanced fluvial conditions between 54 and 30 ka, when runoff must have been higher (Srivastva et al., 2001). At Rayka in the adjoining Mahi basin, the last major fluvial aggradation is dated to 50-30 ka and shows wide spread fluvial aggradation under persistent hydrological flow (Juyal et al., 2000). Out side the realm of Thar Desert, Singh et al. (1999) based on rich faunal assemblages, suggested a humid phase between 40-30 ka in the southern Ganga Plain. Chronology of the fluvial sequences studied in the Sabarmati, lower Mahi and Orsang basins indicate that a regionally extensive fluvial phase operated in the southern margin of Thar Desert during MIS-3. This is contrary to the observations of Burns et al. (2001), where they do not see any increase in precipitation on land.

In a rather gently undulating alluvial plain the rivers have a deeply incised course exposing the Quaternary sequences. According to Merh and Chamyal (1997), older rivers were flowing southwest to west from the rocky highland guided by east-west to northeast-southwest trending fractures, crossing various step faults and depositing their load on Tertiary basement (Maurya et al., 1995, Fig. 1.5B). The older fluvial system was responsible for the deposition of the fluvial sediments in the region. Merh and Chamyal (1997) advocated that

the region experienced major tectonic activity after the deposition of aeolian sand that resulted not only in the shifting of the rivers to their present course but also incised the Quaternary sediments in the desert margin area. This hypothesis looks plausible in view of the fact that palaeocourse of Sabarmati, Mahi and Orsang rivers show a southwestward flow and the present rivers have shifted southeastward (Sareen et al., 1993; Sridhar et al., 1996; Srivastava et al., 2001; Sant and Karant, 1993; Agrawal et al., 1996; Maurya et al., 2000). In addition to this, trough cross-stratified gravel in Mahi and Orsang river basins suggest that southwest flowing streams deposited them.

The shifting of the rivers to their present course has been attributed to tectonism as discussed above (Sareen et al., 1993; Sridhar et al., 1994; Tandon et al., 1997; Merh and Chamyal, 1997). Ahmed (1986) suggested that Aravallis have risen up to 700 m between Tertiary and Late Holocene, and the region experienced continued tectonic activity. Presence of tilted terraces, river courses entrenched within their own deposits and badland topography are indicative of tectonically active nature of the region that has been attributed to the reactivation of pre-Quaternary faults (Agrawal et al., 1996; Merh and Chamyal, 1997). There is no ambiguity about the initiation of incision that occurred in these river basins after the deposition of aeolian sand. This has been dated between 21 ka (Orsang basin) to 10 - 12 ka (Sabarmati and Mahi basins). Thus, it is reasonable to assume that the anti clockwise swing of the rivers occurred sometimes between 21 to 10 ka (Fig. 1.4). Additionally, in order to constrain the timing of incision, the scroll plain sequence at Mahudi in Sabarmati basin is significant. The luminescence age of 4.5 ka obtained from scroll plain-I suggests that incision in the Sabarmati basin pre dates 4.5 ka at least and definitely post dates 21 ka (Fig. 3.2). The anti clockwise swing of the rivers could be tectonically induced, however the incision appears to have been modulated by climate as well for the following reasons.

1. A sea level lowering of ~100m has been suggested for western coast during the last glacial maximum (Hashimi et al., 1995). During this period rivers draining into the Cambay basin would have been lengthened across the continental shelf due to fall in sea level. Bathymetric contours off Cambay show that inner shelf (<100 m water depth) is located at a distance of 175 km from Tarapur (Cambay). Presence of submarine terraces and terrigenous sediments at depth 35 and 140 m suggests presence of palaeo coastline during low sea stand (Rao and Wagle, 1997). Under such circumstances, incision would have begun at the edge of the inner shelf and progressed upstream.
2. Fisk (1944) advocated extensive upstream effects of eustatic sea-level changes. However, recent studies have shown that base level lowering of rivers in response to eustatic sea-level lowering did not occur >80 km up valley from the coastline (Leigh and Feeney, 1995). That is because in an alluvial coastal plain the geomorphic effects of sea level lowering are moderate and restricted to the shelf and deltaic areas (Blum and Savatore, 1994; Koss et al., 1994; Miall, 1988; Schumm, 1993). In view of this the incision in the Mahi and Sabarmati basins that lie proximal to the coast could have an aided effect of base level lowering caused by sea-level change during the Last Glacial Maximum. However, in the distal locations of Sabarmati and Orsang basins, the effect may have been insignificant. Instead, neotectonic activity in association with the improved climatic condition would have favoured the incision in these basins. Though the incision started after the deposition of aeolian sand (21 to 10 ka) it would have been accelerated with the onset of southwest monsoon between 17 and 11.5 ka respectively (Sirocko et al., 1993). This could have paved the way for the fluvial regime to re-

establish itself as indicated by the incision of 12±2 ka dune at Sabarmati and 10±3 in Mahi basin. Similar evidence of river incision during the warm postglacial has been reported from north central India (Williams and Royce, 1982; Williams and Clark, 1984) and from the Deccan Plateau (Kale and Rajaguru, 1987).

3. During the Holocene with rise in sea level the exposed continental shelves would have once again inundated and sea would have occupied the lower reaches of the Mahi basin such as Kothiyakhad and Sultanpur. This period witnessed decrease in the ability of the rivers to carry sediment and facilitating backfilling in the river basins (Williams et al., 1998). A good example of backfilling is the development of Mid Holocene S_2 surface near Mahi estuary (Fig. 1.6) comprising sediments of continental and marine origin (Rachna Raj et al., 1998). They are developed near Kothiya Khad and Sultanpur suggesting remnants of original valley floor and now being incised with falling mid Holocene sea level. Further inland, in the Sabarmati basin around Mahudi, development of the scroll plains suggests that significant amount of sediments were retained inland at least during the Mid Holocene time (Fig. 3.2). This is in contrast to the low sea level stand when continental sediments tend to bypass. However, the process of in filling would have been slow because of restricted sediment supply due to improved climatic condition. Nevertheless, without the support of tectonics, incision in Upper alluvial plains of Sabarmati and Orsang river basins would not have been possible. Evidence towards tectonic activity during Holocene comes from the presence of ingrown meanders in Sabarmati basin suggesting episodic tectonic activity at 3 ka and 0.3 ka respectively (Fig. 3.2C, Srivastava et al., 2001). Evidence similar to this is also reported from the lower Mahi basin (Maurya et al., 1998).

Prior to the onset of aeolian deposition, the southern margin of Thar Desert experienced regional-scale fluvial sedimentation and the transition from fluvial to aeolian sedimentation was gradual. After around 30 ka, the fluvial regime started dwindling (Srivastava et al., 2001) and aeolian deposition began. Of the two events of dune deposition mentioned above, Event-1, which age wise corresponds to the LGM, was widespread in the region (Fig. 5.1A) (Juyal et al., 2003). This evidence is at variance with Mainland Thar Desert where the aeolian activity was subdued during LGM on account of its association with SW monsoon (Chawla et al., 1992; Kar, 1993).

Presence of alluvium and a low sea level stand for most of the time interval under consideration (Sridhar et al., 1994; Hashimi et al., 1995) indicates that in general, the dune accretion was not supply-limited. The controlling factors should have been the wind vector and the moisture/vegetation cover. This is in contrast to the core of Thar Desert where LGM ages are largely missing from aeolian records (Chawala et al., 1992; Kar et al., 2001). Such dune deposition around the LGM in southern margin suggests that climate was critically balanced in respect of dune forming conditions such that both sand deflation and their subsequent stabilization occurred. Grain size analyses of the samples show a dominance of fine sand fraction (0.25 mm - 0.18 mm). Wiggs (1997) suggests that the grain size between ~0.06 mm - 0.5 mm is in general transported by saltation. Evidence of transport by saltation and the LGM age of the sediments indicate that the earlier suggestions by Pant and Chamyal (1990) and Khadkikar et al. (1999), designating these deposits as loess, are not tenable. Palynological and geochemical data from saline lakes in the Thar suggest that monsoon rainfall was weak or absent during the LGM and was re-established in the Holocene (Singh et al., 1990; Bryson and Swain, 1981). Ample evidence exists to suggest that the western India experienced low rainfall, low winds and overall arid climate during the LGM (Duplessy,

1982; Kar et al., 2001). Weaker winds associated with weaker SW monsoon could not have transported such sediments in suspension. Consequently it is reasonable to consider that source-proximal dune deposition around LGM was facilitated by the following factors:

(i) absence of orographic barrier between the Arabian Sea and the Aravalli Hills facilitated dune deposition by the onshore winds;

(ii) increased local sediment supply due to exposed alluvium and lower sea level; and

(iii) moisture availability due to the proximity of Cambay Gulf (Bryson, 1989) for dune stability.

Further, the alluvial plains of the southern margin would not have allowed long distance transport of sand grains, by sharing the momentum of the impactile particles and in the process reducing its energy, thus facilitating only a source proximal dune deposition (Glennie, 1999). Presence of foraminiferal tests in the dunes deflated from the exposed Arabian shelf further indicates the existence of onshore winds in the region during the LGM (Kameshwar Rao et al., 1989). The aeolian samples dated within 1 m from the surface yielded ages of 17 and 19 ka at Sultanpur and Dabka. These sites are located at Mahi estuary (Fig. 3.7), and the absence of post-glacial dune sand indicates that it might have been deflated inland after the establishment of SW monsoon. This is demonstrated at Tajpura ~50 km east of Dabka where a near-continuous dune record from LGM to 12 ka is preserved. Thus in the southern margins the dune building activity during the glacial time was largely facilitated by its geographic location.

Microliths occur extensively over the dune tops at Pavagarh (Tajpura), Langhnaj, Mitli, Visadi, etc. (Zeuner, 1952; Subbarao, 1952; Sankalia, 1965; Allchin and Goudie, 1971). At Pavagarh, microliths occurred on the surface and a few centimeters below the dune crest (Allchin and Goudie, 1971; Allchin et al., 1978). At Langhnaj and Akhaj, the microliths

were found in a buried soil horizon, ~ 1 m below the surface, such that the sand overlying them was attributed to a later phase of aridity by Zeuner (1952) and Sankalia (1965). Allchin and Goudie (1971), however, suggested that the 1 m thick dune on top of the microlith reflected mixing by recent

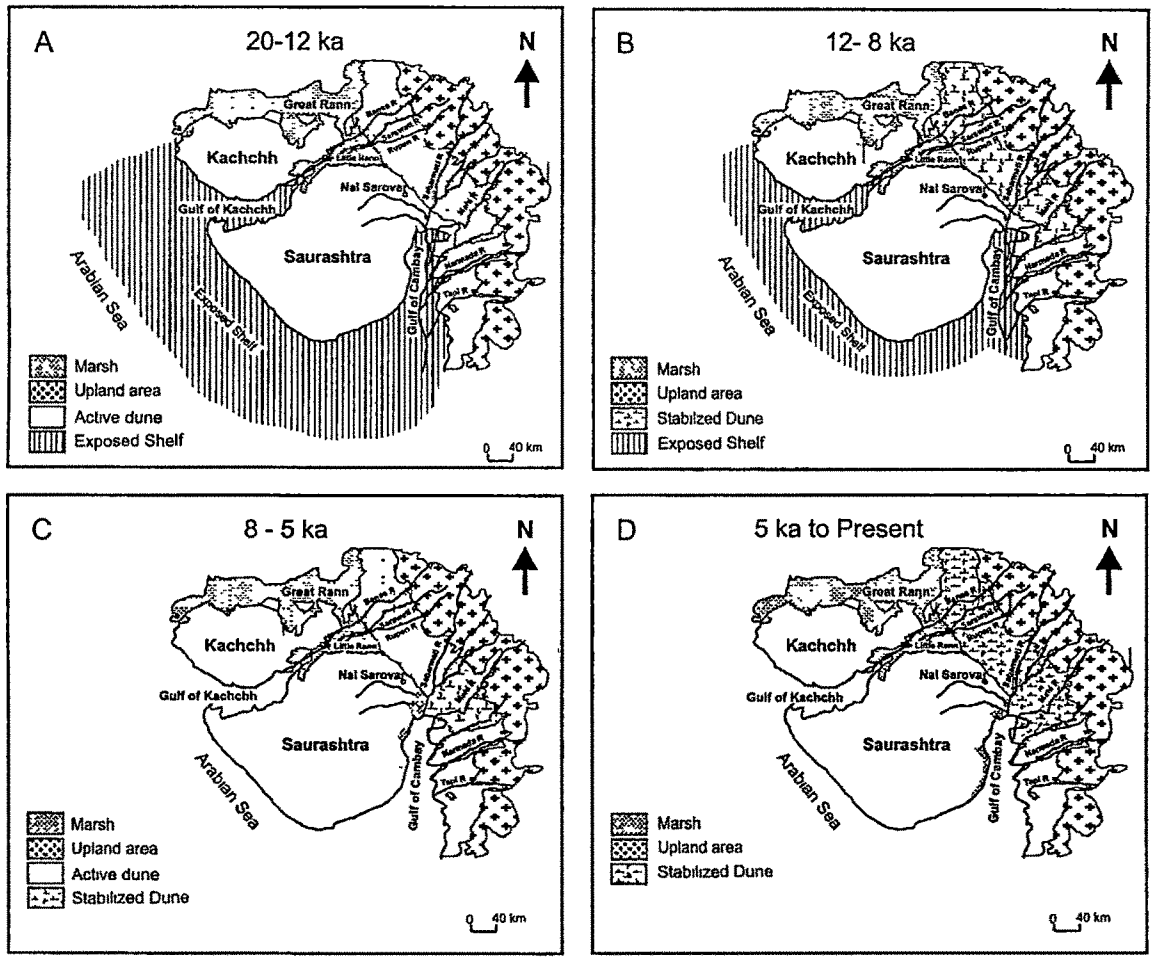


Figure-5.1. Sequential evolution of North-Central Gujarat during the Late Quaternary (Juyal et al., 2003). Relative sea level lowering is schematic based on Hashmi et al. (1995).

human activity. According to them, the microlithic people lived in a more humid environment than that which existed prior to their arrival.

From the viewpoint of chronology, uncalibrated radiocarbon ages on the bone from Langhnaj of 3875± 110 year B.P. and 3990±110 year BP (corresponding to 4095-4435 calender years and 4296- 4775 calender years BP) and their possible contamination by modern carbon, led Agrawal and Kusumgar (1969) to postulate that the microlithic occupation could be significantly older. From extrapolation of the TL dates on sands at Langhnaj (Singhvi et al., 1982), a maximum age of 10.5 ka for the microliths at Langhnaj was inferred by Wasson et al. (1983). The microliths at Akhaj are in their primary context for the following reasons: (a) they occur 1.5 m below sand with weak pedogenesis, (b) they are confined to 25 cm thick horizon and (c) the upper and lower horizons of microliths are devoid of any artifact. The base of the microlithic horizon is dated to 11±3 ka, whereas its top is dated to 9±1 ka (Fig. 3.6). This is the first direct dating of the microliths in northern and central Gujarat and accords well with ages estimated by Singhvi et al. (1982). The evidence of human occupation in the form of microliths and the age bracket of 10±3 to 8±1 ka for the fluvially reworked aeolian sand at Dharoi (Fig. 3.6) indicate a relatively humid phase during which the dune building activity was subdued/absent (Fig. 5.1B). Similar evidence of reduced dune deposition was seen during 10-6 ka in core regions of the Thar Desert, which was attributed to an intensified monsoon circulation and enhanced vegetation (Singhvi and Kar, in preparation). The Arabian Sea core data off Oman coast show progressive strengthening of SW monsoon around 13 ka, 9.9 ka and 8.8 ka, respectively (Sirocko et al., 1993).

During the Holocene a progressive younging in age in the final phase of dune deposition is seen. In the Mahi basin, the present data and an earlier published age of 10 ka (Juyal et al., 2000) suggest that the dune building activity ceased during the period 12-10 ka.

Similarly, the age of 5 ka at Langhnaj in the Sabarmati basin (Singhvi et al., 1982), and the present data on Aakhaj indicates that the dune deposition continued until around 6-5 ka in these areas (Fig. 5.1C). In north central Thar Desert, enhanced dune building activity between 8-5 ka and during 4 ka, 2 ka and 0.7 ka are observed (Thomas et al., 1999), which are not seen in the southern margin area.

The present study, therefore, indicates that after the early Holocene (11-8ka) humid phase, conditions favourable for dune deposition progressively shifted northward in the Sabarmati basin. This implies that since the early Holocene humid phase in the Mahi basin, environmental conditions could not have exceeded the geomorphic threshold for dune deposition. This is despite evidence of abrupt climatic changes in this period (Enzel et al., 1999), recorded in Lunkaransar Lake in northen Thar. Although the change in solar insolation during the Holocene was gradual, changes in North African climate and vegetation were comparatively abrupt (Petit-Maire and Guo, 1996). Such an abrupt change typical in the dry land regions suggests a feedback mechanism within the climate system, which amplify and modify external forcing, leading to abrupt climatic events.

Climate simulations in Sahara and Arabia using the Climber-2 model (as detailed in Claussen et al., 1999) suggest that during the mid-Holocene, vegetation change in these regions was abrupt compared to slowly varying orbital forcing. This was attributed to an internal feedback in the climate system. Vegetated land surfaces have lower albedo and hence absorb more solar radiation, which eventually lead to an increase in greenhouse effect (Claussen et al., 1999). A similar scenario for the southern Thar margin can be suggested after 10 ka. With enhanced moisture associated with the re-establishment of SW monsoon around 12 ka, an internal feedback mechanism was established. Climate change after 8 ka, as seen in the Sabarmati basin, was unable to perturb the vegetation-induced

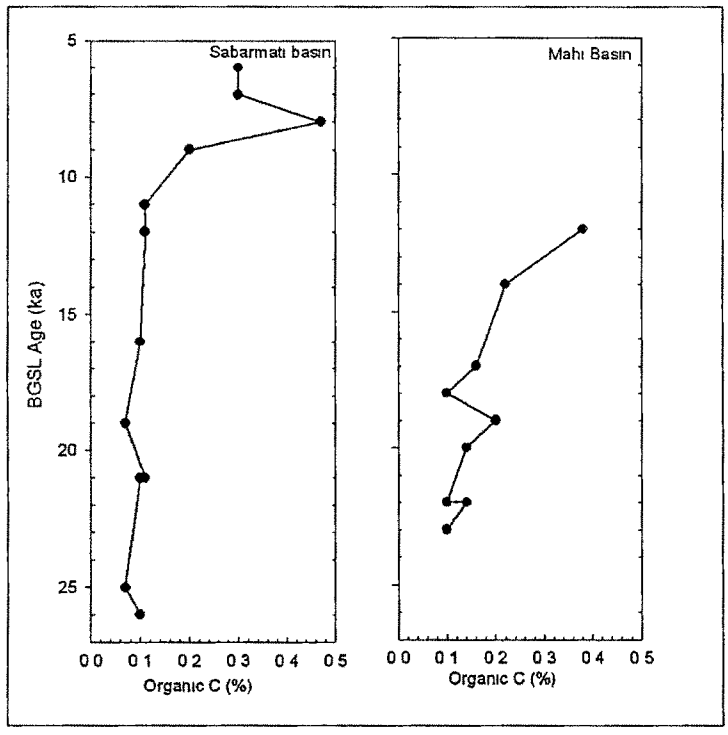
moisture/precipitation cycles in the Mahi basin. Compared to this, the northern Sabarmati basin remained moisture-deficient until around 5 ka (Fig. 5.1D). Following this, a phase of landscape stability was achieved and it continues till today. On the other hand, episodic dune building activity continued in the north central Thar around 4 ka, 2 ka and 0.6 ka (Thomas et al., 1999) suggesting a definite shrinkage of aeolian activity belt from 10 ka to 5 ka.

Studies in Thar Desert have shown that dunes are poor in organic carbon due to sparse vegetation eroded physiography of sand dunes and lack of sufficient moisture. In addition to this plant residue even if generated, is blown away by winds in absence of vegetation cover (Bhandari, 1988). Weaver (1954) opined that less organic matter in the arid soils is partly due to smaller amount of vegetation from which it is formed and partly due to its rapid decomposition. In view of this the data on fossil dunes of desert margin are in conformity with the above observations and its variation through time allows inferring the vegetation/moisture condition prevailing during the periods of dune accretion in the region. However, it is assumed that no secondary changes in organic carbon content have taken place since its deposition along with the sand, such as oxidation and removal of residual plant material by wind etc. This may be partly true considering the dominance of very fine sand in fossil dunes that would have provided close packing hence preventing the carbon from either physical translocation or oxidation. With this premise identical samples are luminescence dated from the sequences discussed above.

All the samples measured show no measurable nitrogen and the organic carbon concentration varies from 0.07 to 0.47%. In the modern samples from stabilized dunes of Thar, Dhir (1977) has reported a mean value of 0.11%. The basin wise plot of percentage organic carbon variation against age is shown in figure 5.2. In Mahi basin there is a gradual increase in organic carbon from 23 ka (with marginal decrease around 18 ka). This is

followed by a steady increase till 12 ka, a period which corresponds to the landscape stability in Mahi basin. Compared to this, in the adjoining Sabarmati basin, there is a monotonous trend of organic carbon fluctuation centering on 0.1% value until around 11 ka. This is succeeded by a steady increase reaching a value of >0.4% around 8 ka After this the concentration decreased and remained constant at 0.3 % (Fig. 5.2).

The spatial variability in dune deposition during postglacial times is seen in Mahi and Sabarmati basins. In the former dune accretion stopped after 12 ka where as the latter shows



5.2. Variations in the organic carbon content of stabilised dunes in the Sabarmati and Mahi River basins (raw data is given in Appendix-4).

resumption of dune building activity after 8 ka. Since dune stabilisation is directly related to the availability of moisture hence vegetation, the gradual increase in organic carbon since 18 ka in Mahi basin and peaking around 12 ka indicates better vegetation cover compared to Sabarmati basin. Since dunes post dating 12 ka were not located in Mahi basin, it can be

inferred that post-Holocene climatic perturbation could not reactivate the processes responsible for dune accretion due to the establishment of vegetation cover. Evidence for the regional landscape stability comes from the adjoining Sabarmati basin where a distinct increase in organic carbon after 11 ka and peaking around 8 ka is observed. Following this, the organic carbon concentration decreases and remains constant at 0.3% during 7 - 6 ka (Fig. 5.2). This is relatively higher compared to the modern value of 0.11% (Dhir, 1977). Though the above data are preliminary in nature, however, the available trend is quite encouraging suggesting the possibility of using the dune organic carbon as a proxy for reconstructing the relative change in vegetation during the dune building activity.

In the Higher Central Himalaya, geomorphological configuration of Garbayang and Goting basin indicates that THF acted as natural barrier against the advancing valley glaciers. This is evident by the presence of terminal moraines at Chhiyalek (Garbayang) and Khal Khuras (Goting). This event is placed at MIS-4. Since no subsequent moraine intercalation in lacustrine deposits is seen, it can reasonably be inferred that the lacustrine sedimentation in Garbayang commenced after the MIS-4.

The sedimentation pattern suggests a proglacial lacustrine environment. The upper lacustrine sequence indicates varve sedimentation continued around 20±3 ka. Between 20±3 ka to <13±2 ka, sedimentation was dominantly varve in character (Fig. 4.7, Unit-1). This was succeeded by thicker laminae (~3 cm) along with rhythmic appearance of fine sandy-silt laminations suggesting enhanced discharge from the glaciers. The lake then reverted back to cooler condition after 13±3 ka during which fresh water supply reduced and anoxic conditions for the preservation of thick clay rich organic laminations prevailed (Fig. 4.7, Unit-2). Coarser detrital flux, less carbonaceous matter and distinct calcareous laminae suggesting resumption of fresh water influx into the lake.

The above reconstruction of lacustrine environment is strengthened further by the magnetic and elemental data. A drop in susceptibility around 18±3 ka (LGM) is seen. Asymmetrical saw-tooth shape curves of susceptibility variations and S-ratio up to 13 ka and beyond follows this (Fig. 4.8). The low values seldom revert back to the 18±3 ka level. High frequency fluctuations in susceptibility and S-ratio between 18 ka and 13 ka indicate that the climate frequently oscillated between warmer and cooler conditions. An interesting feature associated with susceptibility and S-ratio is the sharp rise corresponding to warmer intervals and gradual decrease towards cooler phases (Fig. 4.8). Such features are typical of a glaciated terrain (ice sheet) where snow cover affects regional and global climates. In such areas minor changes in environmental condition (e.g. slightly warmer summer) can cause snow to disappear rapidly, resulting a change of albedo due to exposed landcover giving a greater warming effect (Adams et al., 1999). Though speculative, sharp changes in χ (associated with warm intervals) could be the manifestation of a runaway decadal scale changes in snow reflectivity over the Tibetan plateau that lies north of Grabayang basin and has profound effects on global climate (Ruddiman and Kutzbach, 1989). Between 12-11 ka (interpolated age), a marked abrupt drop in susceptibility, S-ratio and elemental concentration (Fig. 4.8) indicate that the lacustrine sediments did register the postglacial cooling. Coincidentally the timing corresponds to the Younger Dryas period (Alley, 2000; Adams et al., 1999) associated with North Atlantic climatic perturbation (Bond et al., 1993). In continental sequences Younger Dryas events correspond to reduction in African and Asian monsoon strength (Street-Perrott and Perrott, 1990, Gasse and Van Campo, 1994). More recently, evidence of postglacial cooling in Southeast Africa is attributed to the onset of north winds associated with the Younger Dryas (Johnson et al., 2002). Following this climate appears to have improved gradually and with full establishment of Holocene climate and catastrophic melting

of valley glaciers resulted into the deposition of the topmost gravel dated to 10 ka. Evidence similar to this are also obtained from the Bay of Bengal where a magnitude increase in sediment load was found between 11-7 ka. This has been attributed to enhance discharge in the Ganga-Brahmputra system (Goodbred Jr. and Kuehl, 2000).

In the adjoining Goting basin, lacustrine succession show an overall concordance in the variation of the elemental data and susceptibility with subtle difference in terms of absolute magnitude. Alumina levels range between 20.2 and 17.2 (wt. %) and TiO_2 values vary between 0.66 and 0.8 (wt %). Broadly two distinct domains of contrasting values can be seen in figure 4.13 A consistent high values Fe, Ti, Al and susceptibility are located between >24±2 ka and <18±3 ka. Following this a marked decrease is seen till 16 ka and beyond. In addition to this, sediments older than 18 ka show high amplitude and low frequency fluctuations, which is succeeded by high frequency oscillations of low amplitude after 18 ka (Fig. 4.13).

In the recent past increasing evidence suggest that a link between Northern-Hemisphere glaciation and Indian monsoon system exist. Poter and Zhisheng (1995), first time demonstrated that increase in grain size in the loess deposits of China are linked to the North Atlantic cooling caused by episodic surges of ice bergs (Heinrich events), thus suggesting a teleconnection between the two. Similarly, the climate change prior to 11 ka in tropical Africa was closely linked to the cold conditions in the Northern Hemisphere (Johnson et al., 2002). Bard et al., (1997) have shown that inter hemispheric synchrony of abrupt postglacial warming has been suggested to be in phase with that of the Northern Hemisphere. Pattern and timing of the summer monsoon enhancements in western Chinese loess plateau show a correlation with that of the North Atlantic climatic record suggesting a teleconnection between tropical ocean air masses and North Atlantic climate system (Fang et

al., 1999). Gupta and Thomas (2003) based on benthic foraminifera record from eastern equatorial Indian Ocean show that Indian monsoon varied dramatically since past 5.5 Ma. According to them, though not certain of the mechanism, however they documented a strong link between changes in the intensity of the Indian monsoon, biotic activity in the Indian Ocean and North Hemisphere glaciation. The above evidence are indicative of the fact that Northern Hemisphere glaciation significantly modulated the global climate during the late Quaternary. There are arguments for the Tibetan plateau uplift and growth of large continental ice sheets through positive feed back mechanisim (Raymo and Ruddiman, 1992) and synchrony in Northern Hemisphere glaciation and phase of uplift of the northen Tibetan (Zheng et al., 2000). However, the recent evidence from Tibet by Schafer et al. (2002) negate the albedo of the Asian continent as a critical parameter for regional to hemisphere-wide climate change. This is based on their study on glaciation in Tibet suggesting limited ice cover at least during >170 ka. In view of this, the climate instability recorded at Goting that lies close to southern fringe of the Tibetan plateau possibly relate to the Northern Hemispheric glaciation. The role of Tibetan Plateau in adjusting the Asian and Northern-Hemispheric atmospheric circulation by latitudinal migration (north-south) of westerly jet during warm (interstadial) and cold (stadial) phases (Fang et al., 1999). Thus, it is likely that during the cold stadials, westerly jets would have penetrated beyond the Himalayan foot hills and probably reached the southern and western plains. This is evidenced by the dune building activity in the desert margin (Juyal et al., 2003) and loess deposition in the Central India (William and Clark, 1984).

The summer insolation calculated at 45^0 N indicates lowering of solar insolation around 28 ka that also marks the beginning of increase in global ice volume which peaked around 21 ka (Berger, 1978). Considering the error associated with age (i.e. age+error), the

response of Goting and Garbayang lacustrine successions were not monotonic. They show abrupt shift from a relatively warmer and wetter condition to a cooler condition after around 21 ka (18±3 ka) (Figs. 4.8 and 4.13). This is in phase with the peak global ice volume low insolation estimated by Berger (1978) and relates well with the Heinrich event –2 of North Atlantic (Bond et al., 1993). Porter and Zhisheng (1995) demonstrated a correspondence between episodes of loess deposition in China and Heinrich events that has been attributed to increasing strength of winter monsoon linked to North Atlantic via westerlies. Climatic evidence of global nature such as LGM and Younger Dryas obtained from the lacustrine succession of the higher Central Himalaya (Figs. 4.8 and 4.13) suggested a teleconnection between the Northern Hemispheric galciation and Central Himalayan climate during the Late Quaternary.

Evidence of regional cooling and weak southwest monsoon has been suggested for less extensive valley glaciation during 22 to 16 ka in the Central Himalaya (Benn and Owen, 1998). This work also suggests the absence of glacial moraine intercalation with lake deposits at Garbayang and Goting. Thus implying that valley glaciers remained much above the limit of penultimate glaciation (~60 ka) between 21 to 17 ka. Similar evidence have been reported from east and west Tibet indicating overall cold and dry condition (Schafer et al., 2002). However, the period was dominated by fine structure of low magnitude high frequency climatic instability in the lacustrine record. Such fluctuations during low summer insolation and global ice volume suggest millennial scale climatic controls, independent of orbital scale forcing (Grigg and Whitlock, 2001). Due to large uncertainity associated with the IRSL ages, short term fluctuations remained unresolved at this stage of the study.

Limestone constitutes one of the major lithofacies in Himalaya, and some of the lakes are located predominantly in limestone terrain (Kusumgar et al., 1992; Kotlia et al., 1997,

2000). Unless checked and if possible corrected for hardwater effect, uses of such ages for deducing palaeoclimatic inferences may be misleading or even erroneous (Geyh et al., 1998; Child and Werner, 1999). Though large uncertainty associated with IRSL chronology prevents us from correcting for the hardwater reservoir effect, however, it does indicate that the bulk radiocarbon ages in some cases are >50% over estimated.

Evidence of seismicity suggest that the Higher Central Himalaya, flanking southern Tibet responded to neotectonic activity associated with north-south and east-west extension structures. Events such as gorge formation, truncation of lateral and end moraines and perched glacial valleys are associated with the seismicity related to north-south extension (THF). These features terminate against the rising footwall of THF implying continued upliftment pre dating these events. An indirect age estimate for continued activity along THF is provided by an OSL age of 63 ka on the oldest valley glaciation from Gangotri glacier (Sharma and Owen, 1996). Pant (1999) based on the existence of morphologically similar advancements in Goriganga and Kali river basins, assigned MIS-4 to this event. It is thus reasonable to suggest that reactivation of north-south extension in Central Himalaya pre dates MIS-4 and its activity continued episodically as indicated by four distinct events that are bracketed between 24-17 ka and 14-13 ka respectively (Figs. 4.17). Subsequent events relate to east-west extension structures, and a luminescence age on terrace T_1 indicates that events postdate 11 ka (4.20). The most recent activity was in 1980 that caused ~3 m NE striking surface rupture in upper most outwash gravels at Garbayang. This was triggered by an earthquake which had an epicentre ~50 km south of the THF (along the MCT) that had also caused vertical as well as lateral movement in the region (Paul, 1986).