One of the most attractive Quaternary sites of India is in the Saurashtra peninsula. The structure of the peninsula itself is intriguing, as 12.7% of the Indian coastline surrounds it while only about 1.7% of Indian Subcontinent is confined to this peninsula. The Quaternary deposits of the peninsula (Fig. 1.1) consists of: (i) Carbonates geologically known as 'Millolites' and commercially as "Porbander Limestone", which extend over 5,300 km² upto an inland of 100 km from the coast and to an altitude of 200 m AMSL, (ii) Corals which are confined mostly to Okha-Dwarka region, and (iii) Oyster beds and beach rocks which are confined to the near-coastal areas (< 10 km from coast).
Fig. 1.1. Location of Saurashtra peninsula in India (insert) and detailed map of Saurashtra giving important towns, rivers and some prominent miliolite sites.
The name millolite was proposed by Carter (1849) who first reported millolites and found in them a large amount of foraminifera belonging to the genus 'Miliolina'. In literature, such carbonate deposits are referred as calcarenites, limestone deposits, lime muds, and aeolianites. However, to keep continuity with the published literature, I shall continue to use the term millolite for this carbonate deposit.

1.1 EARLIER STUDIES

The very presence of relatively thick (~12 m) deposit at Bamanbore which is 170 km from the millolite-bearing coast (Fig. 1.1) has generated controversies about its occurrence since Fedden (1934) who first mapped it. Based on visual observations, he classified this deposit as subaqueous and observed that this rock is a finely oolitic freestone, almost free from sand or other foreign particles. According to him, the farther its occurrence is from the coast, the purer is the limestone. Evans (1900) argued that in some places the preponderance of evidence favours aeolian origin, while on the other hand, many beds in all probability are sediments deposited in shallow water. For Chapman (1900), millolite rocks represented accumulations of aeolian material derived from littoral calcareous mud. The first petrographic study on 13 samples collected from different localities coupled with a systematic field evidences was
made by Shrivastava (1968a) who concluded that the formation consists mostly of beach sediments which were formed in agitated, warm and shallow waters of tropical shores. He considered the occurrence of millolites all over the tertiary coastal plains fringing the Deccan traps at high elevations, as an indication of a higher sea-level stand during the Pleistocene compared to that of today. According to Biswas (1971), the millolite rocks of Saurashtra coast were deposited earlier (Early Pleistocene) than the inland rocks (Late Pleistocene to Early Holocene) and the inland rocks were formed by the deposition of wind transported coastal deposits. From the studies carried out on the Quaternary deposits of Bhadar valley in Saurashtra, Lele (1973, 1975) opined that millolite is a product of direct sedimentation in a submarine/littoral environment by the transgression of the sea from southern and western sides of the peninsula and consequent submergence of different parts of Saurashtra. Sperling and Goudie (1975) believed that there are sound arguments in favour of aeolian hypothesis. Govindan et al. (1975), on the basis of their study of the Quaternary formations of the Lower Hiran valley in Saurashtra support the hypothesis of a marine origin for millolites but they do not rule out the possibility that a part of near-coastal millolites are of aeolian origin. From their extensive field studies, Rajaguru and Marathe (1978) and Marathe et al.
(1977) recorded the occurrence of brownish clay bands within the millilolite limestone. On the basis of its textural and petrographic characters, Rajaguru and Marathe (1978) suggested that millolites up to 40 m AMSL are marine including those at Shingoda and Umrethi dam sites (elevation of Shindoga = 104 m, Umrethi = 75 m). Verma and Mathur (1978), from their field and laboratory data on coastal and inland millolites, suggested that both marine as well as aeolian types are present in Saurashtra. According to Merh (1980), both marine and aeolian millolites coexist in the remote inland locations, Bamanbore and Chotila (Fig. 1.1).

Millolites occur as obstacle dunes, valley-fills, dune/beach ridges and as sheets. In hills like Barda and Alech, millolites are seen all around the hills (Verma and Mathur, 1978), contrary to the observation of Biswas (1971) and Sperling (1979) that their occurrences are confined to the south and south-westerly slopes of hills. Also, millolites do not occur on the top of Chotila hill, contrary to the observation by Krishnan (1968).

Shrivastava (1968 a) reported that the millolites along the coast are friable while inland ones are well-cemented. Lele (1975) observed that with increasing distance from coast, the limestone gets finer where the shells and oolites are more compactly embedded. The textural parameters of the modern and beach sediments give a clear picture.
for the better understanding of the depositional processes but in the case of ancient consolidated limestones like millolites, this study is not feasible due to the hardness of the deposit. Thin section technique is useful only if the detrital rock is monomineralic, having good sorting with small cement (Verma and Mathur, 1978). Only about 20% of the samples collected for the present study are friable where one can study the grain-size and grain-form parameters. Hence this study is too limited to arrive at any safe conclusion, regarding the marine (Shrivastava, 1960a; Lele, 1973, 1975) or aeolian origin (Biswas, 1971; Sperling and Goudie, 1975; Agrawal et al., 1978; Sperling, 1979) origin of millolites.

The presence of certain foraminifera made earlier workers to conclude that all millolites are of marine origin (Carter, 1949; Fedden, 1884; Auden, 1952; Krishnan, 1963). According to Shrivastava (1968a) the tests are broken, abraded and rounded by marine currents and got mixed with the microfaunal assemblages. On the contrary, another group of workers (Chapman, 1900; Biswas, 1971; Sperling, 1979) argued that the microfaunal tests were rolled and abraded by wind action during transport. The presence of foraminifera in the sands and in the recent dune sands of the Rajasthan desert was cited as an evidence for the wind transport of foraminifera from coast to inland (Chapman, 1900; La Touche, 1902; Sastri, 1961; Jacob et al., 1952; Allchin et al.,
1970; Sperling, 1979) but it was contended that the foraminifera found in the dunes of Rajasthan resembled to those that occur in Tertiary rocks of Kutch (La Touche, 1902; Godbole, 1972). It appears that sufficient systematic study on the identification of different species of foraminifera are yet to be done and hence conclusions based just on the absence/presence of forams without identification may be dubious, as according to Krishnan (1952), major part of Saurashtra and parts of Western Rajasthan were under sea during Tertiary.

Absence of macrofossils in inland miliolites was taken to be an evidence for wind transport by saltation (Biswas, 1971; Allchin et al., 1978; Sperling, 1979). Half-way up the central mountains of Girnar, habitat of small gastropod, CAMPTOMYX THEOBALDI was reported by Chapman (1900). In no other place this was reported. This interesting biological evidence belonging to Quaternary remains a probable/possible indicator that only the upper part of the mountain rose above sea (Verma and Mathur, 1978). Few invertebrate fossils and echinoids have also been reported from these miliolites which suggest that the deposition of miliolites took place under warm shallow water marine environment (Verma and Mathur, 1978).

Lele (1973) observed round quartz grains picked from few miliolite samples and attributed to water action while the features such as upturned plates, cleavage planes,
dish shaped depression, rounded abraded grains, rolling topography over the plain surface observed on two quartz grains, one from Chotila and one from Dungarpur, were attributed to wind action (Agrawal et al., 1970). According to Hussain et al. (1900), quartz is detrital and a minor component which is generally of aeolian origin but it may have nothing to do with the origin of the major component viz. CaCO$_3$.

1.2 TECTONISM AND SEA-LEVEL CHANGES

According to Krishnan (1968), the occurrence of millolites at high elevations is a clear proof of the elevation of the coast in recent times. Shrivastava (1960a,b) and Lele (1975) explained the occurrence of inland millolites at high elevations as due to tectonic upliftment. Biswas (1971) ruled out any post-Pleistocene uplift. Gupta (1973), based on the U-Th ages of corals from Okha-Dwarka region, concluded that Saurashtra coast remained stable during the Upper Pleistocene. Rao (1961) based on gravity and magnetic work in the alluvial areas of Northeast Saurashtra, Thorat (1979) based on the bathymetric setting, and Marathe (1961) based on the altitudinal differences in the occurrences of millolites of Hiran valley concluded that Saurashtra was tectonically unstable during the Late Pleistocene. Merh (1980), reviewing the earlier studies, summarised five likely levels of millolite occurrences which can be attributed to
marine transgressions during inter-glacials. Based on the aerial photography and Landsat imagery, Sood et al. (1961) and Sood (1983) reported the presence of strand lines (believed to be palaeoshore lines) in the coastal strip between Porbander and Diu (Fig. 1.2). They also presented evidences (discussed in Chapter II) against tectonic stability of Saurashtra during the Quaternary. Stone age tools which are lying below millolites have been reported in Hiran valley (Fig. 1.2) (Sankalla, 1965; Rajaguru and Marathe, 1973; Allchin et al., 1978; Marathe, 1981).

1.3 AGES

The least studied and most poorly understood aspect of millolites is their age. All earlier workers assigned Pleistocene to sub-recent ages, to the millolite formations. Agrawal et al. (1978), realising that millolites are not good material for $^{14}$C dating, did date few samples by the radiocarbon method and obtained ages in the range of 16.3 to 34.7 kyr. Hussain et al. (1980) applied the U-Th decay series methods to millolites and successfully dated a few samples which yielded 100-170 kyrs. It should be noted here that the U-Th decay series methods are the most suitable ones for dating Quaternary marine and terrestrial carbonate deposits (Ku, 1976; Ku et al., 1979).
Fig. 1.2. Exploded view of the Strandline and Hiran valley area. Area under detailed study is also indicated on the Saurashtra map (insert).
1.4 AIM AND SIGNIFICANCE OF THE PRESENT INVESTIGATION

The main thrust of this thesis is to date these carbonate deposits which have important bearing in the following:

(i) A systematic study on the age of the millolites provides a handle to decipher the tectonic history of Saurashtra peninsula and the estimation of uplift rates in far-off places from the major Plate boundary (Epeirogenic movements) would provide additional insight into the Quaternary Plate tectonic models. Apart from the combined effects of glacio-eustasy and regional movements, if well documented, the relative sea level record can be deciphered.

(ii) The question whether millolite formation is episodic (if so, the ages of episodes are important) or continuous is inexplicably interlinked with the Quaternary evolution of Saurashtra peninsula, and has yet to be answered. Quantitative assignment of ages to episodes of millolite formation and distribution of ages may enable to the understanding of the millolite genesis. It would be interesting to see whether any real age differences between aeolian type and marine type millolites exist.
Field investigations suggest that there are both marine (horizontal bedding) and aeolian features (cross bedding etc.) in the nearby areas and these different sequences are useful for understanding the Quaternary environmental changes.

Developing a chronological framework for the Palaeolithic cultures based on the Palaeolithic tools found interstratified between milliollites, would enable the reconstruction of the chronology of the various stages in the cultural and biological evolution during the Middle and Late Pleistocene. So far, the chronology of the Palaeolithic sites remained elusive in the Indian context as no suitable index fossils and radiometrically datable objects are reported anywhere in India.

The origin of inland milliollites is still debatable. The present study involves extensive sampling, dating by the $^{230}\text{Th}/^{238}\text{U}$ method, chemical and mineralogical (carbonate + detrital) distributions, stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) and $^{14}C$ measurements in addition to the conventional studies (which have been carried out by earlier workers) such as sedimentology and palaeontology. In addition to providing a time frame for the evolution and distribution of milliollites as well as for the Early Man in Saurashtra, the present study
is aimed at providing a comprehensive theory for the origin of miliolites. The Chapters are sequentially discussed as follows: In Chapter-II, the geological and geomorphological setting along with all available evidences for the tectonic instability of Saurashtra are synthesised. Experimental techniques employed in this study are briefed in Chapter-III and the results are presented in Chapter-IV. Discussion of the results is given in Chapter-V and conclusions are highlighted in Chapter-VI.