CHAPTER 2
LITERATURE REVIEW

General

As defined in the previous chapter, the present study aims to understand the geological evolution of the southern Kachchh within the time frame of Quaternary giving special emphasis on the Miliolite Formation. This chapter therefore presents a review of literature that is available and widely cited regarding the miliolite limestone, its relevance to the relative sea level changes and also its importance in understanding the neotectonic activities in this part of the region.

Miliolite nomenclature

The bioclastic carbonate deposits of interior part of Saurashtra, were first reported by Carter (1849, 158p.) as 'granular deposits' composed of oolitic particles' of calcareous sand united together in to firm compact rock on the Arabian sea coast having predominance of the forams belonging to Genus 'Miliolina'. Fedden (1884) continued usage of the term 'Miliolite limestone' after Carter (1849) and additionally described the 'coast fringing rocks' which is a coarse grained variety (Calcirudite) of the age coeval deposits which are later described as the 'Shell Limestone' by Bhatt and Patel (1998). This nomenclature leaves an impression that these carbonates are basically bioclastic limestone with Miliolidae as the main allochemical constituent, and suggests a marine origin. Although used extensively in the literature, the term Miliolite has been a misnomer because of the presence of a larger fraction of allochems other than *Miliolidae* (Biswas, 1971; Brückner et al.,1987).

Wynne (1872) were the first to report the miliolite occurrence of Kachchh and described them under the name of Concrete and consider them to be calcareous Sandstones (Carbonate Sandstones) of recent ages in the interior parts. While describing its use in the southern railways head quarter at Chennai (then Madras) and some buildings in Mumbai, Watson (1911) even used a term 'Porbandar stone' after its shipping as building stone blocks being done from the port town Porbandar in Saurashtra. The terms like Bela or Dungda (50X30X50cm) and Toda (70X30X15cm) are also being used by the local quarrymen.

Marine vs Aeolian theory

Fedden (1884) described the Miliolite as biogenically rich, oolitic freestone and Quaternary rocks of Saurashtra with a special mention of Chotila hill near Rajkot, where according to him "miliolite formed a fringe around the truncated top at a height of 1173 ft above sea level, suggest a product of shallow littoral marine origin".

Blake (1897) noticed in Kachchh, peculiar sporadic distribution of these deposits found suspicious for marine deposit, further pointed out that if these were marine deposits, larger marine shells should have been present along with the delicate and tiny *Miliolidae*. As an alternative, Blake (1897) initiated firstly that a strong wind might have carried the small carbonate particles from south or west nearest coastal areas and would be stopped by an obstacle in more southerly exposure composed of white and cemented with calcareous matter.

Foote (1898) described the miliolite rocks of the Kodinar as fine oolitic freestone composed of greater part of foraminifera whose tests formed the nuclieli of the oolitic grains of which the limestone is composed, and related them to a shallow marine deposition.

Also Evans (1900) studies of Saurashtra put forth an aeolian origin for some of the carbonate sand deposits, but invoked a higher strandline up to near Junagadh. He wrote, "There seems to be every reason to believe that Junagadh limestone was formed by aeolian action ... but it is impossible to believe that this calcareous material could have been blown 30 miles over barren plains. We must assume that at the time when it was formed, the present site of the city Junagadh was close to the margin of the sea". He believed that the miliolites were formed in shallow waters between tidal limits and were littoral accumulations, the inland deposits thus being "the product of transportation by wind action on the ancient coastal sediments".

Chapman (1900) also studied the Junagadh occurrences in Saurashtra and considered that the miliolite rock represents accumulations of aeolian material derived from "littoral calcareous mud" (which originally inhabited moderately shallow to littoral marine areas).Worn and polished morphology of the grains in miliolite limestone was suggestive of their abrasion by the transporting action of wind. However, he suggested that some of the miliolitic rocks of Saurashtra coast comprised deposits in the shallow marine waters and stated that these rocks cannot be older than Late Pliocene. Because of their inland occurrence and the petrography of samples (from Junagarh, Porbandar, and Jamnagar that typically contain foraminifera, pellets, ooids, and molluscan shell fragments), debates about their origin as either marine or aeolian began (Evans, 1900; Pilgrim, 1908; Lele, 1973).

Biswas (1971) suggested that the coastal sediments, transported by a persistent wind blowing towards the northwest, were deposited against physiographic obstructions in Kachchh. Mathur (1978) and Verma (1979) in their doctoral theses, have described south Saurashtra Miliolites, and consider these rocks are deposited by both marine as well as aeolian processes.

Biswas (1971) described the Miliolite occurrences of Kachchh in detail as peletoidal calcareous sandstone consisting essentially of quartz, calcareous pellets and cement. He envisaged the strong north-westerly winds for transporting these calcareous sands from south-eastern Saurashtra coast to as far north as Kachchh and to the various islands in the Great Rann.

Glennie (1970) also supported Evans (1900) and wrote in his book on ‘Desert sedimentary environments’ that the ‘this calcareous sand of western India are of aeolian origin’.

Goudie et al. (1977) made a critical review of the ideas of Biswas (1971) and Lele (1973), and propounded a possible aeolian origin for these deposits. Lele (1973) On the other hand, studied Bhadar valley and Chotila hill in Saurashtra and recapped the idea of Fedden (1884) and inferred a shallow marine / littoral environments origin for these lime stones based on the foraminiferal present in his study. In explanation of 300m above mean sea level at Chotila hill, he invoked tectonism. However, Goudie et al (1973) also described interesting dune morphology of the fossil dunes of Miliolites from Una-Veraval areas of Saurashtra.

Govindan et al. (1975) studied of the Quaternary formations of the Lower Hiran Valley in Saurashtra, and invoked a marine origin for the miliolite under zone of coastal environment.

Sperling and Goudie (1975) made a significant review of the ideas of Biswas (1971) and Lele (1973), and advocated a possible aeolian origin for these deposits, and suggested that “there are sound arguments in favour of an aeolian hypothesis in explaining the origin of a substantial part of the miliolite deposits of Kachchh and Saurashtra, while there may be more than one type of foraminiferal limestone of Pleistocene age".

Agrawal and Roy (1977) carried out the SEM studies of quartz grains of coastal as well as inland miliolites of Junagadh, Dungarpur and Chotila areas and concluded that the inland miliolite are definitely deposited by aeolian processes.

Verma and Mathur (1978) however suggested that the coastal occurrences of miliolites even up to 80 m amsl are related to the higher sea level and their present disposition is due to the epierogenic movements.

Allahabadi (1986) described the field occurrences of miliolites from all over the Kachchh, and on the basis of transport and depositional pattern, modes of occurrence, petrographic characters and available history of sea level changes in the region inferred that the all miliolite occurrences of Kachchh are of aeolian origin and the sediments were derived from the exposed coasts of the Kachchh only during a relative sea level.

Bhatt (2003) in reviewed the available understandings and also his own work on the Quaternary carbonate deposits of Kachchh and Saurashstra. Accordingly, the occurrences of shell limestone and miliolites together being huge dune field associated with the beach ridges related to ancient sea level. The inland deposits of Saurashtra and that of the Kachchh are mostly obstacle deposits partly modified by the fluvial processes as evident by the presence of gravels and pebbles of the substrate rocks inter-layered with carbonate sand forming small to moderate size trough.

Further in 2006 a DST sponsored field workshop on Quaternary carbonate deposits of Saurashtra was organized by Bhatt which recorded in-depth deliberations on the subject by many eminent scientist like Dr. Ken Glennie of University of Aberdeen; Prof. S. N. Rajaguru and Prof. Ashok Marathe of Deccan Collage, Pune; Dr. S. K. Biswas of ONGC; Dr. U. B. Mathur of Geology Survey of India, Jaipur; Dr. Rajiv Nigam of National Institute of Oceanography, Goa and Dr. N. Juyal and Dr. Ravi Bhusan from PRL, Ahmedabad.

Sea level changes

Sastri and Pant (1959) examined and mapped raised beaches associated with miliolite and other calcareous deposit of Saurashtra, raised beaches occurring at a height of 4.5m amsl assume an eustatic rise of the sea level during Pleistocene, and suggested that these limestones were products of Pleistocene marine transgression. On the basis of their foraminiferal content, they assigned a Pleistocene to Sub-Recent age to these rocks.

Shrivastava (1968) made a detailed petrographic study of the miliolite rocks of southern Saurashtra, and considered most of them including the inland ones, to be of marine origin. He attributed this sea level rise to the Quaternary tectonism, postulating down-faulting of entire Saurashtra in Pleistocene causing widespread marine transgression during which the formation of miliolite rocks took place. Following this the process of uplifting commenced during the Post-Pleistocene times, which is still continuing.

Hardas and Merh (1968) considered miliolite of Kachchh a product of marine deposition during Pleistocene or sub recent times, either due to a rise in sea level during the post-glaciations period or due to subsidence of Kachchh region. They have considered the rock to comprise a chemically formed marine limestone that could be named as sandy fossiliferous oomicrites.

On the basis of petrographic studies of Hiran valley miliolite of Saurashtra Rajguru and Marathe (1977) and Marathe et al. (1977) concluded that up to 40 km inland and about 100m above mean sea level the miliolites are seem to have formed in fluctuating high energy littoral and coastal dune environment to low energy tidal flat environment. On the archeological basis they have suggested miliolite limestone of higher reaches of Middle Pleistocene age, while coastal miliolites are of late Pleistocene age. They have also come to the conclusion that an early man saw the relationship between land and sea changing at least twice in the coastal parts of southern Saurashtra.

Ganapathi (1981) and Ganapathi and Merh (1986) found that the coastal dune accumulations related to the successive transgression and regression of the sea during and Late Pleistocene to Holocene between Gopnath and Mahuva coast were of more than one generation.

Ganapathi et al. (1984) have stated their height difference being related to the differential uplifts or subsidence along numerous faults that have cut the Saurashtra peninsula into several segments, where the sheet miliolite deposits of both along the coast and river valleys were deposited, in a marine environment.

Desai et al. (1982) suggested on Kachchh miliolite occurrences on account of the isostatic uplift and differential neotectonism. The low lying valley fill sheet deposits were of marine origin, whereas those abutting against the hills and ridges comprised obstacle dunes.

Deshpande and Sharma (1984) believe that Quaternary carbonate (miliolite) strata of western, southern and south-western coastal region of Saurashtra are of Mio-Pliocene and Pleistocene age, and have attempted to describe the stratigraphy and environment condition stated both high energy intertidal and supratidal deposition.

Mathur et al. (1986) stated that the Miliolite and Chaya Formations were deposited in or at near the strandline of a shallow Quaternary sea which fluctuated due to eustatic changes of southern Saurashtra during his study on the Quaternary stratigraphy.

Deshpande and Biswas (1986) stated about miliolite occurrences of Kachchh as well as Saurashtra of coastal region of Saurashtra of shallow marine intertidal and lagoonal environments, whereas the inland deposits were the recycled coastal marine deposits by aeolian and fluvial processes during Holocene.

Allahabadi and Patel (1986) described the various diagenesis processes by which the loose aeolian miliolitic sand have been consolidated subsequently to their depositional and transformed into miliolite limestone through various physical, chemical and biogenic alterations. The process of compaction and cementation has been brought through about in vadose environment mainly under influence of fresh water. The source of sparite cement in Kachchh miliolite is mainly endogenic and is on account of dissolution of aragonite and high-Mg calcite constituent and precipitate as low-Mg calcite mainly by meteoric waters. The precipitation and growth of cement in Kachchh aeolianites were controlled by various factors like, climate, mode of distribution of miliolitic sand, mineralogy of allochems, availability of fresh water, rate of super saturation of solution (fresh water) and nearby geological formations. Depending upon these factors Kachchh Miliolite shows varying degree of cementation.

Geochronology

After late 1980 due to its relation with regional sea level changes the Miliolites received a special attention for its geochronology. A range of techniques from as basic as Ca / Mg ratio to ^{14}C, ^{230Th} / ^{234}U and ESR were employed by different workers (Agrawal, 1971; Baskaran et al., 1989a & b; Bruckner et al., 1987). Recently OSL geochronology was made available for the Saurashtra Miliolites by Sharma et al. (2017) and that for the Kachchh Miliolites by Kundu et al. (2010). Bhattacharya et al. (2013, 2014) and Das et al. (2016a) provided the OSL geochronology of the fluvial sequences associated with the Miliolites of the Katrol Hill Range to infer the palaeoclimate and/or tectonic changes in the study area.

Agrawal (1969, 1971) dated some of the aeolianites of Kachchh by ^{14}C method and assigned Late Pleistocene age to them. Gupta (1972, 1977) also provided ^{14}C dates of dead corals and shells from the raised beaches of Saurashtra to indicate higher sea-level during the Late Quaternary, and not uplift of the coast during recent times.

Baskaran et al. (1989a) made available ^{230Th} / ^{234}U ages of the bulk Miliolite samples from Saurashtra and suggested a period of Middle Pleistocene (170kyr BP) to Early Late Pleistocene (45kyr BP) for its deposition. Baskaran et al. (1989b) suggested three age brackets for distinct miliolite deposition episodes i.e. M-I (50-70 kyr), M-II (75-115 kyr) and M-III (140-210kyr). M-I and M-II confined to inland areas, whereas M-III present in coastal small area <15km. Chakraborti et al (1993) also dated Kachchh Miliolite occurrences using ^{230Th} / ^{234}U method to propose an average age to be around 110 kyr.

Sharma et al. (2017) suggested that the radiometric dating of bulk Miliolite could give a range of ages; minimum being that of diagenesis to maximum being that of carbonate sediment generation, and hence advocated OSL chronology for reworked carbonate deposits like Miliolites. The OSL ages of Miliolites in the KHR of Kachchh range from 11.8 ka to 3ka (Kundu et al., 2010; Bhattacharya et al., 2013 & 2014; Das et al 2016a), which is in conformity with Sharma et al. (2017) that shows a prominent inland Miliolite deposition episode extending from coastal plain of Una to inland areas like Bamanbor (18-11ka), during the period of lower sea level.

Neotectonics

Late Quaternary geology of Kachchh remained focused on the major structural elements and associated neotectonics for the reason that the area manifests strong influence of it on its landscape that over masked significance of this unique Late Quaternary sedimentary record in Kachchh.

Recent worked carried out on neotectonics includes that of Chung and Gao (1995), Malik et al.(1999), Sohani et al. (1999, 2003), Thakkar et al. (1999, 2001, 2006), Biswas and Khatri (2002), Maurya et al. (2003c, 2008, 2017), Mathew et al. (2006), Patidar et al. (2007, 2008), Morino et al. (2008), Kundu et al. (2010), Chauhan and Thakkar (2014), Biswas (2016b) and Das et al. (2016a and 2016b).

Chung and Gao (1995) and Maurya et al. (2003c) provided detailed field documentation on the tectonic geomorphological characteristics of the Katrol Hill Range area and deduced that the Katrol Hill Fault (KHF) is a reverse fault dipping towards south direction.

Malik et al. (1999) stated that that the earthquakes with larger magnitudes ≥ 5 and lower magnitudes < 4 have occurred in the vicinity or along major E-W trending faults in Kachchh region, and they have observed that more number of earthquakes with $M > 5$ are concentrated along the ABF, and only two events with $M \geq 5$ (i.e.1821 and 1956) are recorded along the KHF.

Sohoni et al. (1999 & 2003) interpreted the deposition of Miliolite over the substrate in front of KHR as warping and related it with the tectonic uplift along KHF. According to the mall major set of joint found in Kachchh Mainland rocks and more pronounced in Tertiary rocks i.e NNE-SSW to NE-SW, WNW-ESE to NW-SE and E-W, however, the occurrences of E-W and N-S sets in Quaternary suggest flexuring activity along major fault within KHR and suggest continuous tectonic instability in this region during Quaternary, but the Quaternary Miliolite rocks shows only one well define set of joint (NE-SW).

Based on stratigraphic studies of Mainland Kachchh (Thakkar et al. 1999, 2001, 2006) and tectonic evolution (Maurya et al., 2003c) it was suggested that the present configuration of the landscape is due to the modification of the Early Quaternary physiography by the Late Pleistocene-Holocene tectonic activity. Thakkar et al. (1999) stated that the Quaternary deposits of the area such as alluviam and colluviam fans, channel deposit and miliolites help in categorizing Quaternary tectonic events in to two phases; reactivation of E-W trending faults during Early Pleistocene led to the present landscape configuration and formation of extensive alluvial and colluvial fans along these faults. The post miliolite phase resulted in movements along teraservers fault.

Maurya et al. (2003c) have investigated the Late Quaternary of the arid zone of Kachchh and suggested that Late Quaternary sedimentation and geomorphological evolution of Kachchh have followed regional pattern of paleoenvironmental and tectonic changes; colluvium at the base of range front scarps of the KHF overlain by miliolite suggest pre-miliolite early neotectonic activity which possibly occurred during the early Quaternary (middle Pleistocene).

Patidar et al. (2007, 2008) suggest that the landscape and drainage of the KHR have developed in response to neotectonic uplift along the KHF. As per them the incision by south-flowing rivers suggest southward directed neotectonic tilting of the range due to movements along the KHF that has occurred in three events of which the Event 1 occurred sometime in the late Pleistocene, while the Events 2 and 3 occurred in the early Holocene and late Holocene (< 2 ka), respectively.

Morino et al. (2008) mapped active fault traces along Bhuj Fault and Katrol Hill Fault, and trenching at Wandhay dam, Khari River along the KHF revealed occurrence of at least three large magnitude seismic events during geologic past. These events occurred along 3 major fault strands: F1, F2 and F3 the pattern of deformation was clearly revealed by the displaced terrace units as well as the overlying younger channel-fill deposits. The loose unconsolidated sediments and fault scarps developed on the alluvial-colluvial fan surfaces possibly suggest that these faulting events had occurred during late Holocene or recent historic past.

Maurya et al. (2008) in their Late Quaternary geomorphic evolution of coastal zone of Kachchh study conclude that the coastal alluvial plain provides evidence in support of tectonic uplift during early Holocene and in the last 2000 years. They stated that the raised beaches and mudflats observed along the coastline are the result of tectonic uplift that led to formation of fluvial terraces and the drying up of the Little Rann during the last 2000 years and the narrow coastal zone of southern mainland Kachchh showing a high degree of geomorphologic diversity has been primarily shaped by fluvial and coastal processes controlled by the inherited structural fabric and late Quaternary tectonic activity.

Kundu et al. (2010) Provide OSL dates from the Khari river section and inferred that the youngest event of tectonic uplift along KHF occurred at ca. 2.0 ka that shows uplift of about 1 to 2 m only.

Bhattacharya et al. (2013, 2014) studied the uplift and incision activities of fluvial sequences in the KHR area, and suggested that the younger < 3 ka uplift event is responsible for the incision of the valley-fill and the channel-fill sediments along with the bedrock incision; the time averaged Katrol Hill Range is uplifting at the rate of~4 mm per year, implying seismically active terrain. The According to their study the older tectonic activity pre-date 19.9 ka whereas the younger activity began sometime after 7.1 ka and probably continues till today. An extended phase of landscape stability (subdued tectonic activity) can be bracketed between 19.9 ka and 7.1 ka during which the channel aggradation responded to the regionally enhanced monsoon particularly around 9.4 -7.1 ka.

The studies of Das et al. (2016a and b) suggest that the terrain in the vicinity of NKHF and SKHF is uplifting at around 0.8 and > 0.3 mm / yr, respectively. The estimates are on the lower side compared to the observations made by Bhattacharya et al. (2014) along the valley and channel-fill sequences in the Khari and Gunawari rivers which are 3.1 and 4 mm/yr, respectively. Simultaneously, the incision in the Rukmawati River basin, post 11 ka, is ascribed to have occurred due to lowered sea level during the LGM and early Holocene period. They hypothesized that the aggradation was climatically modulated since 37 ka, however, the incision which began after 11 ka was a cumulative contribution of enhanced bedrock uplift (in the upper reaches) after 11 ka and sea level lowering in the southern alluvial plain.

Maurya et al. (2017) reviewed new data on neotectonic evolution of active faults in the Kachchh Basin and stated that the KHF shows highest intensity of neotectonic activity followed by the KMF, IBF, SWF and GF; vertically incised sections and deflection in the lower-order drainages within the vicinity of KHF fault suggests neotectonic activity along the KHF. Accordingly, the Quaternary sediments in the fault zones comprise colluvio-fluvial deposits, aeolian and valley-fill miliolites and coarse to finegrained alluvial deposits that indicate major neotectonically controlled aggradational phases. Offset in the Quaternary sediments, three surface faulting events in the last 30 ka, the youngest occurred at 3 ka BP.

Bhattacharya et al. (2014) gave the terrain uplifting rate of ~4mm per year assign with the time averaged of KHR incision rate. Based on OSL chronology, Prizomwala et al. (2016) reported an average uplift rate along the eastern KMF to be >1.04 mm / yr during the Late Pleistocene-Holocene period and a long term average incision rate of 1.41 mm / yr. Das et al. (2016b) suggests that the terrain in the vicinity of NKHF and SKHF is uplifting at around 0.8 and > 0.3 mm/yr, respectively.

Although actual an uplift of only up to 2m along the KHF at ca. 2ka has been documented by Kundu et al. (2010) in the Khari river section north of the KHR. Similarly, Sohoni et al. (1999) interpreted the deposition of Miliolite over the substrate in front of KHR as warping and related it with the tectonic uplift along KHF. These suggest that the tectonic uplift along the KHF is of episodic and low magnitude nature, and calculation of any uplift rate would be misleading.