Summary of the Ph.D. Thesis entitled

LATE QUATERNARY GEOLOGICAL EVOLUTION OF SOUTHERN KACHCHH, WESTERN INDIA WITH SPECIAL REFERENCE TO MILIOLITE FORMATION

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Background

The present day climatic patterns, landscape changes and sea levels could be predictably studied under the umbrella of the study of Quaternary geology, and hence it is of vital importance in developing sustainability for the mankind (Dawson, 1992; Shajan 1998).

The present study is aiming to understand the geological evolution of the southern Kachchh during late Quaternary time, primarily based on the unique kind of bioclastic sedimentary record (Miliolite Formation) that occurs on inland hilly landscape of the Katrol Hill Range (KHR).

The Quaternary Period is the current and most recent of the three periods (Paleogene, Neogene and Quaternary) of the Cenozoic Era in the geologic time scale of the International Commission on Stratigraphy (ICS).Quaternary covers 2.5 million years (Ma) and is divided into two epochs: the Pleistocene(2.588Ma to 11.7 ka) and the Holocene (11.7ka to present). Geologists have now defined the last 4,200 years as a new chapter in Earth's history, the 'Meghalayan Age' (IUGS, 2018). This age began at the time when an agricultural society around the world "experienced an abrupt and critical mega-drought and cooling".

The Quaternary sediments in Gujarat represent three depositional environments viz., marine, fluvial and aeolian. The interplay of paleoclimate and glacio-eustasy factors controlled the shaping of the landscape of Gujarat during Quaternary period (Merh, 1995). On the basis of landscape characteristics, sediments types and geological history, the Quaternary sedimentation has given rise to three distinct geomorphologic units which are still active sites of the sedimentation. These are;

1. The Ranns of Kachchh,
2. Coastlines of Kachchh, Saurashtra and South Gujarat, and
3. Alluvial plains of Central and North Gujarat.

Late Quaternary geological history of the Gujarat state has been studied in detail with special emphasis on Mainland Gujarat (Merh and Chamyal, 1993; Chamyal and Juyal, 2005 and references therein). There are two principal areas in Kachchh, which have witnessed significant Quaternary sedimentation. One is the flat saline wasteland of the Ranns, which includes the

Great Rann of Kachchh and the Little Rann of Kachchh which is obviously the product of marine deposition. Khonde et al. (2017).

The KHR constitutes a conspicuous physiographic high which is formed due to the tectonic uplift along KHF situated south of the Bhuj. Major rock mass of this is composed of the shale and sandstones of Jhuran and Bhuj Formations of Jurro-Cretaceous age with patchy occurrences of the Miliolite Formation of Middle to Late Pleistocene age. These were largely ignored by the previous workers who mostly focused on the seismicity and tectonic activities during the late Quaternary. The present study has mainly dealt with this fascinating sedimentary record as it bears the clues for better understanding of the evolution of the southern Kachchh in general and the Katrol Hill Range (KHR) in particular.

The importance of miliolite deposits in understanding the evolution of the southern Kachchh has been realized by the present author and therefore the study has remained focused on the miliolites of the Katrol Hill Range with an attempt to achieve the following objectives.

Objectives

1. To evaluate the Miliolite Formation of Kachchh for its significance in late Quaternary history of the region.
2. To reconstruct the late Quaternary paleoenvironment and geological history of southern Kachchh.

Methodology

To achieve the above objectives following methodology was adopted.

1. Literature review.
2. Geomorphological mapping using remote sensing data and SOI topographic maps.
3. Reconstruction of lithostratigraphy through regional correlation and lateral mapping of late Quaternary sequences exposed in natural and artificial cuttings.
4. Collection field data and sampling.
5. Textural and compositional studies using standard sedimentological procedures and also using advances techniques like SEM-EDS, XRF, Kappa-bridge, etc.
6. OSL Geochronology
7. Synthesis of the data to reconstruct geological evolution model of the study area.

Literatures, geochronology and neotectonics of study area.

The study area lies in southern Kachchh between latitude 22°.50'-23°.15'N and longitude 69.10°-69.50°, occupying an average area of 1000 sq km. The four windows which were studied extensively due to its conspicuous occurrences of the miliolites are described further as Kotda-Roha Area (KA) Fakirwadi Area (FA), Gangeswar Area (GA) and Varli Area (VA) in this chapter for its geomorphology and local geological set up with a summary of the available understanding on the Quaternary sequences.

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.

Available literature of miliolite limestone relevance to the relative sea level changes and also its importance in understanding the neotectonic activities in this part of the region. 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. Recently OSL geochronology was made available for the Saurashtra Miliolites and Kachchh Miliolites.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.

Baskaran et al. (1989a) made available ^{230}Th / ^{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 $^{230}Th/^{234}U$ method to propose an average age to be around 110 kyr.

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.

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/a. 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.

Geological set up of the study area

The Katrol Hill Range (KHR) constitutes a conspicuous physiographic high which is formed due to the tectonic uplift along Katrol Hill Fault (KHF) situated south of the Bhuj. Major rock mass of this is composed of the shale and sandstones of Jhuran and Bhuj Formations of Jurro-Cretaceous age with thin patchy occurrences of the Miliolite limestone of Middle to Late Pleistocene age.

Katrol dome exist in eastern side from where the prominent hill range starts and extend westward up to Naira River. KHR hosts Late Quaternary sediments in the form of colluvium, fluvial gravels and carbonate sand (miliolite). The KHF is one of the most significant faults in Kachchh, which show several evidences of active tectonics during the Quaternary time (Sohoni and Karanth, 2003; Thakkar and Goyal, 2004; Patidar et al., 2008 & 2007; Chauhan et al., 2016). In the Gangeshwar dome along the northern side of the Katrol Hill scarp, patches of shale belonging to the Jumara Formation were encountered. This is the oldest unit in the study area that contains ammonite fossils. On its northern side the Bhuj Formation sandstone abuts against the KHF indicating the up thrown nature of the southern side which largely exposes shale and sandstone of the Jhuran Formation.

The KHF is 75 km long, on surface it is expressed as steep north facing scarp in the KHR, located in the central part of the mainland Kachchh Basin and exhibits a rugged mountainous landscape that exposes well-lithified rocks (sandstones, limestones and shales) of Mesozoic age.

Style of Miliolite deposition

The Late Quaternary carbonate deposits (Miliolite) occupies various physiographic levels in the Katrol Hill Range, and occurs in a patchy manner lying over the substrate of either Mesozoic rocks or buried colluviums developed over it. These were documented from various localities of the study area and are described in detail in this chapter. Based on the mode of occurrences, sediment body geometry, physiographic level and nature of sediments, three distinct types of mode of occurrences were recognized viz., Type-I Obstacle dune deposits, Type-II Valley fill deposits and Type-III Fluvial reworked sheet deposits. The Type-I deposits are characterized by a typical triangular geometry resting unconformably on the slopes of the Katrol Hill Range. The substrate rocks are mainly shale and sandstone of the Jhuran and Bhuj Formations. In some places, the Deccan Trap Formation basalt hills have also provided obstacles. Type-II deposits are occupying the rocky amphitheatres and valleys associated with these hills, probably as slope wash during the onset of wetter phases. The type-III is secondary reworked deposits of pebbly, gravelly mixed carbonate sand that also contain pebbles of earlier deposited Type-I miliolite. These are younger and have been thought to be deposited by seasonal fluvial activities in Holocene time.

Lab Analysis an OSL Chronology

To understand the depositional dynamics of any sedimentary system it is necessary to have detailed examination of its textural and compositional attributes. This shed light on the sediment source, pathways and burial at the place of the study the OSL is a more suitable technique that provides an age estimation for the burial of the quartz grain for such kind of reworked carbonate deposits. Therefore, although very limited samples were analyzed for the OSL geochronology with the kind help of the ISR, Gandhinagar. Also investigated the prime constituent under study-the miliolites for its grain size and related parameters as well as its constituents such as allochems, detritals, cement and ultra-structures and micro-chemistry using SEM-EDS. An attempt is also made to present primary data on its bulk magnetic susceptibility, of course with limited application. To understand the detrital interference and diagenesis of these rocks, limited samples were analyzed using XRF facility of the Institute of Seismological Research (ISR), Gandhinagar.

Landscape Evolution

Maurya et al. (2003) on the basis of the exposed Late Quaternary fluvial sequences of southern Mainland Kachchh recognized three distinct geomorphic surfaces S1, S2 and S3. Accordinly, S1 developed over the corse gravelly facies is the oldest defining the featureless alluvial plain that has gentle southward slope; S2 surface is the extremely dissected surface characterized by deep ravines, essentially produced by incision-gully erosion faces that carved on the pre-exist S_1 surface, whereas S3 surface is developed by significant amount of incision of young streams and exposed Quaternary sequences and characterized a low flat terrace surface .

The late Quaternary aulting events and tectonic uplift along the KHF has been studied by Patidar et al. (2007 and 2008) that was further also provided the OSL geochronology by Kundu et al. (2010) have suggested that the Faulting (F1) episode in the Khari river section is of < 30ka whereas, the F2 is of < 2ka age. Neotectonic activities along the KHF then must have intensified the incision of the Quaternary sequences (Patidar et al. 2007, 2008; Kundu et al. 2010; Das et al. 2016). Based on the incision of these sequences including the Miliolites Das et al. (2016) also proposed a rate of uplift along the KHF to be about 2 to 5 mm/yr. However, their estimates of rate of uplift cannot be precise due to the fact that the erodibility of miliolitic units is almost twice than that of the substrate rocks The phases of deposition and erosion during Late Pleistocene and Holocene have followed climatic changes of regional dimension and imprinted as facies and sub facies that characteristics of sediments are pre, syn and post miliolite phase. As per the available ages of Type-I deposits, the syn-miliolite phase covered 20 to 10ka (Late Pleistocene to Early Holocene), whereas the post Miliolite phase that consist of Miliolites of Type-II and III occurred during 10 to 7ka. Table 7.1 presents a summary of the stratigraphic set up and its relation with various episodes recorded in the late Quaternary sedimentary record of the KHR area.

Overall the miliolites of the KHR suggest that these marine sediments must have been deposited during the drier periods as obstacle dune deposits (aeolian) on the hill slopes which were then reworked with the initiation of monsoon activities as valley fills characterized by much more sediment availability than the stream power. Later the sediment availability has decreased and incision of valley fill deposits stared giving rise to thinner reworked fluvial sheets.

The evolution of the landscape of the KHR in Kachchh can be summarized in four distinct stages as described in discussion.

Stage-I: Due to the onset of inversion tectonic the Kachchh basin was closed by the end of the Pliocene time and major structural elements such as Nagarparkar Fault, Kachchh Mainland Fault and Katrol Hill Fault started manifesting the uplift of the area that gave rise to prominent physigraphic highs oriented along east-west (Maurya et al., 2017).

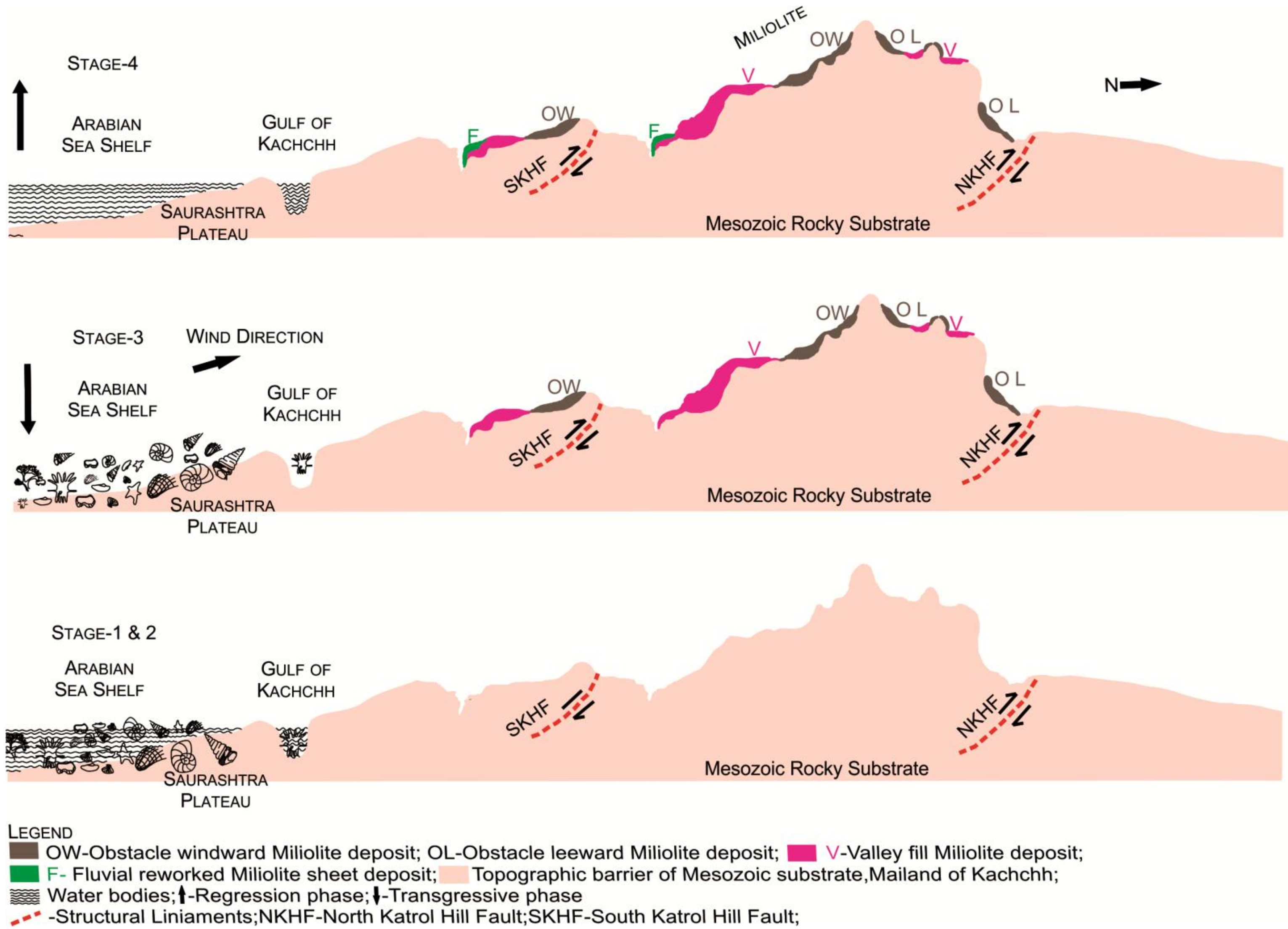
Stage-II: During the Middle to Late Pleistocene time the coastal areas of Saurashtra and Kachchh experienced relatively higher sea levels and warmer climate that could provide better habitat conditions for marine biological activities to generate bioclastic carbonate sand along its coast. The radiometric ages of the Miliolite (Baskaran et al., 1989a) support this inference in context with the global sea level changes.

Stage-III: During Late Pleistocene time i.e. 60-20ka the sea level started dropping and lowered to about 110m from the present day level by the 20ka (Hashimi et al., 1995; Muhs, 2013). This made the carbonate sand available to the deflation process by onshore winds.

Stage-IV: After the onset of Indian Summer Monsoon by about 13ka (Das et al., 2017) the availability of the carbonate sand was reduced and with increased moisture, it started stabilizing. Episodic surface runoff reworked the sediments from the slope and from the valley that got mixed with the locally derived gravels and pebbles to form fluvial sheets on the banks that contained Miliolite pebbles and gravels also, along with carbonate sand that contributed to cement and consolidate these sheets (Type-III Miliolite). The OSL ages of about 11.8-7.1ka of valley fill Miliolite at Gunavari (Bhattacharya rt al., 2014) support this inferences.

Phases	**Sedimentary Units / Facies Association**	**Sub facies characteristics of Sediments**	**Occurrences**	**OSL Age and Environment (Bhattacharya et al., 2013, 2014, Das et al., 2016a, Sharma et al.,2017, Present study.,2018)**	**Geomorphic Surfaces (S1,2 & 3) (Maurya et al. 2003b) and Faulting event 1,2 & 3 (Patidar et al. 2008) (Kundu et al. 2010)**
Post Miliolite **(7.1ka to Rec)**	Scarp derived colluviums Youngest Deposit. Terraces facies	Angular to sub angular pebbles and cobbles embedded in sandy to gravelly matrix. The deposit comprises of debris facies consists dominantly of class with subordinate matrix, whereas the wash facies is comprised of dominantly sandy matrix with dispersed clasts and occasional nested (embedded, surrounded and fixed) set in clasts.	At base of the front scarp. Scarp-derived colluviam is the youngest of the Quaternary deposits. At places overlies the alluvium whereas at other places it rest on directly on the fluvial miliolite.	Late Holocene Shallow braided stream channels under reduced level of neotectonic activity. **(~3.0ka)**	F2(event 3) **< 2ka** Khari section Fault.
	Alluvial deposits. Incision-erosion facies.	Fine sand, silt and clay. Scattered distributions fine-grained channelized alluvium. Incision3to5m and erosion 8 to15 m deep gully form high cliffs along the river banks. Comprise fine to coarse sands with layers of cross-stratified gravels.	Sporadically along the various north flowing streams.		Uplift of S3 - significant amount of incision by young streams and exposed Quaternary sequences
Syn Miliolite phase OSL ages **(20-7.1 ka)**	Reworked miliolite fluvial-Sheet facies **(Type-III)**	The horizontally stratified sandy sheet of miliolite deposits having fluvial deposition signature mixed with pebbles, cobbles of country rocks. It include well-stratified sediments, presence of gravel rich layers, fluvial sedimentary structures such as small scour and fill, cross bedding and large clasts of Mesozoic rocks.	Extensively deposited along river valleys.	**fluvial-Initiation of monsoon (11.8 to 7.1ka)**	
	Valley fill miliolite Facies **(Type-II)**	Thick pile of loosely uncontaminated-clean in nature, full of miliolitic sand fine to medium sand size grains, buff dirty white yellowish to reddish cream in colour.	Occupying Mesozoic depression along river valleys flood plain.	Early Holocene Gorges formation	
	Obstacle Facies Wind ward and lee ward miliolite **(Type-I)**	Distinct internal large scale aeolian cross bedding and uniformly well sorted fine to medium sand grains size carbonate rich sand, friable, moderately cemented, upper surface became matt black due to weathering.	Obstacle dunes, all higher evaluation on along the south slope of the hill range and at the base of the north facing front scarp.	**MIS-2 (LGM) Declining monsoon** **on set of aridity (20.3ka to 8.0) Dustier-MIS-3**	S2- Incision-erosion **>20Ka** Vertical incision and lateral planation of Mesozoic and Tertiary F1, (event 2)< 30ka. Khari section Fault. F3,(event 1) occurred sometime in Late Pleistocene
Pre-Miliolite phase **(> 20ka)**	Oldest Coarse gravelly faces Reactivation of KHF	Boulder unsorted colluviam Boulder-size fragment of Shale, thin bedded of sand stone and siltstones. Degradation of scarp. These deposits suggest pre-miliolite neotectonic activity along the KMF.	Alluvial fans in front of the scarps.Colluviam at the base of range front scarps (Base of Quaternary, at places colluviam overlies the Mesozoic)	Debris flows and sediment gravity flows, as small Coalescing and denudation in KHR. Late Pleistocene **MIS-5**	- featureless alluvial plain-gentle Southward slope. Where S2 & S3 are developed
Mesozoic Stratum					

Stratigraphy, lithological characteristics, occurrence, ages and depositional events of Late Quaternary sequences in KHR, Kachchh.



A conceptual model of Late Quaternary history of Katrol Hill Range with reference to the Miliolite deposition in Kachchh