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Subir Sarkar *Editors*

Mesozoic Stratigraphy of India

A Multi-Proxy Approach

The Society of Earth Scientists
2008

Springer

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ISSN 2194-9204 ISSN 2194-9212 (electronic)
Society of Earth Scientists Series
ISBN 978-3-030-71369-0 ISBN 978-3-030-71370-6 (eBook)
https://doi.org/10.1007/978-3-030-71370-6

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

An Overview of the Mesozoic (Middle Jurassic to Early Cretaceous) Stratigraphy, Sedimentology and Depositional Environments of the Kachchh Mainland, Gujarat, India

Mahender Kotha

Abstract The Mesozoic rocks in the Kachchh Basin, with their varied lithological characters and depositional facies, have been a focus of geologists' attention since the pioneering work of Wynne and Fedden in 1872–74, more than a century ago. The prolific megafauna, especially the Upper Jurassic ammonites, of the Mesozoic succession of Kachchh is well known globally that attracted paleontologists, while the wide range of condensed sections exposing Bathonian to Pleistocene drew the stratigraphers' attention. The Jurassic ammonite fauna of Kachchh is essential for its regional significance and broad provincial interest. Although an excellent volume of data is available on the Jurassic succession of India, most of that focus attention on paleontology and stratigraphy. The varied depositional, erosional, and biogenic structures present in the Mesozoic sequence of Kachchh are quite interesting. The exposed Mesozoic sequence of Kachchh Mainland consists of rocks ranging from Middle Jurassic to Early Cretaceous, is divided into four formations viz. Jhurio, Jumara, Jhuran, and Bhuj in ascending order. The Jhurio and Jumara formations, belonging to Middle Jurassic, represent a mixed carbonate–clastic sequence, while the Jhuran Formation (Late Jurassic) and Bhuj Formation (Early Cretaceous comprises an essentially clastic succession. In all, 13 lithofacies associations with varying depositional conditions are observed from the entire exposed Mesozoic succession of Kachchh Mainland. Sandstone and shales are the dominant lithologies of the succession, while the carbonate rocks occur only to the Middle Jurassic exposures. Petrographically, the sandstones belong to the predominant quartz arenite to feldspathic arenite categories, followed by a few lithic arenites, and the associated carbonate lithologies belong to a variety of types, ranging from mudstone to grainstones, and exhibit a variable microfacies character and diagenetic modifications. The present work highlights an overview of the sedimentological account of the Mesozoic succession of Kachchh Mainland and discusses the distribution of the variety of clastic and carbonate facies types and their use of the paleoenvironmental reconstruction for understanding the paleogeography of Kachchh Basin.

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S. Banerjee and S. Sarkar (eds.), *Mesozoic Stratigraphy of India*, Society of Earth Scientists Series, https://doi.org/10.1007/978-3-030-71370-6_4

Keywords Kachchh mainland · Mesozoic sedimentation · Lithofacies association · Stratigraphy · Paleogeography · Facies

1 Introduction

The sedimentary basin of Kachchh (also known as Kutch), well known for its prolific megafauna, especially the Upper Jurassic ammonites, possesses a vital perspective for paleontologists, stratigraphers, and sedimentologists. The abundance of fossil faunas and the wide range of condensed sections exposing Bathonian to Pleistocene have attracted both paleontologists and stratigraphers (Fig. 1a, b). Arkell (1956) quoted this classic area as probably the most favored locality in the world for Upper

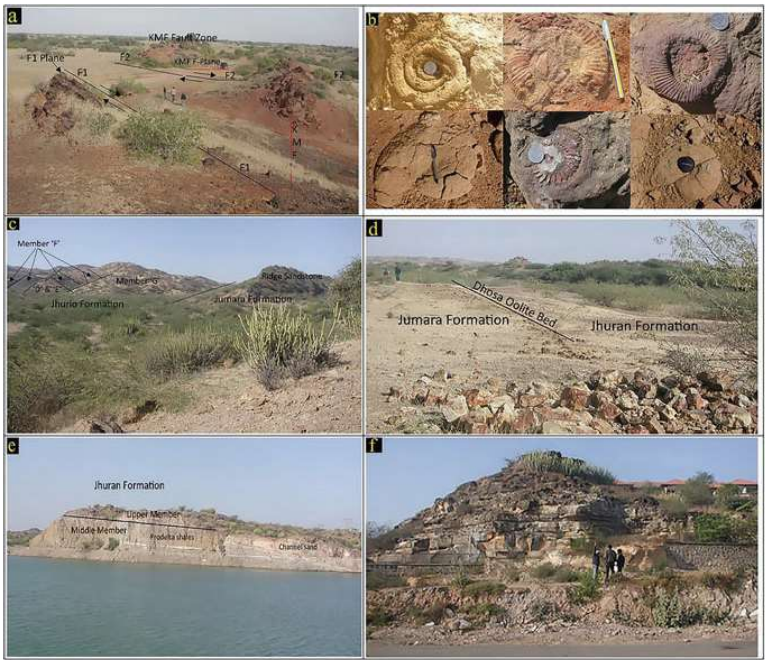


Fig. 1 Field photographs of Mesozoic outcrops: **a** Glimpse of Kutch Region and its geological importance, **b** Ammonoid fossil specimens preserved in the Mesozoic succession of Kutch, **c** Jhurio Formation as exposed at the core of the faulted Jhurio Dome, **d** Type section of Jumara Formation, northern periphery of Jumara dome. Top of Jumara Formation marked by Dhosa Oolite bed, **e** Middle (Shale) and Upper (Sandstone) members of the Jhuran Fm as seen in the Khari Nadi cliff near Rudramata temple and **f** Reference section of Bhuj Fm at Mandvi/ Lakhpat Road Junction along Ring road, opposite Prince Residency Hotel, Bhuj (coin diameter = 2.5 cm)

Jurassic Ammonites. He also pointed out that the lower part of Callovian is probably more fully developed in Kachchh than anywhere else.

The east–west aligned pericratonic sedimentary basin of Kachchh with vast plains dissected by a few low rising hills came into existence during the Late Triassic – Early Jurassic at the time of rifting of Africa and India (Biswas 1981). The basin has experienced periodic carbonate sedimentation interrupted with a vast siliciclastic deposition from Middle Jurassic to Neogene. The Mesozoic rocks are exposed in six highland areas viz. Kachchh Mainland, Wagad, Pachham, Khadir, Bela, and Chorar, whereas the Tertiary strata are exposed in the adjacent plain lands. Regional structural elements of the Kachchh Mainland consist of two parallel fault flexures along the NW–SE striking master faults (Biswas 1981, 1982, 1987, 1991). The Jurassic rocks are best developed in the northern flexure. A string of culminations observed along this flexure with depressions between them. These zones of culminations stand out in domal forms at Jara, Jumara, Nara, Keera, Jhura and Habo hills, where inliers of Middle Jurassic (relatively older) rocks, the Jhurio and Jumara formations occur at the core of these domes. The dried-up nalas, cliff sections, and road cuts provide good exposures of Mesozoic outcrops for sample collection (Mahender and Sharma 2010). While attempting to briefly review the work done earlier on stratigraphic and sedimentological aspects, this paper also presents a comprehensive account of the sedimentation history of the Mesozoic succession of Kachchh in order to understand the provenance and depositional environments.

Although the list of investigations on Kachchh is enormous, much of the available literature focuses attention mainly on the paleontology and stratigraphic aspects (Wynne 1875; Waagen 1871; Spath, 1933; Rajnath 1932, 1942; Agarwal, 1957, 1975; Ghosh, 1969; Biswas 1970, 1971, 1974, 1977, 1981, 1991; Singh and Kanjilal 1974; Krishna et al. 1983, 2000; Krishna 2017). Some of the past studies integrate the sedimentological aspects with geochemical characteristics of the Mesozoic Sediments of Kutch Basin (Shukla and Singh, 1990; Phansalkar et al. 1992; Khadkikar 1996; Dubey and Chatterjee 1997; Osman and Mahender 1997; Mahender and Sharma 2010; Ahmad et al. 2006, 2014). The detailed lithostratigraphic classification of Mesozoic of Kutch was proposed by Biswas (1977) based on detailed field studies. Some of the most recent contributions of Mesozoic of Kachchh are as follows: Mesozoic foraminiferal study (Gaur and Talib 2009; Talib et al. 2012), study of Ammonoidea assemblage of Callovian and Upper Jurassic Bivlaves (Bardhan et al. 2009, 2012), endemism and phylogeny of Bathonian–Callovian Ammonoidea (Dutta and Bardhan 2016), hydrocarbon exploration (Patil et al. 2013), possible oceanic anoxia in Jurassic (Arora et al. 2015, 2017); detrital zircon and monazite for tracking the source of Mesozoic Sediments of Kutch (Chaudhuri et al. 2020a), paleogeographic implications of glauconite composition (Banerjee et al. 2016; Bansal et al. 2017), systematics, endemism and phylogeny of Bathonian–Callovian Ammonoidea (Dutta and Bardhan 2016), Upper Jurassic soft Sediment deformation structures as a testimony to seismites (Kale et al. 2016), stable isotopic studies and its potential for paleoecologic, paleoclimatic, and paleogeographic reconstructions of Middle to Jurassic belemnites and brachiopods (Alberti et al. 2012a, b), overview of the lithostratigraphy, biostratigraphy and paleoenvironment of the Middle to Upper

Jurassic sedimentary succession (Alberti et al. 2017), oldest turritelline gastropods of Upper Jurassic (Das et al. 2018), compositional evolution of siliciclastic sediments recording the tectonic stability of a pericratonic rift during the Mesozoic Kutch Basin (Chaudhuri et al. 2018, 2020a,2020b,2020c,2020d). The present paper gives an overview of the stratigraphic sedimentology, and the depositional environments Mesozoic sequence of Kachchh Mainland.

2 Geological Background

The Mesozoic sedimentary strata, ranging in age from Middle Jurassic (Bathonian) to Early Cretaceous as exposed in Kachchh Basin is divided into four formations viz. Jhurio, Jumara, Jhuran, and Bhuj in ascending order (Biswas 1977). The Mesozoic rocks overlie the Archean basement and disconformably underlies the Late Cretaceous basic flows of the Deccan Trap in the southern and western parts and Tertiary sediments in the eastern part of the basin. The sequence was developed due to repeated marine incursions during the Middle Jurassic to lower Cretaceous period followed by major tectonic movements and Deccan Trap volcanism in the Late Cretaceous time (Biswas 1977). The present work is based on (a) systematic sampling along selected traverses, (b) samples from cliff sections, and (c) spot sampling from specific localities presents an overview of the systematic stratigraphic sedimentology of the Mesozoic Sequence of Kachchh Mainland. The general distribution and occurrence of outcrops and their field character can be found in Mahender et al. (2008) and Mahender and Sharma (2010).

3 Systematic Stratigraphy

The Mesozoic stratigraphy of Kachchh Basin comprises strata ranging in age from Middle Jurassic (Bathonian) to Recent (Holocene) (Table 1). Mesozoic rocks, are divided into four formations viz. Jhurio, Jumara, Jhuran, and Bhuj in ascending order (Biswas 1977). The first two formations (Jhurio and Jumara) belong to the Middle Jurassic, the Jhuran Formation is Late Jurassic, and the topmost Bhuj Formation belongs to an Early Cretaceous age (Biswas 1977, 2005). The Tertiary sediments lie over the Trap and the Mesozoic sediments wherever the Trap is absent. A detailed description of each Mesozoic formation is given in the following paragraphs, and a summary of the generalized Mesozoic lithostratigraphic succession Kachchh mainland is presented in Table 2.

Table 1 Litho–stratigraphic classification of the Mesozoic rocks of Kutch (after Biswas 1987)

Stages	Kutch Mainland Group		Pachchham Island Group			Eastern Kutch Group		
			Member		Formation	Khadir– Bela– Chorar Islands	Wagad Highland	
			Goradongar	Kaladongar				
Tertiary	**Formation**	**Member**						
Maastrichtian –Danian	Deccan Trap	Basalt Flows						
Albian	**Bhuj**	**Upper Member:** massive sandstones						
Aptian		**Ukra Member:** Green glauconitic shale/ferruginous bands with fossil.						
Hauterivian to Barriasian		**Ghuneri Member/ Lower Member:** sandstones/shales/ferruginous bands/Shales with plant fossils.						
	Jhuran	**Katesar Member**: massive sandstones						
Tithonian		**Upper Member :** fossiliferous sandstones, shales, hard calcareous sandstones					Recent Deposit	Recent Deposit
Kimmeridgian		**Middle Member:** mainly shales, fossiliferous, with sandstone interbeds.					WEST——— EAST	**Wagad Sandstone**
		Lower Member: sandstones/shales/arena—ceous limestones with fossils					Gamdau Member / **Wagad Sandstone**	
Oxfordian	ordian	HIATUS	Recent Deposit Miocene Shales Paleocene laterites	Recent Quaternary		Quaternary to Recent Deposits	Kanthkote Member.	

(continued)

Table 1 (continued)

		Dhosa Oolite Member			Tertiary, Quaternar y and Recent			Patasar Shale Member	
Callovian	Jumara	Gypseous Shale Member				Bambhanka/ Gangta Bet Member	Gadhada Formation	Nara Shale Member	Washtawa Formation
								Kharol Member	
		Ridge Sandstone Member.							
		Shelly Shale Member	Modar Hill Formation		**Modar Hill Formation**	Ratanpur Sandstone Member		Not Exposed	Not Exposed
Aalenian–Bathonian	Jhurio	**Member G:** Thin bedded white Limestone and Nodular Limestone	Raimalro Limestone Member		Goradongar Formation	(Raimalro Lst. Marker) Hadibhada ng Sandstone Member	Khadir Formation		
		Member F: Purple sandstones / Packstones	Gadaputa Sandstone Member						
		Member E: Bedded rusty grainstone with golden oolites	Goradongar Flagstone Member			Hadibhadang Shale Member			
		Member D: Gray Shales							

(continued)

Table 1 (continued)

		Member C: Brick red weathering rusty grainstones with golden oolites	Middle Sandstone Member	(Leptosphinctes pebbly rudstone) Babia Cliff Sandstone Member	**Kaladongar Formation**	Cheriyabet Conglo–merate Mbr.			
			Lower Flagstone Member			? Basement			
		Member B: Gray Shale	Eomiodon Red Sandstone Member	Narewari Wandh Sandstone Member					
		Member A: Thin bedded yellow white limestones, shales and rusty brown limestone with golden oolites. ? ? ? **Basement**	Sadara Coral Limestone Member ~~~~~~~~~~ ? Basement	Dingy Hill Member ~~~~~~~~~~ ? Basement					

Table 2 Mesozoic Lithostratigraphy of Kachchh Mainland (adapted from Biswas 1981)

AGE	Fm	Mbr	Lithological field characteristics	Geographical extension	Type section/ typical sections
Neocomian to Albian	BHUJ (350–900mt +)(Thickening W.wards)	U	Light colored, medium to fine grained sandstone, kaolinitic claystone and sandy iron–stone bands. channel fills; X–bedded–planarand tabular, cut and fill; plant fossils, fossil wood	Exposed extensively in the mainland in two wide belts stretching from Bachau on the east to Ghuneri on the west, occupying lowlands between the hill ranges; entire city of Bhuj is located on this formation Monotonous sandy plains ribbed with cuestas formed by hard ironstone or lateritic bands, some of which are capped by Trap flows, are the typical expression of the topography where Bhuj rocks occur	Several reference sections of which the Rukmavati section, south of Bhuj, from Jamatara downstream up to Trap is considered as the main reference section Other impressive sections are seen in and around Bhuj and also near the Tapkeshewar Temple hill range
		M	Green glauconitic sandstones and shales, thin fossiliferous limestones and red ironstone bands containing pelecypods, gastropods and ammonites; fossil wood;		
		L	Red and yellow sandstones: ferruginous, fine grained. moderately sorted; coarse grained arenites in channel fills showing fining up. X–bedded (planar) ripple marked; abundant leaf impressions. Occasional coal beds		

(continued)

Table 2 (continued)

AGE	Fm	Mbr	Lithological field characteristics	Geographical extension	Type section/ typical sections
Kimmeridgian to Neocomian	JHURAN (420 – 850 M+) (Thickening westwards)	Katesar	Greenish yellow sandstone: calcareous and ferruginous feldspathic wacke, v –med. gd; mod. to well sorted; X–bedded (planar, trough and festoon); Trigonia and Astarte sps	Exposed extensively along the southern flanks of the northern and central hill ranges in two wide E–W strips; present as inliers in the Bhuj Formation extreme east and west at the centres of domes and anticlines In the central part of the Kachchh Mainland, only the Lower, Middle and lower part of the upper member are extensively exposed	Type section for most part of the formation (except Katesar member) is seen along the stream around Jhuran Village, 40 km. East of Bhuj; the upper part of the sequence(Katesar Member) is exposed along Katesar River and in Mundhan Antincline(4 km. SW of Mundhan) Other sections are seen in and around Bhuj, and in Kharinadi valley around Rudramata temple, 16 km N of Bhuj, which serves as a good reference section
		U	Mainly sandstones with subordinate shale. Sandstones: fine to med, mod. well sorted feldspathic wacke; Current bedded (tabular, festoons and herringbone), ripple marked; convolute bddg, load casts, cut and fills common. Local pelecypod and plant beds		
		M	Mainly grey shales with fine grained, fissile sandstone bands. Highly fossiliferous in west and sparsely so to the east; ammonites, pelecypods, belemnites; cut and fill stuctures		

(continued)

Table 2 (continued)

AGE	Fm	Mbr	Lithological field characteristics	Geographical extension	Type section/ typical sections
		L	Shale/sandstone alternation. Sandstones: fine gd, mod sorted feldspathic wacke; X–bdd, ripple marked; more fossiliferous in the west		
Callovian to Oxfordian	JUMARA (280 m)	U	Greenish grey, gypseous glauconitic shales well laminated thin limestone alternations. Characteristic oolitic bands near the top. Highly fossiliferous; (mainly cephalopods, brachiopods, pelecypods and corals)	Exposed as inliers at the centre of the domal and anticlinal hills along the northern edge of the Mainland and in central Charwar Range in more or less circular and elliptical outcrops. Being soft formation, it usually gives rise to a grey undulating topography; is very widespread extending from Banni graben (subsurface) to Kachchh mainland; recognized in shelf part of the offshore and in the wells	Jumara Dome, Western Kachchh The Jhurio and Habo dome sections to the east of the type section are important reference section
		M	Base Biomicrite, middle yellow calcareous sandstone, top conglomerate. Fossiliferous with pelecypods. Represented in the west by fossiliferous limestones with golden oolites		

(continued)

Table 2 (continued)

AGE	Fm	Mbr	Lithological field characteristics	Geographical extension	Type section/ typical sections
		L	Olive and grey shales with thin limestone bands, containing rich crop of fossils: ammonites, corals, brachiopods, pelecypods, belemnites etc		
Bathonian to Callovian	JHURIO (300 m)	U	Interbedded micritic and sparitic (bio- and oo-sparite) limestones with "golden oolite ", with iron–oxide coated pseudo–oolitic bands in the lower part. Fossiliferous: cephalopods, brachiopods, pelecypods etc	Widely is exposed as small inliers in three hills (Habo, Jhurio and Jumara, from east to west) along the northern margin of the Mainland Major part of the Jhurio hill is represents this formation and numerous good sections are seen in radial streams	Jhurio Hill, 38 km. North of Bhuj Others sections are seen in Habo and Jumara hills. In Habo and Jumara hills only the upper part is exposed. In Habo it crops out at three places in the northern flank of the hill south of Dhrang and Fulae. North of Jumara it is exposed in the hill adjacent to the Rann
		M	Thickly interbedded shales and limestones (mainly "golden oolites"–Oolitic intrasparrudite). Fossiliferous: brachiopods, pelecypods, cephalopods etc		
		L	Interbedded shales and limestones, with lenticular "golden oolites". Fossiliferous		

3.1 Jhurio Formation (Author: Biswas 1977; Also Known as Patcham Series)

A thick sequence of dominant limestone with interbedded shale and occasional bands of "golden oolite" and sandstone has been named as Jhurio Formation. The formation shows a change in facies, from carbonate in the west to clastics in the east.

3.1.1 Type Section

Jhurio Hill, 38 km. North of Bhuj.

3.1.2 Geographical Extension

This formation has a vast extent. It is present in the Kachchh Mainland and has been recognized in the subsurface also. The formation is exposed as small inliers in three hills (Habo, Jhurio, and Jumara, from east to west) along the Mainland's northern margin. The formation is thickest in the Jhura Dome (Fig. 1c). The hill's major part is composed of this formation and numerous good sections are seen in radial streams. In Habo and Jumara hills, only the upper part of the formation is exposed. In Habo, it crops out only at three places in the northern flank of the hill south of Dhrang and Fulae. It is also exposed in the hill adjacent to the Rann to the north of Jumara. The steeply dipping hard limestone beds form the whitish country of high relief featured by cuestas and annular valleys.

3.1.3 Lithology

The lower part comprises thin beds of yellow and grey limestones occasionally containing golden oolites, in grey shales. The middle part comprises thick beds of grey, yellow weathering shales alternated with thick beds of golden oolitic limestones. In contrast, the upper part of the formation is made up of thinly bedded white to cream coloured limestones with thin bands of golden oolites. The formation has been formally subdivided into seven informal members, named as A to G by Biswas (1977), based on the limestone, golden oolite, and shale occurrences. In Habo hill, only the topmost part of the formation is exposed. In the Jumara section, the top member is underlain by olive–grey gypseous shale with thin bands of coral bioliths equivalent to member F.

3.1.4 Lithofacies

This formation represents two lithofacies associations (Table 3), which include the quiet water subtidal carbonate association (LFA–1) and mixed siliciclastic carbonate shallow marine association (LFA–2) (Osman and Mahender 1997).

Table 3 Lithofacies association (LFA) of Mesozoic sequence of Kachchh Mainland

Age	Fm	LFA	Lithofacies name	Lithofacies characteristics	Photograph
Late Jurassic – Early Cretaceous	Bhuj	13	Bioturbated Sandstone lithofacies	Coarse grained, ferruginous sandstone with extensive bioturbation. Physical structures are partially to completely obliterate	
		12	Silty sandstone lithofacies	Well–bedded, fine to medium grained sandstone with much matrix, cross–bedded, Ripples are common	
		11	Interbedded sandstone−siltstone lithofacies	Thick fine to medium grained sandstones alternating with siltstone shale beds. The siltstone/shales beds are ferruginous	
		10	Cross–bedded sandstone association	Coarse–grained sandstone with well–developed cross bedding of various size and types	
	Jhuran	9	LFA–9. Interbedded Siltstone–Shale association	Carbonaceous, dark silty shales interbedded with fine lenticular/wavy sand beds	
		8	LFA–8. Sandstone with interlayered shale	Fine–medium grained, moderate to well sorted sandstones current bedded (tabular, festoon and herring bone types) with abundant feldspars and matrix	

(continued)

Table 3 (continued)

Age	Fm	LFA	Lithofacies name	Lithofacies characteristics	Photograph
		7	LFA–7. Fossiliferous shale with thin sand/silt interbeds	Shales, grey in colour with alternating thin beds of sandstones. Shales highly fossiliferous. Fossiliferous (Ammonites, pelecypods, belemnites)	
		6	LFA–6. Interbedded shale–sandstone association	Fine grained, moderate to well–sorted sandstone, arkosic/ feldspathic wacke types, Cross–bedded, ripple marked	
Middle Jurassic	Jumara	5	LFA – 5. Cyclic shallow–water peritidal carbonate–shale association	Thin succession of shale, followed by laminated lime mudstone or peloid packstone. Cycles not regular; increasing thickness of carbonate beds with decrease in associated shale; shallow water, tidally influenced cyclic deposits;	
		4	LFA – 4. Quiet Water Lagoonal shale – carbonate association	Shale and limestone; shale gypseous, comprise chlorite and kaolinite. Limestone is fossiliferous wackestone and is dolomitized	
		3	LFA – 3. Predominantly terrigenous valley–fill association	Sandstone followed by a few conglomerate and rare shale beds. The sandstone displays herring–bone cross–stratification	

(continued)

Table 3 (continued)

Age	Fm	LFA	Lithofacies name	Lithofacies characteristics	Photograph
	Jhurio	2	LFA – 2. Mixed siliciclastic carbonate shallow marine association	Varied lithology, including rippled, X–bedded sandstone, burrowed sandstone, siltstone, peloid packstone; sandstone fine–medium grained, mod. sorted exhibiting a coarsening upward sequence	
		1	LFA–1. Quiet water subtidal carbonate association	Predominantly carbonate mudstone (burrowed) with rare to common interbeds of peloid, bioclastic wackestone–packstone; beds relatively thinner, laterally, vary into lime mudstone–wackestone–packstone	

3.1.5 Boundaries

The lower boundary is not exposed in the type section. The upper contact with the overlying Jumara Formation is conformable and well–marked by the contrast of its white limestones and the green shales of the Jumara Formation. The geomorphic expression of the limestones forming high relief against the low areas of shales help to mark the boundary easily.

3.1.6 Thickness

In the type section, the thickness of the formation is 287 m. In Jumara and Habo Hills, the exposed thickness is only 70 m. (+) and 16 m. (+) respectively.

3.1.7 Paleontology

Common Fossils include Rhynchonella, Terebratula, Kachchhithyris, Allectryonia, Ostrea, Astarte, Trigonia, Belemnites, and ammonites (Macrocephalites). This formation is incredibly rich in fossils in the Jumara dome, where the shales and biostromes are packed with corals, brachiopods, pelecypods, and ammonites.

3.1.8 Age

The benthic foraminifera belongs to *Epistomina regularis* – *E. ghoshi* Assemblage zone, *Lenticulina dilectaformis* Partial–Range–Zone, *Tewaria Kachchhensis* partial–Range–Zone in stratotype indicate Bathonian–Callovian age (Pandey and Dave 1993). The formation was deposited in a littoral to the infra littoral environment, neritic transgressive environment.

3.2 Jumara Formation *(Author: Biswas 1971; Also Known as Chari Series)*

Monotonous grey to dark grey, laminated, rarely silty, and often calcareous shale sequence overlying the Jhurio Formation was named after its type section of Jumara Dome at the western Kachchh. The formation shows a gradual increase in thickness from east to west.

3.2.1 Type Section

Jumara Dome, Western Kachchh. The Jhurio and Habo dome sections to the east of the type section are important reference sections.

3.2.2 Geographic Extent

The formation is exposed as inliers at the center of the domal and anticlinal hills along the northern edge of the Mainland and in the central Charwar Range, in more or less circular and elliptical outcrops. Being a soft formation, it usually gives rise to a grey undulating topography. The Jumara Formation is very widespread, extending from Banni graben (subsurface) to Kachchh mainland. It has also been recognized in the shelf part of the offshore and the wells.

3.2.3 Lithology

In the type section, the formation is characterized by monotonous olive–grey, gypseous, laminated shales with thin, red ferruginous bands, alternating beds of limestone, and occasional sandstone inter–beds. It has been sub–divided into four informal members numbered I to IV based on the limestone or sandstone inter–beds dividing the continuous shale sequence (Biswas 1977). Thin fossiliferous oolitic limestone bands occur in the shales near the top of member IV, the famous “Dhosa Oolite beds” or “Stage.” It is a very characteristic horizon and used as the main key bed in Mainland stratigraphy. In these sections and Chorar Range outcrops, more sandstone beds appear in the lower part. East of the type section, in the Manjal dome, the lowest exposed bed is a limestone developed locally, embracing the lower and upper parts of the members I and II.

The Jhurio and Habo dome section to the east of the type section are important reference sections. In these sections and Charwar Range outcrops, more sandstone beds appear at the lower part. East of the type section, in Manjal dome, the lowest exposed bed is a limestone, developed locally embracing the lower and upper parts of the members III and II. Further east in the Keera dome, a significant portion of the member I has been replaced by a golden–oolite–shale lithosome that resembles the middle part of the Jhurio Formation.

3.2.4 Lithofacies

Three lithofacies associations are recognizable in this formation (Table 3), which include the predominantly terrigenous valley–fill association (LFA–3), quiet water lagoonal shale—carbonate association (LFA–4) and cyclic shallow–water peritidal carbonate–shale association (LFA–5) (Osman and Mahender 1997).

3.2.5 Boundaries

The top and basal part of the formation is exposed only in Jhura, Habo, and Jumara hills. The lower boundary is defined by conformable limestone shale contact, and Dhosa Oolite Member marks the upper boundary (Fig. 1d). The contact is marked by the topmost oolitic band, which is conglomeratic and separates the unfossiliferous grey shales (of Jhuran Formation) and the green fossiliferous shales with oolite bands.

3.2.6 Thickness

The thickness of the formation (273.5 m as observed in the type section) is more or less uniform throughout the study area.

3.2.7 Paleontology

This formation is the richest of all in fossil content. Varieties of ammonites, Belemnites, brachiopods, pelecypods, corals, and gastropods are found throughout the formation. Besides mega fossils, the formation is rich in foraminifera.

3.2.8 Age

The benthic foraminifera recorded from the type area is referred to as *Tewaria kachchhensis* Partial Range–Zone, *Proteonina difflugiformis*, *Astacolus anceps* Assemblage–Zone and *Epistomina majungaensis* Range–Zone (Pandey and Dave 1993). The fossil assemblage gives an age of Callovian– Oxfordian to the formation.

3.2.9 Environment

A littoral to shallow marine circa littoral (below the wave base) environment of deposition is inferred for the formation.

3.3 Jhuran Formation (Author: Biswas 1977; Also Known as Katrol Formation)

The thick sequence of alternating beds of sandstone and shale has been named the Jhuran Formation. The Jhuran formation, defined by the underlying Dhosa Oolite Member of the Jumara Formation and the overlying non–marine sandstone of the

Bhuj Formation, is divided into four informal member—(lower, middle, upper, and Katesar members).

3.3.1 Type Section

Along the stream around Jhuran Village, 40 km east of Bhuj City and the type section for the upper part of the sequence (Katesar Member) is exposed along Katesar River and in Mundhan Anticlines (4 km. SW of Mundhan).

3.3.2 Geographic Extent

The formation is extensively exposed along the southern flanks of the northern and central hill ranges in two wide E–W strips. It is present as inliers in the Bhuj Formation at extreme east and west and in the central part of domes and anticlines. The Lower, Middle and lower part of the upper member is extensively exposed in the central part of the Kachchh Mainland, the main sections of which are better exposed (Fig. 1e) in and around Bhuj, and in Kharinadi valley around Rudramata temple, 16 km N of Bhuj, which serves as a useful reference section for the most part of the Jhuran Formation in the study area.

3.3.3 Lithology

The lower part comprises alternating yellow and red sandstone and shale beds with thin bands of hard yellow, fossiliferous, pebbly, calcareous sandstone, occasionally containing golden oolites in grey shales. The middle member in the present study area is represented by a monotonous succession of dark grey to black well–laminated shales, occasionally gypseous, weathering in olive–gray color. Thin red bands of ferruginous sandstone, micaceous siltstone, and yellow ochreous mudstone are typical in shales. The shales are unfossiliferous in the present area although they are fossiliferous in the western part. The Upper member in the present study area is represented with red and yellow, massive current bedded sandstone with intercalations of shale, siltstone, and at places, calcareous sandstone bands in the middle. The formation is uniform in lithologic character throughout, excepting the interfingering relationship between the members and the sandstone and shale beds.

3.3.4 Lithofacies

Four lithofacies type associations have been identified (Table 3) in this formation, which comprises LFA–6: Interbedded shale–sandstone association, LFA–7: Fossiliferous shale with thin sand/silt interbeds, LFA–8: Sandstone with interlayered shale, and LFA–9: Interbedded Siltstone–Shale association (Mahender and Sharma 2010).

3.3.5 Boundaries

Although it is generally conformable, a local disconformity is observed at the lower boundary of the Jhuran Formation. Jhuran shales resting over the eroded Dhosa Oolite Member. The upper contact with the overlying Bhuj Formation is gradational.

3.3.6 Thickness

The formation is thickest in the Jara–Mundhan area of NW mainland, where it is 865 m thick and thins down to the eastward to 442 m in the type Section. In the central mainland, the formation thickness is at its minimal (−380 m).

3.3.7 Paleontology

Common fossils include belemnites, ammonites, pelecypods, gastropods, and locally corals and echinoids. The irregular occurrence of plant fossils has been noted at many places in association with beds carrying marine fossils.

3.3.8 Age

Kimmeridgian to (pre–Aptian) Valangian age has been assigned by the earlier workers based on the available faunal evidence for this formation.

3.3.9 Environment

The paralic facies and the physical and biological characteristics of the sediments of different members tend to suggest a repeated paleogeographic shift from sub littoral to supra littoral environment and a continental environment in the upper part.

3.4 Bhuj Formation *(Author: Biswas 1971; Also Known as Umia/ Bhuj Series)*

A thick sequence of non–marine sandstones of uniform character constitutes the youngest formation of the Mesozoic sequence of Kachchh. The formation has been named after Bhuj. The formation is bounded by the Jhuran Formation below and the Deccan trap flows above.

3.4.1 Type Section

There are several reference sections of which the Rukmavati section, south of Bhuj, from Jamatara downstream up to Trap, is considered as the main reference section. The other impressive section of this formation can be seen around the Bhuj City (Fig. 1f) and near the Tapkeshewar Temple hill range. The formation is divided into two informal members viz. the Lower and Upper members in Kachchh mainland, whereas laterally in the west they are designated as Ghuneri (Lower) and Ukra (Upper).

3.4.2 Geographic Extent

The Bhuj rocks are exposed extensively in the mainland, occupying about 3/4th of the total Mesozoic outcrop area. The main exposures are seen in two wide belts stretching from Bachau on the east to Ghuneri on the west, occupying lowlands between the hill ranges. The entire city of Bhuj, in fact, is located on this formation. Monotonous sandy plains ribbed with cuestas formed by hard ironstone or lateritic bands, some of which are capped by Trap flows, are the typical topographic expression of Bhuj rocks. Bhuj sandstone being a good aquifer, plains on these rocks are extensively cultivated.

3.4.3 Lithology

The present study area exposes only the Lower and Upper members of the formation. The Lower Member is characterized by the cyclic repetition of ferruginous or lateritic bands, shales, and sandstones. The Upper Member consists of whitish to pale brown, massive, current-bedded, coarse-grained, well–sorted sandstones with kaolinitic shale and ferruginous band alternations at some intervals. The sandstones are pale brown to buff, soft, friable, usually current bedded (large scale tabular), fine to coarse-grained, well-sorted, loosely cemented quartz arenites, are usually micaceous, ferruginous, and/or calcareous. Some coarse-grained varieties are feldspathic arenites. Shales are grey, silty, well laminated with limonitic partings, and locally carbonaceous.

3.4.4 Lithofacies

Four lithofacies associations are described in the formation (Table 3), which includes (i) Cross–bedded sandstone association (LFA–10), (ii) Interbedded Sandstone–Siltstone association (LFA–11), (iii) Silty Sandstone with interlayered shale (LFA–12), and (iv) Bioturbated Sandstone Lithofacies association (LFA–13) (Mahender and Sharma 2010).

3.4.5 Boundaries

The formation is bounded by the planes of disconformity. The lower contact, though partly gradational at some places, show a disconformable contact. The upper boundary of the Bhuj formation is marked with the Deccan Trap flows resting on the formation's eroded undulating surface.

3.4.6 Thickness

The thickness of the formation (273 m as observed in the type section) is more or less uniform throughout the study area.

3.4.7 Paleontology

The formation, in general, is devoid of fossil fauna in the eastern part; however, in the western part, in the Ukra member, some fossils are reported. There are plenty of plant fossils reported from these rocks. The flora is typically Upper Gondwana Ptilophyllum Flora comprising *Ptilophyllum, Williamsonia, Brachyphyllum, Cladophlebis, Equisetum*, etc. besides leaf impressions, large chunks of fossil wood are seen concentrated at places.

3.4.8 Age

The lower time limit of the formation is indicated by the upper limit of the Jhuran Formation, which is the Valanginian. The hiatus due to disconformity between the formations is not known. The lowest age indicator in the Bhuj Formation is the Ukra Member, whose ammonite assemblage indicates an Aptian Age. The leaf impressions and micro–, and macrospores suggest a "Neocomian" age to these rocks.

3.4.9 Environment

Based on the lithology, the absence of fauna and rich assemblage of flora, sedimentary structures (such as large–scale cross–bedding), and marine tongues in the downward direction (in the west), the sediments can be interpreted as the products of delta deposits with distal part (delta front) towards the west and the proximal part (fluvial) to the east in the direction of land.

4 Sedimentology

4.1 Clastic Sedimentology

Sandstones, the abundant lithology of the Mesozoic sequence of Kachchh, units are well–bedded and exhibit a variety of sedimentary structures (depositional, erosional and other), including cross–bedding of various types and scales (Fig. 2a–c); varying scales of rippled bedding in sandstones indicating the shallow nature of the depositional environment (Fig. 2d, f). Large interference ripples also occur in some of the litho units (Fig. 2e). Laminated bedding with alternating fine and coarse laminae has been observed in the sequence at various localities, especially from cliff sections. Several types of trace fossils have been observed in the Middle Jurassic sequence of Kachchh from shaley units. Although the preservation of trace is fossils is better seen in argillaceous units, sandy–carbonate units also exhibit poorly preserved trace fossils such as *Rhizocorallium, Thalssinoides*, etc. The various burrow patterns observed in the succession include vertical burrows, sand-filled burrows and bioturbated horizons (Fig. 2p–r); Jointing is prominently developed in ferruginous and calcareous sandstones and sandy limestones. Two sets of joints are clearly seen, giving rise to blocks of the lithounits (Fig. 2j). At places, columnar jointing (Fig. 2k) is prominently developed in sandstones belonging to Late Jurassic to Early Cretaceous. The pattern is very similar to the columnar structures commonly observed in Basalts. Best exposures of columnar sandstone occur in and around Bhuj. Regular hexagonal columns developed perpendicular to bedding are with four to five sides are frequent. Each column is about 1–1.2 m. height and about 20–30 cm. in diameter; Iron crusts commonly occur (Fig. 2m, n) on the top of oolitic sandy beds at some localities are associated with large iron oncoids. The crusts are 2–4 cm. thick; Concretion layers (Fig. 2h) are widespread within the argillaceous limestone interbeds of Kachchh Jurassic. These beds consist of elongate, cylindrical, and irregular shaped nodules.

4.2 Paleocurrents

Cross–bedding is the most abundant and striking sedimentary structure seen at many localities of the exposed sandstones at various intervals of the sequence. The strike and dip of the cross–bedding units vary abruptly from place to place. The cross–bedding is mostly of high angle wedge type cross–stratification. Large scale planar and herringbone cross–stratification types are also observed in this rock sequence. The dip of the foreset varies from gentle (<10) at a few places to quite steep (>20) at several localities. Abrupt reversals of the direction of dips are also found. The mineral composition, grain–size changes, and their weathered surfaces define the cross–strata. The azimuth and dip of the cross–bedding data of over 200 readings recorded from various localities to calculate the vector mean direction by following the procedures of Curray (1956) indicate a paleocurrent direction towards the west

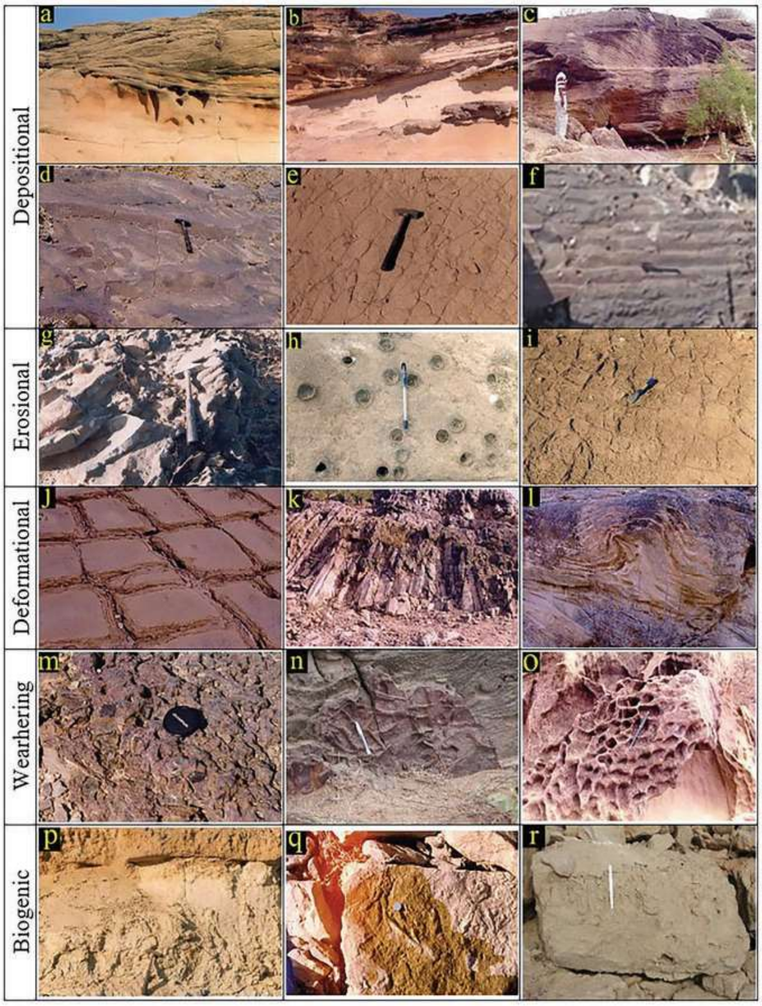


Fig. 2 Variety of Sedimentary Structures observed in Mesozoic rocks of Kachchh Mainland: **a** Large-scale, cross–bedding structure within Bhuj Formation, **b** Well developed cross-bedding exhibited by Jhuran sandstones, **c** Large-scale, composite cross-bedding structure of ferruginous sandstone, Habo Dome, **d–e** Large straight crested, slightly sinuous wave ripples shown, **g** Groove casts/marks preserved in sandstones, **h** eroded concretionary structures displaying circular, even depressions, **i** syneresis/desiccation cracks, **j** Jointing pattern (regular evenly spaced) characteristic of fossiliferous, ferruginous sandstone of Jumara Fm, **k** Columnar type jointing displayed in Bhuj sandstone, **l** Syn-sedimentary deformation exhibited by sandstone, **m**, **n** Typical outcrop surfaces formed due to weathering, **p** burrowing and bioturbation leading to complete disturbed bedding, **q** Fine-grained shaly limestone displaying burrowing and trace fossils, Jhura Hill, **q**, **r** trace fossils due to burrowing and boring by organisms (pen length = 14 cm, hammer length = 38 cm)

and southwest (from 222.89 to 246.52; Table 3). The locality wise distribution of dip azimuth and calculated vector mean data are given in Table 4.

4.3 Texture

The clastic textural attributes (viz. size, shape, sphericity, and roundness parameters) are of significant help to describe and classify the various sandstone types in addition to understand their: provenance, transporting mechanisms, and depositional environments. The grain–size distribution patterns of the representative sandstone samples exhibit, in general, a marked unimodal to bimodal nature of the rocks, which compliments the results of the paleocurrent analyses. The summary of textural parameters, as observed in the sandstones, is given in Table 5. A stratigraphic variation in the textural parameters between mixed–clastic carbonate sequence of Middle Jurassic and the predominantly clastic sequence of Late Jurassic– Early Cretaceous as observed in the sandstones can be visualized from Table 5, representing the minor changes in transportation and depositional conditions. The plotting of size data on bivariate discriminatory diagrams of Moiola and Weiser (1968) (Fig. 3a, b) shows a mixed beach to dune/river environment of deposition. However, no stratigraphic separation was observed, supporting little variation in depositional conditions.

4.4 Composition

The sandstones of Mesozoic succession, in general, are fine to medium-grained, moderate to well sorted, and cemented by quartz, hematite and Calcite (Fig. 4). Matrix occurs as crushed lithic grains, small quartz grains, and phyllosilicates and varies considerably (5–22%) or more with cement varying up to 28–41%. Cementation by quartz, hematite/ferruginous, calcite (less frequently in the Late Jurassic—Early Cretaceous). Framework grains in most sandstones are composed of detrital quartz and feldspar grains, lithic, and fossil/carbonate fragments. These sandstones can be broadly grouped into three categories viz. type 1 sandstones (quartz arenites, that are distinguished by abundant quartz, alkali feldspars with devoid of rock fragments (Fig. 4a), sub-rounded to sub–angular quartz grains with sutured contacts, monocrystalline quartz predominating over polycrystalline quartz, with heavy minerals tourmaline and rutile; type 2 sandstones (feldspathic arenites), which are characterized by moderate quartz, and moderate plagioclase feldspars and rock fragments (Fig. 4b, d); more or less similar textural characteristics of those of type1 sandstones and heavy mineral composition include tourmaline, epidote, garnet; type 3 sandstones (sub–litharenites), characterized by relatively low quartz content, moderate feldspars and rock fragments with abundant sedimentary lithic fragments cemented with quartz and poikilotopic calcite cement. While the calcite cemented type 1 and 2 sandstones (Fig. 4e–h) belong in general to Middle Jurassic, the silica cemented varieties are

Table 4 Summary of the paleocurrent analysis of cross-bedding data

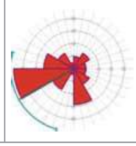
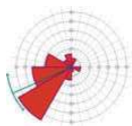
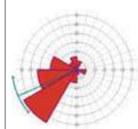
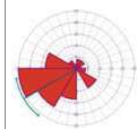
	Bhuj (around)	Jhuran	Jumara	Jhurio
Class interval (degrees)	30	30	30	30
No. of readings	98	84	69	66
Maximum %	23.80	38.30	33.30	25.00
Mean %	8.30	10.10	11.10	9.10
Standard deviation	6.05	8.24	10.24	7.79
Vector mean (degrees)	246.52	222.89	245.89	239.59
Confidence interval (degrees)	44.62	19.45	17.45	20.85
R–mag	0.27	0.55	0.62	0.49
Current rose diagrams				

Table 5 Stratigraphic variation of sandstone textural, compositional and chemical parameters

Sandstone textural parameters						Framework grains			REE	
Fm	stats	Mz	SD	Sk	KG	Qz	Fs	Rx	∑REE	LR/HR
Bhuj	Mean	2.1606	0.4887	0.1934	0.9409	92.30	5.80	1.90	186.631	13.901
	σ	0.6492	0.1297	0.1755	0.5103	2.16	1.58	0.83	105.849	6.672
	Min	1.1195	0.3157	− 0.1163	0.2643	88.00	3.00	1.00	18.979	6.617
	Max	3.1697	0.7061	0.4521	1.8155	96.00	8.00	4.00	348.207	25.000
Jhuran	Mean	2.0617	0.5252	0.2660	0.9764	88.90	8.10	3.00	162.340	17.829
	σ	0.4249	0.1145	0.2455	0.3881	3.36	3.31	1.83	92.496	4.747
	Min	1.2134	0.2975	− 0.1328	0.3324	84.00	4.00	1.00	33.807	8.603
	Max	2.8685	0.6753	0.6199	1.6620	94.00	12.00	6.00	316.629	23.407
Jumara	Mean	1.6933	0.9347	0.0390	1.1260	75.55	3.81	4.41	153.04	13.56
	σ	0.8383	0.2553	0.2284	0.2219	11.98	0.58	2.10	31.14	4.78
	Min	0.4703	0.6199	− 0.2334	0.7421	67.07	3.4	2.92	117.84	8.48
	Max	2.7518	1.2801	0.2847	1.2830	84.02	4.22	5.89	222.25	25.09
Jhurio	Mean	1.9059	0.5774	0.1842	1.0584	86.43	3.86	3.30	128.90	11.095
	σ	0.8542	0.1704	0.2250	0.2110	2.03	1.55	0.70	92.51	8.299
	Min	0.3628	0.2516	− 0.1355	0.5738	85.00	2.76	2.80	29.82	8.299
	Max	2.9282	0.7514	0.5135	1.2738	87.87	4.95	3.79	341.40	31.056

Mz–Mean Size, SD– Standard Deviation, Sk–Skewness, KG– Kurtosis, Qz–Quartz, Fs–Feldspar, Rx–Rock Fragments, **∑REE**– Total REE, LR/HR–LREE/HREE

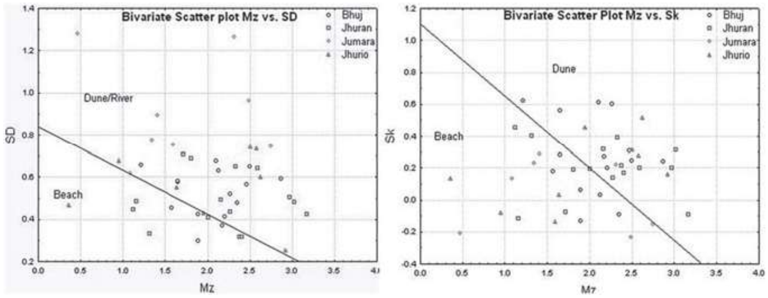


Fig. 3 Bivariate textural plots of Moiola and Weiser (1968) for discriminating depositional environments: **a** Mean–size (Mz) versus standard deviation (SD), **b** Mean–size (Mz) versus skewness (Sk)

observed only in the upper part (Late Jurassic – Early Cretaceous) of the succession. The type 3 sandstones are seen only in the Late Jurassic—Early Cretaceous (Fig. 4a–d).

4.5 Diagenesis

The detrital framework composition of sandstones of Kachchh Mainland has been altered by diagenesis, leading, in particular, to the reduction of the feldspar and unstable lithic fragments, which is supported with the presence of large matrix and cementing material (Fig. 5b, g). The significant diagenetic changes observed include the compaction, dissolution, and cementation (quartz, calcite, feldspar), resulting in reduced primary porosity. As observed in the thin sections, the sandstones, in general, are subjected to low mechanical compaction, probably just before cementation indicated by moderate packing density and the presence of the early cement. The primary porosity is primarily due to the early calcite cementation (Fig. 5h), resulting in scarce or limited quartz overgrowths. Only occasionally, the sandstones show local development of large overgrowths and chert cement. Iron oxide (hematite) cementation and feldspar cementation is ubiquitous and forms an important authigenic phase of the diagenesis of the Mesozoic sandstones. Among the carbonate cemented sandstones, two types of calcite cement are observed. The pore-filling and patchy carbonate (sparite and micrite) occur as an early diagenetic cement (Fig. 5g, h), and the large crystals of calcite (poikilotopic) probably form by neomorphism. In some Late Jurassic to Early Cretaceous samples, Ferroan dolomite and anhydrite/gypsum occur as late–stage cement.

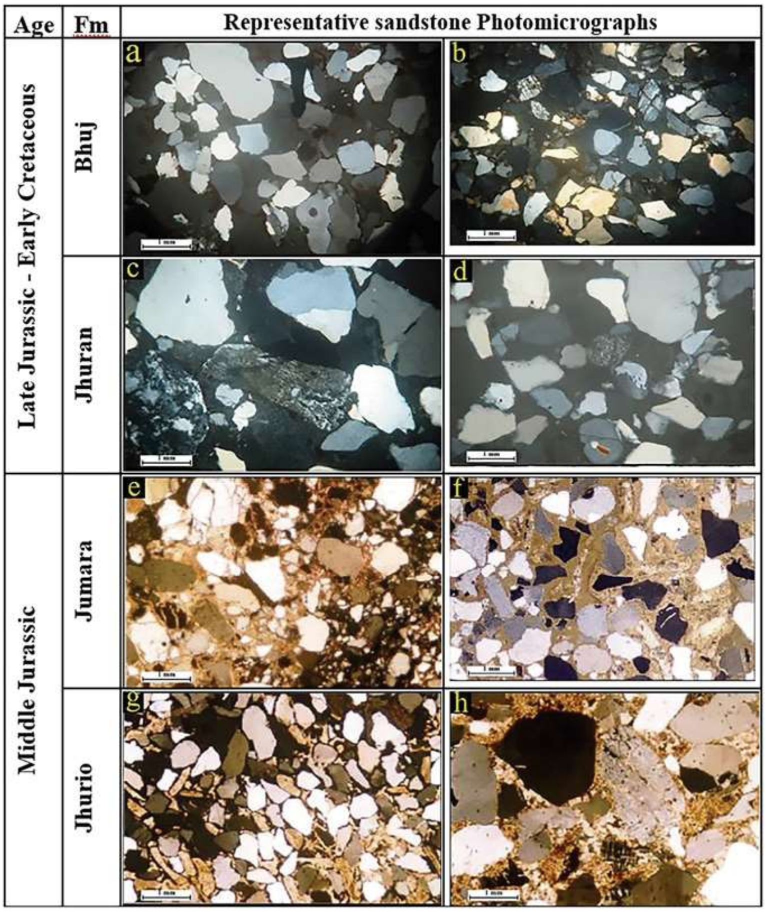


Fig. 4 Photomicrographs of representative Mesozoic sandstones of Kachchh Mainland (xpl): **a** Fine- to medium-grained, moderately-sorted sandstone, b Feldspathic arenite displaying Fe-oxide replacement, **c** Medium- to coarse-grained sandstone showing variable types of Rock fragments, **d** Fine- to medium-grained sandstone showing altered feldspar (in the centre), **e** Subangular to sub rounded, poorly sorted quartz wacke showing lithic fragments of limestone and glauconite pellet (left centre), **f** Sandstone cemented by large poikilotopic calcite crystals. Note the typical high order interference colours of calcite, **g** Subrounded to well rounded, well sorted calcite cemented quartz arenite. Matrix between the grains contain opaque iron oxide, and **h** Feldsphathic sandstone showing dissolution and alteration of feldspars and subsequent calcite cementation

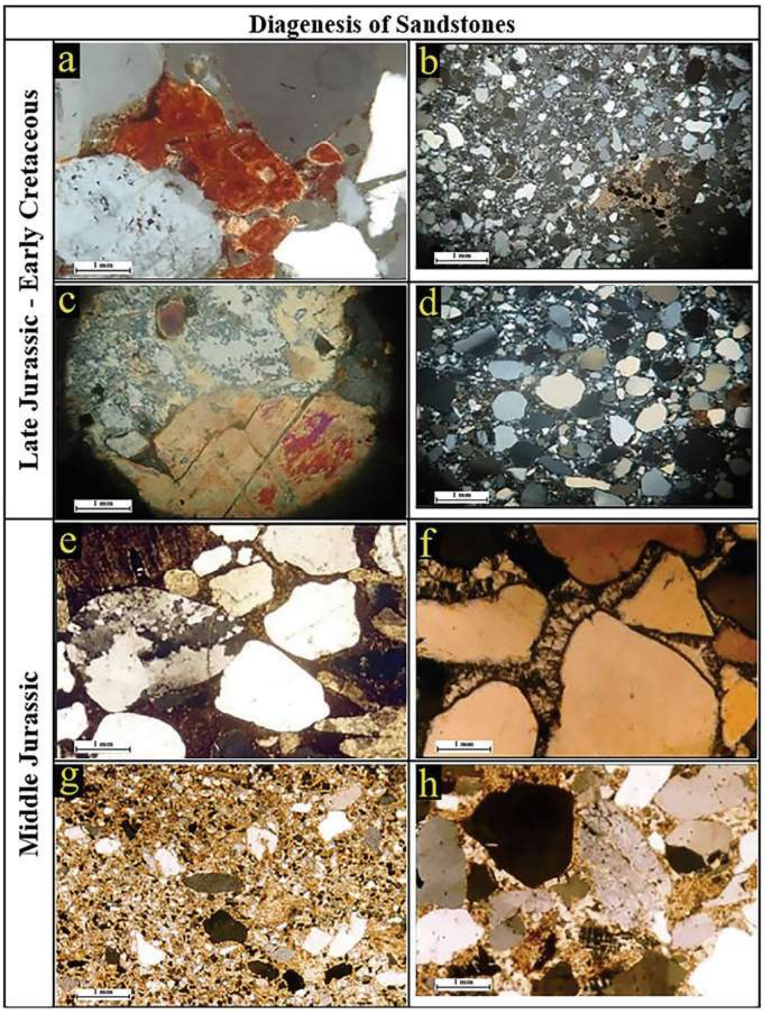


Fig. 5 Photomicrographs of the Mesozoic Sandstones displaying the various post–depositional diagenetic changes: **a** Sandstone displaying altered feldspar (lower left) and ferruginized rhomb-shaped crystals of dolomite of Jhuran Formation, **b** Fine- to medium-grained quartz wacke displaying large poikilotopic calcite cementation, **c** Gypsum/anhydrite cementation of fine sandstone, **d** Sandstone displaying Textural inversion (poorly sorted with well-rounded quartz grains) Bhuj Formation, **e** Calcarenite showing polycrystalline (composite) quartz. The sutured boundaries between crystals clearly indicate metamorphic source, **f** Sandstone displaying pore filling silica cementation in the form of isopachous fringe around quartz grains, **g** Calcarenite showing rounded quartz and chert grains together with smaller subangular to sub rounded quartz grains in a fine-grained matrix **h** Poorly sorted, quartz arenite showing grains coated with kaolinitic cement and subsequent iron oxide impregnations

4.6 Fine Clastics

The fine-grained mudrocks (shales) Mesozoic succession consists of well laminated shales, silty shales and calcareous shales of various colours and shades. The composition of the fine clastics as observed from the results of the XRD analyses comprises clay minerals (essentially of smectite, chlorite, kaolinite and illite) and silty quartz). While kaolinite is observed throughout the succession, chlorite is restricted only to the Late Jurassic to Early Cretaceous part of the succession.

5 Carbonate Sedimentology

5.1 Carbonate Allochems

The carbonate rocks (bedded/oolitic/nodular limestones) and calcareous shale units are predominantly observed only at the lower and middle part of the succession in Jhurio and Jumara formations. The limestones are hard, compact and often nodular with varied framework composition and range from clean, well–sorted packstone–grainstones to unsorted mudstone–wackestone types. The framework components observed in the carbonate rocks include a variety of carbonate allochems (pellets (Fig. 6a), ooids (Fig. 6b), intraclasts (Fig. 6c), terrigenous (Fig. 6d) and skeletal grains (Fig. 6e–l)), orthochems, including micrite and sparite with different morphological varieties, viz. microspar, sparite (Fig. 7c), fringe cement (Fig. 7i), coarse blocky mosaic, and syntaxial rim cements (Fig. 7d).

The carbonate rocks, based on texture and framework composition, are categorized into mudstones, pelletal wackestone, oolitic wackestone–packstone, molluscan packstone–grainstone and grainstone types following the Dunham (1962) classification of carbonate rocks.

5.2 Carbonate Diagenesis

Diagenesis of carbonates encompasses all the sediment processes due to physical, chemical, and biological changes immediately after deposition until realms of incipient metamorphism at elevated temperatures and pressures. Diagenesis has great relevance, especially in limestones due to their susceptibility to such modifications, which provides valuable information on the depositional and post-depositional conditions.

The carbonates of the Mesozoic sequence of Kachchh Mainland have undergone diagenetic modifications in almost all stages of diageneses. The significant diagenetic changes observed in these rocks include compaction (Fig. 7a), dissolution (Fig. 7b), cementation (Fig. 6a, b), neomorphism (Fig. 7c), micritization (Fig. 6f, 7e)

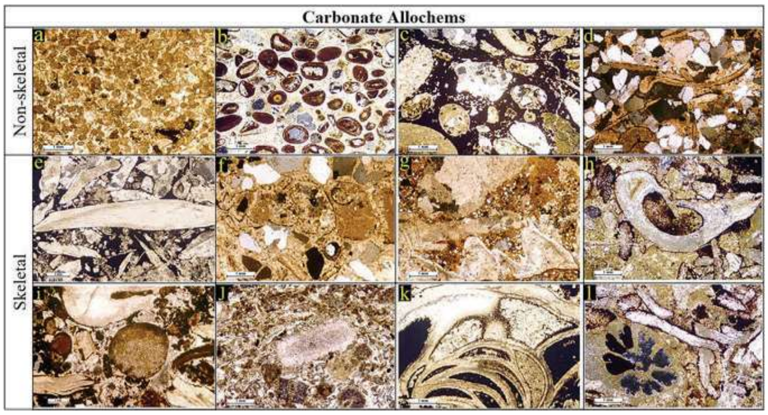


Fig. 6 Photomicrographs of Middle Jurassic carbonates displaying the different carbonate allochems with varying states of preservation (xpl): **a** Peloidal grainstone showing tight packing due to compaction, **b** Oolitic grainstone showing ooids with relatively thin cortices containing quartz and bioclasts as nuclei, **c** Lithocalstic grainstone with ferruginous cement, **d** Sandy molluscan grainstone showing casts of bivalves, algal and echinoidal bioclasts, **e** Molluscan grainstone with well-preserved bivalve showing original foliated internal structures, **f** Gastropodal wackestone with micrite-filled ghost structure of gastropod shell, **g** Brachiopod shell showing the preservation of internal structure of obliquely arranged fibres, **h** Crinoidal grainstone with large brachiopod shell fragment (cavity filled with internal sediment) with well–preserved foliated structure, **i** Echinoidal-bryozoan grainstone showing iron–oxide impregnated bioclasts (echinoid spine) suggesting replacement of bioclasts, **j** Algal-crinoidal packstone displaying the micritization of a crinoid skeletal fragment, **k** Micrite-filled internal chambers of a foraminifer displaying the aggrading neomorphism, **l** Algal wackestone with abundant silt-sized quartz and well preserved possible sponge spicule (rod-shaped) in centre and **m** Coralline-molluscan grainstone showing section of a coral and algal skeletal elements. The coral walls and septa are seen micritized (lower left)

and replacement (Fig. 6e, f). The observed diagenetic changes in these rocks include dissolution, cementation, neomorphism, micritization, replacement, and compaction. The evidence of compaction observed in these rocks include tight packing (Fig. 7a) and squeezing, bending, and even fracturing of some skeletal grains (Fig. 7e). Selective dissolution of aragonitic or high-Mg calcitic fossils and ooids are seen selectively dissolved, producing secondary (oomoldic type) porosity (Fig. 7b). Such dissolution produces secondary porosity. The Middle Jurassic carbonates, in many samples, exhibit the process of micritization wherein the carbonate allochems (skeletal and non–skeletal) are completely or partially micritized with the continuous and boring activity of algae (Fig. 6f, i, l). The replacement of the original calcite by dolomite cement (Fig. 7e) and silica (Fig. 7f) is considered a late–stage diagenetic process.

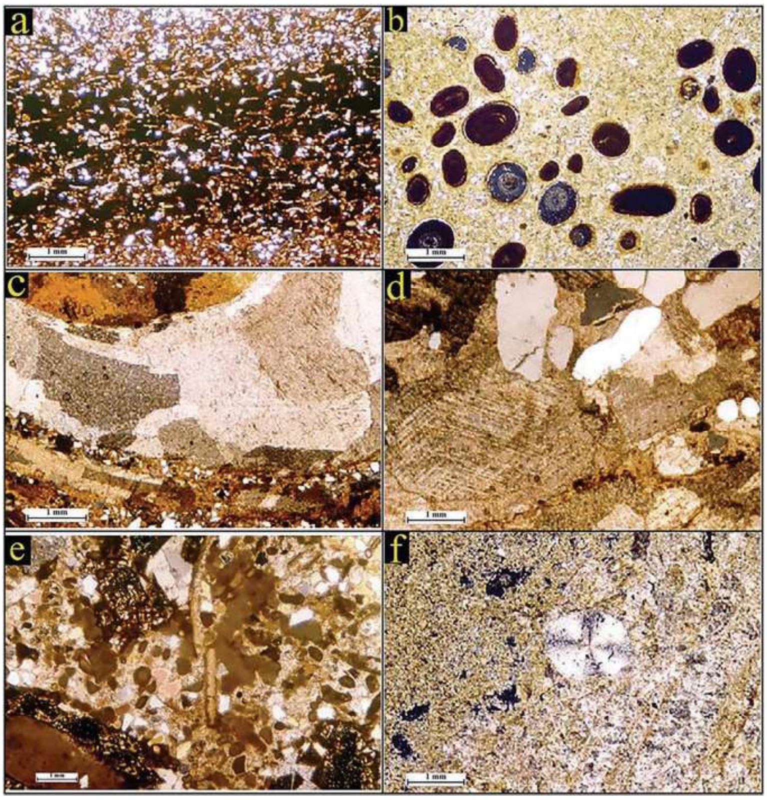


Fig. 7 Photomicrographs (xpl) displaying the various diagenetic changes of Mesozoic carbonate rocks: **a** Laminated (light and dark) ferruginous limestone with tightly compacted very thin tests/shells of bivalves **b**, **c** Replacement of original aragonitic shell fragment of mollusc by neomorphic sparry calcite. Note the ghost of primary layers in the spar (lower left), **d** Syntaxial rim cementation of echinoid skeleton, **e** Sandy–molluscan biosparite showing replacement of calcite by dolomite (dolomitization—dark patches), and **f** Silicification and chert formation in limestone

6 Depositional History

The interpretation of the environment of a litho–unit should be based on consideration of several parameters: physical (bed geometry, primary structures), lithological (petrographic, mineralogic, granulometric, textural, and diagenetic), biological (biota, trace fossils), chemical, and stratigraphic relationship, together in a process to response model. Minimal emphasis was given in the past for an integrated study to substantiate their conclusions with detailed sedimentologic observations.

6.1 Provenance

Based on the detailed petrographic and heavy mineral analyses, Chaudhuri et al. (2018) interpreted the provenance of Mesozoic sandstones resulting from two different sources, the felsic basement rocks of Nagar Parkar ridge complex in the north and the Aravalli and Delhi Super Group in the east. The paleocurrent analyses and sedimentological study of the sandstone from the present study suggesting a westerly to south paleoslope support the above indicating the movement of sediment from north and east. As observed from the thin section petrographic study, the framework composition of the sandstone suggests a mixed igneous and metamorphic source of supply of sediments. The fine to medium-grained, hard, compact sandstones containing abundant undulose quartz, lithic fragments over feldspars characterize a metamorphic source. The abundant opaque minerals and the presence of strained quartz and microcline further support the metamorphic source. The relatively coarse-grained sandstones with abundant feldspars and non–undulose quartz, inclusions of rutile in quartz suggest an igneous origin. A shift in sandstone type from Arkosic (Jumara Formation) to subarkosic (Bhuj Formation) is interpreted by Chaudhuri et al. (2018). The heavy mineral composition, consisting of rutile, ilmenite, and magnetite, suggests an acidic to a basic igneous source. QFL plots of framework composition indicated a basement up–lifted provenance of Middle Jurassic sandstones and a combined basement–uplifted and craton interior provenance for the Late Jurassic to Early Cretaceous sediments. In the present study, the plotting (Fig. 8a, b) of the Mesozoic sandstone framework compositional data on the tectonic provenance diagram (QFL) of Dickinson (1979, 1985) shows the majority of the sample falling in the recycled orogenic and craton interior provenance without much differentiation of the Middle Jurassic versus Late Jurassic–Early Cretaceous

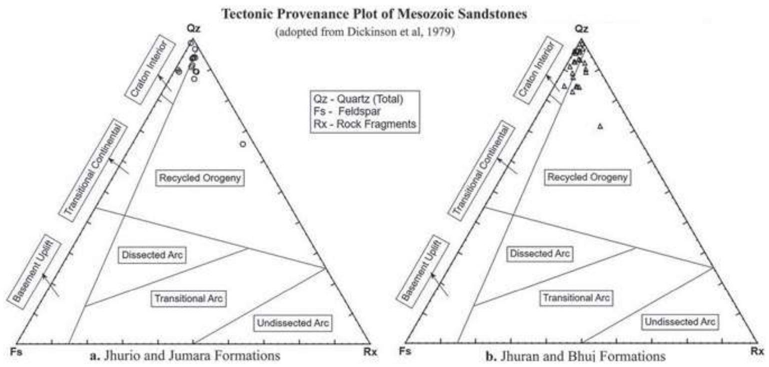


Fig. 8 Ternary QFR plots for sandstone provenance analysis (Dickinson and Suczek 1979; Dickinson 1985) for understanding the tectonic provenance of Mesozoic sandstones of Kachchh

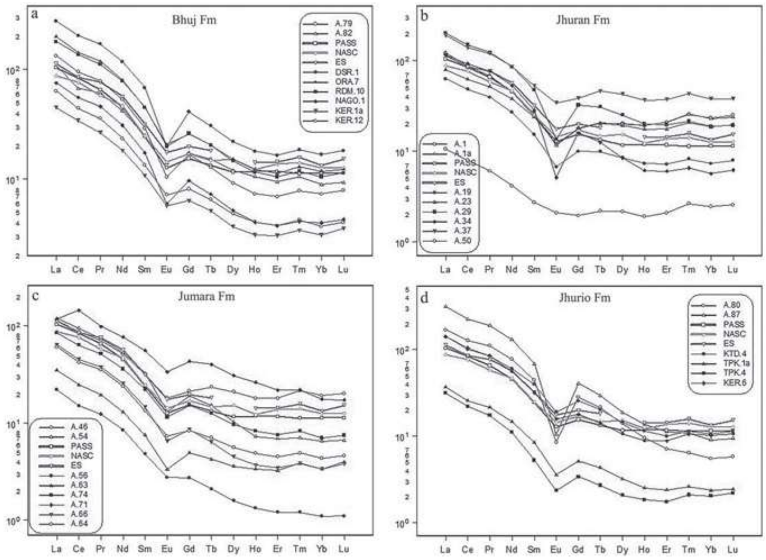


Fig. 9 Stratigraphic variation in chondrite-normalized REE plots for the data

sandstone. The rare earth element (REE) content of the rocks characterize post–Archean sediment, and the homogenization is due to erosion and transportation. The REE content of Middle Jurassic sandstones (mean from 129 to 153) is close to the crustal average. In contrast, the Late Jurassic to Early Cretaceous (Jhuran and Bhuj Formations) show a slightly higher value (above crustal average) of the total REE (Table 5). However, a greater enriched LREE and fractionated LREE and flat HREE is observed from the chondrite normalized REE patterns for the entire Mesozoic sediments (Fig. 9a–d). Although no regular vertical or spatial variation/separation is observed in the texture and composition of the sandstone when interpreted independently, the use of Canonical discriminant statistical analyses of the combined textural and mineralogical composition all the sandstones provided in differentiating the different lithological units (Fig. 10).

6.2 Depositional Environment

Most of the earlier studies on the reconstruction of the paleoenvironments of the Mesozoic stratigraphic units were qualitative and based mainly on local studies and general observations of gross lithology and ecology of fossil fauna/flora (Ghosh 1969). Subsequent studies of Krishna et al. (1983) and Howard and Singh (1985)

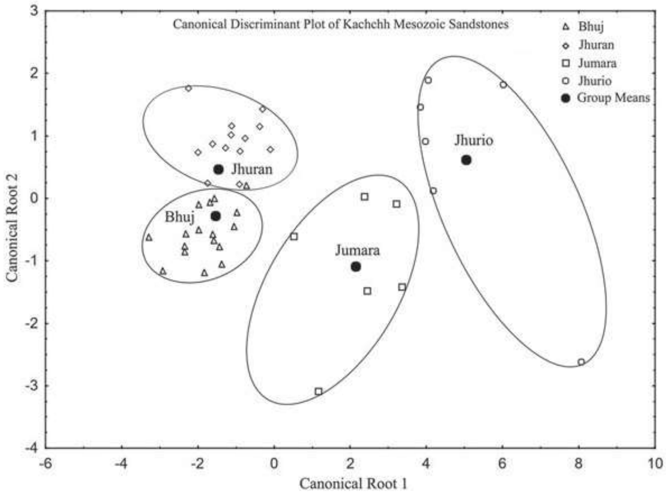


Fig. 10 Canonical discriminant plot of combined textural and framework compositional data of sandstones showing clear separation of Mesozoic formations of Kachchh Mainland

interpret the depositional environments based mainly on trace fossils with some supporting evidence from gross lithology. A comprehensive study of the basin framework, depositional processes, and environments, and the evolution based on the detailed study of the gross facies and its quantitative assessment of the basin is given by Biswas (1981). Based on a detailed study of Ammonoid fauna, shallow marine, inner to middle shelf environment of deposition has been suggested for the Middle Jurassic Jhurio and Jumara formations (Fürsich et al. 1992, 2001; Krishna et al. 2000). The vertical environment profiles of lithologic sequences indicate two distinct mega–cycles Kachchh (Biswas 1982): a transgressive, followed by a regressive cycle, with several transgressive/regressive sub–cycles and micro–cycles corresponding to the fluctuations of sea levels in unstable shelf condition. An outer to inner shelf environment of deposition for the Jhuran Formation is interpreted based on their sedimentological study (Arora et al. 2015, 2017).

The clastic textural study suggests a mixed depositional condition of fluctuating coastal beach–shallow marine environment. The average grain–size of these rocks resembles that of nearshore, beach–shallow marine sands. In general, the clastic grains are moderate to well–sorted, negative to positively skewed, and mesokurtic. According to Friedman (1967, 1969), standard deviation values of Mesozoic sandstone textures fit into the category of moderately sorted to well–sorted sand; and are similar to those of the beach sands. The depositional environments as interpreted independently from the field observation of the sedimentary structures and textural characteristics and composition of the sandstones all support each other indicating, in general, a mixed fluvial–aeolian–beach–shallow marine environment of deposition of Mesozoic sediments. Petrographically the coarse clastics correspond to Quartz arenite and Feldspathic arenite types with little mud suggesting greater winnowing action of the depositional medium.

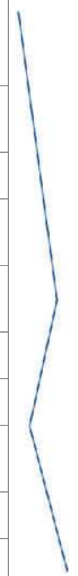
The mineralogical composition and sandstone in association with textural characteristics and paleocurrent data suggest their derivation from a recycled crystalline igneous and metamorphic source probably from north and east, perhaps from the Aravallis in the East and Nagar Parkar ridge in the north. Table 6 summarizes the stratigraphy and sedimentation history of the Mesozoic sequence of Kachchh Mainland.

7 Conclusions

The present integrated study of the lithofacies association with detailed clastic and carbonate sedimentology of the Mesozoic sequence of Kachchh, while substantiating the earlier interpretations, also provides additional data to interpret provenance and depositional environments.

(a) The Mesozoic sequence of Kachchh mainland represent 13 Lithofacies associations comprising various sediment characteristics with a host of sedimentary structures dominated by Cross–bedding depositional structures.
(b) The paleocurrent analyses of cross–bedding structures of sandstones support the sediment provenance source from the north (possibly Nagar Parkar massif) and east and northeast (Aravalli source).
(c) In general, the depositional environments of the Mesozoic sequence vary from a beach to shallow marine for the lower part to fluvial to shallow marine in the upper part.
(d) The Mesozoic sediments of Kachchh mainland, as indicated by their structural and petrographic textural characteristics, have been subjected to various post–depositional modifications that lead to modification of the original depositional characteristics and porosity changes.

Table 6 Summary of the Depositional Characteristics of the Mesozoic Succession of Kachchh Mainland (after Biswas 1981; Osman and Mahender 1997; Mahender et al. 2008; Mahender and Sharma 2010)

Age	Fm	Litho-facies	Bedding/ Geometry	Lithology	Dominant Structures	Biota	Texture	Clay Minerals	REE Patterns	Provenance	Environment	Probable Sea Level − 0 +
Early Cretaceous	Bhuj	LFA13 LFA12	Well Bedded (X- & planar bdd,) Blanket	Sandstone	Large scale Cross-bedding, Bioturbation, Jointing, Soft sediment deformation	Plant fossils	Fine-med, Well Sorted	Kaolinite Chlorite	∑REE close to crustal average, Greater Degree of Enriched LREE, Fractionated LREE and flat HREE, Significant Negative Eu Anomaly	Recycled crystalline igneous and metamorphic source of Nagar Parkar ridge in the north and Aravallis in east,	Fluvial-Upper Deltaic plains	
		LFA11 LFA10	Well Bedded (X-bedded), Blanket	Ferr. S.st, Shale, cyclic, coal beds		Plant & Trace Fossils	Fine to Med, V. well sorted	Kaolinite, Chlorite			Lr Deltaic plain (Distributary)	
Late Jurassic	Jhuran	LFA 9 LFA 8	Bedded / Tabular	S.st, minor shales	Cross-bedding, Ripple Marks, Concretions & Nodules	Poorly fossiliferous	Fine, Mod Sorted	Kaolinite Chlorite			Delta Front	
		LFA 7	Thin bedded / wedge	Shales, thin s.st bands		Marine Fossils	Fine, Mod. sorting	Illite, Chlorite Kaolinite,			Pro-delta	
		LFA 6	Thin Bedded / Tabular	Sandstone& Shale		Marine Fossils	Fine, Mod. Sorting	Kaolinite, Illite			Shallow Marine to Sub-littoral	
Middle Jurassic	Jumara	LFA 5	Thin bedded	L.st.& shale	Cross-bedding, Ripple marks, Trace fossils, Burrows, soft sediment deformation, scour marks	Abundant Diverse	Non-clastic	Kaolinite Chlorite	∑REE close to crustal average, Enriched LREE over HREE, Fractionated LREE and flat, Negative Eu Anomaly		Sub-littoral	
		LFA 4	Bedded	S.st, shale & L.st		Abundant	Fine, Mod sorted, + ve	Kaolinite chlorite			Sub-littoral	
		LFA 3	Well Bedded (X-bedded)	S.st, shale & conglomerate		Few (molluscs)	Medium, Well sorted + ve	Kaolinite			Beach (Littoral)	
	Jhurio	LFA 2	Bedded	Shale, L.st and S.st	Boring and Burrows, surface crusts, Trace fossils	Abundant	Fine, Mod sorted, -ve	Kaolinite Chlorite			Wave zone	
		LFA 1	Thin bedded	L.st and shale		Few	Non-clastic	Kaolinite, illite			Quiet water below wave zone	

Acknowledgements The author acknowledges the financial support received through grant nos. ES/23/194/94 and ES/23/VES/095/2000 from the Science and Engineering Research Board, Department of Science and Technology, Government of India. The author is thankful for the support and facilities extended by Goa University for the conduct of this work.

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