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ORIGINAL PAPER

The inner ramp facies of the Thanetian Lockhart Formation, western Salt Range, Indus Basin, Pakistan

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Abstract The Lockhart Formation from a major carbonate unit of the Paleocene Charrat Group in Upper Indus Basin, Pakistan represents a larger foraminiferal–algal build up deposited in a cyclic sequence of the carbonate ramp. The foraminiferal–algal assemblages of the Lockhart Formation are correlated here to larger foraminiferal biostratigraphic zone, i.e. Shallow Benthic Zone (SBZ3) of the Thanetian Age. Inner ramp lagoon, shoal and fore shoal open marine are three main facies associations represented by wackstone and packstone foraminiferal–algal deposits. These facies are present in a cyclic order and displayed a retrograding carbonate ramp indicating the Thanetian transgressive deposits associated with eustatic sea level rise. The correlation of the microfacies of the Lockhart Formation (Upper Indus Basin) and facies of the Dungan Formation (Lower Indus Basin) provide detailed configuration of the depositional setting of the Indus Basin during the time interval represented by the Thanetian Zone SBZ3.

Keywords Paleocene · Indus Basin · Foraminifera · Pakistan · Lockhart

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Introduction

A large body of literature exists in the Paleocene Lockhart and Dungan formations (e.g. Davies 1930; Meissner et al. 1974; Shah 1977; Wells 1984; Yeats and Hussain 1987; Pivnik 1992; Afzal 1997; Shafique 2001; Hanif et al. 2012). However, the previous literature on these formations often lacks a combined approach to integrate stratigraphical, biostratigraphical and paleoenvironmental framework. Recently, some attempts have been made to describe the foraminiferal content and depositional environment of these formations, but the important Thanetian algal assemblages were not studied in detail (e.g. Afzal et al. 2011; Hanif et al. 2012). The present work offers an integrated approach to interpret the depositional and paleoenvironmental settings of the Lockhart Formation in a biosequence stratigraphic framework. All the data are integrated to present a depositional picture for the Lockhart Formation within the basin in comparison with other Tethyan foraminiferal–algal assemblages of the Thanetian stage. Finally, a depositional picture of the Indus Basin for the time period represented by the deposition of Lockhart and part of the Dungan formations, i.e. Thanetian (Shallow Benthic Zone (SBZ3) age equivalent to Plantkic foraminiferal Zone P4) is presented.

Materials and methods

Paleocene carbonates are well exposed in Indus Basin, Pakistan. Some of the best-known exposures of these strata are in Salt Range and Sulaiman Range (Fig. 1). The Nammal Gorge is one of the famous sections of the Salt Range. The Paleocene succession is well exposed in this section and comprises of the Charrat Group including the Hangu, Lockhart and Patala formations in ascending order. The Paleocene Lockhart Formation was measured, logged and sampled in the following three sections of the western Salt Range, Pakistan; (1) Dhok Kas, (2) Nammal Gorge and (3) Mari Indus (Kalabagh). The Lockhart Formation present in all the three sections is predominantly composed of nodular limestone with minor shale interbeds, and that is why the term "Lockhart Formation" is preferred over the previously used "Lockhart Limestone" in the present study. Only the limestone samples were thin sectioned for petrographical analysis; shale samples were not analysed for the present study, however, the shales were processed and analysed in Hanif et al. (2012). The lower contact of the Lockhart Formation is covered in the Dhok Kas Section; however, in the Nammal Gorge and Mari Indus (Kalabagh) sections, it overlies the Hangu Formation (Figs. 2, 3, and 4). The upper contact is covered both in the Dhok Kas and Mari Indus (Kalabagh) sections; however, in the Nammal Gorge Section, the Lockhart Formation underlies Patala Formation (Figs. 2, 3, and 4). The Nammal Gorge Section provides a fairly complete section for the Paleocene Lockhart Formation where the Lockhart Formation can be divided into two lithofacies: the lower lithofacies is composed of thin nodular limestone interbedded with shale representing a lagoon, whereas the upper lithofacies is predominantly composed of nodular limestone, with larger foraminifera visible to the naked eyes and representing a foraminiferal shoal.

In the Lower Indus Basin, the contact between the Paleocene and the Cretaceous is disconformable (e.g. Williams 1959) although it is transitional in places according to the Hunting Survey Corporation Ltd. (1961). The marine Paleogene succession in the Lower Indus Basin consists of four formations which in ascending order are the Dungan, Shaheed Ghat, Baska and Kirthar formations. The Paleocene Dungan Formation was measured, logged and sampled in the Rakhi Nala Section, Lower Indus Basin in an earlier study by Hanif et al. (2012). The current study is primarily based on the

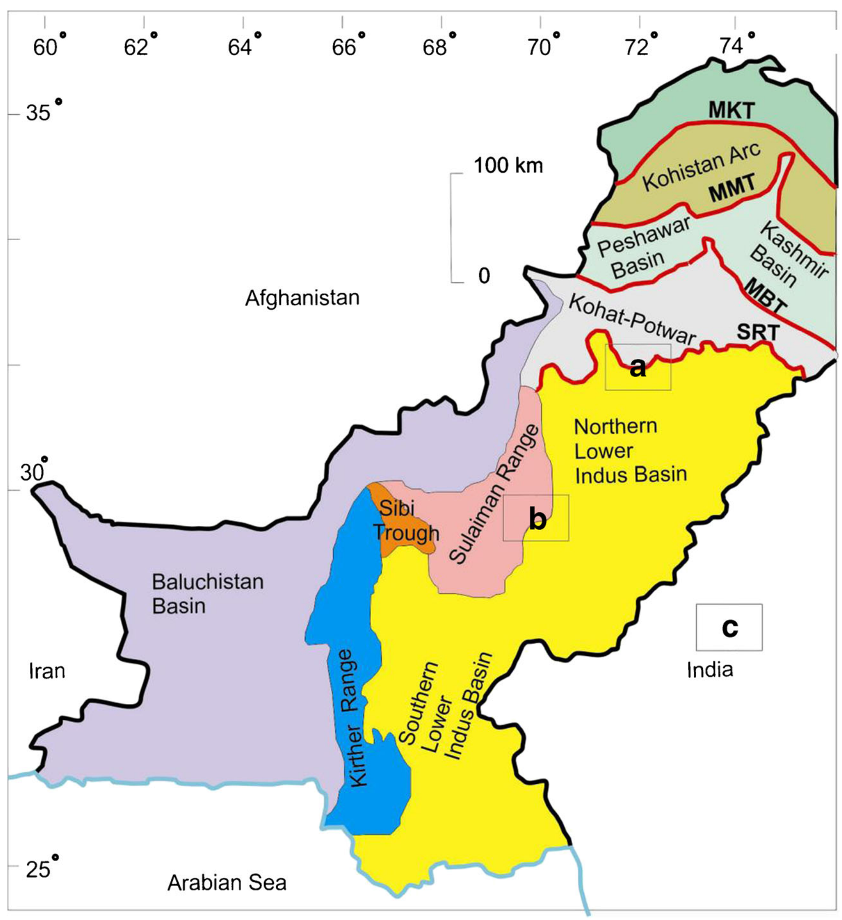


Fig. 1 Geological map of Pakistan showing field locations and main geological features (modified after Hanif et al. (2012); **a** Dhok Kas, Nammal Gorge and Mari Indus (Kalabagh) sections, western Salt Range (Upper Indus Basin, Pakistan), **b** Rakhi Nala Section (Sulaiman Range), and **c** Tanot-1 Well, Jaisalmer Basin, Rajesthan (India). *MKT* Main Karakoram Thrust, *MMT* Main Mantle Thrust, *MBT* Main Boundary Thrust, and *SRT* Salt Range Thrust

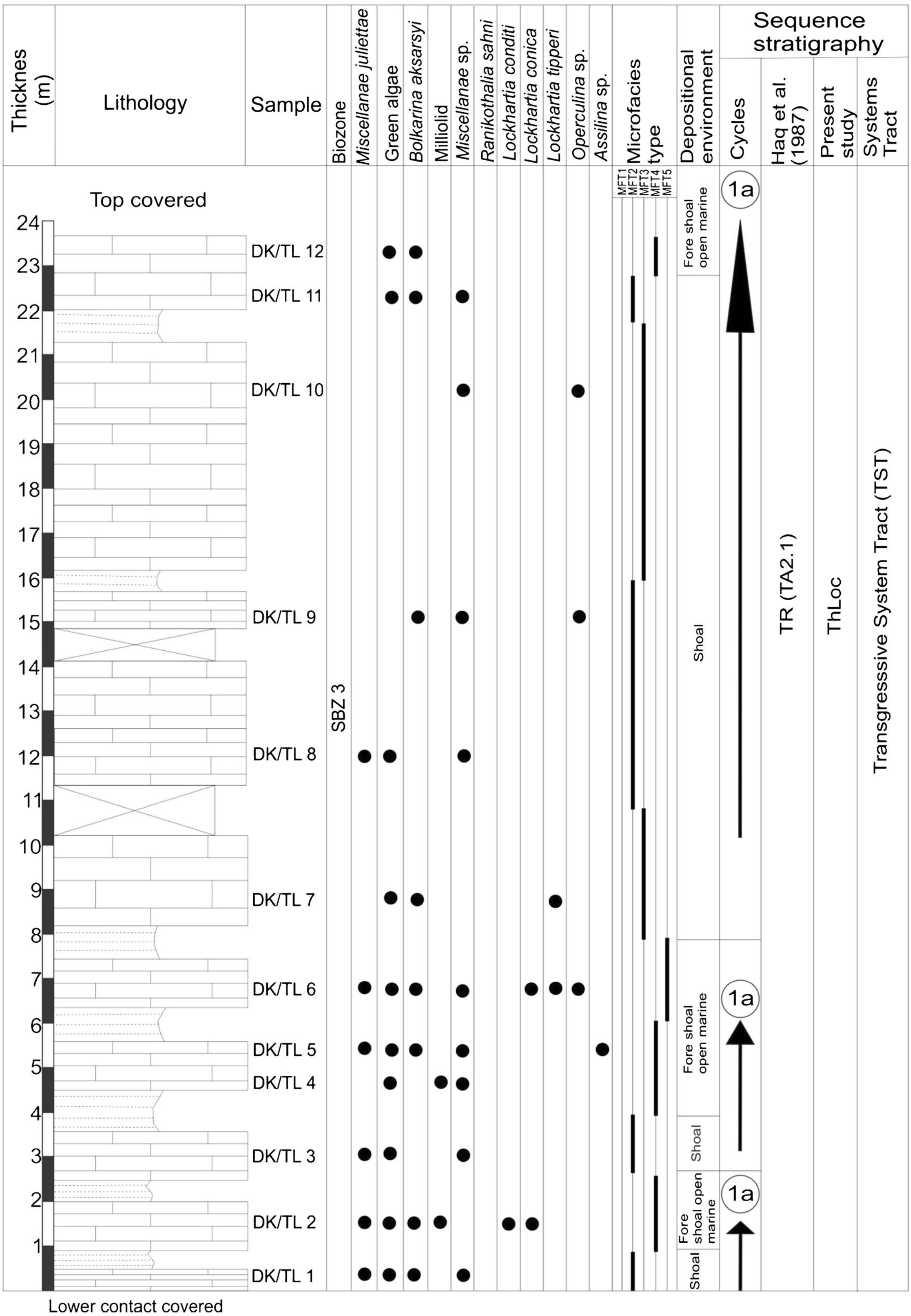


Fig. 2 Lithological log of the Lockhart Formation, Dhok Kas Section (Upper Indus Basin) showing distribution of foraminifera, microfacies, depositional environments, depositional cycles (*upward-pointing arrows*) and depositional sequence

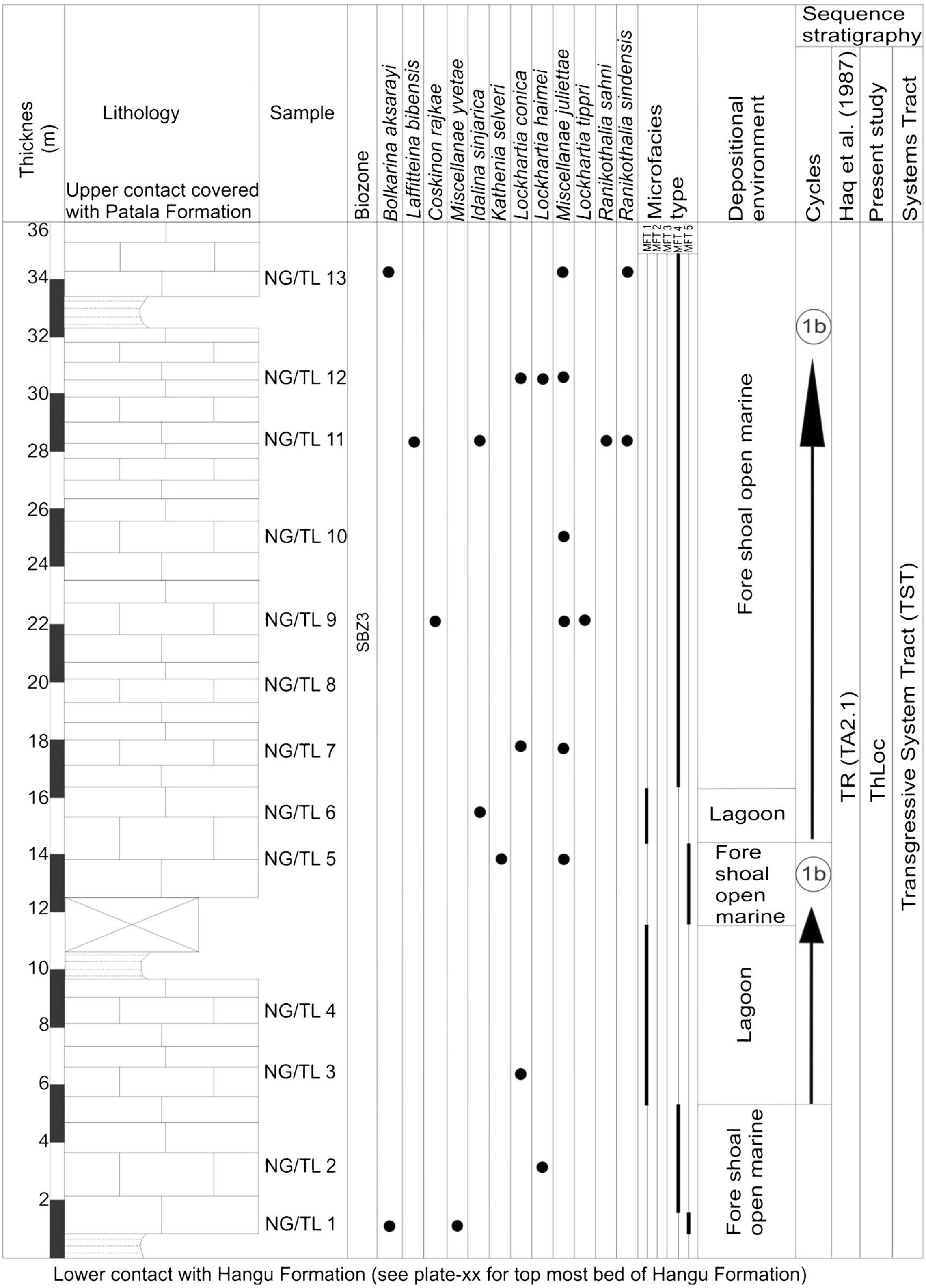


Fig. 3 Lithological log of the Lockhart Formation, Nammal Gorge Section (Upper Indus Basin) showing distribution of foraminifera, microfacies, depositional environments, depositional cycles (*upward-pointing arrows*) and depositional sequence

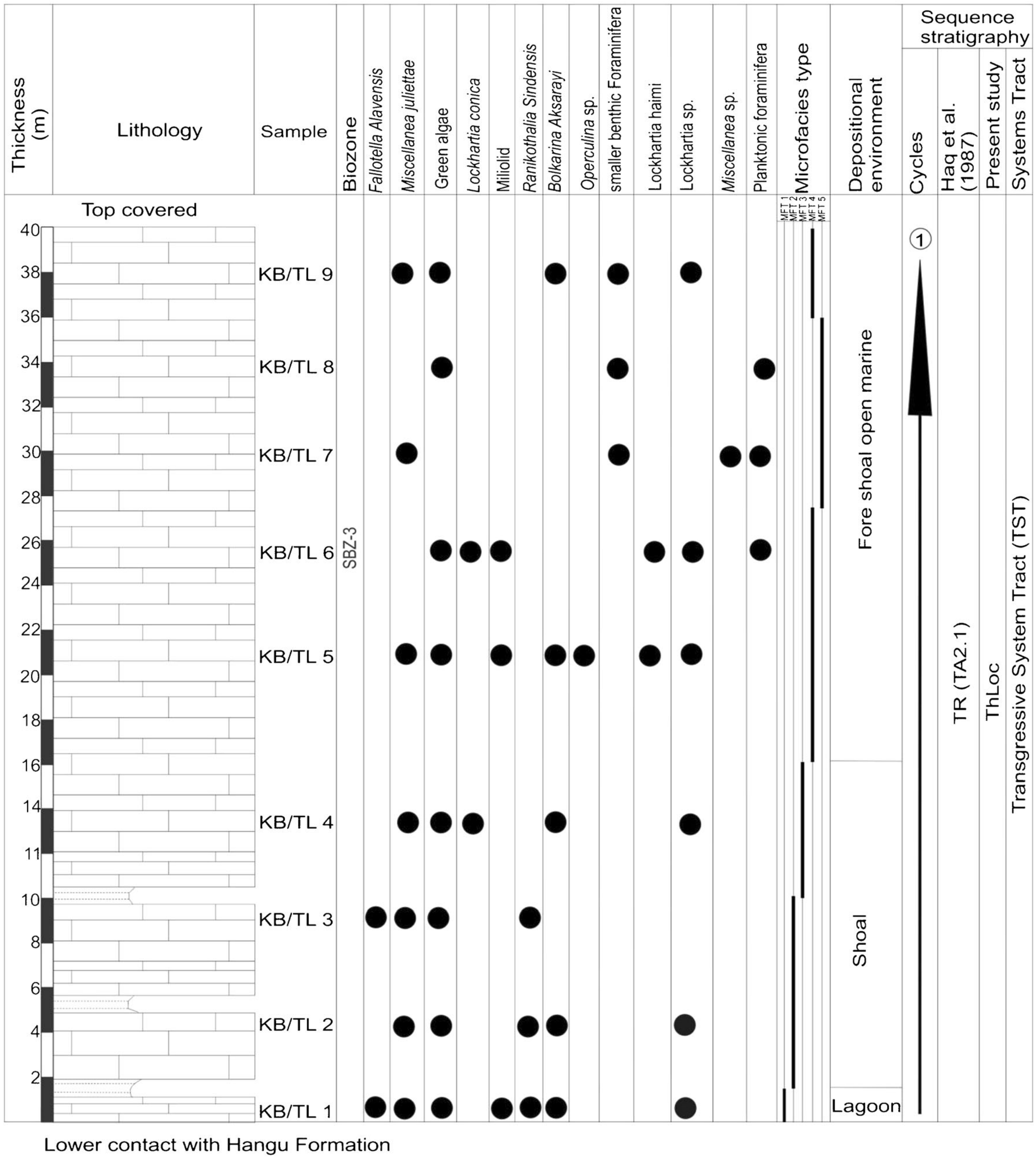


Fig. 4 Lithological log of the Lockhart Formation, Mari Indus (Kalabagh) Section (Upper Indus Basin) showing distribution of foraminifera, microfacies, depositional environments, depositional cycles (*upward-pointing arrows*) and depositional sequence

Paleocene Lockhart Formation of the western Salt Range (Upper Indus Basin); the Dungan Formation was studied only for correlation purpose. The detailed lithostratigraphy of the Rakhi Nala Section is given in previous literature (e.g. Warraich et al. 2000). The Dungan Formation is composed of dark black-coloured siltstones interbedded with hard quartzitic–glauconitic sandstone beds in the lower part and thin to thick bedded, dark grey limestone weathering brown buff in the upper part (Warraich et al. 2000).

Results

Larger foraminiferal biostratigraphy of the Lockhart Formation

Samples from the Lockhart Formation in the Nammal Gorge Section have yielded biostratigraphic markers such as *Miscellanea juliettae*, *Miscellanea yvettae* and *Coskinon rajkae* (Figs. 2, 3, 4 and Plates 1, 2, 3) which suggest that the

Lockhart Formation can be regarded as representing the interval equivalent to the SBZ3 of Serra-Kiel et al. (1998). The only occurrences of *Laffitteina bibensis* and *Idalina sinjarica* in Nammal Gorge (in samples NG/TL 1, NG/TL 6 and NG/TL11, respectively) indicate the occurrence of zone SBZ2 which has never been reported from any part of the Upper Indus Basin. Although direct correlation with planktic foraminiferal zones is not possible due to the absence of planktic foraminifera in the studied sections, the SBZ3 has been shown to be the equivalent of the late *Globanomalina pseudomenardii* Zone (late P4), representing the Thanetian (Serra-Kiel et al. 1998).

Microfacies and depositional environment

The nodular Lockhart Formation exposed in Dhok Kas, Nammal Gorge and Mari Indus (Kalabagh) sections of the western Salt Range is a cyclic sequence of wackestones and packstones of larger foraminifera and calcareous algae deposited in inner carbonate ramp setting. The foraminifera, calcareous algae and microfacies character allow subdivision of the Lockhart Formation broadly into three facies: (1) Inner Ramp lagoon, (2) Inner Ramp foraminiferal shoal and (2) Fore-shoal open marine.

The distribution of the microfacies and facies association is given in Figs. 2, 3 and 4, and Table 1 in Appendix. Representative photomicrographs and the depositional model are given in Plates 1, 2, 3 and Fig. 6, respectively. Petrographic data from all the three sections is provided in Tables 2, 3, and 4 in Appendix.

Inner ramp lagoon

Bioclastic dasycladales wackstone (MFT1) was deposited in a back-shoal lagoon (e.g. Plate 1a, b). This MFT is characterised by the abundance of bioclasts and dasycladale algae. The larger foraminifera is the second dominant allochem type including *Ranikothalia* sp., *Ranikothalia sindensis*, *Lockhartia* sp., miliolids, *M. yvettae* LEPPIG and Orbitoidae. Echinoids are present as minor constituent. The fragments of coral (present in Mari Indus Kalabagh section only) might have been derived from a nearby patch reef. The frequent reworking of bioclasts by waves/currents indicates moderate-high energy conditions. The abundance of dasycladale algae is also an indication of well-lit conditions.

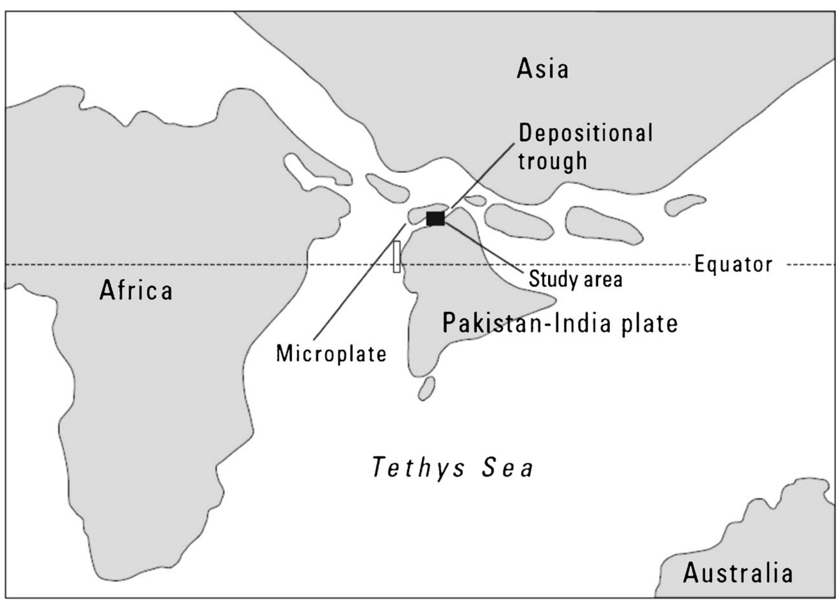


Plate 1 Photomicrographs showing microfacies of the Mari Indus (Kalabagh) Section, Upper Indus Basin, western Salt Range (Pakistan). **a** Bioclastic dasycladale wackstone (MFT1) showing tabulate coral fragments (*Co*), dasycladale green algae (*D*), *Ranikothalia* sp. (*R*); sample # KB/TL 1. **b** Bioclastic dasycladale wackstone (MFT1) showing dasycladale algae (*D*), *Miscellanea yvattea* (*My*), miliolid (*Mi*); sample # KB/TL 1. **c** Bioclastic foraminiferal wack-packstone (MFT2) showing bivalves (*Bi*), bioclasts (*Bc*), Rotalia (*Ro*), *Ranikothalia sindensis* (*Rs*) and *Miscellanea yvattea* (*My*); sample # KB/TL 2. **d** Bioclastic foraminiferal wack-packstone (MFT2) showing fenestrate bryozoans (*Bf*), *Ranikothalia* sp. (*R*); sample # KB/TL 2. **e** Bioclastic foraminiferal packstone (MFT3) showing *Miscellanea juliettae* (*Mj*); sample # KB/TL 4. **f** Bioclastic dasycladale foraminiferal wack-packstone (MFT4) showing dasycladale algae (*D*); sample # KB/TL 5. **g** Bioclastic dasycladale foraminiferal wack-packstone (MFT4) showing smaller benthic foraminifera (*Bs*), dasycladale algae (*D*), echinoids (*E*); sample # KB/TL 8. **h** Bioclasitc dasycladale foraminifera wack-packstone (MFT4) showing Orbitoidae (*Or*), dasycladale algae (*D*); sample # KB/TL 9

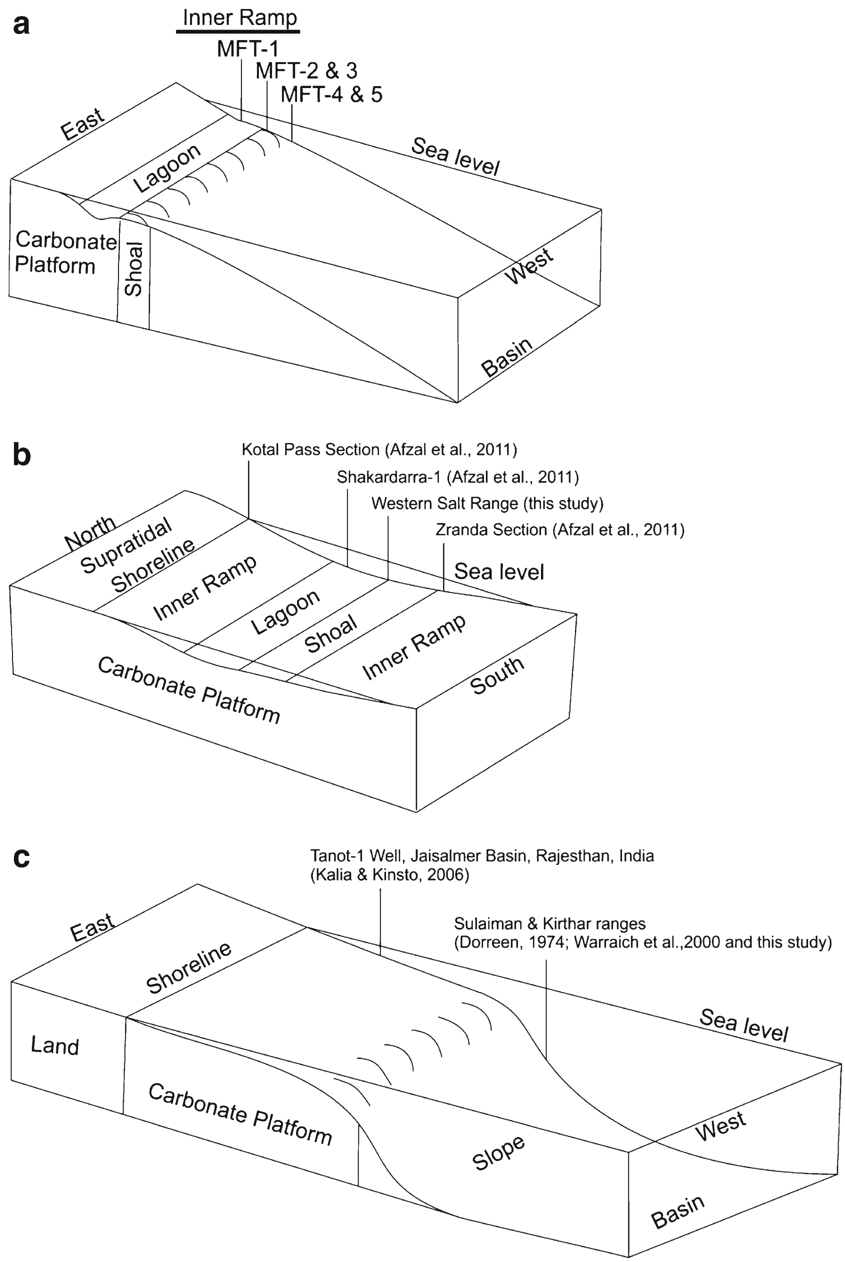


Plate 2 Photomicrographs showing microfacies of the Dhok Kas Section, Upper Indus Basin, western Salt Range (Pakistan). **a** Bioclastic foraminiferal wack-packstone (MFT2) showing dasycladale algae (*D*), *Miscellanea juliettae* (*Mj*), *Lockhartia* sp. (*Ls*), and recrystallized bioclast (*Bc*); sample # DK/TL 3. **b** Bioclastic foraminiferal wack-packstone (MFT2) showing species of dasycladale algae (*D*), *M. juliettae* (*Mj*), *Lockhartia* sp. (*Ls*), and recrystallized bioclast (*Bc*); sample # DK/TL 8. **c** Bioclastic foraminiferal packstone (MFT3) showing *Bolkarina askarayi* (*Ba*), dasycladale algae (*D*), biserial foraminifera (*Bfo*), *Lockhartia* sp. (*Ls*), and recrystallized bioclast (*Bc*); sample # DK/TL 7. **d** Bioclastic dasycladale foraminiferal wack-packstone (MFT4) showing dasycladale algae (*D*), *M. juliettae* (*Mj*), *Lockhartia* sp. (*Ls*), recrystallized bioclast (*Bc*) and bivalves (*Bi*); sample # DK/TL 2. **e** Bioclastic dasycladale foraminiferal wack-packstone (MFT4) describing *Bolkarina askarayi* (*Ba*), dasycladale algae (*D*), recrystalized bioclast (*Bc*) and bivalves (*Bi*); sample # DK/TL 4. **f** Bioclastic dasycladale foraminiferal wack-packstone (MFT4) describing *Bolkarina askarayi* (*Ba*), dasycladale algae, recrystallized bioclast (*Bc*) and *Lockhartia* sp. (*Ls*); sample # DK/TL 5. **g** Bioclastic dasycladale foraminiferal wack-packstone (MFT4) describing *Bolkarina askarayi* (*Ba*), dasycladale algae (*D*), and *Lockhartia* sp. (*Ls*); sample # DK/TL 12. **h** Bioclastic foraminiferal wackstone (MFT5) showing smaller benthic foraminifera (*Bs*), *Lockhartia tippri* (*Lt*), *Lockhartia* sp. (*Ls*) and recrystallized bioclast (*Bc*); sample # DK/TL 6

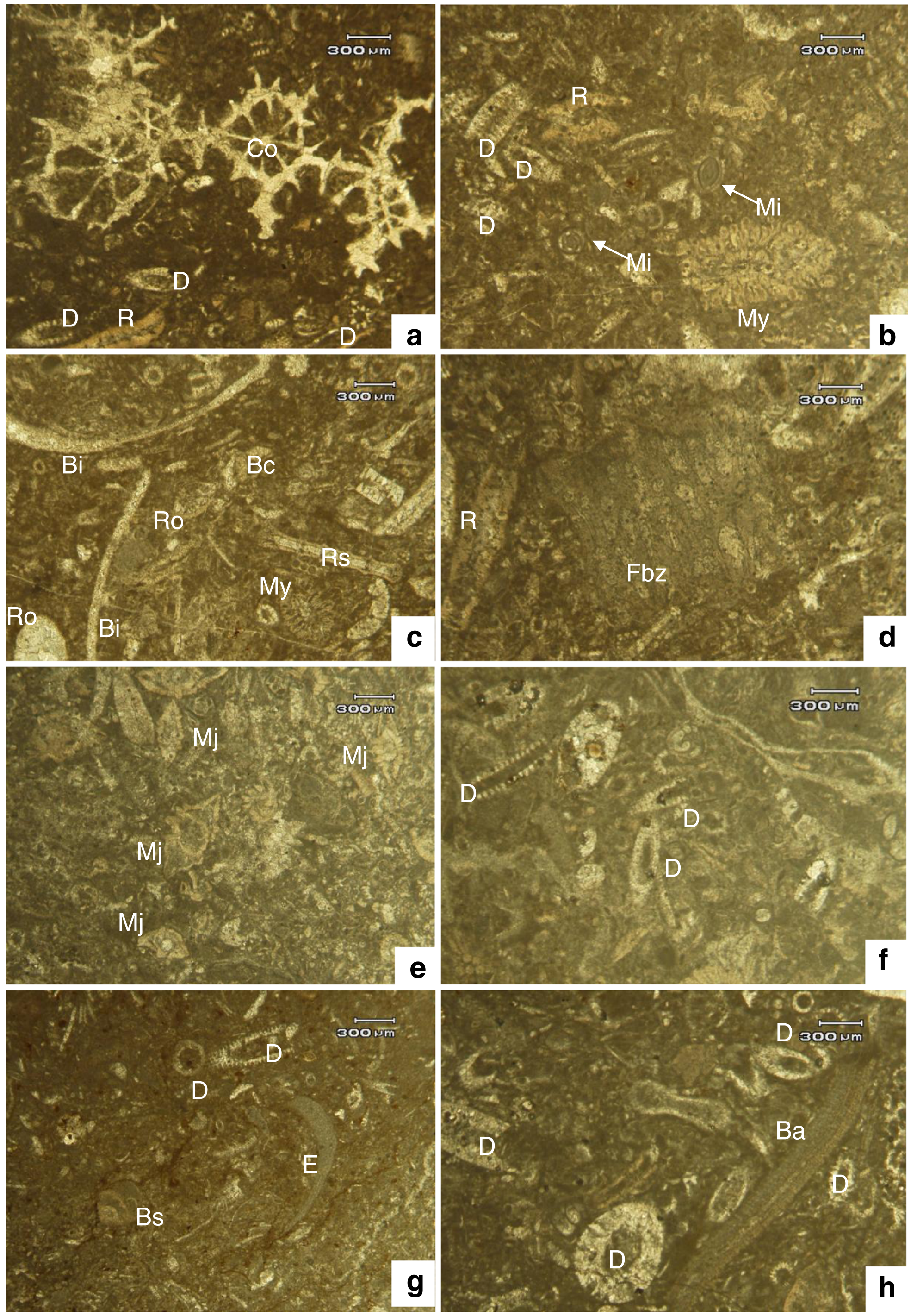


Plate 3 Photomicrographis showing microfacies of the Nammal Gorge Section, Upper Indus Basin, western Salt Range (Pakistan). **a** Bioclastic dasycladale wackstone (MFT1) showing dasycladale green algae (*D*) embedded in fine grained micritic back ground; sample # NG/TL 4. **b** Showing dasycladale green algae (*D*) in bioclastic dasycladale wackstone (MFT1); sample # NG/TL 4. **c** Bioclastic dasycladale foraminiferal wack-packstone (MFT4) describing *Miscellanea juliettae* (*Mj*), dasycladale algae (*D*), *Coskinon rajkae* (*Cr*), bivalves (*Bi*), recrystallized bioclast (*Bc*) *Lockhartia* sp. (*Ls*); sample # NG/TL 9. **d** Bioclastic dasycladale foraminiferal wack-packstone (MFT4) describing dasycaldale algae (*D*), *Ranikothalia sahni* (*Sh*), *Idalina* cf. *sinjarica* (*Icf*), miliolid (*Mi*), and rcrystallized bioclast (*Bc*) *Lockhartia* sp. (*Ls*), sample #NG/TL 11. **e** Bioclastic dasycladale foraminiferal wack-packstone (MFT4), *Bolkarina askarayi* (*Ba*), *M. juliettae* (*Mj*), *Miscellanea* sp. (*Ms*) and recrystallized bioclast (*Bc*); sample # NG/TL 11. **f** Bioclastic dasycladale foraminiferal wack-packstone (MFT4), *M. juliettae* (*Mj*), *Lockhartia tippri* (*Lt*), dasycladale algae (*D*), and recrystallized bioclast (*Bc*); sample # NG/TL 9. **g** Bioclastic dasycladale foraminiferal wack-packstone (MFT4), *M. juliettae* (*Mj*), *Lockhartia* sp. (*Ls*) and dasycladale algae (*D*); sample # NG/TL 12. **h** Bioclastic foraminiferal wackstone (MFT5) describing *M. juliettae* (*Mj*), bivalves (*Bi*) and *Lockhartia* sp. (*Ls*); sample # NG/TL 1

Inner ramp foraminiferal shoal

Bioclastic foraminiferal wack-packstone (MFT2) and bioclastic foraminiferal packstone (MFT3) represent a foraminiferal shoal facies that contains bioclasts, larger foraminifera, coral fragments, bivalves, gastropods, echinoids, bryozoans and dasycladale algae (e.g. Plate 2a,c). The larger foraminifera include Orbitoidae, *R. sindensis*, *Ranikothalia* sp., *M. yvettae*, *Miscellanea* sp. and *M. juliettae*. The moderate diversity values, the absence of miliolids and the relatively less frequent dasycladale algae indicate normal salinity conditions. Coral fragments as observed in back shoal lagoon (Mari Indus, Kalabagh Section) are also present in this facies and indicate the presence of a patch reef in close vicinity. The reworking of bioclasts by waves/currents is relatively more pronounced and indicating higher energy conditions than the back shoal lagoon.

Fore-shoal open marine)

The bioclastic dasycladale foraminiferal wack-packstone (MFT4) and the bioclastic foraminiferal wackstone (MFT5)

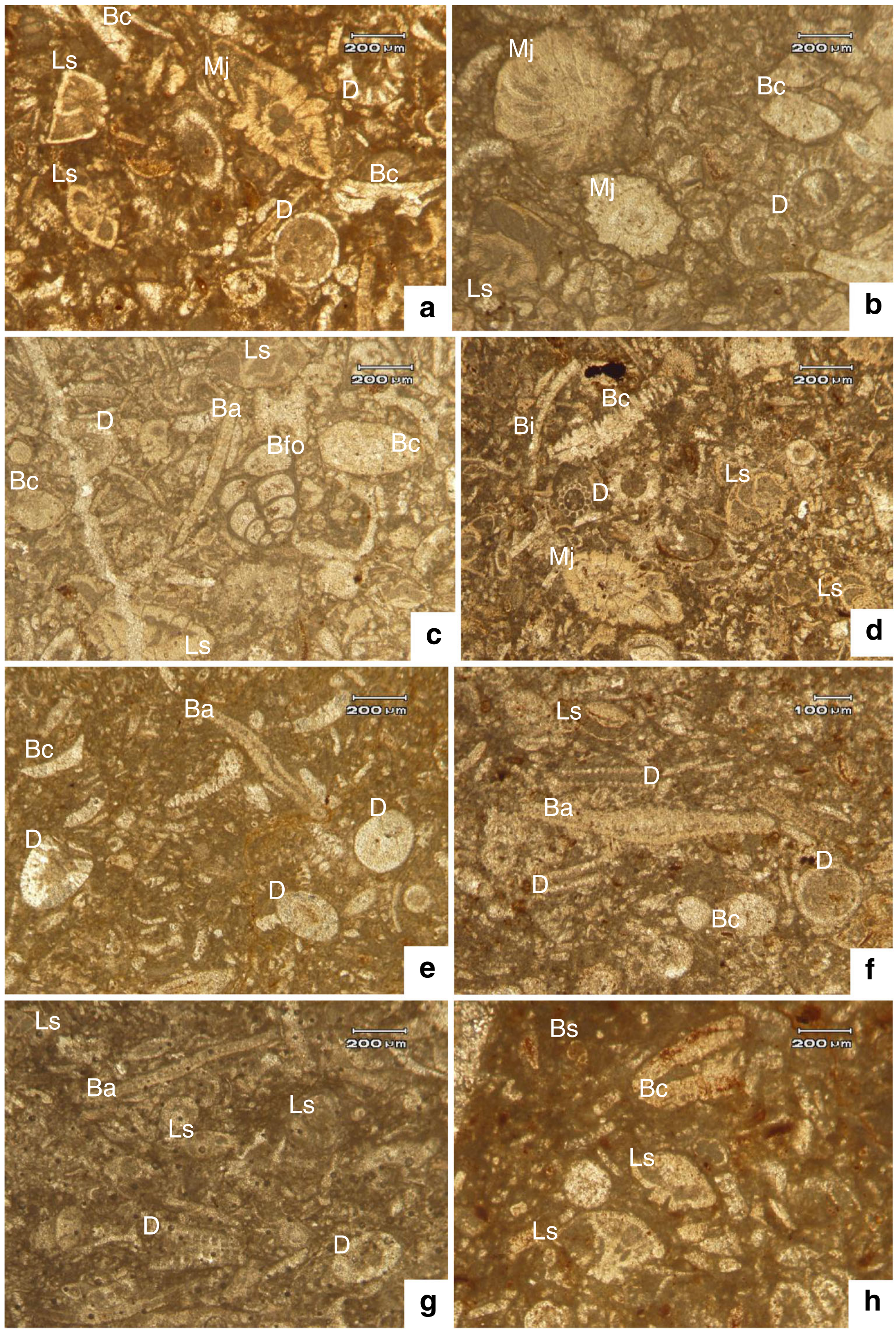
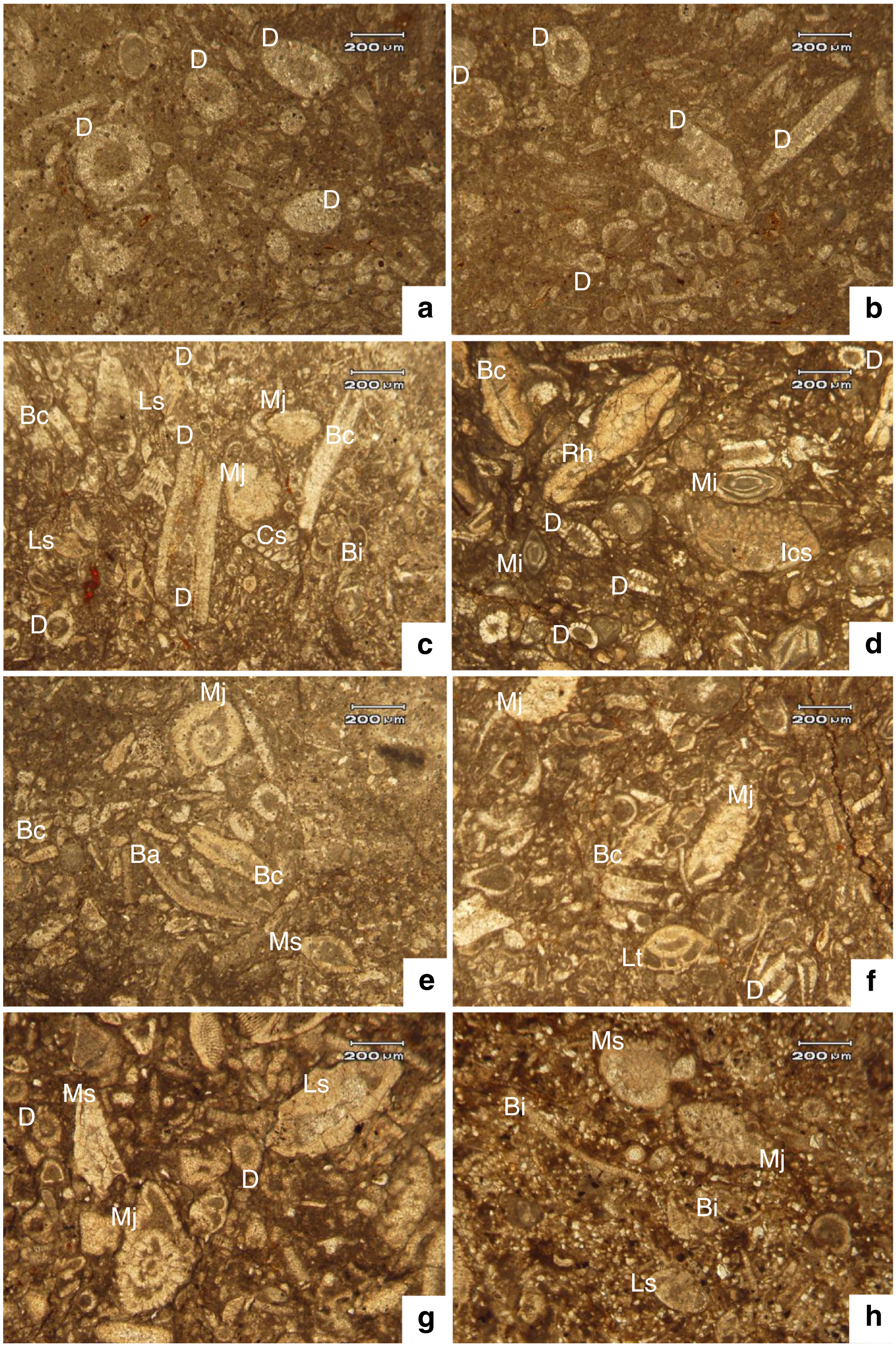


Fig. 5 Late Paleocene continental configuration of the Pakistan–Indian plate and a microplate showing a Paleocene–Eocene depositional trough (modified from Wardlaw and Martin (2007). The microplate is part of the Afghanistan plate, *shaded rectangle* represent the approximate position of Upper Indus Basin, Pakistan (see Fig. 6a,b for depositional settings). *Empty rectangle* represents approximate position of the Lower Indus Basin (see Fig. 6c for depositional setting)



represent deposition in a fore-shoal open marine environment (e.g. Plate 3c, h). This microfacies is composed of a relatively diverse biota including larger foraminifera, smaller benthic foraminifera, gastropods, echinoids, bryozoans and dasycladale algae. The larger foraminifera include *M. juliettae*, *Lockhartia* sp., *Miscellanea* sp. and Orbitoidae. The diverse biota along with the presence of smaller benthics and bryozoans indicate normal open marine salinity conditions. The reworking of bioclasts by currents as observed in the back-shoal lagoon and foraminiferal shoal facies represent moderate to high energy conditions.

◀ **Plate 4** Photomicrographs showing facies of the Dungan Formation, Rakhi Nala Section, Sulaiman Range, Lower Indus Basin (Pakistan). **a** Photomicrograph of lower part of the Dungan Formation at Rakhi Nala, Sulaiman Range, and showing quartz sandstone facies devoid of any age diagnostic planktic foraminifera; sample # Td17. **b** Photomicrograph of lower part of the Dungan Formation at Rakhi Nala, Sulaiman Range, showing quartz sandstone facies, *Subbotinae* (*a*) and *Morozovella* (*b*) species are present; sample # Td9. **c** Photomicrograph of lower part of the Dungan Formation at Rakhi Nala, Sulaiman Range representing mixed planktic foraminifera quartz sandstone facies with dominant morozovellids; sample # Td13. **d** Photomicrograph of upper part of the Dungan Formation at Rakhi Nala, Sulaiman Range representing planktic foraminiferal siltstone facies, *Morozovella* sp. cf. *M. aequa* (*a*) is present; sample # Td34. **e** Photomicrograph of upper part of the Dungan Formation at Rakhi Nala, Sulaiman Range representing planktic foraminiferal siltstone facies, *Morozovella* sp. cf. *M. aequa* (*a*); sample # Td34. **f** Photomicrograph of lower part of the Dungan Formation at Rakhi Nala, Sulaiman Range representing mixed planktic foraminifera quartz sandstone facies, *Morozovella* sp. cf. *M. gracilis* (*a*) is present; sample # Td13. **g** Photomicrograph of upper part of the Dungan Formation at Rakhi Nala, Sulaiman Range, representing planktic foraminiferal siltstone facies; sample # Td31. **h** Photomicrograph of upper part of the Dungan Formation at Rakhi Nala, Sulaiman Range representing planktic foraminiferal siltstone facies, showing change in planktic foraminiferal assemblages from morozovellid-dominated to subbotinid/acarininid-dominated assemblages, sample # Td46

Interpretation

A comparison of the microfacies of Lockhart Formation with those of Wilson (1975) and Flügel (2004) can be made as follows;

The microfacies of the Lockhart Formation apparently resemble the standard microfacies types, i.e. SMF10 and SMF18. The SMF10 is a bioclastic packstone and grainstone with coated and abraded skeletal grains and represents deposition in an open shelf lagoon and on an open sea shelf. The skeletal grains observed in the Lockhart Formation are neither coated nor abraded therefore, the microfacies of Lockhart Formation are not compatible with these depositional environments. The SMF18 represent bioclastic grainstones and packstones with abundant benthic foraminifera or calcareous green algae and represent deposition on a restricted platform to shelf lagoons with open circulation. This microfacies is also a close approximate of the ramp microfacies RMF13 and RMF17. The diagnostic characteristic of SMF18 is the abundance of benthic foraminifera. However, the microfacies of the Lockhart Formation are dominantly composed of bioclasts with a few dominant skeletal grains of either foraminifera or algae or both. Therefore, the microfacies of the Lockhart Formation are not compatible with the depositional environment of the SMF18.

The wackstone and packstone microfacies of the Lockhart Formation are similar to the RMF20 and RMF27, respectively, of the ramp microfacies of a homoclinal carbonate ramp of Flügel (2004; see Fig. 6a). The depositional environment of the RMF20 is considered to be a lagoon on inner ramp and the depositional environment for the RMF27 is a shoal facies. The shoal may occur on both inner and outer ramp. The shoal facies of the Lockhart Formation in western Salt Range is associated with an inner ramp lagoon; therefore, it is considered as inner ramp shoal.

Discussion

Depositional cycles and sequence stratigraphy

The deposition of the Lockhart Formation initiated in a backshoal lagoon (MFT1) followed by a deepening upward trend representing by the deposition of foraminiferal-shoal facies (MFT2, MFT3) and fore-shoal open marine facies (MFT4 and MFT5). Detailed microfacies analysis of limestone of Lockhart Formation led to the recognition of deepening upwards cycles in the studied succession. On the basis of vertical succession and the associated depositional environments of the defined microfacies associations, six deepening upward cycles of mainly intertidal–subtidal in character are observed in this study. These cycles (including one major cycle (≥40 m thick), i.e. cycle 1 and five minor cycles (≥2 m thick)) are defined and the microfacies variations within these cycles are given below:

Cycle 1 This major cycle is characterised by a lagoonal facies at the bottom followed upwards by shoal and fore-shoal open marine facies. The vertical succession of facies in this cycle indicates a sea level rise and associated upward deepening. Cycle 1 is present only in the Mari Indus (Kalabagh) Section (Fig. 4).

Cycle 1a This cycle is more or less similar to cycle 1. The main differences are twofold: (a) this cycle is small scale as compared to cycle 1 and (b) this cycle lacks basal lagoonal facies. The cycle consists of shoal facies at the base followed by fore-shoal open marine facies upward that indicate an overall sea level rise and associated deepening trend similar to the one observed in cycle 1. Cycle 1a is repeated three times in Dhok Kas Section (Fig. 2).

Cycle 1b This cycle is similar to previous cycles in terms of facies association, depositional environment and sea level fluctuation. Deposition in cycle 1b initiated with a lagoonal facies followed upwards by fore shoal open marine facies; however, the shoal facies is lacking. This cycle is repeated two times in the Nammal Gorge Section (Fig. 3).

A sequence stratigraphic interpretation is put forward based on the microfacies association of the deepening upward cycles and landward–basinward shifts in diagnostic facies belts. Vertical stacking pattern of the defined deepening upward cycles shown in Figs. 2, 3 and 4 are used to determine system tracts and large-scale sequences.

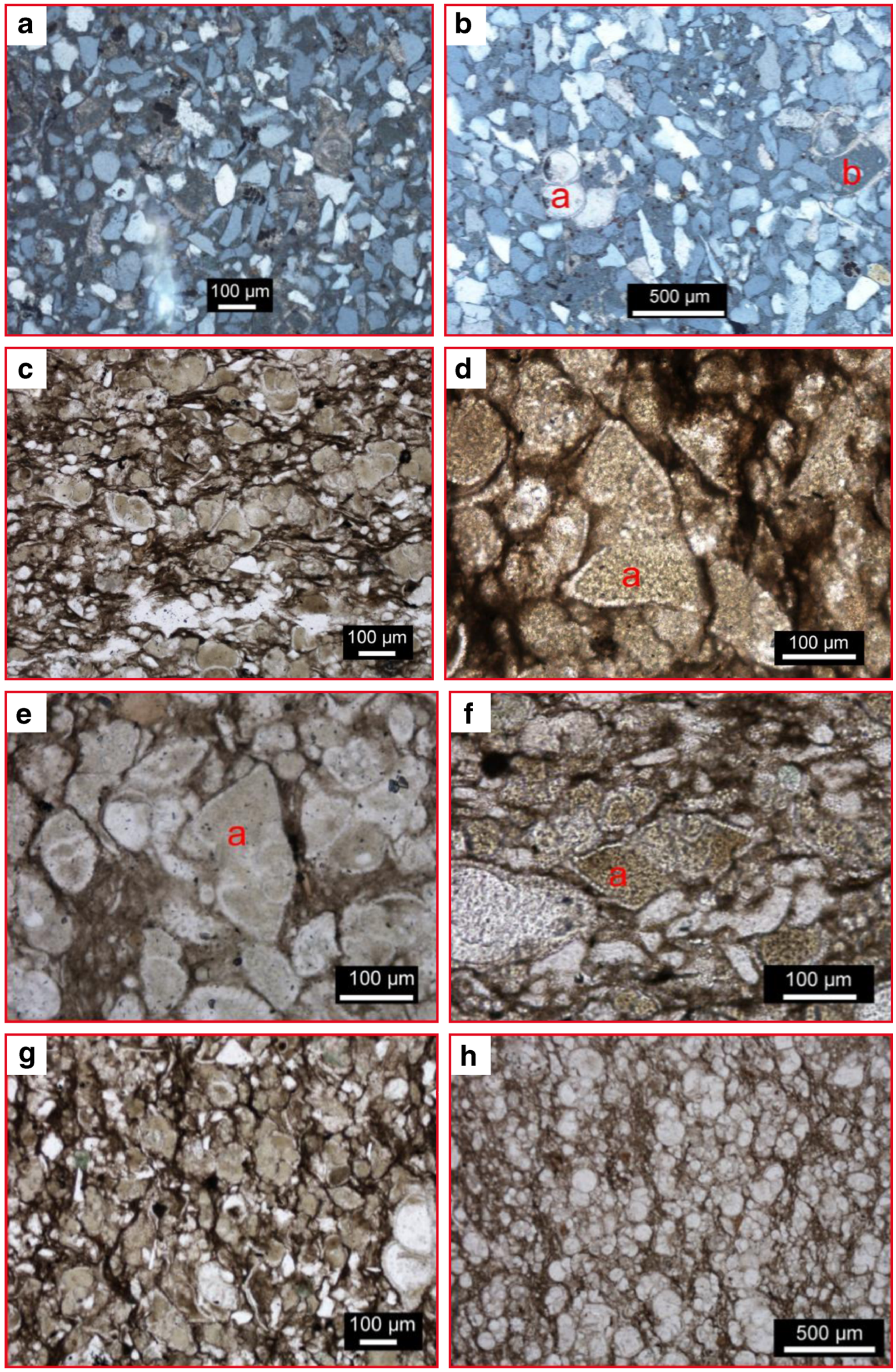


Fig. 6 Cartoons showing the depositional settings of the Indus Basin during Thanetian (SBZ3) times. **a** East–west distribution of different microfacies types (MFT'S) based on sections; Dhok Kas, Nammal Gorge and Mari Indus (Kalabagh), western Salt Range, Upper Indus Basin (*MFT* microfacies types). **b** The north–south distribution of different depositional environments in Upper Indus Basin, Pakistan. **c** The east–west distribution of different depositional environments in the Lower Indus Basin, Pakistan

The Thanetian foraminiferal–algal deposits of the Lockhart Formation, Upper Indus Basin represent a third-order transgressive system tract which corresponds to TR system tract and a third-order sequence TA2.1 of Haq et al. (1987). This third-order TST from the Lockhart Formation is named ThLoc, and is older than the Thanetian third-order sequence ThPat reported from the Paleocene Patala Formation by Hanif et al. (2013). ThPat is a depositional sequence of the Patala Formation which is a high-stand system tract. ThPat (Patala Formation) stratigraphically overlies ThLoc (Lockhart

Formation); therefore, both these third-order sequences are associated with the Thanetian eustatic sea level rise of Haq et al. (1987).

Intrabasinal comparison

Upper Indus Basin

The abundance of bioclasts clearly distinguishes the inner ramp lagoon and inner ramp foraminiferal shoal facies of the western Salt Range from the supratidal–intertidal, subtidal, restricted lagoon, protected lagoon facies belts of Afzal et al. (2011). Some similarities exist between the inner ramp lagoon and inner ramp shoal facies of the western Salt Range with lagoon shoal facies and open lagoon/inner ramp facies of Afzal et al. (2011). The presence of high fragmentation and packstone textures are common sedimentary features of the lagoon shoal facies of Afzal et al. (2011) and inner ramp shoal of the present study, suggesting a hydrodynamically active setting for the inner ramp foraminiferal shoal facies of the western Salt Range. The inner ramp lagoon facies resemble the open lagoon/inner ramp facies belt of Afzal et al. (2011), the presence of abundant dasycladale algae in both facies provide the basis for the similarity. The main differences are (1) the relatively less matrix giving a wackstone texture in the study area instead of a micritic-rich boundstone texture and (2) abundance of smaller rotallids in the open lagoon/inner ramp facies of Afzal et al. (2011).

The Kotal Pass Section of Afzal et al. (2011) represents a facies range from supratidal to the shallow open inner ramp, the Shakardara-1 well consists of facies ranging from shallow open inner ramp to deeper open inner ramp and the Zranda Section contains facies ranging from intertidal to shallow open inner ramp. The western Salt Range (this study) facies represent inner ramp lagoon and inner ramp foraminiferal shoal facies. Therefore, by combining the sections of Afzal et al. (2011) and sections from the present study, a local picture of the Lockhart depositional environment along a north–south transect in the Upper Indus Basin can be drawn as follows; the carbonate platform was not a uniform depositional environment at the time of deposition of the Lockhart Formation (see Fig. 5 for paleogeography). It was composed of a depositional low in the present Kohat Plateau represented by Shakardara-1 of Afzal et al. (2011). This depositional low was surrounded by highs in the north (represented by Kotal Pass Section) and in the south represented by the western Salt Range and Zranda sections (Fig. 6b).

Lower Indus Basin

The Lockhart Formation of Thanetian age (SBZ3 Zone) of the Upper Indus Basin is age equivalent to part of the Dungan Formation (i.e. Planktic foraminiferal zone P4 of Warraich et al. (2000) of the Sulaiman Range). In the Kirthar Range, part of the upper Ranikot Formation (i.e. *Globorotalia velascoensis* Zone of Samanta (1973) and Dorreen (1974)) is the age equivalent of the Lockhart Formation. The equivalent sediments in the Sulaiman Range (i.e. part of the Dungan Formation) are dominantly composed of siltstone and yielded abundant planktic foraminifera (>90 %) and therefore, represent deposition in an open marine environment beyond the outer shelf (e.g. Eames 1952; Warraich et al. 2000; Hanif et al. 2012). The equivalent part in the Kirthar Range (i.e. part of the upper Ranikot) is dominantly composed of dark grey shales and contain abundant planktic foraminifera (e.g. Samanta 1973; Dorreen 1974). The dark grey shales and abundant planktic foraminifera in the Kirthar Range also indicate deposition in an open marine environment beyond the outer shelf similar to the depositional settings in the Sulaiman Range.

By combining results from this study with information from the literature (e.g. Eames 1952; Samanta 1973; Dorreen 1974; Hanif et al. 2012) a regional picture of the depositional environments during the Thanetian (SBZ3) can be drawn (Fig. 6c). The Lockhart Formation in the Upper Indus Basin represents a carbonate ramp (e.g. Afzal et al. 2011 and this study). However, in the Sulaiman and Kirthar ranges, Lower Indus Basin, deposition took place in open marine settings, most probably in bathyal settings as indicated by smaller benthic foraminifera and the high planktic ratio (Hanif et al. 2012).

In order to reconstruct the depositional environment of marine sedimentary rocks, foraminifera have been widely used in previous studies worldwide. For example, Grimsdale and Van Morkhoven (1955), Smith (1955) and Ingle (1980) used the percentage of planktic foraminifera to determine the distance to the shore. They noted that the plankton percentage increases from shelf to open ocean and exceeds 50 % in the deeper environments of the outer shelf. A similar approach using the planktic/benthic (P/B) ratio has been applied to modern patterns of planktic and benthic foraminiferal distributions by Gibson (1989) and the data obtained were compared with the results from Paleogene sediments. He found that the results derived from the P/B ratios are reliable and in accordance with the paleoenvironmental interpretations made from other methods. There are, however, a number of philosophical objections to the application of P/B ratios for paleoenvironmental interpretation citing such things as “differential dissolution or oxygen conditions” (e.g. Adelseck and Berger 1975; van der Zwaan et al. 1990; Murray 1991). Despite these, Warraich et al. (2000) and Hanif et al. (2012) have observed high P/B ratios (i.e. 98–99 %) in association with high values of species richness and diversity in the Dungan Formation (Sulaiman Range). They suggested that the deposition of the Dungan Formation occurred in a deep marine environment. Furthermore, Warraich et al. (2000)

noted that the westward thinning of the limestone interbeds indicated a westward dipping slope environment. A carbonate-rich turbidite facies exists in the lower part of the Dungan Formation, which hampers the identification of the early Paleocene planktic foraminiferal zones (e.g. Warraich et al. 2000; Samanta 1973; Kalia and Kinsto 2006).

The neritic Paleogene sedimentary sequence in the Jaisalmer Basin (India) is the eastward extension of the Indus Basin. In the Jaisalmer Basin, planktic foraminiferal zones were described by Kalia and Kinsto (2006) for the late Paleocene–Early Eocene succession in the Tanot-1 well (Fig. 1). Similar to the lower part of the Dungan Formation of the Raki Nala succession in the Sulaiman Range, the lower part of their Ranikot Formation is composed of quartz sandstone and claystone and did not yield any planktic foraminifera. The upper part of their Ranikot Formation is predominantly composed of marlstone and claystone with subordinate quartz sandstone. This upper part of the Ranikot Formation and the succeeding Laki Formation, which is composed of carbonate rocks, yielded the planktic foraminiferal zone P4 which is equivalent to SBZ3.

According to Kalia and Kinsto (2006), the planktic foraminiferal zone P4 is composed of sandstone, claystone, siltstone, marl and limestone beds in the upper Ranikot Formation and lower Laki Formation of Rajesthan (India). This zone is dominantly represented by shale and abundant planktic foraminifera in Sulaiman Range, Pakistan. During the Paleocene P4, the deposition of a dominantly limestone facies in the uppermost Ranikot Formation in Rajesthan (India) represents a carbonate platform. The deposition of a dominantly planktic foraminiferal shale and siltstone facies in the upper part of the Dungan Formation (Plate 4d, e, g and h) of the Sulaiman Range (Pakistan) yields Paleocene planktic foraminifera P4 and abundant planktic foraminifera; therefore, it represents deposition on a westward dipping slope under deep marine conditions (Warraich et al. 2000). Therefore, by combining the results from both these areas along east–west transect, it can be suggested that during Paleocene planktic foraminifera zone P4 (equivalent to SBZ3) deposition in the Indus Basin in Tanot-1 well occurred on a carbonate platform (e.g. Kalia and Kintso 2006; Rabha and Kalia 2007; Bhandari 2008), while the Sulaiman Range (in the west) represents an open marine environment of deposition (e.g. Hanif et al. 2012; Fig. 6c).

Conclusions

The foraminiferal–algal assemblage of the Lockhart Formation indicates deposition during SBZ3. The deposition took place in inner ramp setting representing a lagoon to shoal to fore-shoal sub-environments. The deepening upward cyclic stacking represents a third-order sequence named as ThLoc associated with the Thanetian eustatic sea level rise.

The microfacies/facies analyses and correlation of the Lockhart and Dungan formations revealed the fact that the Indus Basin was not a uniform and continuous basin, the Indus Basin was a north–south oriented basin occupied by carbonate platform settings in the north (Upper Indus Basin) and in the east (Jaisalmer Basin, Rajestan India, Lower Indus Basin); however, the western part of the Lower Indus Basin (Rakhi Nala, Sulaiman Range) was under deeper water settings (e.g. a slope or bathyal setting).

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Appendix

Table 1 Microfacies, faunal contents and interpretation of the depositional environments of Lockhart Formation, western Salt Range, Pakistan

Microfacies	Faunal contents	Interpretation
Bioclastic dasycladales wackestone (MFT1) (Plate 1a,b)	dasycladale algae, *Ranikothalia* sp., *Ranikothalia sindensis*, *Lockhartia* sp., miliolids, *Miscellanea yvettae*, coral, Orbitoidae and Echinoids	Inner Ramp Lagoon
Bioclastic foraminiferal wacke-packstone (MFT2) and bioclastic foraminiferal packstone (MFT3) (Plate 2a,c)	Coral fragments, bivalves, gastropods, echinoids, bryozoans, and dasycladale algae, Orbitoidae, *R. sindensis*, *Ranikothalia* sp., *M. yvettae*, *Miscellanea* sp. and *Miscellanea juliettae*	Inner ramp foraminiferal shoal
bioclastic dasycladale foraminiferal wacke-packstone (MFT4) and the bioclastic foraminiferal wackestone (MFT5). (Plate 3c,h)	Gastropods, echinoids, bryozoans and dasycladale algae, *M. juliettae*, *Lockhartia* sp., *Miscellanea* sp., and Orbitoidae	Fore-shoal open marine

Table 2 Petrographic data in percentages from the Lockhart Formation, Dhok Kas Section, western Salt Range, Pakistan

Thin section #	Larger foraminifera	Algae	Bioclasts	Gastropod	Smaller benthic foraminifera	Echinoids	Matrix	Grain: Matrix	Microfacies types
DK/TL1	24	05	25				46	1:1	MFT-2
DK/TL 2	22	06	38		02		32	2:1	MFT-4
DK/TL 3	17	08	36		02		37	2:1	MFT-2
DK/TL 4	12	06	47	01			34	2:1	MFT-4
DK/TL 5	12	05	39	01	01		42	1:1	MFT-4
DK/TL 6	16	04	33				47	1:1	MFT-5
DK/TL 7	12	07	52	03		01	24	3:1	MFT-3
DK/TL 8	13	05	44	02		02	34	2:1	MFT-2
DK/TL 9	17	07	41				35	2:1	MFT-2
DK/TL 10	18	05	38				39	2:1	MFT-3
DK/TL 11	06	04	13				77	3:1	MFT-2
DK/TL 12	12	03	45				40	1:1	MFT-4

Table 3 Petrographic data in percentages from the Lockhart Formation, Nammal Gorge Section, western Salt Range, Pakistan

Thin section #	Larger foraminifera	Algae	Bioclasts	Gastropod	Smaller benthic foraminifera	Matrix	Grain: Matrix	Microfacies types
NG/TL 1	07	08	50	03		32	2:1	MFT-5
NG/TL 2	09	06	45			40	2:1	MFT-4
NG/TL 3	06	13	34			47	1:1	MFT-1
NG/TL 4	02	15	42			41	1:1	MFT-1
NG/TL 5	08	05	29			58	1:1	MFT-5
NG/TL 6	15	06	25			54	1:1	MFT-1
NG/TL 7	17	9	32	01		41	1:1	MFT-4
NG/TL 8	16	03	37			44	1:1	MFT-4
NG/TL 9	16	06	36		02	40	2:1	MFT-4
NG/TL10	25	06	40			29	3:1	MFT-4
NG/TL11	21	09	31	02		37	2:1	MFT-4
NG/TL12	15	13	41		03	28	3:1	MFT-4
NG/TL13	19	10	19	03		49	1:1	MFT-4

Table 4 Petrographic data in percentages from the Lockhart Formation, Mari Indus (Kalabagh) Section, western Salt Range, Pakistan

Thin section #	Larger foraminifera	Algae	Bioclasts	Gastropod	Smaller benthic foraminifera	Matrix	Grain: Matrix	Microfacies types
KB/TL1	08	06	28	02		56	1:1	MFT-1
KB/TL 2	07	04	46	03		40	1:1	MFT-2
KB/TL 3	09	03	23	01		64	2:1	MFT-2
KB/TL 4	13	02	40	02		43	1:1	MFT-3
KB/TL 5	07	03	26		01	63	2:1	MFT-4
KB/TL 6	08	06	47		02	37	2:1	MFT-4
KB/TL 7	05	01	23		01	70	2:1	MFT-5
KB/TL 8	05	03	25	01		66	2:1	MFT-5
KB/TL 9	10	06	35	02	01	46	1:1	MFT-4

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