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Sequence stratigraphic significance of sedimentary cycles and shell concentrations in the Upper Jurassic–Lower Cretaceous of Kachchh, western India

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Abstract

Upper Jurassic and Lower Cretaceous siliciclastic shallow water sediments of the Kachchh Basin, western India, form strongly asymmetric coarsening-upward cycles, which are interpreted as recording changes in relative sea level (deepening–shallowing cycles). These cycles correspond to depositional sequences, in which deposits of the lowstand systems tract are not present, the sequence boundary coinciding with the transgressive surface. Shell concentrations are found in the transgressive lags at the base of the transgressive systems tract (TST), in the maximum flooding zone (MFZ), and at or close to the top of the highstand systems tract. They belong to six assemblages, five of them dominated by large bivalves such as *Seebachia*, *Herzogina*, *Gryphaea*, *Gervillella*, *Megacucullaea*, *Pisotrigonia* and *Indotrigonia*, the sixth by the coral *Amphiastraea*. Three types of shell concentrations can be distinguished that differ from each other in a number of ecological and taphonomic features, such as species diversity, preservation quality, orientation in cross-section, percentage of disarticulation, and degree of biogenic alteration. Characteristic features of concentrations at the base of the TSTs are moderate time-averaging, sorting, a preferred convex-up orientation, and nearly total disarticulation of shells. They are suggestive of an environment in which reworking and local transport were frequent events. Similar features are shown by concentrations near the tops of the HSTs, except that there shells were largely concentrated in lenses and in pavements rather than in beds as in the transgressive lags. Associated sedimentary structures indicate deposition above fair weather wave base in a high-energy environment. Concentrations occurring in the MFZ, in contrast, are autochthonous and highly time-averaged, having accumulated during times of low rates of sedimentation below storm wave base. This is supported by their high preservation quality (comparatively high percentage of articulated shells, shells of infaunal organisms commonly preserved in life position), biogenic alteration being the most important taphonomic agent. The dominant elements of these shell concentrations, i.e. *Seebachia*, *Megacuccullaea*, and *Indotrigonia* in the Upper Jurassic, and *Pisotrigonia* in the Lower Cretaceous, are endemic to the Ethiopean faunal province and belong to lineages that rapidly evolved during this time period.

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Keywords: Jurassic; Cretaceous; shell beds; taphonomy; sequence stratigraphy; western India

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1. Introduction

Whereas the sequence stratigraphic significance of most aspects of sedimentary rocks, such as grain size distribution, sedimentary structures, and mineralisation has been well established, there are comparatively few studies that explore the usefulness of fossils in defining sequence boundaries and systems tracts. Examples are studies by Bonnet et al. (1994), Cubaynes et al. (1995), Garcia et al. (1996), Abbott and Carter (1997), and Brett (1998). Nonetheless, biogenic hardparts usually carry a wealth of ecological and taphonomic information that is of potential use for identifying key sequence stratigraphic surfaces and units. This is particularly true of shell beds in which, apart from the ecological information, the biofabric as well as the taphonomic signatures of individual components provide us with information about environmental parameters such as energy level, about residence time on the sea floor, and rates of sedimentation. Due to this, fossils concentrated in shell beds have received more attention than other macro-organisms in sequence stratigraphic studies. Examples are Banerjee and Kidwell (1991), Abbott and Carter (1994), and Abbott (1997, 1998), who demonstrated convincingly that shell beds can be used to define the bases and tops of transgressive systems tracts (TSTs).

In the present paper we provide yet another example of how distinctive types of shell beds occur at different positions within sedimentary cycles and provide evidence for the sequence stratigraphic interpretation of sedimentary successions.

2. Geological framework

The shell beds occur in the Oxfordian–Tithonian (Upper Jurassic) and Lower Cretaceous rocks of the Kachchh Basin, a fault-controlled pericratonic basin situated at the western margin of the Indian Plate (Biswas, 1991). It originated in the Triassic, was inundated by the sea no later than the early Mid Jurassic (Fürsich et al., 2001) and formed a small appendix of the so-called Malgassy Gulf, a southward extension of the Tethyan Ocean, situated between Africa and India. Except for minor carbonate sediments in the Bajocian–Bathonian, the basin was filled with fine- to coarse-grained siliciclastics. The Upper Jurassic starts with a major marker horizon, the Lower to Middle Oxfordian Dhosa Oolite member (Table 1), a highly condensed unit that records a relative sea-level highstand (late TST; Fürsich et al., 2001). Upper Oxfordian and lower Kimmeridgian sediments are absent except in the eastern, nearshore part of the basin (e.g. Wagad Dome; Fig. 1), where they are represented partly by ferruginous, ammonite-bearing sandstones, partly by cross-bedded sandstones of deltaic and non-marine origin (e.g. Biswas, 1993; Dubey and Chatterjee, 1997). In the central part of the Jurassic outcrop belt, Kimmeridgian–Tithonian sediments (Katrol Formation) consist of sandstones that become increasingly silty and shaly westward in the direction of the Malgassy Gulf. The Tithonian to lowermost Cretaceous ('Neocomian') Umia Formation is a sandy unit that contains thin intercalations of highly glauconitic beds, and shell beds at several levels. The Katrol and Umia formations are partly lateral equivalents and a clear distinction between the two formations is not always possible. For this reason, Biswas (1980) combined the Katrol and Umia formations in his Jhuran Formation, and recognised part of the Umia Formation of earlier authors merely as a member (Katesar member). According to Biswas (1993) the boundary to the overlying 'Neocomian'–Aptian (?Albian) Bhuj Formation is gradational; according to I.B. Singh (personal communication, 2002) it is characterised by a strongly bioturbated horizon that can be followed throughout the area.

3. Material and methods

Shell concentrations discussed in this paper were studied at the following localities and stratigraphic levels (see also Fig. 1):

(a) Upper Oxfordian/Middle Kimmeridgian of Wagad Dome (Kanthkot Member of the Wagad Sandstone Formation; Biswas, 1980).

Two shell beds have been recognised by Biswas

Table 1
Lithostratigraphic schemes of Upper Jurassic–Lower Cretaceous rocks of the Kachchh Basin. The scheme used in this paper is partly that of Rajnath (1932), partly that of Biswas (1980). (Additionally, data from Spath, 1927-1933).

	Western Kachchh							Wagad Dome
	Present paper	Rajnath 1932		Spath 1933		Biswas 1980		Biswas 1980
Lower Cretaceous	Bhuj Fm	Bhuj Series	Beds with *Palmoxylon* Beds with *Ptilophyllum* *Zamia* Beds			Bhuj Fm	Upper mb	Not exposed
		Ukra Beds	calcareous shales	Umia Group	Beds of Ukra Hill with ammonites, etc.		Ukra mb Ghuneri mb	
Tithonian	Umia Fm	Umia	barren rocks *Trigonia* beds barren sandstones Green Oolitic Beds interbedded with shales barren sst. & shales		Upper Umia Plant (and *Trigonia crassa*) Beds, pars ? Umia Ammonite bed	Jhuran Formation	Katesar mb Upper mb	Wagad Sandstone
Kimmeridgian	Katrol Fm	Katrol	Hard Sandstone barren Upper - mainly shales Middle - mainly sandstone Lower - mainly shales	Katrol Group			Middle mb Lower mb	Kanthkot mb
Callov.-Oxford.	Chari Fm	Chari		Chari Group		Jumara Formation		Washtawa Formation

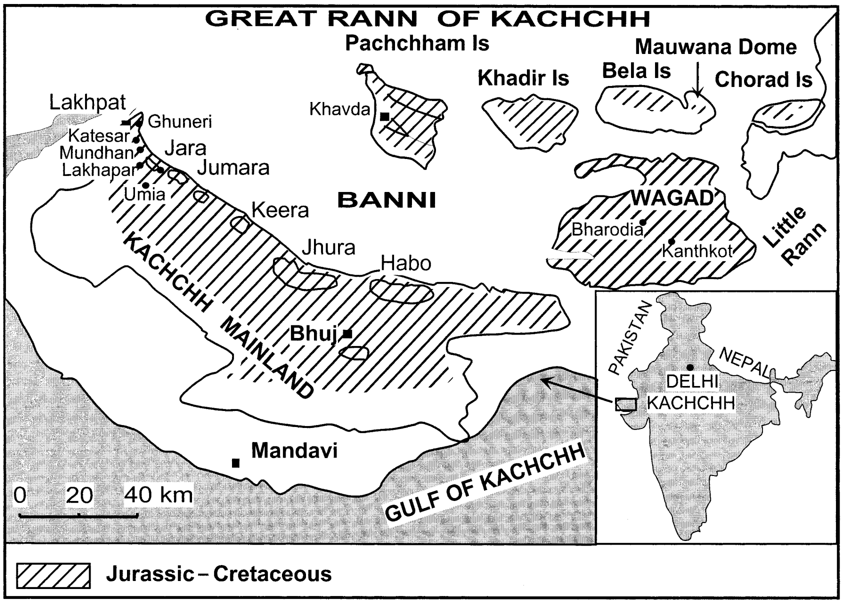


Fig. 1. Geological sketch map of Jurassic–Cretaceous rocks of Kachchh and position of localities mentioned in the text.

(1993) and Deshpande and Merh (1980), one, the Kanthkot Fossiliferous Band, in the middle of the Kanthkot Member, the other one, the Bharodia Astarte Bands, at the top of that member. Both are dominated by large bivalves, in particular *Seebachia*. The two levels are separated by about 80 m of sandstone, and contain an ammonite fauna that is characteristic of the uppermost Oxfordian to Middle Kimmeridgian (J.H. Callomon, personal communication, 2000; Krishna et al., 2000). Short sections were recorded near Kanthkot Hill (Kanthkot Fossiliferous Band) and at Bharodia village (Barodia Astarte Bands).

(b) Tithonian of western Kachchh Mainland (Katrol Formation).

North of Lakhapar, the upper part of the Katrol Formation (= part of upper member of Biswas' (1980) Jhuran Formation) is composed of well developed, strongly asymmetric, coarsening-upward cycles. Shell concentrations are locally developed at the tops of these cycles.

(c) Tithonian to Lower Cretaceous ('Neocomian') Umia Formation of western Kachchh Mainland (= part of upper member and Katesar Member of Biswas' (1980) Jhuran Formation).

Trigonioid–astartid shell concentrations occur at the top and at the base of coarsening-upward cycles at Umia village, east of Ghuneri village, and in the Mundhan anticline. Diverse shell beds and/or concentrations of gryphaeid oysters are found in highly ferruginous, poorly sorted sandstones in the Mundhan anticline, north of Lakhapar, and east of Katesar.

At these localities, sections were measured. Apart from lithological details and sedimentary structures, trace fossils and body fossils were recorded. In the case of shell concentrations, faunal composition, orientation patterns in cross-section, percentage of articulation, and, where possible, degree of encrustation and boring and quality of preservation were noted.

4. The sections: facies and sequences

4.1. Sections

At Bharodia, the lower part of the 15 m thick section (Fig. 2) is highly ferruginous and contains two levels of shell concentrations. These levels, although only 3 m apart, contain ammonites that differ distinctly in age: Topmost Oxfordian/Middle Kimmeridgian in the case of the lower level, Middle (*Crussoliceras divisum* Zone) to lower Upper Kimmeridgian (*Aulacostephanus eudoxus* Zone) in the case of the upper level (J.H. Callomon, personal communication, 2000). A third shell bed is found 10 m higher up at the top of a small coarsening-upward sandstone unit.

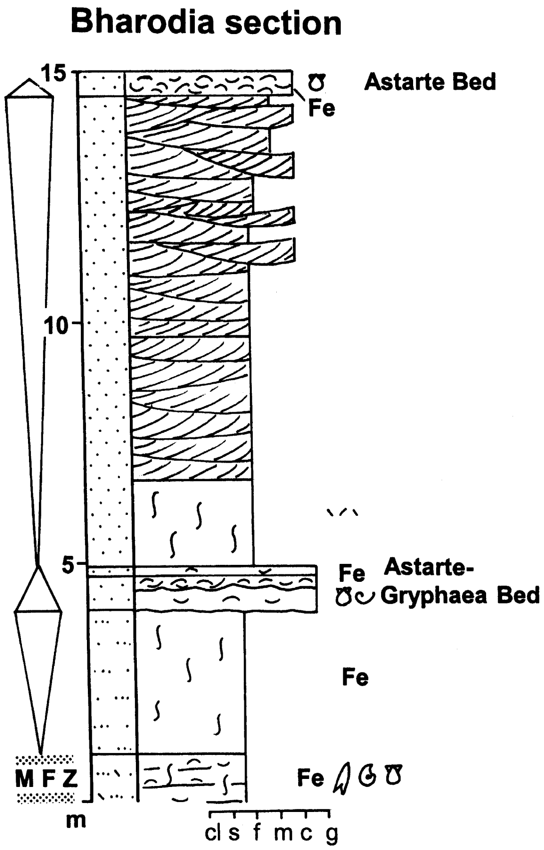


Fig. 2. Section through the uppermost Oxfordian to lower Upper Kimmeridgian at Bharodia. MFZ: Maximum flooding zone. For key of symbols see Fig. 5.

The Lakhapar section exhibits a distinct cyclic sedimentation pattern (Fig. 3). The cycles, varying between 5 and nearly 100 m in thickness, are strongly asymmetric and coarsen upwards. The uppermost two cycles are depicted in Fig. 4 to provide more details. Extensive bioturbation,

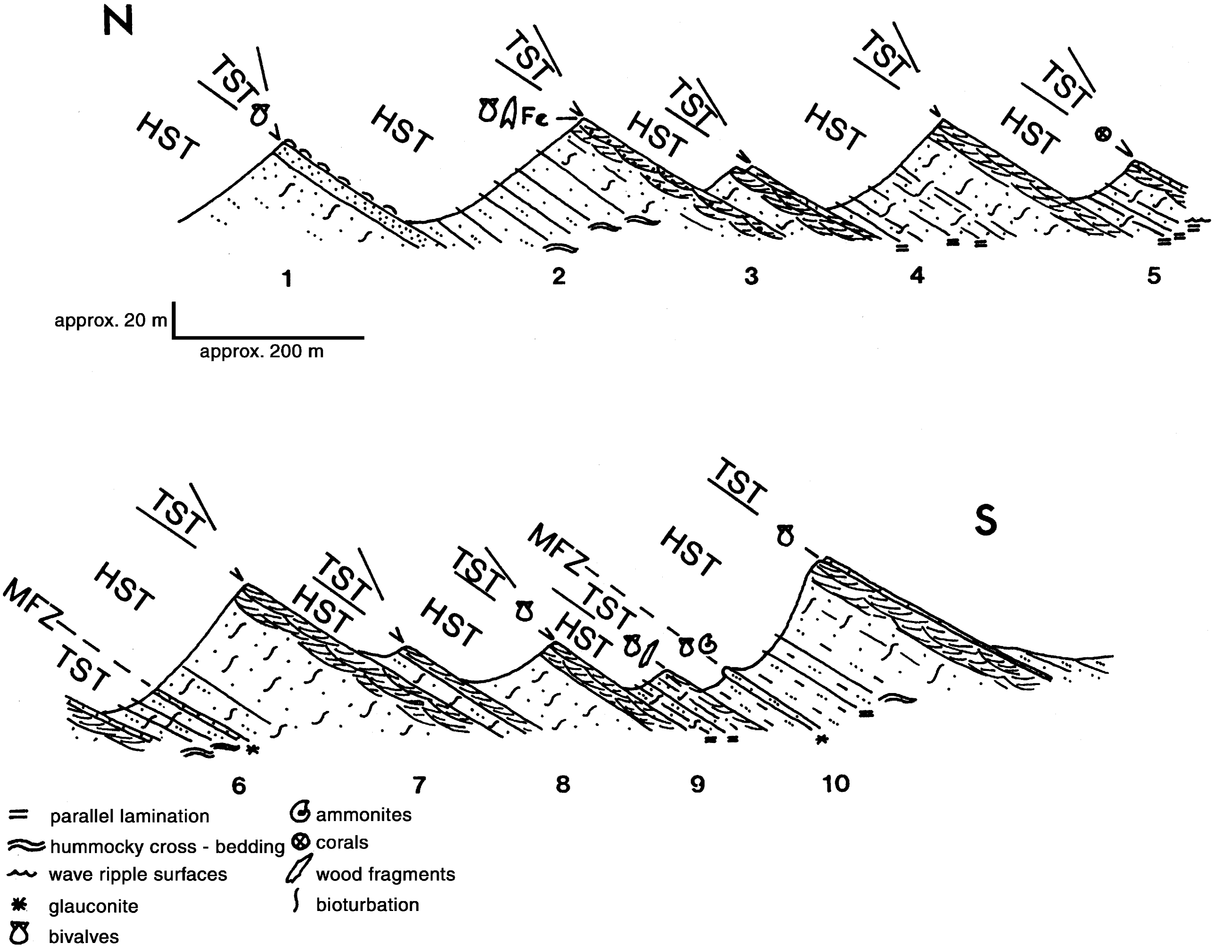


Fig. 3. Schematic cross-section through the Umia Formation (cycles 2–10) north of the village of Lakhapar. The numbers denote the individual cycles. The strongly cemented transgressive lags (TST) form ridges and ledges whereas the highstand sediments (HST) are usually soft and friable. Cycles 9 and 10 are depicted in detail in Fig. 4.

partly by *Planolites* and *Thalassinoides*, is found in the finer-grained beds, whereas in the coarse-grained cross-bedded units *Ophiomorpha* and, more rarely, *Diplocraterion parallelum* prevail. Fossils are concentrated at two levels: At the tops of the coarsening-upward cycles and, in one case, in highly ferruginous silty sandstone within the cycle. The remaining parts of the section are unfossiliferous.

At Umia village, again, strongly asymmetric coarsening-upward cycles are developed (Fig. 5). Fossils are concentrated either in the coarsest-grained units or in beds directly overlying them (Fig. 6A). There is a slight possibility that the upper part of the section above the fault is a repetition of the older beds seen at the base. Although the general succession is very similar, differences in lithology, degree of cementation, and composition of shell concentrations exist that favour the interpretation of the section as a continuous unit.

East of the village Ghuneri, shell beds occur within a 1.5 m thick unit intercalated between medium- to coarse-grained sandstones (Fig. 7).

In the sections east of Katesar (Fig. 8) and across the Mundhan anticline (Fig. 9), the upper part of the Katrol Formation and the Umia Formation also exhibit distinct coarsening-upward

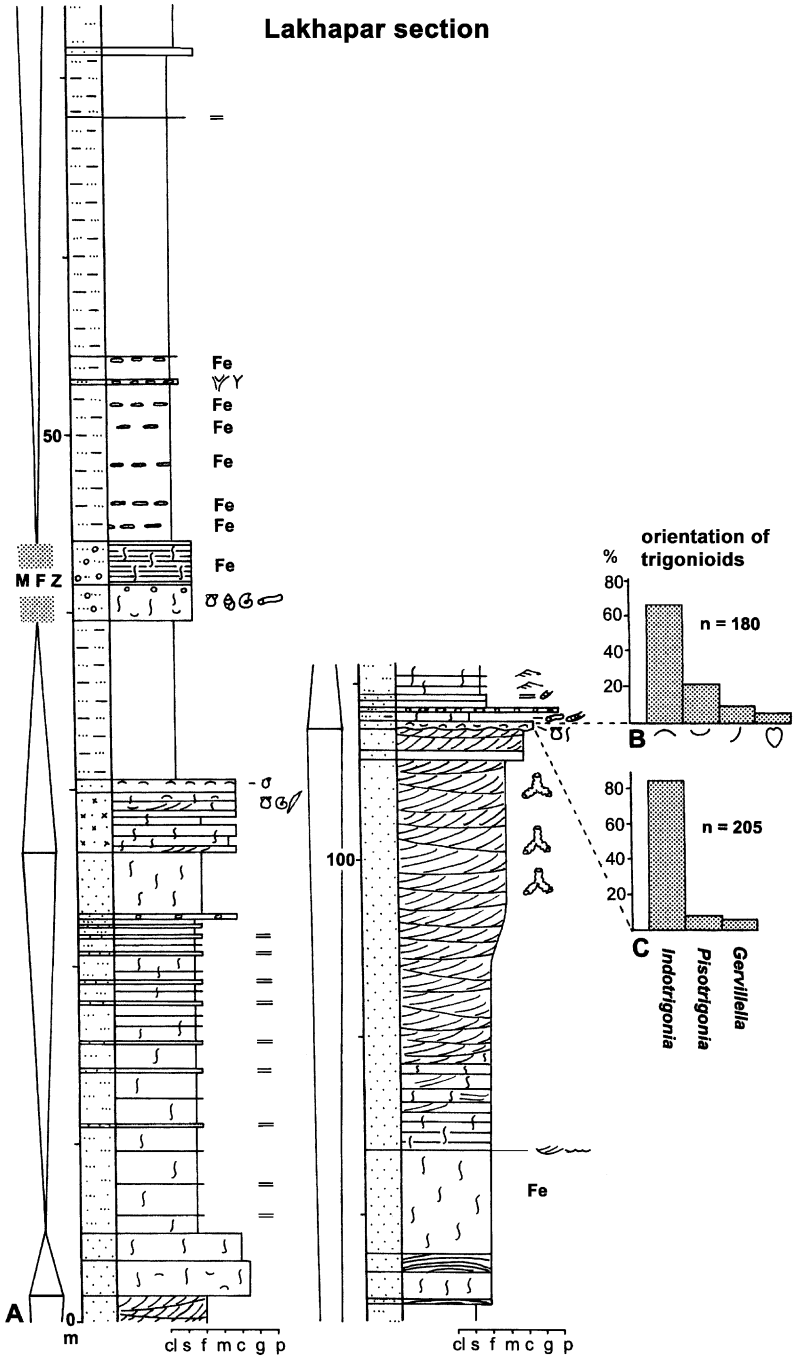


Fig. 4. Two strongly asymmetric TST–HST cycles (cycles 9 and 10 in Fig. 3) in the top part of the Umia Formation north of the village of Lakhapar. The well developed MFZ of the upper cycle contains the Megacucullaea Bed. The section is topped by TST sediments of the next cycle, containing at its base an *Indotrigonia–Pisotrigonia* shell bed with disarticulated, preferrentially convex-up oriented shells. For key of symbols see Fig. 5.

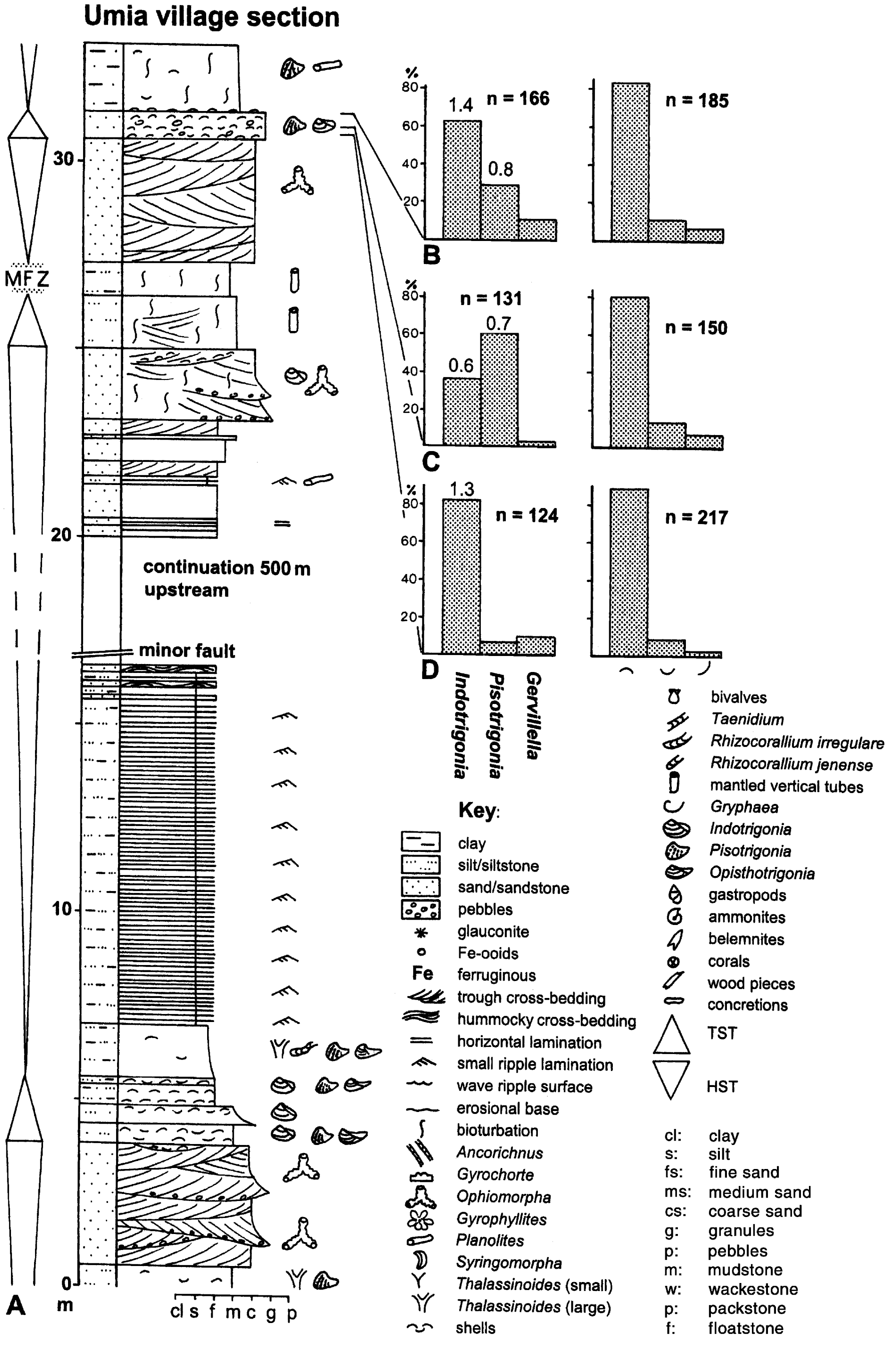


Fig. 5. (A) Section through part of the Umia Formation along the river bed at Umia village. The top of the section is exposed where the river bed passes the village. (B–D) Taxonomic composition and orientation of shells of three consecutive shell beds near the top of the section. The numbers on top of the bars denoting the relative abundance of taxa refer to the ratio of right and left valves.

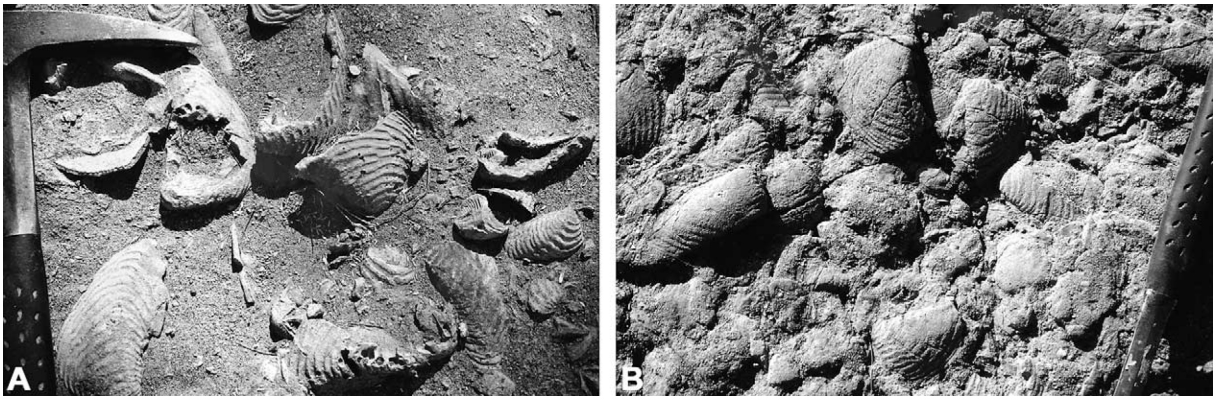


Fig. 6. (A) Bedding plane view of shells of *Indotrigonia beyschlagi*, heavily bored by bivalves. Umia Formation at Umia village section. Hammer for scale. (B) Bedding plane view of convex-up oriented shells of *Indotrigonia beyschlagi*. Top of Trigonia Ridge Sandstone Bed northeast of Lakhapar. Hammer for scale. Both concentrations occur in early TST sediments.

cycles, but fossils are only rarely found at the tops of these cycles. Instead, they occur in highly ferruginous, silty sandstone, several metres in thickness, in the lower part of the cycle.

4.2. *Facies*

The following major facies associations can be distinguished.

4.2.1. *Medium- to coarse-grained cross-bedded sandstones*

The medium- to coarse-grained, rarely fine-grained sandstones are clean, quartzose, rarely arkosic, and exhibit large-scale trough cross-bedding. They occur in units 2–30 m thick or consist of beds 40–60 cm thick. Lenses of conglomerate may be intercalated. Bioturbation (*Ophiomorpha*, *Diplocraterion*) is rare or absent. Body fossils are generally rare and include broken belemnites and fragments of ammonites. Solely in the Umia section, disarticulated valves of *Indotrigonia* and *Pisotrigonia* are found as lenticular concentrations on the foresets of large cross-beds.

Sedimentary structures and grain size indicate that the sandstones formed under high-energy conditions, above fair weather wave base, in very shallow water. They can be interpreted as sand bars and megaripple/submarine dune fields. Representing the shallowest sediments recorded, they belong to the late sea-level highstand (HST).

4.2.2. *Bioturbated fine- to medium-grained, rarely coarse-grained sandstones*

The sandstones are massive or bedded and occur in packages between 0.5 and several metres in thickness. Body fossils are absent except for the occurrence of reworked heads of the coral *Amphiastraea* near the base of the Mundhan Anticline section (Fig. 9).

Usually, this facies directly underlies the cross-bedded medium- to coarse-grained sandstones of the facies in Section 4.2.1. The lack of primary sedimentary structures indicates that rates of sedimentation and reworking were low enough so that the substrate could become thoroughly bioturbated. Depth of deposition was below fair weather wave base, but most probably above storm wave base. Evidence of storm activity was, however, subsequently removed by bioturbation. A lower shoreface position, at the lower end of submarine dunes or bar complexes, is envisaged. In sequence stratigraphic terms these sediments formed during mid sea-level highstand.

4.2.3. *Bioturbated silt, fine-grained and silty fine-grained sandstones with occasional intercalations of sharp-based sandstone beds*

The bioturbated layers are either massive or well bedded and often poorly sorted. The intercalations generally consist of 5–40 cm thick, well sorted, fine-grained sandstone. Their bases are sharp, and commonly associated with flute casts

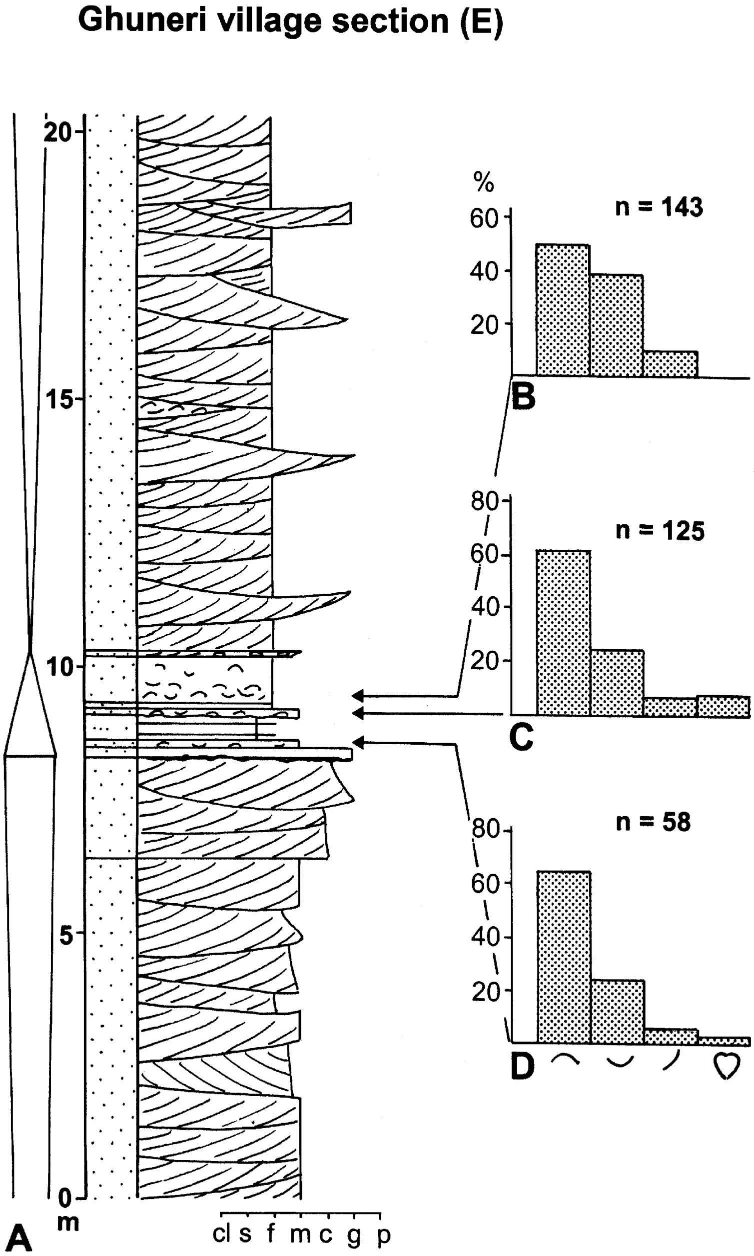
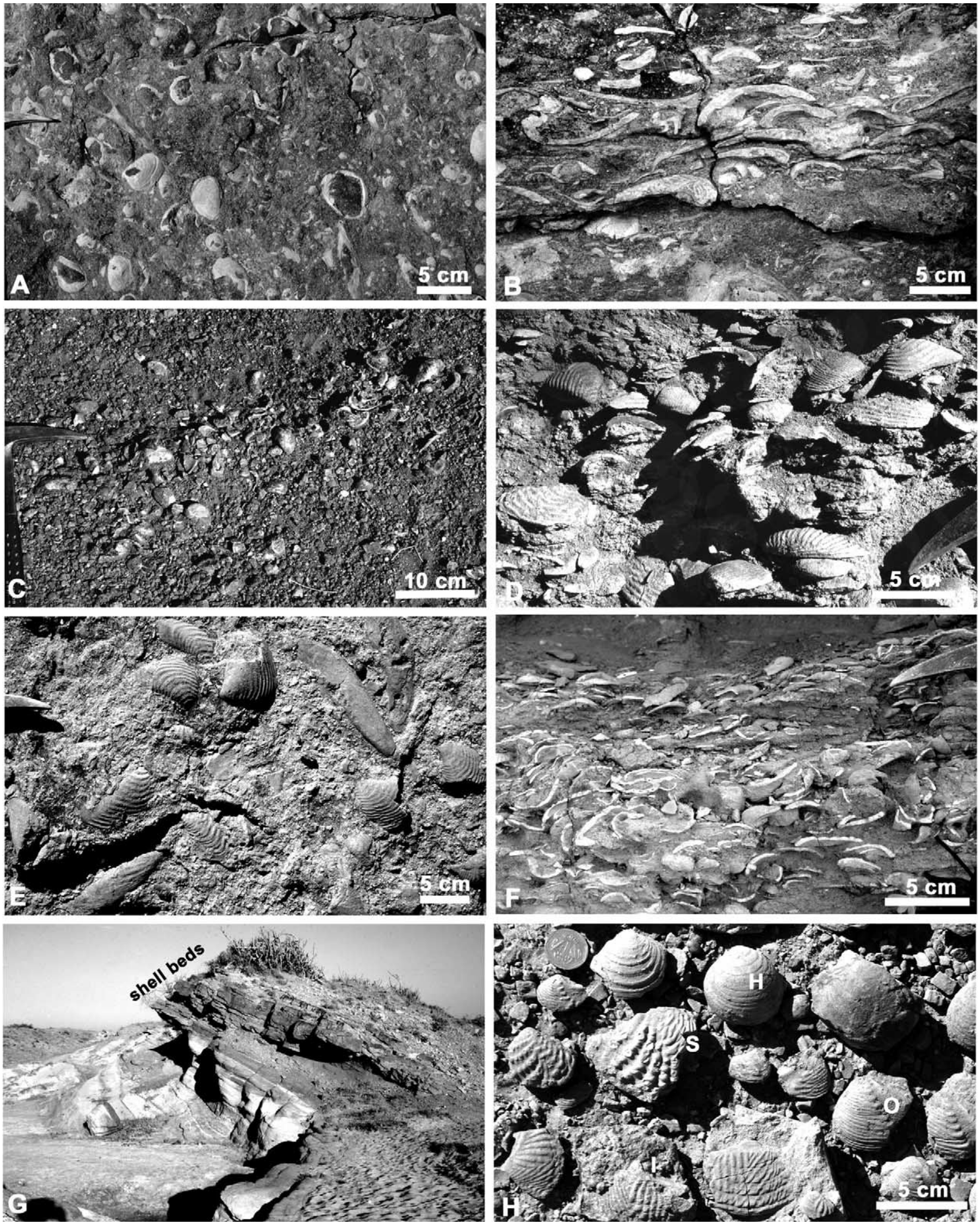


Fig. 7. (A) Section through part of the Umia Formation east of Ghuneri village (see also Plate 1G). (B–D) Orientation of shells in cross-section (convex-up, convex-down, oblique) and percentage of articulated shells in three consecutive trigonioid–*Herzogina* shell beds.

and tool marks. Primary sedimentary structures include small-scale ripple bedding, parallel lamination, and hummocky cross-bedding. Occasionally, ripple surfaces can be observed. Associated trace fossils are *Gyrochorte*, *Planolites*, *Syringomorpha*, *Taenidium*, and *Ancorichnus*. Body fossils are absent. Within a given section, the density of the intercalation usually increases up-section, as


A
5 cm
B
5 cm
C
10 cm
D
5 cm
E
5 cm
F
5 cm
G
shell beds
H
H
S
O
I
5 cm

does the thickness of the beds. In the extreme case, such as in the Umia section, interlayered bedding is developed (Fig. 5).

The well sorted sandstone intercalations can be interpreted as storm deposits, partly resulting from storm-induced currents, partly from storm surges. Together with the intervening bioturbated beds they represent deposits of the storm-influenced shelf. The increase in density and thickness of storm beds in many sections reflects a trend towards greater proximality. The facies formed during early sea-level highstand.

4.2.4. *Bioturbated argillaceous to sandy silts*

Usually several metres thick, this facies is relatively monotonous. Brown, ferruginous concretions may be associated, occurring scattered or in layers. Recognisable trace fossils are two size classes of *Thalassinoides* (diameters: 1 and 3 cm). In the Lakhapar section (Fig. 4; between 44 and 55 m), several of the concretion layers can be shown to represent lithified fills of segments of *Thalassinoides*. This kind of concretion formation is a common process, usually taking place early on during diagenesis (Fürsich, 1973).

Lack of sedimentary structures, high degree of bioturbation and the fine-grained nature of the sediment indicate that the facies represents low-energy, offshore environments below storm wave base. The ferruginous nature of some of the beds suggests relatively low rates of sedimentation. The sediments most likely formed during late transgression or during early sea-level highstand, close to the maximum flooding zone (MFZ).

4.2.5. *Highly ferruginous, very poorly sorted silt- to sandstones*

The brown to olive-coloured sediment consists of a mixture of clay, silt and sand with dispersed very coarse grains or granules of quartz. Bedding is well developed, with alternating well and poorly cemented layers, but bed surfaces are generally undulating due to irregular cementation. In the Katesar section (Fig. 8; between 51 and 61 m), the harder layers are concretionary in nature and alternate with finer-grained soft layers. The highly ferruginous nature of the sediment is mainly due to ferruginous ooids which occur in variable concentrations. In the MFZ of cycle 10 at Lakhapar (Figs. 3 and 4), the concentration of ooids in some beds is so high that the rock corresponds to a sandy bio-oopackstone.

The shelly sediment is highly bioturbated, but apart from *Thalassinoides*, *Planolites*, and strongly lined horizontal tubes, no ichnotaxa were recognised. In the Lakhapar section (Fig. 4; at 41.5 m) small (1–2 cm in diameter) pebbles of calcareous siltstone occur dispersed or concentrated in small patches. Near the base of the Katesar section (Fig. 8; at 15.8 m) the facies is represented by a merely 0.1 m thick, pebbly, ferruginous, silty fine-grained sandstone. The pebbles, 1–2 cm in diameter, consist of calcareous fine-sandy siltstone or laminated fine-grained sandstone and are associated with a well preserved fauna of small gastropods and bivalves. A high density and diversity of fossils, including benthic as well as nektic forms, is a characteristic feature of the facies and will be discussed in more detail below. Wood fragments may also occur.

The ferruginous nature, high degree of bioturbation, and high concentration of fossils all point to low rates of sedimentation under generally low-energy conditions, although the presence of small intraformational pebbles in some of the beds point to phases of erosion either by exceptionally high-energy events or longer-term currents. Some of the pebbles may represent episodically re-

Plate I. (A) Bedding plane view of the Astarte–Gryphaea Bed at Bharodia village; top of Kanthkot Member, Wagad Sandstone Formation. (B) Cross-section through the Astarte–Gryphaea Bed at Bharodia village. (C) Bedding plane view of *Gryphaea* lenticle in the MFZ of the Mundhan Anticline section (Umia Formation; Fig. 9). (D) Cross-section through *Indotrigonia*-dominated shell bed near base of Umia village section (Umia Formation; Fig. 5). (E) Bedding plane view of loosely packed shell bed with *Indotrigonia beyschlagi*, *Gervillella aviduloides*, and *Pisotrigonia parva*; Umia village section at 31.3 m. (F) Cross-section through trigonioid shell bed of the Umia Formation at Ghuneri village section (Fig. 7, level C). (G) Cross-bedded sandstone of Umia Formation topped by trigonioid shell beds, Ghuneri village section (see also Fig. 7). (H) Elements of the trigonioid shell beds east of Ghuneri village. Apart from the astartid *Herzogina* (H), several trigonioid taxa are common, such as *Steinmanella* (*Transitrigonia*) *mamillata* (S), *Iotrigonia vscripta* (I), and *Opisthotrigonia spissicostata* (O).

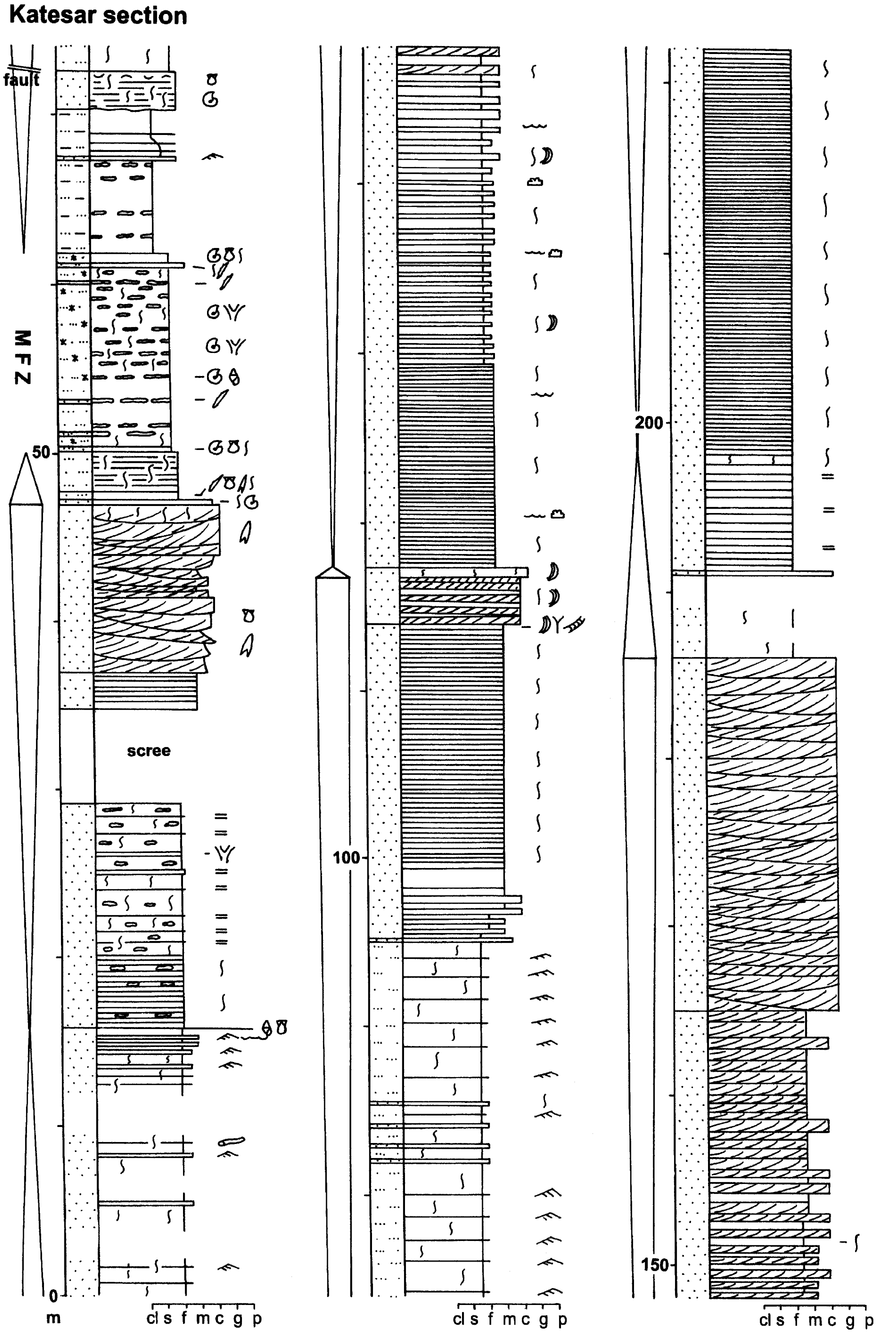


Fig. 8. Section through the top part of the Katrol Formation and basal Umia Formation north of Katesar village. For key of symbols see Fig. 5.

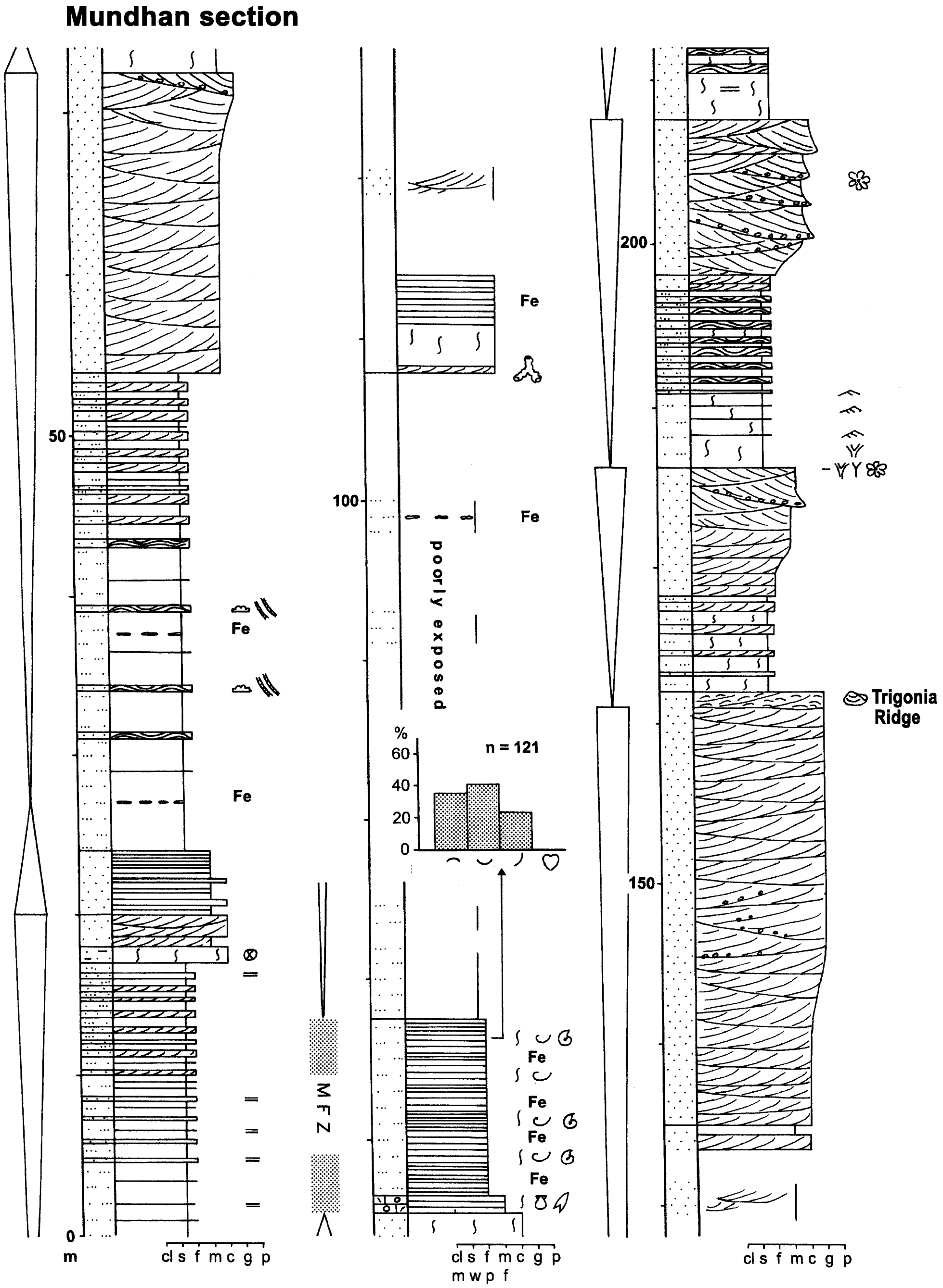


Fig. 9. Section through the top part of the Katrol Formation and basal Umia Formation at the Mundhan Anticline. For key of symbols see Fig. 5.

worked and fragmented burrow fills that underwent early diagenetic, concretionary lithification. Within the sequence stratigraphic framework, the facies corresponds to maximum flooding indicative of the highest relative sea level.

4.2.6. Thin, gravelly, poorly sorted, medium- to coarse-grained sandstones

The sandstones range in thickness between 0.2 and 2 m, in the latter case consisting of several beds. In most cases, they are about half a metre thick, poorly sorted, with scattered quartz granules and are heavily bioturbated, remains of large-scale cross-bedding being only rarely preserved. Their base is invariably sharp and erosional. Occasionally, internal erosion surfaces are present (e.g. in the Bharodia section; Fig. 2, at 4.7 m). Commonly, low-diversity bivalve assemblages are concentrated as shell beds, shell pavements or lenticles, as will be discussed in more detail below. Only rarely, a moderately diverse fauna is present. Wood pieces are found occasionally.

This facies shows characteristic features of transgressive lags, which formed by reworking of the top of the underlying unit. Characteristic is an intermittently high-energy level, very little sediment input, and a concentration of large, thick shells. Original stratification has usually been destroyed by bioturbation, which is also responsible for the poor sorting of the generally coarse sediment. The nature of the lags is, to a large extent, determined by the depth at which transgression occurred and by the grain size of the underlying beds (which also largely reflects the bathymetric position of the unit). In sequence stratigraphic terms, the sharp erosional base corresponds to the transgressive surface and the transgressive lag belongs to the early TST.

4.2.7. Poorly sorted, muddy, fine- to coarse-grained, bioturbated sandstones

The sediments, usually not more than 1 m in thickness, range from fine- to coarse-grained; features common to all occurrences are their very poor degree of sorting (with admixtures of clay particles, quartz granules or even small sandstone pebbles) and strong bioturbation. Associated trace fossils include *Rhizocorallium irregulare*, branched *Cylindrichnus*, and *Planolites*. Skeletal elements include scattered *Gryphaea*, belemnites, and *Pisotrigonia*.

The wide range of grain size can be explained by strongly varying hydrodynamic conditions during which different types of sediment were deposited, which were subsequently mixed by bioturbation. This and the thin nature of the sedimentary packages suggest low rates of sedimentation. The facies type directly overlies transgressive lag deposits and can be interpreted as representing conditions during early transgression (early TST).

4.3. Sedimentary cycles

From the arrangement of facies in the sections a cyclic sedimentation pattern is apparent. This fact was also recognised by Krishna et al. (2000), although their account lacks any sedimentary details. The cycles are strongly asymmetric, distinctly coarsen upward (in some cases the beds also thicken upward), and the cycle boundary is defined by a distinct drop in grain size. These cycles can be interpreted as deepening–shallowing cycles. The deepening phase is represented by comparatively little sediment, most of the sedimentary record representing the shallowing phase. When applying sequence stratigraphic terminology, the cycles correspond to depositional sequences composed merely of TSTs and highstand systems tracts (HSTs). There is no record of lowstand systems tract (LST) sediments, and the sequence boundary coincides with the transgressive surface, as is so often the case in shallow water siliciclastic sediment packages, and as is also characteristic of the older (Bajocian–Oxfordian) sedimentary successions of the Kachchh Basin (Fürsich et al., 1991, 2001). This implies sedimentary gaps at the cycle boundaries.

The boundaries of the deepening–shallowing cycles, however, do not fully correspond to those of the coarsening-upward cycles. The topmost (and usually coarsest) beds of the coarsening-upward cycles, in fact, invariably belong to the base of the following deepening episode. The interpretation of these top beds as reworked residues of late HST sediments (transgressive lags) is supported by their coarse nature, their concentration of skeletal elements, and by the presence of a distinct erosional surface at their base (see also Brett, 1995; Fürsich et al., 2001).

The MFZ of these cycles, separating TST and HST deposits, is variably well developed. For example, several metre thick sediments of the MFZ in the Lakhapar section at 39.5–44 m (Fig. 4) contrast with a 0.1 m thick layer in the Katesar section at 15.8 m (Fig. 8). In some cases, the MFZ is characterised by sediments and faunas indicative of condensation.

Minor differences in the thickness and sedimentary expression of the cycles can be explained by the degree of relative sea-level change and thus depend on the depth of the sea floor at the end of the shallowing and deepening phases. For example, the upper cycle in the Lakhapar section in Fig. 4, as well as the equivalent cycles in the Katesar section (Fig. 8; base at 47 m), and the Mundhan Anticline section (Fig. 9; base at 72.5 m), are relatively thick (80–100 m), exhibit a thick package of fine-grained early HST sediments, and are characterised by a well developed MFZ. The sedimentary cycle most likely corresponds to a major rise in relative sea level (deepening) followed by equally pronounced shallowing (filling up of accommodation space). In contrast, the lower cycle in the Lakhapar section (Fig. 4; base at 1.6 m) is comparatively thin (25 m). Its deepest position was still on the storm-dominated shelf/ramp (presence of laminated tempestites) and this was probably the reason for lack of preservation of the MFZ. During HST, the sea floor shallowed only to a lower shoreface position, as is indicated by the presence of bioturbated fine-grained sandstone at the top. The differences in amplitude of adjacent relative sea-level oscillations possibly are a result of the interplay of different forcing mechanisms, such as eustasy, regional tectonics, and climatically controlled sediment supply. With the available information it is, however, impossible to disentagle the influence of the various forcing mechanisms.

5. Shell concentrations

The investigated sedimentary successions are, for the most part, completely unfossiliferous, most likely due to diagenetic dissolution of calcareous skeletons. At certain levels, however, shell concentrations occur in the form of shell beds, pavements, and lenses. The concentrations can be classified either as polyspecific (medium to high diversity) assemblages or pauci- to monospecific assemblages. According to faunal composition, five types can be distinguished: trigonioid-dominated, astartid-dominated, oyster-dominated, *Amphiastraea*-dominated, and high-diversity bivalve-dominated assemblages. Except for the coral-dominated assemblage, all concentrations consist overwhelmingly of bivalves. In the following, the various types are briefly described with respect to their ecological and taphonomic features and interpreted in terms of environmental significance.

5.1. Amphiastraea *assemblage*

Monospecific low-density concentrations of the cerioid scleractinian coral *Amphiastraea* are found in a transgressive lag in the lower part of the Lakhapar section and in cross-bedded late HST sediments in the Mundhan Anticline sections (Figs. 3 and 8). The coral heads are up to 30 cm in diameter, fragmented, bored, and abraded. In the Lakhapar section they appear to have colonised the sea floor during transgression at times of stable bottom conditions and suffered subsequent reworking, whereby the more fragile associated fauna was destroyed. Reworking in connection with transport is also indicated by the Mundhan Anticline occurrence. *Amphiastraea* is known to be adapted to life in siliciclastic environments and most likely could endure higher rates of sedimentation than most other corals. This is also demonstrated by its distribution pattern in older Jurassic sediments of Kachchh (Fürsich et al., 1994; Pandey and Fürsich, 2001) as well as in other areas of the world (e.g. Fürsich and Werner, 1986).

5.2. Gryphaea *assemblage*

Concentrations of *Gryphaea* are found in the Mundhan Anticline and Katesar sections as well as at Bharodia (Figs. 2, 7 and 8). At the first two localities, the oysters occur in loosely packed concentrations and in small lenses at the base and top of the MFZ. Associated elements are the bivalve *Gervillella* and ammonites. Most oysters are disarticulated and many have been bored by acrothoracic barnacles. Counts of the strongly convex left valve showed only a slight preference for convex-up oriented shells. A concentration of shells by physical processes (waves, currents) appears unlikely. The accumulations can be explained as the result of low sedimentation rates during maximum flooding (basin starvation). This led to a concentration of the biogenic hardparts, some of which were probably re-oriented by scavenging or burrowing organisms. The dominance of large, thick-shelled calcitic taxa such as *Gryphaea* most likely is the result of the greater resistance of such forms to synsedimentary and early diagenetic dissolution processes which are thought to have been responsible for the lack/scarcity of small and thin shells.

At Bharodia, *Gryphaea* occurs in a 20 cm thick bed of ferruginous, poorly sorted coarse-grained to gravelly sandstone that has been interpreted as a transgressive lag deposit. Fossil density is high and the diversity is moderate. Associated faunal elements include ammonites, belemnites, and a range of bivalves such as *Gervillella*, *Seebachia*, *Pleuromya*, *Actinostreon*, *Neocrassina*, and *Megacucullaea*. Nearly all shells are disarticulated and overwhelmingly oriented convex-up. Imbrication has been noted in some cases. The shells of *Gryphaea* are invariably strongly abraded. Abrasion, lack of articulation, and convex-up orientation all point to repeated phases of reworking of the shells as one would expect during transgression.

5.3. Trigonioid assemblages

Mono- to paucispecific assemblages of trigonioids occur at two levels: (1) the Tithonian Trigonia Bed of Rajnath (1932)/Trigonia Ridge Sandstone Bed of Biswas (1980, 1993) that can be followed from near Katesar in the west to beyond Jara Dome in the east, for a distance of more than 10 km; (2) the Neocomian Trigonia Bed at Ghuneri.

5.3.1. Indotrigonia–Pisotrigonia *assemblage*

According to Biswas (1980, 1993) the Trigonia Ridge Sandstone Bed actually consists of three calcareous sandstone beds, 0.6–1.2 m thick, that contain mainly *Trigonia* (= *Indotrigonia beyschlagi*). The fossil content varies considerably, however. In the Mundhan Anticline and Lakhapar sections, only a single Trigonia bed was encountered (Fig. 6B), and in the Katesar section, the corresponding sandstone was unfossiliferous. At Umia (Fig. 5), in contrast, several concentrations of *Indotrigonia* occur within the 33 m of section exposed.

At Lakhapar, the Trigonia Ridge Sandstone Bed is 0.3–0.5 m thick, packed with large, thick-shelled bivalves that form a paucispecific concentration consisting of *Indotrigonia beyschlagi* (86%), *Pisotrigonia* (8%), and *Gervillella* (6%) (Fig. 4C). More than 95% of the shells are single valves and 66% are found in a current-stable convex-up orientation (Fig. 4B). Shell density varies from shell-supported to matrix-supported. The strongly weathered bed surfaces did not allow observations on additional taphonomic aspects such as degree of boring and encrustation. Together with the sedimentological features of the bed, the available taphonomic features (orientation of disarticulated shells convex-up, signs of abrasion) point to deposition by currents in a generally high-energy environment.

At Umia, altogether eight levels with shell concentrations of varying degrees of packing occur. Near the top of large-scale trough-cross-bedded, coarse to gravelly sandstones (at 3.8 and 25 m in Fig. 5) shells are invariably disarticulated, oriented convex-up and usually concentrated in lenses, fill up to 50 cm wide scours, or form pavements on large foresets. In muddy, bioturbated sands and poorly cemented sandstones they occur in low density, but are again disarticulated and oriented convex-up. In poorly sorted, muddy, coarse-grained sandstone trigonioids occur in medium packing density, forming shell concentrations up to 30 cm thick that are comparatively well preserved. Shell orientation and degree of disarticulation are the same as in the foregoing examples. The fauna consists of three to four taxa (*Indotrigonia beyschlagi*, *Opisthotrigonia ret-*

rorsa, *Pisotrigonia parva*, and *Gervillella aviculoides*) of varying relative abundance (Fig. 5) but with *Indotrigonia* or *Pisotrigonia* invariably dominating. Biostratinomic data from three consecutive shell concentrations just below the top of the section (31–32.5 m) (Fig. 5B–D) reveal pronounced size sorting (no small, thin shells being present), a dominance (80% or more) of convex-up oriented shells, and a moderate degree of sorting with respect to right and left valves. These features corroborate the interpretation of this unit as transgressive lag (see above), although the few concentrations occurring in cross-bedded sandstones of the late HST do not differ in taphonomic character except for their lenticular, rather than laterally continuous, nature. The 20 cm thick *Indotrigonia beyschlagi* shell bed in the section at 5.4 m differs from the TST shell concentrations in that more than 70% of the bivalves are bored and encrusted. As this bed tops several concentrations interpreted as TST deposits and is followed by silty–sandy clay with scattered *Pisotrigonia*, it is here interpreted as corresponding to the MFZ, a view supported by the high degree of biogenic alteration of the shells which indicates a relatively long residence time on the sea floor.

The combination of the preferred convex-up orientation of disarticulated shells of large infaunal bivalves (suggestive of reworking) and a poorly sorted, muddy, coarse-grained sandy substrate (indicative of low turbulence conditions) appears to be a contradiction. It can be explained by the alternation of high-energy episodes that shaped the biofabric and concentrated coarse particles with low-energy phases, during which fine-grained particles settled out of suspension and bioturbation destroyed primary sedimentary structures, mixed the sediment, but did not alter the orientation of large shells.

*5.3.2. Trigonioid–*Herzogina *assemblage*

In the vicinity of the village Ghuneri, trigonioid shell beds of several ages crop out. In this paper we do not refer to the Lower Cretaceous trigonioid concentrations (part of the Ukra Formation) that are found southwest of the village, but to trigonioid–*Herzogina*-dominated assemblages southeast of the village. Four consecutive shell beds are intercalated between massive, cross-bedded sandstones (Fig. 7). The dominant faunal element is the astartid bivalve *Herzogina* (70%) followed by several taxa of trigonioids (the commonest being *Steinmannella* (*Transitrigonia*) *mamillata*, 14%; *Iotrigonia vscripta*, 8%; *Opisthotrigonia spissicostata*, 4%; *Pisotrigonia parva*, 2%, and *Opisthotrigonia retrorsa*, 2%). Although *Herzogina* dominates, the trigonioids are clearly the more spectacular elements of the fauna, due to their large size and the large number of morphological varieties. All bivalves were shallow infaunal suspension-feeders. More than 90% of the bivalves are disarticulated, and convex-up orientation prevails (Fig. 7). Some shell beds exhibit a sharp base, in one of them shell density distinctly decreases up-section. The biofabric suggests high-energy conditions; the lack of small faunal elements indicates size sorting. The orientation pattern points to deposition by currents, the decrease in shell density in shell bed 3 to waning current velocity. These features agree with the interpretation of these shells as having lived and having been concentrated during the transgressive phase (TST).

A shell bed of identical composition occurs several tens of metres below this unit, in a 15 cm thick, poorly sorted and weakly cemented, muddy sandstone. Exposures are, however, too poor to obtain more detailed information.

5.4. Seebachia *assemblage*

Levels in which the large astartid bivalve *Seebachia* (*Eoseebachia*) is the most conspicuous faunal element occur, for example, in the upper part of the Katrol Formation of the Lakhapar section (e.g. Fig. 3, top of cycle 2), forming patchy concentrations of low density or patchy pavements. More spectacular are the concentrations found in the Upper Oxfordian–Kimmeridgian Wagad Sandstone Formation of Wagad Dome; the Kanthkot Fossiliferous Band and the Bharodia Astarte Bands of Biswas (1980, 1993). At Bharodia, *Seebachia* (*Eoseebachia*) *sowerbyana* abounds only in the top shell concentration, in contrast to its scattered and occasionally articulated occurrence in the two lower fossiliferous levels at that locality (Fig. 2). This upper bed, a 0.5 m thick, ferruginous, coarse-grained calcareous sandstone at the top of a coarsening upward sequence, consists of disarticulated, convex-up oriented, size-sorted shells of *Seebachia* and conforms in all aspects to a transgressive lag, as already described repeatedly above.

The same can be said about the Kanthkot Fossiliferous Band, which is well exposed near the village of Kanthkot. It consists of 5–7 levels, each 10–20 cm thick, of shell concentrations that occur in a 4–5 m thickly bedded, gravelly, coarse-grained sandstone unit with cross-bedding and megaripple surfaces and thin intercalations of partially bioturbated (by *Rhizocorallium irregulare*) fine- to medium-grained sandstone. Shells are usually concentrated in the finer interbeds, but also occur in the cross-bedded units. The degree of fragmentation varies; most shells are disarticulated and more than 90% are oriented convex-up, but in densely packed levels (usually patchily developed) vertical stacking has also been observed. Biological alteration of shells is rare. The dominant bivalves are *Seebachia* (*Eoseebachia*) *sowerbyana* and *S.* (*Eoseebachia*) *elongata* (Fig. 10). In addition, *Indotrigonia smeei*, *Trigonia* (*T.*) *oomia*, *Gervillella aviculoides*, *Megacucullaea*, and *Indolucina* occur. The species diversity is medium. In terms of life habits, *Indotrigonia* and *Seebachia* most likely were shallow burrowers, whereas *Gervillella* and *Megacucullaea* were byssate taxa. Wedged in between two massive deltafront-sandstone units, the Kanthkot Fossiliferous Band can be interpreted as the result of relative sea-level rise, during which the top of the underlying sandstone was reworked into a transgressive sand sheet composed of megaripples and small bars. This interpretation is supported by sedimentary structures, biofabric, and evidence of size sorting. The shells are clearly reworked as is indicated by their orientation pattern and most likely represent the winnowed and sorted relics of a shallow-water, high-energy community. The relative rise in sea level can be explained either as autocyclic, caused by switching of delta lobes – the shell beds would then represent the delta abandonment phase – or else as caused by true transgression, during which the shoreline regraded. In view of the fact that most changes of relative sea level in the Kachchh Basin appear to have been basin-wide features, the second alternative is favoured here.

5.5. High diversity bivalve-dominated assemblage

In the Lakhapar section (at 41 m, Fig. 4), a 40 cm thick, loosely packed, highly bioturbated shell bed is a prominent feature due to its highly ferruginous nature. Shell density increases towards the top of the bed where it is associated with small calcareous siltstone pebbles. Pebble and shell density vary considerably laterally. The shells are invariably matrix-supported. Convex-up orientation prevails, but is not as dominant as in most of the shell beds discussed above. Species diversity is high and consists of a number of nektic forms (ammonites, belemnites) as well as of benthic taxa. Among the latter, conspicuous elements are the bivalves *Megacucullaea*, *Seebachia* (*Eoseebachia*), *Gervillella*, *Pholadomya* (*Pholadomya*), *Ctenostreon*, *Integricardium*, *Neocrassina*, *Thracia*, *Chlamys*, *Opisthotrigonia*, *Pisotrigonia*, *Integricardium*, several oysters, and brachiopods (terebratulids and *Acanthothyris*). The bed is termed here Megacucullaea Bed, after its most distinctive faunal element. In contrast to most other shell beds discussed above, the percentage of articulated shells is relatively high (between 20 and 30%). This is also true of epifaunal and semi-infaunal bivalves such as *Ctenostreon* and *Gervillella* and of all brachiopods. Deep burrowing bivalves such as *Pholadomya* are commonly found in growth position. The degree of shell fragmentation is comparatively low, preservation is generally very good, but shells are occasionally encrusted by oysters and serpulids.

All these features agree with the sedimentological interpretation of the Megacucullaea Bed as part of a MFZ. Formed offshore under relatively low-energy conditions, the bed contains the relics of an autochthonous community that merely suffered intermittent gentle winnowing, but no transport. Concentration of shells was due to low net rates of sedimentation. As a result, time-averaging can be expected to have played a major role in shaping the composition and species diversity of the assemblage. The dominance of

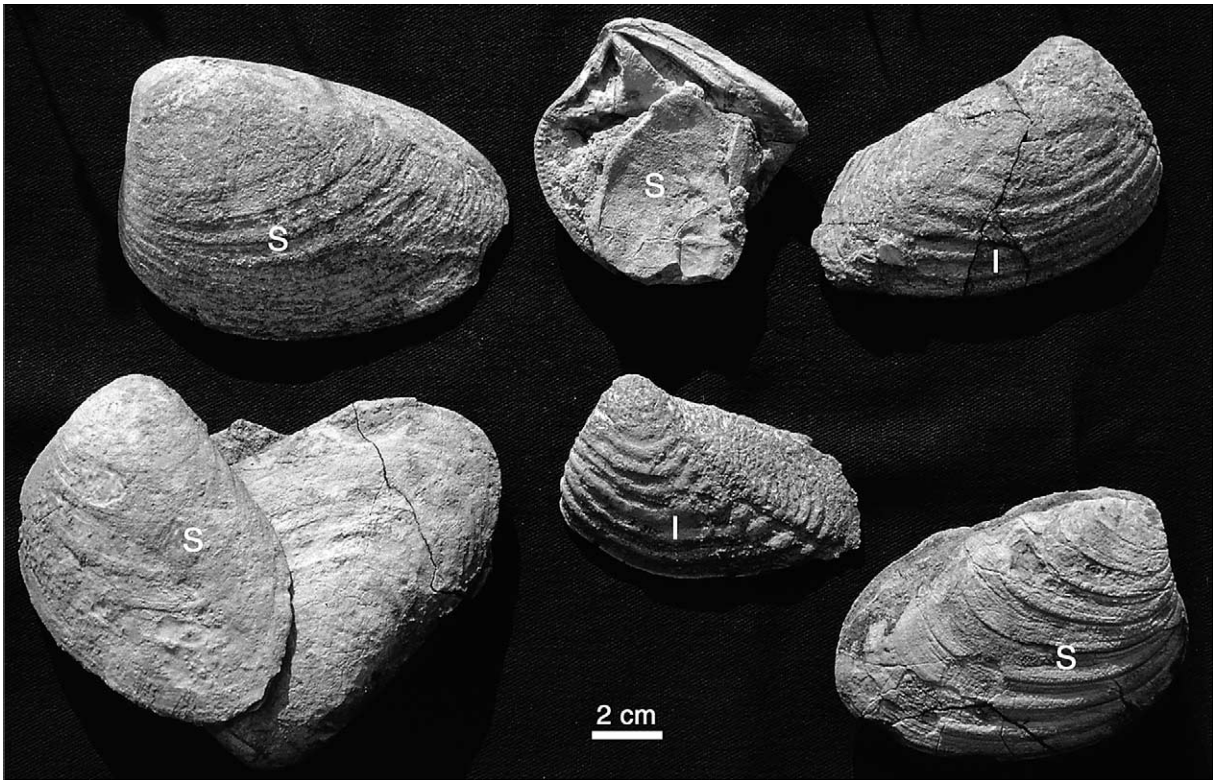


Fig. 10. Elements of the Kanthkot Fossiliferous Band, Kanthkot Member of the Wagad Formation, at Kanthkot, Wagad Dome. S: *Seebachia* (*Eoseebachia*) *elongata*; I: *Indotrigonia smeei*. Scale in cm.

epifaunal taxa may reflect taphonomic feedback (Kidwell and Jablonski, 1983) whereby the increasing availability of secondary hard substrates (shells), due to low rates of sedimentation and winnowing, changed the original character of the substrate and promoted the colonisation by epifaunal taxa.

A similar, albeit less well developed example of a MFZ shell concentration, occurs near the base of the Katesar section (Fig. 8), where *Megacucullaea*, *Trigonia* (*Trigonia*), *Nicaniella*, and small gastropods occur, together with rare ammonites and belemnites.

6. Discussion

6.1. Sequence stratigraphic context of shell concentrations

According to the biostratinomic, sedimentological and palaeoecological features described above, these Upper Jurassic shell concentrations can be related to different phases of depositional sequences (Fig. 11). Early TST shell concentrations, usually in the form of transgressive lags, are characterised by reworked low-diversity faunas, either bivalves or corals that are large, exhibit size sorting, and, most likely, also some diagenetic sorting (see below), and a pronounced convex-up orientation in cross-section. The taxa have undergone local transport, some degree of biological alteration, and can be regarded as parautochthonous. Time-averaging must have been important due to repeated phases of reworking and generally low rates of net sedimentation (Fürsich and Aberhan, 1990). The fossils in a given assemblage probably belonged to different benthic communities, of which only the sturdiest members survived.

Shell concentrations of the MFZ (= backlap shell bed of Naish and Kamp, 1997) are of medium to high diversity, poorly sorted, highly bio-

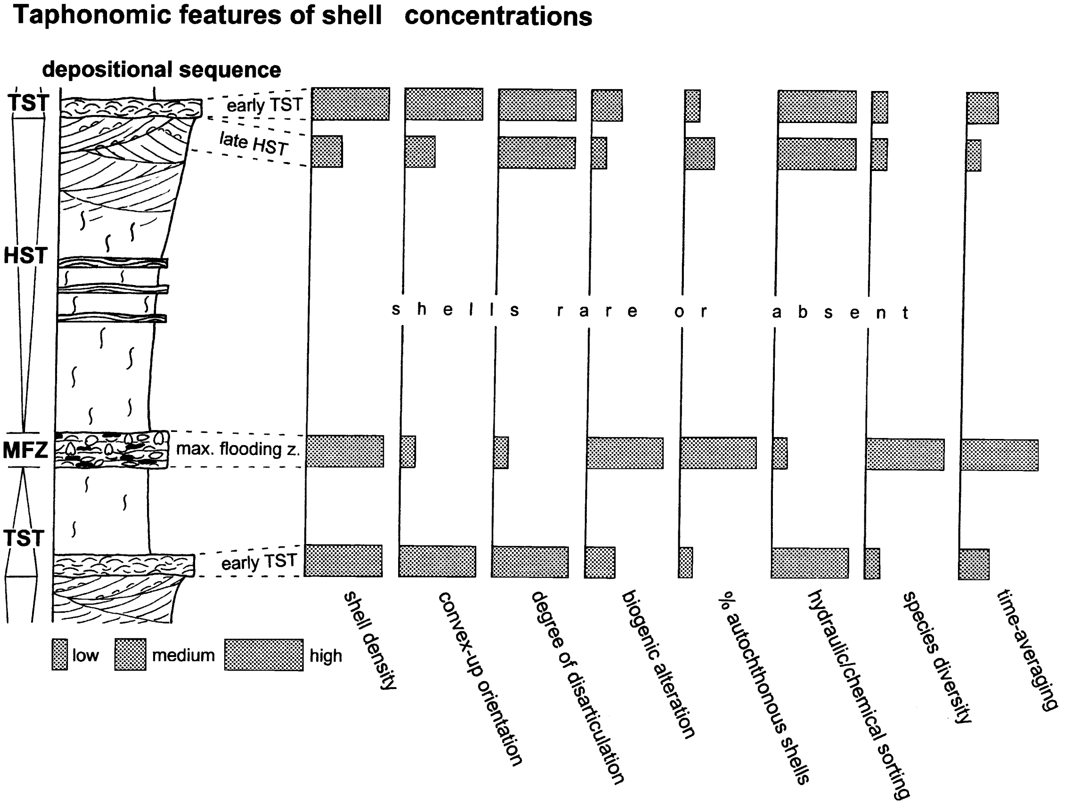


Fig. 11. Schematic depositional sequence and taphonomic features of shell concentrations of the early TST, MFZ, and late HST. For discussion see text.

turbated, are dominated by molluscs and brachiopods, among them also nektic forms (ammonites, belemnites), exhibit random orientation of shells, and a moderate to high degree of biogenic alteration. The relatively high percentage of articulated shells and the presence of burrowing bivalves in their position of growth indicate a generally low-energy environment below even storm wave base and very low rates of net sedimentation. The latter was partly caused by little sediment input due to the offshore position of the depositional environment, partly probably by gentle winnowing. The shells accumulated in situ and are autochthonous or, at the most, parautochthonous. Time-averaging played a significant role, as did taphonomic feedback which favoured the colonisation of the sea floor by epibenthic organisms such as byssate, cemented or free living bivalves and pedicle-attached brachiopods. Due to the low rates of sedimentation, concentration of iron minerals was high and ferruginous ooids and glauconite grains are common constituents of the sediment.

The third type of shell concentration formed during late HST when high-energy conditions prevailed and the sea floor was above the fair weather wave base. Constant reworking produced size sorting and a concentration of large and sturdy shells as pavements or lenses. Diversity was consequently low because delicate and thin-shelled forms suffered breakage. The fauna is clearly parautochthonous to possibly allochthonous and represents the reworked and transported relics of one or several communities. Allochthonous time-averaging (Aberhan and Fürsich, 1990) played some role, whereas autochthonous time-averaging probably was less significant than in the case of the early TST shell concentrations. Biogenic alteration was greatly overshadowed by physical abrasion leaving no evidence of the former.

Shell concentrations of the early TST and late HST do not differ drastically from each other with respect to most taphonomic attributes. A feature to distinguish between them is the much greater lateral persistence in the case of the early TST concentrations (they usually form beds), whereas late HST concentrations commonly form lenticles, pods, and pavements on foresets of large cross-beds.

The Upper Jurassic sediments of the western Kachchh Mainland are distinctly cyclic in nature, conforming to depositional sequences of the TST–HST type, sediments of the LST not being deposited due to lack of accommodation space. As one would expect, the changes in relative sea level differed from cycle to cycle. As a result, the cycles vary with respect to thickness, sediment character, and shell concentrations. For example, the upper cycle shown in the Lakhapar section (Fig. 4) appears to record a large amplitude of relative sea-level fluctuation. This is shown by the thickness of the cycle (80 m), the very characteristic, highly mineralised MFZ with signs of condensation, indicative of deeper offshore conditions, and the well developed high-energy sediments of late HST. Shell concentrations characterising the three stages are well developed. Other cycles within the same section (e.g. Fig. 3, cycle 3) are only a few metres thick, shell concentrations are absent (at the most a few scattered shells occur) and a MFZ cannot be detected. In this case, the relative change in sea level appears to have been comparatively small. Other differences in the character of the cycles and shell concentrations have been caused by the relative bathymetric position of the transgressive surface. In the Bharodia section (Fig. 2), the lower cycle exhibits a well developed MFZ and HST sediments that consist of bioturbated ferruginous silt and thus clearly did not extend into shallow high-energy environments. The following early TST shell concentration consequently exhibits a different faunal composition and a higher diversity than transgressive shell lags that follow high-energy shallow water sediments.

6.2. Role of diagenesis

The lack of any skeletal elements in most of the studied sections is probably not due to the primary absence of any shell-bearing benthic fauna but is more likely the result of synsedimentary or early diagenetic dissolution. This assumption is supported by the presence of trace fossils and evidence of bioturbation, which demonstrate that conditions at the sea floor were not inimical to life. Apparently, low-density shell concentrations and scattered shells were preferentially dissolved and the pore waters thus saturated with $CaCO_3$ migrated to levels with a high primary concentration of shells to form cement, thus increasing the preservation potential of these faunas (compare Fürsich, 1982). Thus, the transgressive lags are invariably strongly indurated due to the presence of a well developed calcareous cement, whereas late TST and early HST sediments are usually uncemented or friable. Except in the case of MFZ concentrations, selective dissolution probably affected most other concentrations, as is suggested by the exclusive presence of large shells. However, mechanical size sorting by winnowing and transport as well as mechanical destruction of small and thin shells by waves and currents also was probably responsible for this feature. In general, due to these processes, faunas characterising the MFZ and early TST have a much higher preservation potential than those of the late TST and most of the HST.

6.3. Palaeoecological implications

From the foregoing discussion it has become clear that the shelly macrobenthos associated with late HST and early TST suffered extensive reworking, mixing, limited transport, mechanical and chemical destruction, and in the case of early TST also time-averaging. What remained offers us a distorted, heavily biased impression of the original communities that colonised the sea floor in the Late Jurassic. Despite the high-energy conditions, shells apparently remained in their general habitat. Most likely these molluscs colonised the sea floor during lower-energy interludes or lived in more sheltered areas provided, for example, by troughs between sand bars as can be seen in the Kanthkot Member of the Wagad Sandstone Formation.

The MFZ concentrations, in contrast, can be interpreted as the autochthonous relics of a highly time-averaged community or communities. Similarly, the high-density faunas occurring at the top of the Umia village section (Fig. 5 at 33 m) appear to be autochthonous, but may have suffered some preferential diagenetic dissolution of shells. Although no quantitative data are available, the presence of several associations during the MFZs can be assumed, dominated either by *Megacucullaea–Seebachia–Gervillella*, by *Gryphaea*, or by *Indotrigonia–Pisotrigonia*.

An interesting feature of these faunas is their temporal persistence that, in the past, led to repeated confusion with respect to correlation (e.g. Biswas, 1993). Thus, *Gryphaea*-dominated concentrations occur both in the ?Middle Kimmeridgian of Wagad Dome of eastern Kachchh (e.g. at Bharodia) and in the Upper Tithonian of western Kachchh (e.g. at Lakhapar and in the Mundhan Anticline section). More spectacular is the persistence of (*Megacucullaea*)–*Seebachia–Gervillella* concentrations which occur in the Upper Oxfordian of Wagad Dome and in the Lower Tithonian of eastern Kachchh. This indicates that, due to the cyclic nature of deposition, the same environments appeared over and over again in time and were colonised by faunas of identical generic composition, although differences exist at the species level. Thus, the Late Oxfordian *Indotrigonia smeei* has been replaced in the Tithonian by *I. beyschlagi*, and whereas in the uppermost Oxfordian Kanthkot Fossiliferous Band *Seebachia* (*Eoseebachia*) *sowerbyana* and *S.* (*Eoseebachia*) *elongata* occur side by side, only the latter occurs in the Kimmeridgian Bharodia Astarte Bands and in the Tithonian MFZ at Lakhapar. The repetition in time confirms that these concentrations must be derived from communities of similar guild structure.

6.4. Biogeographic and evolutionary significance of Seebachia–*trigonioid faunas*

The bivalves *Seebachia* and *Indotrigonia* appear to have been a characteristic element of Late Jurassic and Early Cretaceous benthic communities not only in the Kachchh Basin but also in East Africa (e.g. Dietrich, 1933) where they form shell concentrations in coarse-grained, commonly conglomeratic sandstones (e.g. the Trigonia (= *Indotrigonia*) smeei Bed of Dietrich, 1933). According to M. Aberhan (written communication, 2002) the mainly large and thick-shelled valves are disarticulated, but not fragmented, and are neither bio-eroded nor encrusted. They have been interpreted as concentrations produced by storms, in the case of the Smeei Conglomerate by tsunamis. Such shell beds occur from the Kimmeridgian to the Lower Cretaceous ('Neocomian') (Dietrich, 1927). As mentioned above, the species of *Seebachia* differ between shell concentrations from different ages: *Seebachia* (*Eoseebachia*) *sowerbyana* (Holdhaus, 1913) and *S.* (*Eoseebachia*) *elongata* Fürsich, Heinze and Jaitly, 2000 occur together in the late Oxfordian, the former species also in rocks of Kimmeridgian and Tithonian age. *S.* (*Eoseebachia*) *sowerbyana* also occurs in shelf sediments on the northern rim of the Indian plate (Spiti Shales; e.g. Holdhaus, 1913). The species has also been recorded from the Oxfordian–Kimmeridgian of the Morondava Basin, southern Madagascar (specimens supplied by M. Geiger, Bremen) and, together with *Indotrigonia smeei*, from northern Mozambique (Henriques da Silva, 1966). In eastern Africa, *S.* (*Eoseebachia*) *krenkeli* (Dietrich, 1933) [= *sowerbyana*] occurs in the Upper Kimmeridgian (Heinrich et al., 2001) Nerinea Bed, the distinctly elongated and posteriorly tapering *Seebachia* (*Eoseebachia*) *janenschi* Dietrich, 1933 in the Lower Tithonian Smeei Conglomerate (Dietrich, 1933; Heinrich et al., 2001). The even more elongated and rostrate *S.* (*Seebachia*) *bronni* (Krauss, 1850) from the Lower Cretaceous of the Algoa Basin, eastern South Africa, is a still younger representative of the genus. The temporal and spatial distribution pattern of the various species of *Seebachia* testifies that this bivalve, in contrast to most Mesozoic bivalves, evolved rapidly.

Some trigonioid genera of the Lower Cretaceous trigonioid–*Herzogina* assemblage are also known from the Valanginian Sundays River Formation near Port Elisabeth, South Africa (Cooper, 1991), apparently forming concentrations similar to the ones found east of Ghuneri. The species and most of the genera distinctly differ from those present in the Upper Jurassic of

Kachchh. This and the relatively high diversity of the group in the Lower Cretaceous of South Africa (Cooper, 1991) and the Kachchh Basin (Kitchin, 1903) indicate that these trigonioids were highly successful in colonising and speciating in shallow water environments within the Malgassy Gulf.

Another characteristic faunal element shared between Kachchh, East Africa, and South Africa is the genus *Herzogina*, which also appears to have undergone rapid geographic speciation in the Malgassy Gulf in the Late Jurassic–Early Cretaceous.

Seebachia, *Herzogina*, and several of the trigonioid genera are endemic, being restricted to this southern extension of the Tethys. The occurrence in the Kachchh Basin, East Africa, and southern Africa indicates free larval exchange between these areas. The reason why these taxa did not spread northwards along the shelf of the Tethys towards areas such as Egypt and Tunisia may have been the existence of a biogeographic barrier, most likely in the form of higher seawater temperatures at lower latitudes. We believe the benthic faunas inhabiting the Malgassy Gulf were adapted to water temperatures characteristic of temperate to subtropical climatic belts and were not able to invade the very warm shelf seas of the Tethys at lower latitudes. Because of this, the genera *Seebachia*, *Herzogina*, *Indotrigonia* and *Opisthotrigonia*, to name only the most conspicuous taxa, are regarded as characteristic elements of the Ethiopean faunal province in the Late Jurassic and Early Cretaceous.

7. Conclusions

(1) Upper Jurassic (Oxfordian–Tithonian) and Lower Cretaceous ('Neocomian') siliciclastic shallow water sediments of the Kachchh Basin exhibit a distinct cyclicity, expressed by strongly asymmetric coarsening- and thickening-upward cycles.

(2) These cycles can be interpreted as deepening–shallowing cycles starting at the base with a thin transgressive lag, to be followed often immediately by sediments of the regressive phase. In sequence stratigraphic terms, these cycles correspond to depositional sequences, in which the sequence boundary coincides with the transgressive surface and LST sediments are missing.

(3) Shell concentrations occur near or at the top of the HST, during early TST, and in the MFZ. Six assemblages can be distinguished: The *Amphiastraea* assemblage (a) is characterised by a coral adapted to life in unstable siliciclastic environments. The other assemblages are dominated by large bivalves, either *Gryphaea* (b), *Indotrigonia–Pisotrigonia* (c), trigonioids–*Herzogina* (d), *Seebachia* (e), or by a highly diverse bivalve fauna (f).

(4) According to their occurrence within the depositional sequence, three types of concentrations can be distinguished, varying in preservational quality and other taphonomic, as well as ecological, attributes: The transgressive lags of the early TST are characterised by low-diversity faunas exhibiting pronounced size sorting, moderate preservation quality, a high percentage of disarticulated shells, and a preferred convex-up orientation due to repeated reworking and transport during intermittently high-energy conditions. Shell concentrations of the MFZ exhibit medium to high diversity. Shells are poorly sorted, randomly oriented, often articulated, some of them are preserved in their position of growth, and the degree of biogenic alteration is moderate to high. These highly time-averaged concentrations formed during times of strongly reduced sedimentation in a low-energy environment. Finally, shell concentrations of the late HST occur as lenses and pavements, exhibit size sorting, signs of physical abrasion, and consist only of few species. These concentrations reflect a high-energy environment above fair weather wave base, in which reworking was very frequent.

(5) The preferred occurrence of shells as concentrations was accentuated by synsedimentary or early diagenetic dissolution of shells that occurred scattered in the sediment and by early diagenetic cementation of most of the concentrations.

(6) Whereas the early TST and late HST concentrations are highly distorted relics of former benthic communities, the MFZ concentrations are autochthonous, albeit time-averaged, and reveal the presence of several associations dominat-

ed by *Megacucullaea–Seebachia–Gervillella*, by *Gryphaea* or by *Indotrigonia–Pisotrigonia*. These associations colonised the sea floor for extensive periods of time, in some cases ranging from the Late Oxfordian to at least the Early Tithonian, whereby, however, the composition changed at the species level.

(7) The bivalves *Seebachia*, *Herzogina* and *Indotrigonia* occur in similar environments as in the Kachchh Basin in other parts of the Malgassy Gulf. Together with several other trigonioids such as *Opisthotrigonia* they formed endemic shallow water elements of the Ethiopean faunal province in the Late Jurassic and Early Cretaceous. A characteristic feature of these taxa is their rapid evolution during the investigated time period.

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