Contributions to the Jurassic of Kachchh, Western India. II. Bathonian stratigraphy and depositional environment of the Sadhara Dome, Pachchham Island

FRANZ T. FÜRSICH, DHIRENDRA K. PANDEY, JOHN H. CALLOMON, WOLFGANG OSCHMANN & ANAND K. JAITLY

FÜRSICH, F. T., PANDEY, D. K., CALLOMON, J. H., OSCHMANN, W. & JAITLY, A. K. 1994. Contributions to the Jurassic of Kachchh, Western India. II. Bathonian stratigraphy and depositional environment of the Sadhara Dome, Pachchham Island. - Beringeria **12**: 95-125, 7 text-figs., 1 tab., 2 pls; Würzburg.

Abstract. At Sadhara Dome near the eastern end of Gora Dongar, Pachchham, Kachchh, Middle to Late Bathonian rocks are well exposed. They consist largely of unfossiliferous siliciclastics with two intervals of highly fossiliferous, mixed carbonate-siliciclastic sediments. Lithostratigraphically, the rocks have been assigned in a revised classification to the Khavda (lower) and Patcham Formations (higher). The latter is represented by the Raimalro Limestone Member. Within the Khavda Formation, six members are recognized, four of them informal ones. In descending order they are the Gadagupta Sandstone Member, the Goradongar Yellow Flagstone Member, the Middle Sandstone member, the Lower Yellow Flagstone member, the Eomiodon Red Sandstone member, and the Sadhara Coral Limestone member. The sedimentary succession and its faunal content are described in detail. Four facies-associations are recognized, representing nearshore bar complexes, semi-enclosed brackish bays grading into non-marine coastal plains, nearshore storm-dominated shallow shelf, and transgressive lags. Three benthic associations and one assemblage can be distinguished. The *Eomiodon indicus-Protocardia* sp. association characterizes brackish bays; the *Placunopsis socialis-Eomiodon indicus* association, the *"Corbula" lyrata* association and the *Modiolus imbricatus* assemblage reflect fully marine, shallow shelf conditions. The Bathonian sediments at Sadhara record several shallowing-deepening phases, often in form of asymmetric sedimentary hemicycles. Their genetic history cannot at present be evaluated with certainty, as precise correlations with rocks of comparable age from other parts of the Kachchh "Island Chain" have not yet been established.

■ *Jurassic, biostratigraphy, lithostratigraphy, palaeoecology, palaeoenvironments, Western India.*

Zusammenfassung. In der Sadhara-Aufwölbung, nahe am Ostende der Gora Dongar Hügelkette der Pachchham "Insel" gelegen, sind Sedimente des mittleren und späten Bathon gut aufgeschlossen. Sie bestehen überwiegend aus fossilfreien Siliziklastika mit zwei Einschaltungen sehr fossilreicher, gemischt karbonatisch-siliziklastischer Sedimente. Lithostratigraphisch wurden die Gesteine in die Patcham Formation und Khavda Formation unterteilt. Die Patcham Formation ist durch das Raimalro Limestone Glied repräsentiert, während die Khavda Formation in sechs Glieder unterteilt werden kann. In absteigender Reihenfolge handelt es sich um das Gadagupta Sandstone-Glied, das Goradongar Yellow Flagstone Glied, das Middle Sandstone Glied, das Lower Yellow Flagstone Glied, das Eomiodon Red Sandstone Glied und das Sadhara Coral Limestone Glied. Die letzten vier Glieder werden nur informell benannt. Die Sedimentfolge und ihr Fauneninhalt werden im Detail beschrieben. Vier Fazies-Assoziationen lassen sich ausscheiden, die als küstennahe Barrenkomplexe, als teilweise abgeschnürte brackische Buchten, die in Küstenebenen übergehen, als küstennaher Sturm-beeinflußter flacher Schelf und als transgressive Reliktsedimente interpretiert werden können. In der benthischen Fauna lassen sich drei Assoziationen und eine Faunenvergesellschaftung ausscheiden. Die *Eomiodon indicus-Protocardia* sp. Assoziation charakterisiert Brackwasserbuchten; die *Placunopsis socialis-Eomiodon indicus* Assoziation, die *"Corbula" lyrata* Assoziation und die *Modiolus imbricatus* Vergesellschaftung hingegen vollmarine Flachwasserverhältnisse. Die Sedimente des Bathon bei Sadhara sind aus mehreren Verflachungszyklen aufgebaut, oft in Form asymmetrischer sedimentärer Hemizyklen. Ihr genetischer Ursprung läßt sich nicht mit Sicherheit klären, da eine genaue Korrelation mit Schichten vergleichbaren Alters aus den anderen Teilen der "Inselkette" von Kachchh noch nicht existiert.

■ *Jura, Biostratigraphie, Lithostratigraphie, Palökologie, Paläomilieu, westliches Indien.*

Addresses of the authors: F. T. FÜRSICH, Institut für Paläontologie der Universität Würzburg, Pleicherwall 1, D-97070 Würzburg, Germany; D. K. PANDEY, Dept. of Geology, University of Rajasthan, Jaipur 302 004, Rajasthan, India; W. OSCHMANN, Institut für Geologie und Paläontologie der Universität Tübingen, Sigwartstr. 10, D-72076 Tübingen, Germany; J. H. CALLOMON, Dept. of Chemistry, Christopher Ingold Laboratories, University College London, 20 Gordon Street, London WC1H 0AJ, England; A. K. JAITLY, Dept. of Geology, Banaras Hindu University, Varanasi 221005, India.

Introduction

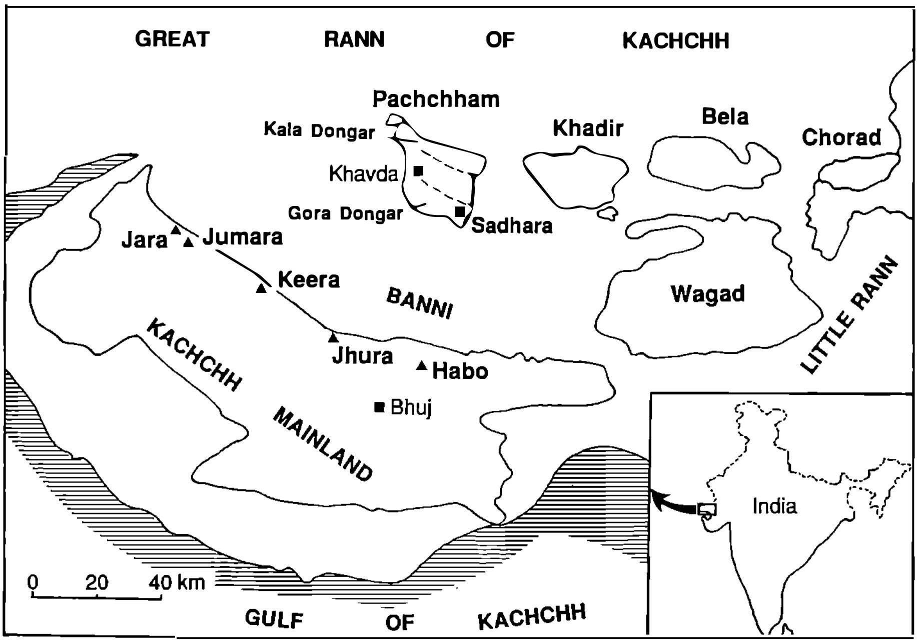
Despite earlier descriptions of the stratigraphy and ammonite succession of the Jurassic of Kachchh (e.g. WAAGEN 1873-1875, RAJNATH 1932, SPATH 1933) and despite numerous papers on local stratigraphy (e.g. MITRA et al. 1979, AGRAWAL & PANDEY 1985, BARDAN & DATTA 1987, JAI KRISHNA & WESTERMANN 1987, JAI KRISHNA et al. 1988), there is still no detailed biostratigraphic framework for the basin as a whole. A lithostratigraphic framework provided by BISWAS (e.g. 1977, 1981) served as the basis for an attempt to reconstruct the depositional history of the basin (e.g. BISWAS 1987, 1991). However, neither a sufficiently detailed sedimentological description of sections nor of the stratigraphic distribution of important faunal elements is available, nor has a rigorous facies analysis been carried out so far. Within the context of a comprehensive new analysis, centering on the interplay between the sedimentological and ecological evolution of the basin, sections on the so-called Kachchh Mainland have been remeasured and the distribution of their faunas quantitatively recorded. These investigations concentrated on the predominantly offshore facies represented on the Kachchh Mainland. For comparison and for information on more marginal environments of the basin, a section was measured through the Middle and Upper Bathonian at Sadhara Dome, Pachchham Island, and interpreted in terms of depositional environments and biofacies.

The section: litho- and biostratigraphy

The Jurassic outcrops in Pachchham transverse the island in two parallel, fault-bounded ranges of hills trending NNW to SSE: Kala Dongar (Black Hills) in the north, and Gora Dongar (White Hills) in the south (Text-fig. 1). The sections overlap to some extent, but those in the north extend further downwards to the oldest sediments exposed anywhere in Kachchh, which are of Upper Bajocian age. Those in the Gora Dongar extend upwards into the Lower Callovian and overlap in age with the oldest rocks exposed on the mainland. The Gora Dongar range extends from the town of Khavda in the west to a typical Kachchh anticlinal dome north of the village of Sadhara in the east - a distance of some 15 km. The Sadhara Dome forms a roughly circular structure, the centre of which has been eroded to expose the lowermost beds along small cliffs and stream-beds. The succession is some 250 m thick and consists predominantly of siliciclastic sandstones, but at the base, at the top and at two intervals inbetween, carbonates and mixed siliciclastic-carbonate rocks are prominent (Text-figs. 2-4). Body-fossils are absent in most of the beds, but when they occur, they do so in profusion. Bivalves are the dominant group; gastropods, corals, and ammonites are also found but are rare, occurring at only a very few horizons.

Lithostratigraphy

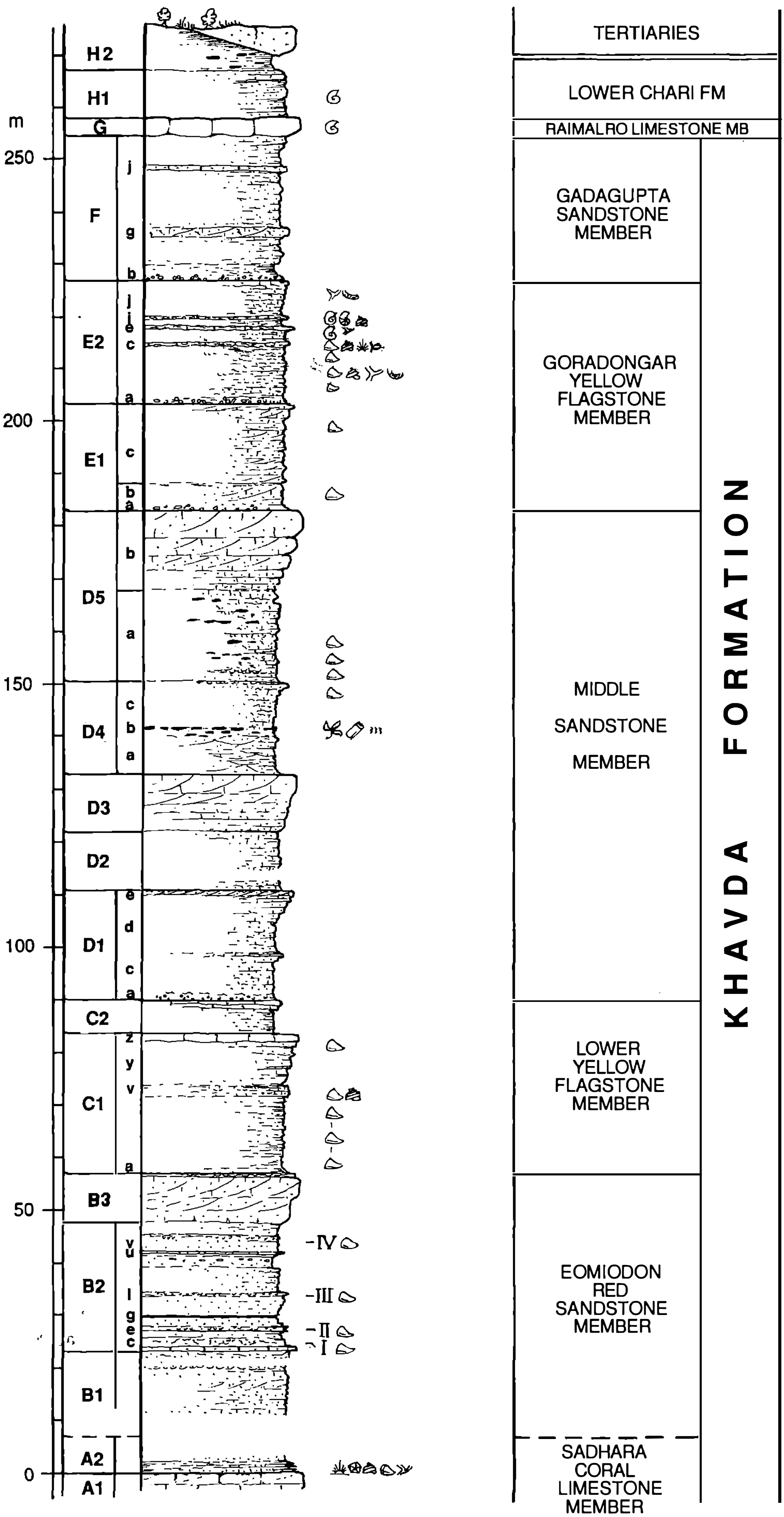
There have been a number of previous descriptions of the Jurassic rocks of Gora Dongar and of formational classifications based upon them. These descriptions have, however, been rather general, based on combined measurements of sections at several widely scattered localities in a basin in which lateral facies- and thickness-changes can be rapid. This, together with the uncertainties in quoted thicknesses, make it difficult to recognize again many of the published formational units in the field. We record our observations at Sadhara therefore in two forms. Text-figs. 2 and 3 are sections drawn as weathering profiles. Although sometimes reflecting factors of secondary importance in detailed facies analysis, they corre-



Text-fig. 1. Locality map.

spond more closely to what is seen in the field and should make it easier to recognize formations and their boundaries again. They also bring out major changes of facies. Text-fig. 4 presents the succession in standard sedimentological form, to which the descriptions in the text largely relate. Thicknesses were estimated by means of a dip-compensated Jacob's Staff and should be reliable to better than 10%. Dips did not exceed 20° and varied only slowly.

Previous formational classifications are summarized in Text-fig. 5, which includes also the traditional names used for the equivalent beds on the Mainland. BISWAS (1977) assigned the Jurassic of Pachchham to the Goradongar (higher) and Kaladongar Formations (lower), both subdivided into several members. He described two type sections, but we have been unable to reconcile part of his descriptions with our observations at Sadhara. The Raimalro Limestone Member of BISWAS (1977) is clearly delimited. It represents a widely-recognizable regional marker whose name is worth retaining. It seems clearly correlateable with the classical Patcham Formation of Jumara on the Mainland. The overlying "Modar Hill Member", said to be 427 ft (130 m) thick, is somewhat mysterious, for detailed mapping by one of us (D.K.P.) has shown that these higher beds occur only along the southern margins of the Gora Dongar in shallow, nearly flat-lying outcrops soon covered by Tertiary and superficial deposits (PANDEY 1983). Their thickness can be only a fraction of that quoted by BISWAS (1977). Their facies and fossils also resemble those of the beds overlying the Patcham Formation on the Mainland, and it seems sufficient to assign them, as there, to the Lower Chari Formation. We therefore find the Goradongar Formation, of which the Modar Hill Member was a major constituent, to be largely superfluous. The underlying Kaladongar Formation can be recognized at Sadhara, but to avoid major redefinition of its boundaries and thereby further increase of the already existing confusion, we prefer to use the term Khavda Formation (PANDEY 1983, PANDEY et al. 1984, AGRAWAL & PANDEY 1985) for all the beds below the Raimalro Limestone of the Patcham Formation. In the Sadhara section we could recognize within the Khavda Formation, in descending order, the following two members of BISWAS' (1977) classification: the Gadagupta Sandstone Member and the Goradongar Yellow Flagstone Member. We have therefore retained them. In BISWAS' classification the Goradongar Yellow Flagstone Member was then followed downwards by the Babia Cliff Sandstone Member, the Kaladongar Sandstone Member and the Dingy Member. These three members are mainly sandy in nature, with occasional intercalations of thin fossiliferous horizons. The members are poorly defined and it is impossible to recognize their boundaries outside the type section in Kaladongar. We therefore subdivide this part of the Sadhara section informally into four members. These members are, in descending order, the Middle Sandstone member, the Lower Yellow Flagstone member, the Eomiodon Red Sandstone member and the Sadhara Coral Limestone member (Text-fig. 5). These four members are 187 m


m
250
200
150
100
50
0
H2
H1
G
F
j
g
b
E2
j
i
e
c
a
E1
c
b
a
D5
b
a
D4
c
b
a
D3
D2
D1
e
d
c
a
C2
C1
z
y
v
a
B3
B2
v
u
l
g
e
c
B1
A2
A1
-IV
-III
-II
-I
TERTIARIES
LOWER CHARI FM
RAIMALRO LIMESTONE MB
GADAGUPTA SANDSTONE MEMBER
GORADONGAR YELLOW FLAGSTONE MEMBER
MIDDLE SANDSTONE MEMBER
LOWER YELLOW FLAGSTONE MEMBER
EOMIODON RED SANDSTONE MEMBER
SADHARA CORAL LIMESTONE MEMBER
KHAVDA FORMATION

in thickness and most likely correspond to BISWAS' Babia Cliff Sandstone member and most of his Kaladongar Sandstone member which together measure 200 m at the type section.

Formalization of these members is postponed until the remaining key sections of the Island rangse have been studied in detail.

A brief description of the members in descending order recognized at Sadhara, both formal and informal, is given in what follows (see also Appendix for detailed description of the section).

Lower Chari Formation (Unit H in Text-figs. 2-3)

Some 12 m of recessive, fine-grained sands and silts are seen east of the village of Sadhara, resting conformably on the resistant Raimalro Limestone below and truncated unconformably by coarse-grained Tertiary sandstones.

Raimalro Limestone Member (BISWAS 1980) (Unit G)

The Raimalro Limestone Member can be clearly recognized all over Gora Dongar and Kala Dongar. It consists generally of resistant, thickly bedded carbonates with occasional chert nodules and forms widespread plateaux, rising to the summits of the hills, from which the formerly overlying, soft, recessive Chari Formation has been lost by erosion. At Sadhara its thickness is greatly reduced (2-3 m). The member consists of hard, fine sandy bioclastic calcarenites with faint traces of large-scale trough crossbedding. Gastropod and bivalve shells are concentrated in lenticles. Lenticular layers of intraformational conglomerate occur at several levels. The limestone contains rare imprints of *Macrocephalites* that are, however, not closely determinable. They are compatible with forms of the Triangularis Zone of the Patcham Limestones of Jumara on the Mainland. Lithological similarities also strongly support direct correlation with the Patcham Limestones of Jumara. The age of the ammonite Triangularis Zone in the framework of international standard chronostratigraphy - lowest Lower Callovian or topmost Upper Bathonian Stages? - has been much debated (e.g. KRISHNA & WESTERMANN 1987 and review by CALLOMON 1993). The question has still not been definitely settled, but consensus seems to be converging on Upper Bathonian. This view will be adopted here and the Bathonian-Callovian boundary taken to lie at the boundary between the Patcham and Chari Formations.

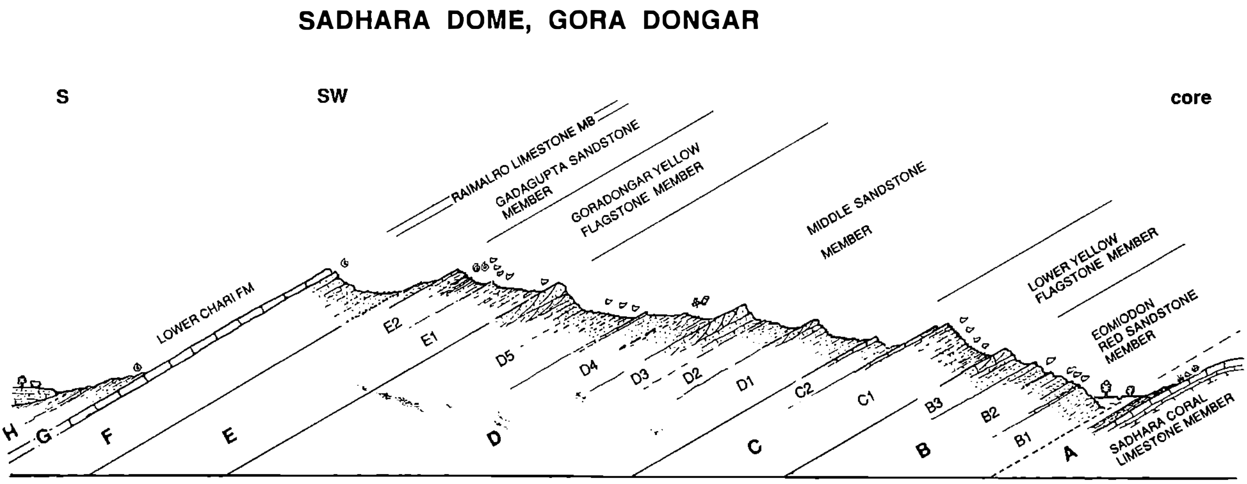
Gadagupta Sandstone Member (BISWAS 1980) (Unit F)

The Gadagupta Sandstone Member, informally erected by BISWAS (1977), corresponds in part to PANDEY's (1983) Taga member. At Sadhara the member consists of 25 m of fine to coarse-grained sandstone, partly bioturbated, partly crossbedded; the uppermost part is silty, in places marly, and may exhibit interlayered bedding. The base of the member is defined by a marker bed consisting of a strongly ferruginous coarse-grained conglomeratic sandstone bed, up to 50 cm in thickness, which overlies, with erosive base, the calcareous sediments of the Goradongar Yellow Flagstone Member. The pebbles of the conglomerate are heterolithic, including quartz and sandstone pebbles, the latter up to 15 cm in diameter. Basal parts of the member locally contain thin shell beds and are bioturbated by *Rhizocorallium irregulare*. The boundary with the overlying Raimalro Limestone at Sadhara is obscured by a volcanic intrusion, but has been observed to be somewhat gradational elsewhere on Gora Dongar, e.g. east of Khavda, through increasing carbonate content of the sandstones.

Goradongar Yellow Flagstone Member (BISWAS 1980) (Unit E)

This member corresponds to the Kharidongari member of PANDEY (1983). It consists of 20.5 m of yellow fine-grained calcareous sandstones at the base (transition beds) overlain by 23 m of yellowish fossiliferous silty to fine sandy marl and micrite with intercalated slabs of calcarenite (Text-fig. 4). The fossils consist mainly of bivalves (e.g. "*Corbula*" *lyrata*, *Palaeonucula cuneiformis*, *Homomya* sp., *Pholadomya lirata*) and occur either as shell pavements and thin shell beds, or else are scattered. At

Text-fig. 2. Weathering section through the Bathonian to Lower Callovian at Sadhara, eastern Gora Dongar.



Text-fig. 3. Section at Sadhara shown in schematic topographic relief to facilitate recognition of units in the field. The section from (A) to (E2) was taken due west of the centre of the dome; beds (F) and (G) are better exposed SW of the centre; and (G)-(H) are best exposed around the dam, east of the village. Dip not to scale, but stratigraphic intervals drawn proportional to thicknesses.

Sadhara, the member starts with a 50 cm thick layer of coarse-grained microconglomeratic pebbly sandstone with erosive base. Its upper boundary is defined by a 40-50 cm thick strongly ferruginous coarse-grained conglomeratic sandstone which forms the base of the next unit. At Kharidongari (north of the village Khari, Gora Dongar) this member is 10 m thick and contains several levels "Golden Oolite" (AGRAWAL & PANDEY 1985), an oosparite of ferruginous ooids coated with semitranslucent skins of carbonate giving the rock a pseudometallic or pyrite-like golden sheen. Bands of golden oolitic limestone were also recorded from the member at Gadaputa Hill at the southwest end of Gora Dongar, where the thickness is 6 m (BISWAS 1980). Ammonites indicate a Middle Bathonian age (see below). The rocks of the member represent a fully marine, shallow shelf environment (see below).

The Goradongar Yellow Flagstone Member forms a prominent marker that can be readily identified all over Gora Dongar and Kala Dongar. It extends further afield, both to Khadir Island to the east of Pachchham, and to the Jhura Dome on the Mainland.

Middle Sandstone member (new) (Unit D)

The Middle Sandstone member is 93 m thick and consists of fine- to coarse-grained, largely unfossiliferous sandstone, as a rule crossbedded, weathering brown to white. A thin micro-conglomeratic sandstone forms its base. The lower third of the member is thinly bedded, ripple- to parallel-laminated; the remaining part is large-scale trough crossbedded or bioturbated. In the middle of the member 9 m of highly ferruginous channelled sandstones are topped by a ferruginous surface rich in large wood fragments. Four thin lenticular shell beds with poorly preserved bivalves such as *Protocardia*, "*Corbula*", *Bakevellia* and *Modiolus* occur several metres above this surface. The Middle Sandstone member is thought to represent three shallowing upward sequences corresponding to lower- to upper shoreface environments.

Lower Yellow Flagstone member (new) (Unit C)

The Lower Yellow Flagstone member can be traced from Gora Dongar throughout Kala Dongar. It consists at Sadhara of 33 m of yellowish, fine sandy marl with numerous thin intercalations of graded calcarenites, shell beds and ripple-laminated sandstones. In the upper half of the member several 1-2 m thick ridge-forming layers of fine sandy shelly biomicrite occur in which bivalves such as *Bakevellia, Mytiloperna,* "*Corbula*" *lyrata*, and *Modiolus* abound. The uppermost 4 m consist of thin-bedded shelly calcareous sandstones, partly laminated, partly bioturbated. The upper boundary lies at the base of a 20 cm thick conglomeratic sandstone layer which forms the lowest part of a thick unit of ripple-bedded sandstones in the overlying member. Likewise, the member is underlain by massive fine-grained sandstone. The Lower Yellow Flagstone member resembles the much younger Goradongar Flagstone Member in lithology, colour, and abundance of marine bivalves, but differs in faunal composition. No ammonites have been recorded from this unit. The bivalve fauna indicates a shallow water, fully marine environment. Due to the soft nature of much of the sediments, the member is poorly exposed at Sadhara. The Lower Yellow Flagstone member is equivalent to part of BISWAS' (1977) Babia cliff Sandstone member and most likely also part of his Kaladongar Sandstone member, both defined in Kaladongar. A precise correlation, however, is at present not possible. PANDEY (1983), PANDEY et al. (1984) and AGRAWAL & PANDEY (1985) included rocks equivalent to the Lower Yellow Flagstone member in their Pachhmaipir member which was defined at the scarp facing the Rann at Pachhmaipir temple, central Kala Dongar, and includes 320 m of sandstones and fossiliferous limestones of Lower to Middle Bathonian age.

Eomiodon Red Sandstone member (new) (Unit B)

The Eomiodon Red Sandstone member consists of 35 m of bioturbated, partly silty, fine-grained sandstones, often poorly cemented, and reddish in colour except in the basal and terminal massive sandstones. Intercalated are ledge-forming beds 10-50 cm thick of beige-coloured, well-sorted fine-grained sandstones, which often are laminated or crossbedded. In the middle of the member, variegated to reddish argillaceous silt dominates. A characteristic element is a series of four beds with profuse, but poorly preserved bivalves, dominated by only a few taxa (*Eomiodon*, protocardiids and "*Corbula*" *lyrata*). The basal 8 m of the member consist of a hard, massive, cross-bedded fine-grained sandstone. The upper boundary is defined by a conspicuous change in colour and grain size, at the base of the fine-sandy marl of the Lower Yellow Flagstone member. Fauna and sediments of the member represent marginal marine to coastal plain environments (see below).

The Eomiodon Red Sandstone member is equivalent to part of the Pachhmaipir member of PANDEY (1983). At present it is not clear whether the Eomiodon Red Sandstone also corresponds to parts of the Dingy Hill member of BISWAS, defined at Narewari Wandh stream and Babia cliff of Kaladongar. BISWAS (1977: 47) records red sandstone and siltstone at two levels in his Dingy Hill member. The upper unit, 4.5 m thick, is overlain by a bed rich in corbulids; the lower unit consists of 100 m of alternating reddish to greenish sandstones and siltstones with thin, hard, brownish sandstone interbeds. Fossils are mentioned, but no details are given.

Sadhara Coral Limestone member (new) (Unit A)

The Sadhara Coral Limestone member forms the basal part of the section at Sadhara; its true thickness and lower boundary are therefore not known. What is seen is characterized by several metres of ripple-bedded to large-scale trough crossbedded, strongly sandy pack- to grainstones overlain by thinly bedded limestones and sandstone that contain a rich ichnofauna of *Thalassinoides*, *Diplocraterion*, *Rhizocorallium*, *Cylindrichnus*, and *Skolithos*, and some benthic molluscs. Characteristic are heads of the colonial coral *Melikerona parva*, which occur at three levels. The Sadhara Coral Limestone represents fully marine shallow shelf environments.

Biostratigraphy

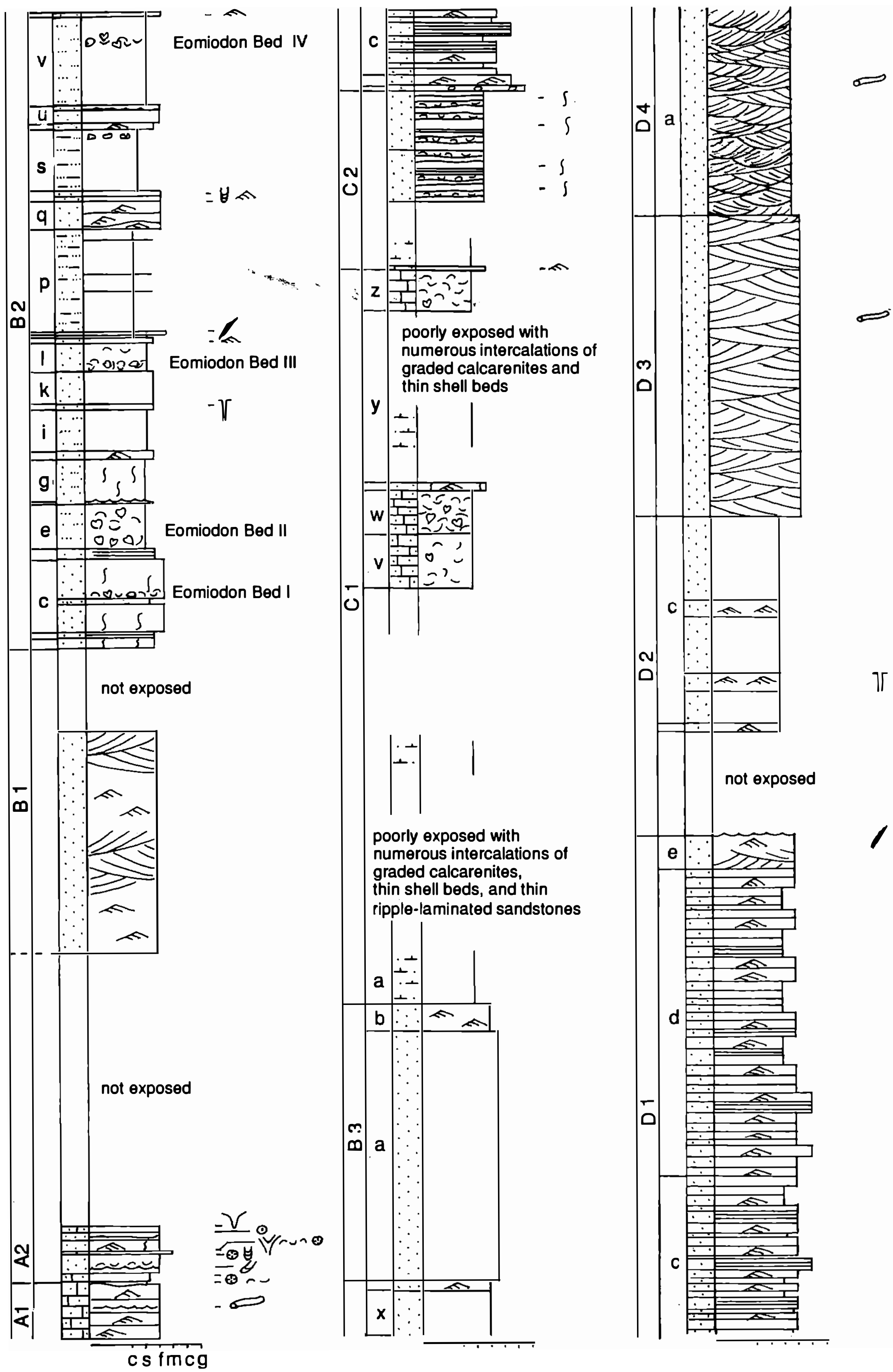
At Sadhara, ammonites have been found at only four levels. The lowest, a unit of shelly, fine-sandy micrites near the base of the Goradongar Yellow Flagstone Member, about 2 m above the base of E2 in Text-fig. 4, yielded *Clydoniceras triangulare* PANDEY & AGRAWAL and *Bullatimorphites* n. sp. A (PANDEY & AGRAWAL 1984a, PANDEY & WESTERMANN 1988). The latter clearly predates typical *Kheraiceras* and points strongly to a Middle Bathonian age (in both Submediterranean and Tethyan senses, as already discussed above: WESTERMANN & CALLOMON (1988).

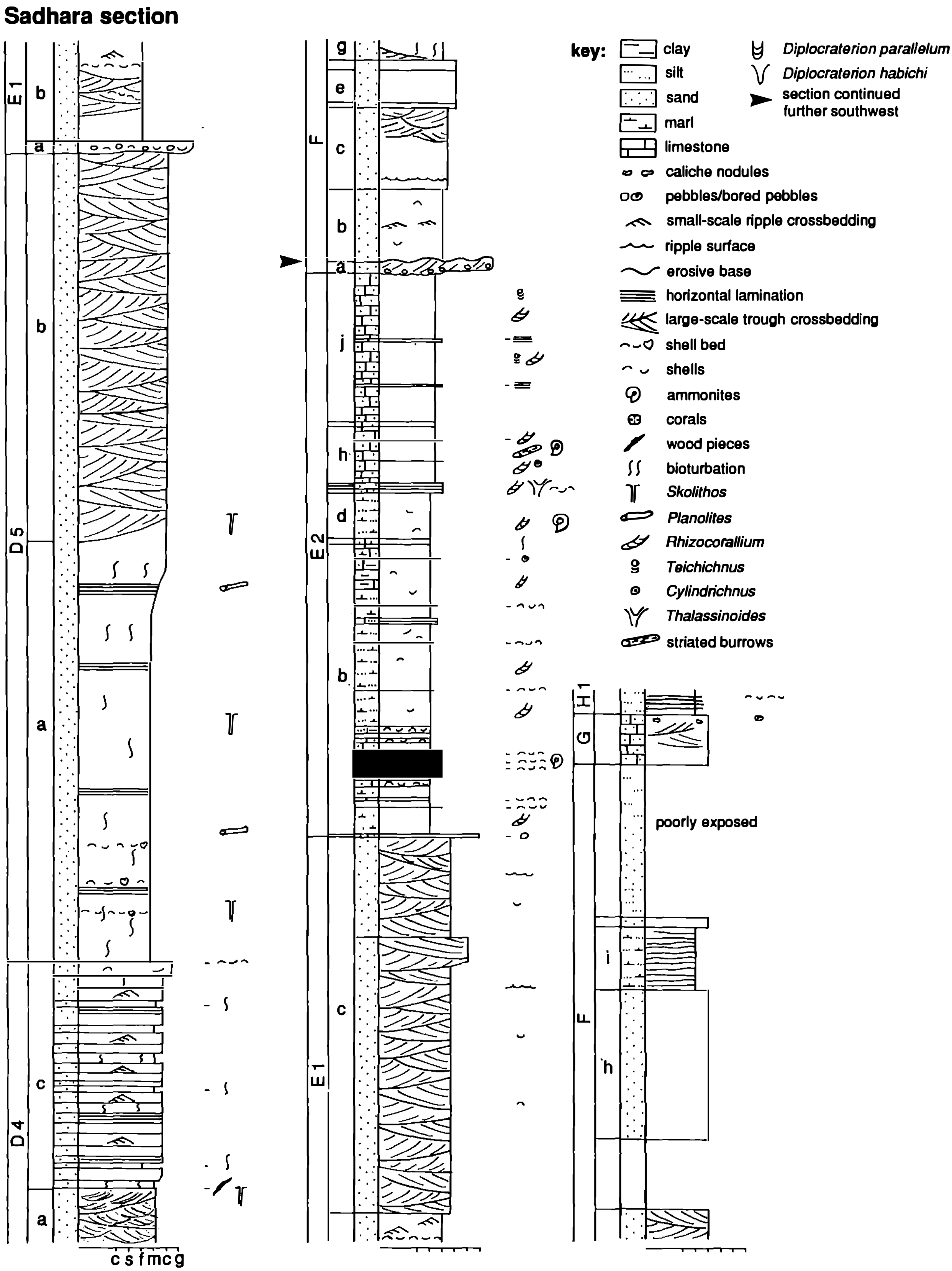
The second level, about 13 m higher up in the same unit E2, contains *Clydoniceras pachchhamense* PANDEY & AGRAWAL, *Micromphalites (Clydomphalites)* cf. *clydocromphalus* ARKELL, *Gracilisphinctes arkelli* COLLIGNON and other species of *Gracilisphinctes* (PANDEY & AGRAWAL 1984a, SINGH et al. 1983). These ammonites also clearly point to a Middle Bathonian age in the Tethyan sense, but possibly to the higher parts that would already be classified as Upper Bathonian in the Submediterranean sense (Hodsoni Zone).

The third level with ammonites is the Raimalro Limestone, unit G. It yields impressions of *Macrocephalites* cf. *madagascariensis* or sp. aff. that cannot be more closely identified. Its age, by correlation with the Patcham Limestones of Jumara already indicated above, is taken to be still latest Late Bathonian.

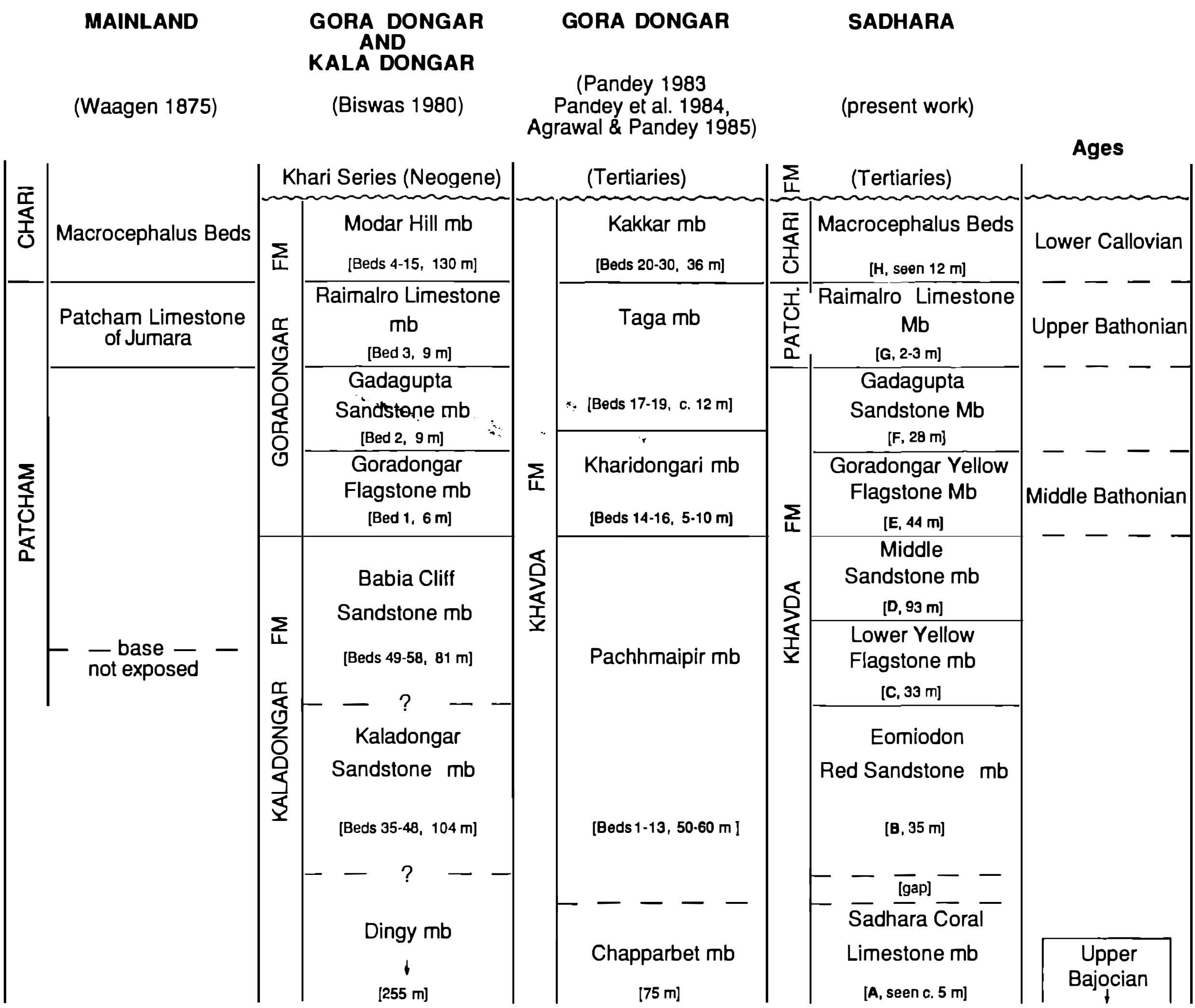
The fourth level lies in the basal few metres of Chari Formation seen to overlie the Raimalro Limestone. It has yielded *Macrocephalites* spp. similar to those found on the Mainland and taken to be of early Early Callovian age.

Sadhara section





Text-fig. 4. Lithology and lithostratigraphy of the Bathonian to Lower Callovian sediments of Sadhara, eastern Gora Dongar.



Text-fig. 5. Lithostratigraphic framework of the Bathonian and Lower Callovian rocks of Pachchham "Island".

As the lowest of the ammonite horizons at Sadhara occurs first in the upper quarter of the section seen there, some at least of the 215 m of beds lying below it may be of Early Bathonian age. At Kala Dongar, beds lying even lower in the succession have yielded an ammonite of Upper Bajocian age (JAITLY & SINGH 1983).

Facies associations

Four facies associations can be distinguished in the Jurassic of the Sadhara Dome. Except for facies association (4) they correspond to large units within the section and are easily recognised in the field.

Facies association (1): Grey to beige-coloured fine- to coarse-grained sandstones

Facies association (1) consists of 1-20 m thick sandstone bodies corresponding to three facies: (a) fine- to coarse-grained sandstones with large-scale trough crossbeds, (b) fine- to coarse-grained sandstones with ripple-bedding, horizontal lamination, and burrowed intervals, and (c) highly bioturbated fine- to medium-grained sandstones.

Facies (1a): Fine- to coarse-grained sandstones with large-scale trough crossbeds

Facies (1a) consists of 1-20 m thick units of moderately to well sorted sandstones which characteristically exhibit large-scale low angle trough-crossbedding. Small ripple crossbedding is frequently associated. Some of the units are topped by oscillation ripple surfaces, which occasionally are also found within the units. Trace fossils are rare and confined to *Planolites* and *Skolithos*; body fossils were found only in two cases, either as scattered disarticulated shells of bivalves (*Protocardia, Palaeonucula*), or forming shell pavements on foresets. The top of one coarse-grained sandstone unit (bed 48 of Text-fig. 4) was highly ferruginous and littered with wood fragments.

Facies (1b): Fine- to coarse-grained sandstones with ripple bedding, horizontal lamination, and bioturbated intervals

The units of facies (1b) are 6 to 20 m thick and are composed of beds 5-30 cm in thickness. The sediment is either fine-, medium-, or coarse-grained, rarely calcarenitic. As a rule horizontally or ripple laminated beds alternate with highly bioturbated intervals that are softer.

Facies (1c): Fine- to medium-grained highly bioturbated sandstones

Facies (1c) is represented by a 17 m thick highly bioturbated fine- to medium-grained sandstone unit. 20-30cm thick beds of laminated sandstone containing the trace fossils *Skolithos* and *Planolites* are occasionally intercalated. At one level within the bioturbated part, shells of the shallow infaunal bivalve *Eomiodon* form a thin, nearly monospecific layer.

Discussion

The presence of occasional bivalves in facies-association (1) indicates a marine genesis of the three facies in the group. The commonly coarse-grained nature of the sediment suggests a nearshore origin. The three facies reflect different energy levels. The highly bioturbated facies (1c) signifies a relatively quiet environment below fair-weather wave base, only occasionally disturbed by storms (as evidenced by parallel laminated intercalations). The large-scale trough crossbedded facies (1a) represents a high energy environment; occasional oscillation ripples point to wave influence. The alternations of bioturbated, ripple crossbedded or laminated beds, characteristic of facies (1b), occupy an intermediate level of energy. In bathymetric terms, the three facies correspond to a shallowing sequence, the bioturbated units occupying the deep and the large-scale trough-crossbedded units the shallow end. The facies succession (1c) - (1b) - (1a) is very similar to that of shelf-beach profiles (e.g. REINECK & SINGH 1971). Accordingly the highly bioturbated facies (1c) can be interpreted as transition zone, facies (1b) as lower shoreface, and facies (1a) as upper shoreface. As actual beach sediments were not encountered in the section, we prefer to interpret facies association (1) as representing different bathymetric segments of a nearshore bar complex rather than actual shoreline deposits.

Near the top of the Goradongar Yellow Flagstone Member, at the transition from typical facies association (3) (mixed siliciclastics-carbonates; see below) to (1a), a laminated fine-grained sandstone occurs, 60 cm thick, with scattered disarticulated bivalve shells and bioturbation by *Rhizocorallium irregulare*. The bed is clearly of marine origin. Several surfaces within the bed are covered with flat-topped microripples (crest-spacings: 8-10 mm) that, except for their larger dimensions, resemble wrinkle marks (Pl. 1, Fig. 5). Both flat-topped ripples and wrinkle marks are generally regarded as characteristic of emersion (e.g. REINECK & SINGH 1980), although they have also been found in deep water flysch deposits. As low energy subtidal conditions appear to have prevailed immediately below and above the bed, an interpretation in terms of intertidal conditions seems unlikely.

Facies association (2): Reddish fine-grained sandstones

Facies association (2) is composed of poorly sorted and often poorly cemented fine-grained sandstones (facies 2a) between which occur thin beds of well sorted sandstone (facies 2b).

Facies (2a): Reddish to variegated, poorly sorted fine-grained sandstone

Facies (2a) typically consists of poorly cemented and poorly sorted, structureless fine-grained sandstones. Grain size ranges from medium-grained (rare) to variably argillaceous and silty. The colour is reddish, more rarely violet to greenish. In one case a 20 cm thick brownish, poorly sorted medium-grained sandstone with wood fragments was intercalated. Several levels, up to 40 cm thick, contain a low-diversity fauna of bivalves, either densely packed or dispersed, dominated by *Eomiodon indicus*. Associated taxa are

Protocardia and "*Corbula*" *lyrata* as well as some rarer elements (Table 1; Pl. 2, Figs. 5, 10).

A variation of facies (2a) is seen in a 220 cm thick, light-grey, argillaceous silty fine sand with caliche nodules near the top (bed B2s of Text-fig. 4).

Facies (2b): Well sorted laminated or ripple-bedded sandstone

Facies (2b) consists of 10 to 30 cm thick beds of fine-grained sandstone that are intercalated between facies (2a) at 1 to 3 m intervals. The colour is rarely reddish, more commonly yellowish brown. The beds are well cemented and usually form ledges between the softer and more easily weathering facies (2a). Sedimentary structures are invariably present and consist of horizontal lamination or small-scale crossbedding of ripple origin. In two cases, sedimentary and biogenic structures replaced each other vertically within a 20 cm thick bed, horizontal lamination being succeeded by small-scale ripple crossbedding which in turn was replaced by *Diplocraterion parallelum*, vertical U-shaped spreiten burrows, which descended from the top. Another trace fossil occasionally associated with the tops of the sandstone beds is *Skolithos*.

Discussion

Facies association (2) clearly records conditions transitional between marine and terrestrial environments. The dominance of reddish colours suggests strong terrestrial influence. The predominantly articulated bivalves at several levels as well as the trace fossils point to marine influence. However, the bivalve *Eomiodon* is well known elsewhere in the Jurassic to characterize brackish water environments (e.g. FÜRSICH & WERNER 1986, HUCKRIEDE 1967), as is "*Corbula*" *lyrata* (e.g. MONGIN 1967). Similarly, the high abundance of individuals and the low species richness and evenness point to a high stress environment, most likely caused by fluctuating salinities (see ecological analysis of the fauna below). The depositional environment may have been a semi-enclosed bay, separated from the open sea by some kind of barrier bar. The well-sorted thin sandstone intercalations are best interpreted as representing anomalous event beds. They could correspond to spill-over lobes generated during heavy storms, which distributed sand of the bar complex, corresponding to facies association (1), across the embayment. This interpretation is supported by the succession of horizontal lamination/ripple lamination/bioturbation structures in some beds, which is evidence of deposition during waning water energy and of post-event bioturbation. Both *Diplocraterion parallelum* and *Skolithos* point to a high energy environment, which contrasts with the bioturbated units. The latter apparently correspond to a low energy background for most of the time.

In contrast, the variegated, unfossiliferous silts as well as the caliche nodules were most likely formed on a coastal plain beyond the reach of marine influence.

Facies association (2) thus represents very shallow marginal marine environments, which occasionally graded into adjacent non-marine coastal plains.

Facies association (3): Mixed siliciclastic-carbonate sediments

Two facies can be distinguished: bioturbated sandy to silty marls and micrites (3a) and bioclastic sandstones, sandy calcarenites and shell beds (3b)

Facies (3a): Bioturbated sandy to silty marls and micrites

The sediments of facies (3a) range from fine-sandy micrite to fine-sandy marl, marly fine sand and calcareous fine-grained sandstones. Fossils are common and consist of diverse bivalves (e.g. *Modiolus*, "*Corbula*" *lyrata*, *Pholadomya*, *Homomya*, *Protocardia*, *Nicaniella*), gastropods (e.g. *Pseudomelania*, *Globularia*, *Pictavia*) and rare corals. Ammonites were found at two levels and nautiloids at one. Trace fossils are represented by the ubiquitous *Rhizocorallium irregulare*, more rarely by *Teichichnus*. The fauna occurs either scattered in the sediment, densely packed in layers up to 150 cm thick, or in well defined shell beds that correspond to facies (3b).

Facies (3b): Bioclastic sandstones, sandy calcarenites and shell beds

In facies (3b) a variety of sediments is represented. It includes fine-sandy shelly micrites, laminated calcarenites, laminated intraclastic fine-grained sandstones, and grainstones. These commonly occur in layers between 3 and 15 cm thick, rarely reaching 20-30 cm. Some of them are graded. Apart from horizontal lamination, small-scale ripple crossbedding occurs; oscillation ripples top some of the beds. Bioturbation occurs and, due to their low density, the trace fossils can be easily identified. They are *Skolithos, Rhizocorallium jenense, Rhizocorallium irregulare, Planolites, Thalassinoides*, and *Diplocraterion habichi*. As a rule only one type of trace fossil occurs in any bed. Body-fossils are common. They occur in near-monospecific layers of *Eomiodon* or *Nicaniella* as well as in more diverse shell beds characterized by "*Corbula*" *lyrata, Modiolus, Pachymytilus*, and *Bakevellia* (Pl. 2). A low-diversity coral fauna is present near the base of the section.

Beds of facies (3b) occur either intercalated between beds of facies (3a) commonly with spacings of 0.5-2 m, or in consecutive beds forming units several metres in thickness.

Discussion

The relatively diverse fauna and the presence of stenohaline organisms such as ammonites, nautiloids and corals indicate a fully marine environment. The high degree of bioturbation and the dominance of the trace of a deposit-feeder, *Rhizocorallium irregulare*, in facies (3a) characterize a quiet environment below fair-weather wave-base. The mixed siliciclastic-carbonate sediment, while still pointing to a relatively nearshore environment, indicates a reduced input of siliciclastics and hence most likely considerably lower rates of sedimentation than those in facies associations (1) and (2). Facies (3b), in contrast, represents sediments deposited in a high energy regime. Typically, they represent "event beds"' recording storms that not only brought sediments into the depositional environment from outside, but also reworked and redeposited local sediment. Commonly this led to concentration of skeletal elements that are either sorted and preferentially oriented convex-up as a result of transport (e.g. in near-monospecific shell beds of *Nicaniella* and *Eomiodon*), or unsorted and randomly oriented through winnowing. Subsequently, some of these beds were bioturbated from the top by organisms belonging to the background fauna (e.g. *Rhizocorallium irregulare*).

Where beds belonging to facies (3b) are closely stacked they represent likely a more generally elevated energy level than simply successive, single high energy events. This is indicated by the presence of trace fossils excavated by suspension-feeders (*Diplocraterion habichi, Skolithos*) and faunal elements adapted to shifting substrates. Such elements include coral heads with spherical growth pattern, which indicates frequent disturbance and change in resting position on the sea floor. A depositional environment just below the fair-weather wave-base is likely.

Facies association (4): Conglomeratic sandstones and conglomeratic sandy micrites

The facies is represented by variable sediments ranging from pebbly fine-sandy micrite to conglomeratic coarse-grained sandstone. The following typical attributes are seen in three examples in beds 51 (top), 54, and 58 of Text-fig. 4 (see also Pl. 1, Fig. 2). These are thin but very distinctive units varying between 10 and 50 cm in thickness; sorting is extremely poor. Pebbles consist of background sediments (up to 15 cm in diameter) and quartz (up to 2 cm in diameter). Shells of bivalves in variable concentration are frequently associated with the layers. One of the beds exhibits in addition large-scale trough crossbedding, megaripple surfaces, and a strongly ferruginous sediment. In two out of three cases, beds of facies association (4) are found at the top of coarsening-upward sequences and are followed by sediments of distinctly finer-grain.

Discussion

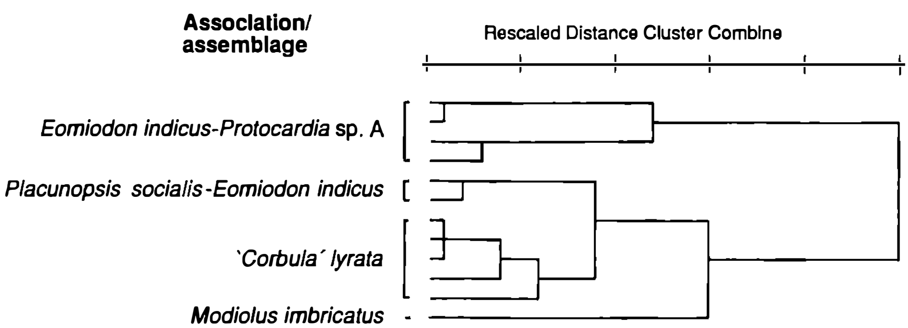
The features of facies association (4) are those typically encountered in lag deposits, and the facies association is interpreted as representing transgressive lags on top of regressive units (see below). Such lags formed during phases of reduced sediment input, which led to concentration of minerals such as iron and of biogenic particles. Intensive reworking, most likely during storms, produced lithoclasts from exhumed older, already cemented layers, and winnowing carried finer material away in an offshore direction. Such lag deposits are a common feature in the Jurassic of Kachchh (e.g. FÜRSICH et al. 1991, 1992; FÜRSICH & OSCHMANN 1993) and testify that the basin underwent cyclic changes of relative sea level.

Palaeoecology

Within the Sadhara section, fossils are concentrated at four levels:
(1) at the base of the section within the Sadhara Coral Limestone member;
(2) within the *Eomiodon* Beds of the Red Eomiodon Sandstone member;
(3) within the Lower Yellow Flagstone member; and
(4) within the Goradongar Yellow Flagstone Member.

The dominant benthic faunal elements are bivalves, rarely associated with gastropods and corals. Preservation ranges from excellent to poor. In sandstones, usually only internal or composite moulds are preserved; in calcareous sediments, shell preservation is common. Shells often occur as pavements within graded calcarenites or on foresets of crossbedded sandstones. Such occurrences clearly represent transported assemblages, which cannot be used for palaeoecological analysis. Other shell concentrations are largely autochthonous, representing winnowed relics of former communities. This is true, for example, of the four *Eomiodon* beds in which most shells are articulated, and also of several horizons within the Goradongar Yellow Flagstone Member where, in addition to burrowing bivalves such as *Pholadomya, Protocardia* and "*Corbula*", also epibyssate taxa such as *Pteria, Inoperna*, and *Grammatodon* are preserved with both valves.

A cluster analysis carried out with SPSS (Ward method) led to the recognition of three associations and one assemblage (Text-fig. 6), which are briefly described in the following. (Statistical data are given in Table 1.)



Text-fig. 6. A cluster analysis of the benthic macroinvertebrates according to the Ward method results in three associations and one assemblage.

Placunopsis socialis - Eomiodon indicus association

The *Placunopsis socialis-Eomiodon indicus* association occurs near the base of the section in fine sandy micrite (Sadhara Coral Limestone member). Species diversities are low (7 and 9 respectively). Dominant taxa are *Placunopsis socialis* (Pl. 2, Fig. 12), *Protocardia keerae* and *Eomiodon indicus*. Bivalves are the most abundant group (more than 80%), followed by gastropods (about 10%) and corals (about 8%). Epifaunal and infaunal elements are equally abundant. Suspension-feeding bivalves and the microcarnivorous corals represent 89% of the fauna, the rest consisting of presumably herbivorous gastropods and a cidaroid.

Most shells are disarticulated and appear to have been reworked, but were probably not far transported. The coral heads of *Melikerona parva* measure up to 15 cm in diameter, are heavily bored (*Trypanites*), and in some cases encrusted by small oysters. Their position within the sediment and their growth pattern shows that they were frequently uprooted.

The corals point to normal marine salinity. Nearly total disarticulation of shells and frequent reorientation of coral heads indicate considerable turbulence, as does the dominance of suspension-feeding bivalves. The fine-grained nature of the sediment, however, shows that water-flows were not high enough to cause extensive winnowing. The relatively low diversity points to some unknown stress factor, possibly trophic, perhaps related to the water-flow regime. The association most likely lived in a shallow shelf environment well above storm wave base, so that reworking was not too infrequent.

Table 1. Relative abundance, life habit, mode of feeding, and taxonomic position of members of the trophic nucleus of the benthic associations and assemblages encountered in the Bathonian at Sadhara. Mode of life: eb: epibyssate, endobyssate; ec: epifaunal, cemented; em: epifaunal mobile; si: shallow infaunal; di: deep infaunal; im: infaunal mobile. Trophic group: d: deposit-feeder/detritus-feeder; h: herbivore; mc: microcarnivore; s: suspension-feeder. Taxonomic group: B: bivalve; C: Coral; G: gastropod.

taxon	rel. abundance (%)	presence (%)	mode of life	trophic group	tax. group
***Placunopsis socialis* - *Eomiodon indicus* association** (2 samples, 72 specimens)					
Placunopsis socialis	23.6	100	ec	s	B
Protocardia keerae	23.6	50	si	s	B
Eomiodon indicus	19.4	100	si	s	B
Globularia cf. *aparayensis*	8.3	50	em	d/h	G
Melikerona parva	6.9	50	ec	mc	C
number of species:	13				
epifauna:	51.4%				
infauna:	48.6%				
suspension-feeders:	80.6%				
microcarnivores:	8.3%				
deposit-feeders:	-				
detritus-feeders/herbivores:	11.1%				
"*Corbula*" *lyrata* association (5 samples, 443 specimens)					
"Corbula" lyrata	26.8	100	si	s	B
Palaeonucula cuneiformis	9.0	60	im	d	B
Protocardia cf. *grandidieri*	5.8	40	si	s	B
Placunopsis radiata	5.6	40	ec	s	B
Homomya hortulana	4.7	20	di	s	B
Trigonia (Trigonia) nitida	4.1	60	si	s	B
Pholadomya (Bucardimya) lirata	3.6	40	di	s	B
Nicaniella extensa	3.6	60	si	s	B
Pholadomya (Pholadomya) inornata	3.2	20	di	s	B
Agrawalimya pseudosulcata	2.9	40	di	s	B
Bakevellia waltoni	2.9	40	eb	s	B
Protocardia (P.) patchamensis	2.2	20	si	s	B
Modiolus glendayi	2.0	60	eb	s	B
Palaeonucula stoliczkai	1.8	20	im	d	B
number of species:	55				
epifauna:	25.7%				
infauna:	74.3%				
suspension-feeders:	82.6%				
deposit-feeders:	11.1%				
detritus-feeders/herbivores:	6.3%				
***Eomiodon indicus* - *Protocardia* sp. A. association** (4 samples, 290 specimens)					
Eomiodon indicus	69.6	100	si	s	B
Protocardia (Protocardia) sp. A	24.1	100	si	s	B
number of species:	8				
epifauna:	1.0%				
infauna:	99.0%				
suspension-feeders:	99.6%				
deposit-feeders:	-				
detritus-feeders/herbivores:	0.4%				
***Modiolus imbricatus* assemblage** (1 sample, 42 specimens)					
Modiolus imbricatus	66.7	100	eb	s	B
Bakevellia waltoni	11.9	100	eb	s	B
Placunopsis radiata	7.1	100	ec	s	B
number of species:	7				
epifauna:	92.8%				
infauna:	7.2%				
suspension-feeders:	99.6%				
deposit-feeders:	-				
detritus-feeders/herbivores:	0.4%				

Eomiodon indicus - *Protocardia* sp. A association

The *Eomiodon indicus* - *Protocardia* sp. A association is represented by four samples and more than 1000 specimens. Characteristic species are the name-giving taxa Pl. 2, Figs. 5, 10), which together form more than 95% of the individuals. The association is characterized by extremely low species diversities ranging from 3 to 6, with a distinct predominance of only one or two taxa. The fauna consists nearly exclusively of suspension-feeding infaunal bivalves.

The association occurs in structureless, silty to fine-grained or medium-grained, in part reddish sandstones. The shells form dense accumulations of between 25 and 160 cm thickness. Due to the coarseness of the sediment, the preservation of originally aragonitic faunal elements is very poor; most occur as internal moulds. The shells appear, however, to have been little disturbed after death, because most are articulated. Their dense accumulations therefore suggest gregarious settlement or else relatively low rates of sedimentation, leading to concentration of biogenic components. As no signs of boring and encrustation were observed on those specimens preserved with shell, reworking leading to prolonged exposure on the sea floor, thus providing time for extensive colonization by epi- and endobionts, was apparently not significant. A long residence time on the sea floor would also have favoured disarticulation.

The strikingly low species diversity is not an artefact, caused, for example, by selective dissolution of aragonitic shells, but reflects environmental conditions. As several of the species, e.g. *Eomiodon indicus*, "*Corbula*" *lyrata*, belong to taxa known elsewhere in the Jurassic to tolerate strong reduction in salinity (e.g. HUCKRIEDE 1967, MONGIN 1967, FÜRSICH & WERNER 1986), brackish water conditions may have been the dominant stress factor. This conclusion is supported by the red nature of the sediments, which is characteristic of marginal marine conditions, and by evidence of terrestrial conditions in adjacent beds (see facies analysis above), such as variegated argillaceous silts and caliche nodules. Judging from the very low diversity of the fauna, a mesohaline salinity regime of 5-18 per mil seems likely. As many euryhaline molluscs tolerate both brackish and hypersaline conditions, and as none of their morphological features are available to differentiate between these (e.g. FÜRSICH 1994), the question might be asked why the *E. indicus* - *Protocardia* sp. A association could not as easily represent hypersaline conditions, especially as caliche nodules are characteristic of a semi-arid climate. Supportive evidence for brackish water may be found in the presence of horizons with abundant wood pieces and small wood logs and in the nature of the sediment, which is obviously land-derived and must have been transported into the sea by rivers. Both carbonates and gypsum, in contrast, are lacking. Thus, on average, brackish water conditions appear more likely than hypersaline conditions. However, marginal marine salinities are commonly unstable and it is well possible that, at times, brackish water conditions were replaced by hypersaline interludes, depending, for example, on seasonal climatic fluctuations.

The strongly bioturbated sediment and the lack of reworking indicates a low energy environment, such as a protected bay or lagoon.

"*Corbula*" *lyrata* association

The "*Corbula*" *lyrata* association is represented by five samples and over 400 individuals. It occurs both in the Lower Yellow Flagstone member and in the Goradongar Yellow Flagstone Member, units which are characterized by carbonate to mixed siliciclastic-carbonate sediments. The association is characterized by low to intermediate diversity values (range: 4-27). "*Corbula*" *lyrata* (Pl. 2, Figs. 11, 13) is the only species present in all samples and accounts for 15 - 42% of the fauna. Suspension-feeders (82%) dominate also this association, but deposit-feeders such as nuculids (11%) and herbivores (6%, represented by a moderately diverse gastropod fauna) are more common than in the other associations. Infaunal elements outnumber epifaunal ones three to one.

The relatively rich fauna and the presence of numerous stenohaline elements such as corals among the benthos as well as the occurrence of ammonites indicate a fully marine environment. Intercalated storm beds point to a depositional environment above storm wave base. As reworking must have been minor, most infaunal element being preserved with two valves, a position well below fair-weather wave-base is suggested. The only exception is the sample with the lowest diversity, in which all bivalves occur as disarticulated shells in a silty marl matrix. In this case reworking seems likely, but the low diversity was probably not the result of taphonomic processes such as sorting and selective destruction, as the preserved components vary considerably in size and shell thickness. More likely environmental parameters such as substrate soupiness may have prevented most epifaunal organisms from settling.

Encrusted and bored shells are extremely rare, which is partly explained by the dominance of infaunal elements, partly by lack of reworking.

Reworking by storm processes played a role, however, in well defined horizons between the autochthonous community relics. There, monospecific convex-up-oriented shell pavements (e.g. of *Nicaniella*) indicate lateral transport and sorting.

The sample with the highest diversity (27 species) records most likely a relatively long time interval during which an originally soupy substrate with its corresponding fauna, e.g. nuculids, *Nicaniella, Quadrinervus*, became firmer and allowed colonisation by deep infaunal suspension-feeding bivalves such as *Homomya* (Pl. 2, Fig. 1), *Pholadomya* (Pl. 2, Figs. 2-4) and *Agrawalimya*, as well as by a more varied epifauna of corals, limid and pectinid bivalves, oysters, and gastropods. The telescoping of various seral stages into one horizon thus led to an increase in species and ecotype diversity.

Modiolus imbricatus assemblage

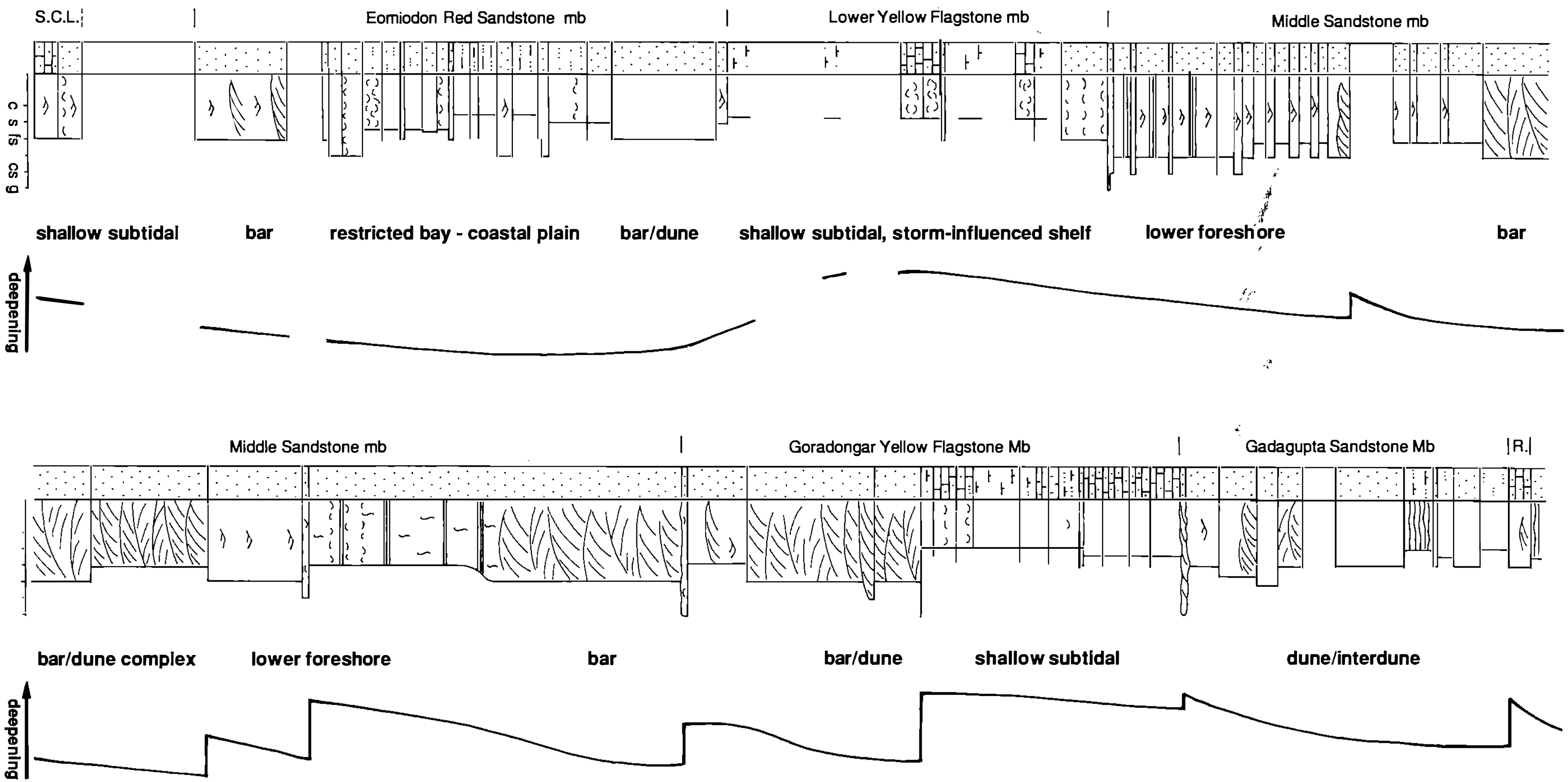
At the top of the Lower Yellow Flagstone member, a 150 cm thick shell bed with a matrix of silty to fine-sandy biomicrite contains a distinctive bivalve fauna dominated by the endobyssate bivalve *Modiolus imbricatus*. More than 90% of the fauna lived epifaunally and all the taxa were suspension-feeders. Elements common here, in contrast to the associations discussed above, are *Bakevellia waltoni* (Pl. 2, Fig. 9) and *Isognomon (Mytiloperna) patchamensis*. The shells must have undergone reworking, but the occurrence of several articulated shells suggests that large-scale transport was unlikely and that the shell bed is the highly time-averaged, locally reworked and winnowed product of a community. Taphonomic feedback appears to have played only a minor role in the formation of the bed, which is indicated by the low diversity and the scarcity of epi- and endobionts: only one shell was bored by a phoronid (*Talpina*) and a second one encrusted by the oyster *Nanogyra*. In this case, time-averaging apparently affected shells of little varying composition and thus the condensed shell bed most likely reflects the composition of the shelly fauna at all times during its formation (e.g. FÜRSICH & ABERHAN 1990: figs. 2-5).

As only a single sample is available, the term "assemblage" is used to characterize the species-grouping rather than "association", as we restrict the usage of the latter term to recurrent species-groupings (e.g. FÜRSICH 1977).

Evolution of the depositional environment

The temporal distribution of the various facies associations leads to the following reconstruction of depositional environments at southeastern Pachchham Island during the Bathonian (Text-fig. 7). The oldest sediments seen, of mixed siliciclastic-carbonate, partly bioturbated by suspension-feeding organisms (represented by the trace fossils *Diplocraterion* and *Rhizocorallium jenense*), partly ripple-laminated, were deposited in a nearshore, shallow subtidal area close to, but below the fair weather wave base. Low diversity faunas dominated by the euryhaline bivalves *Protocardia* and *Eomiodon* suggest brackish conditions at times, but the presence of corals at several levels indicate normal to near-normal salinities for most of the time.

Going up the succession, the next bed seen, an 8 m thick large-scale trough crossbedded and ripple-laminated sandstone body, corresponds most likely to a subtidal bar, followed by about 25 m of facies association (2) recording low energy, highly bioturbated sediments of a large, restricted bay whose evolution was punctuated by high-energy events, during which laminated or ripple-bedded spillover lobes or sheet sandstones formed. Several levels with the autochthonous *Eomiodon indicus* association strongly indicate that the embayment was subject to periods of markedly reduced salinities. Red to variegated colours are evidence of strong terrestrial influence and the presence of caliche nodules at one level is proof of a terrestrial environment, most likely that of a low lying coastal plain. Up-section, the sediments of an embayment give way to yet another sandstone body, interpreted as nearshore marine bar, which is followed by mixed sliciclastic-carbonate sediments of the Lower Yellow Flagstone member, deposited in a shallow subtidal, storm-dominated system with a moderately rich, normal marine molluscan fauna. Reverting to a siliciclastic regime, alternations of bioturbated and laminated and ripple-bedded sandstones represent the lower foreshore of a large subtidal dune complex whose top is highly ferruginous and covered with numerous imprints of wood. We assume that



depositional environments and bathymetric development of the Bathonian at Sadhara deepening took place at this level and that the ferruginous level represents a marine flooding surface. The return then to lower foreshore deposits, which grade into high-energy shoals, interrupted by other deepening phases, is repeated twice. The corresponding marine flooding surfaces are represented by concentrations of poorly preserved shells that represent the reworked tops of the preceding shoals. A distinctive lag deposit is evidence of a more pronounced deepening and forms the base of the Goradongar Yellow Flagstone member. Shell-rich ripple-bedded and large-scale crossbedded calcareous sandstones at its base are replaced up-section by low angle trough crossbeds of another shoal complex, before further deepening, indicated by another transgressive lag, transfers the depositional environment to an offshore shallow subtidal zone, in which reduced input of siliciclastics led to the dominance of carbonates. The highly fossiliferous, strongly bioturbated sediments were only occasionally disturbed by events that concentrated shells and sand-sized bioclasts in thin beds (e.g. Pl. 1, Figs. 1, 3). A bathymetric position near storm wave base is most likely. This fully marine unit, which contains also the only Bathonian ammonites found so far at Sadhara, is followed by poorly documented, partly structureless, partly trough-crossbedded sandstones of the Gadagupta Sandstone member, indicative of yet another submarine bar complex.

The following Raimalro Limestone, only 2-3 m in thickness at Sadhara, consists of a bioclastic fine-grained calcareous sandstone with traces of large-scale low angle crossbedding and several lenticular layers of pebbles, gastropods and bivalves. It is best interpreted as evidence of a renewed phase of deepening accompanied by climatic changes leading to enhanced biogenic carbonate productivity.

The Bathonian rock succession at Sadhara records several phases of deepening and shallowing, causing the depositional environment to fluctuate between offshore shelf and coastal plain. Input of siliciclastic sediment from a terrestrial source and hence rates of sedimentation must have been frequently high, as only in the Goradongar Yellow Flagstone member and the Lower Yellow Flagstone member do carbonates form a significant fraction of the sediment. The dominance of red colours in the marginal marine and coastal plain sediments as well as the presence of caliche nodules point to a semi-arid climate. Freshwater influx must have been considerable at times as is shown by the high sediment input, but brackish conditions may well have alternated with hypersaline ones.

Asymmetric sedimentary hemicycles, so-called paracycles, occur repeatedly within the section (Text-fig. 7). They record shallowing-deepening phases, of which only the shallowing phase is preserved while the deepening phase is represented only by a marine flooding surface. Their origin cannot be established with certainty from a single section. In speculating on what their causes may have been, it is worth bearing in mind two numbers. The first relates to the range of water-depths spanned by the depositional environments deduced from the facies: from effectively zero to something below fair-weather wave-base - 40 m? The second is the integrated accommodation-space filled by the sediments during the time-period recorded in the section, deduced from the total thickness of the sediments: 270 m. To first order, sediment supply kept pace with subsidence; and the source of this sediment presents the first-order problem. It can only be discussed in larger-scale, regional terms. The relatively minor, second-order fluctuations documented by the facies analysis can have had correspondingly more local causes. Further discussions must await comparisons with more detailed analyses of the accessible successions through beds of similar ages in Kala Dongar, in Khadir and Bela Islands to the east, and in the Jhura and Habo Domes on the Mainland to the south.

Conclusions

(1) North of the village of Sadhara, near the eastern end of Gora Dongar, Middle to Late Bathonian rocks are well exposed. The largely siliciclastic sediments represent environments which range from semi-enclosed bays and non-marine coastal plains to shallow neashore bars and storm-dominated shallow shelf.

Text-fig. 7. Section of Bathonian sediments at Sadhara interpreted in terms of depositional environments and asymmetric shallowing-deepening cycles.

(2) Ammonites were found at three levels and give Middle and Upper Bathonian ages. The highest of these, in the Raimalro Limestone, correlates with the lowest seen in the Patcham Limestone in the classical section at Jumara on the Kachchh Mainland.

(3) Lithostratigraphically, the sediments below the Raimalro Limestone belong to the Khavda Formation of PANDEY et al. (1984) in which five members have been recognized: the Gadagupta Sandstone Member and the Goradongar Yellow Flagstone Member of BISWAS (1977), and three new informal members, viz. the Lower Yellow Flagstone member, the Eomiodon Red Sandstone member, and the Sadhara Coral Limestone member.

(4) Benthic faunas are restricted to a few levels within the section. They largely represent autochthonous to parautochthonous relics of former communities and have been grouped into three associations and one assemblage: the *Eomiodon indicus-Protocardia* sp. association, the *Placunopsis socialis-Eomiodon indicus* association, the "*Corbula*" *lyrata* association and the *Modiolus imbricatus* assemblage. The first of these lived in brackish bays, whereas the remaining ones represent fully marine environments.

(5) Both fauna and sediments at Sadhara record several shallowing-deepening phases in the evolution of the basin, often in form of hemicycles.

Acknowledgements

We would like to thank the District Magistrate of Kachchh for permission to carry out field work at Gora Dongar; Mr. P. H. BHATTI, Bhuj, for his help in solving logistic problems, and the National Geographic Society (grant # 3597-87) and the Deutsche Forschungsgemeinschaft (grant Fu 131/18-1) for financially supporting the field work. MARTIN ABERHAN, Würzburg, helped with the cluster analysis and MICHAEL HEINZE, Würzburg, assisted with the identification of the fauna. A travel grant from the National Environmental Research Council (U.K.) to JHC is also gratefully acknowledged.

References

AGRAWAL, S. K. 1982. Kachchh Mesozoic: Some Problems and Recent Contributions.- Recent Researches in Geology **8**: 397-415; Delhi.

AGRAWAL, S. K. & KACKER, A. K. 1978. Succession and the fossil molluscs of Jurassic rocks near Mouwana, Eastern Bela Island, Distt. Kutch, Gujarat.- Recent Researches in Geology (Chiplonkar volume) **4**: 482-497; Delhi.

AGRAWAL, S. K. & KACKER, A. K. 1980. Biostratigraphy of Bathonian Callovian Beds of Mouwana Dome, Eastern Bela Island, Distt. Kutch (Gujarat).- Recent Researches in Geology (M.R.Sahni volume) **5**: 631-649; Delhi.

AGRAWAL, S. K. & PANDEY, D. K. 1985. Biostratigraphy of the Bathonian-Callovian Beds of Gora Dongar in Pachchham "Island", District Kachchh (Gujarat).- Proceedings of the Indian National Science Academy **51**: 887-903; New Delhi.

AGRAWAL, S. K. & TRIPATHI, V. S. 1980. A note on the Umrapur Section, Khadir Island, District Kutch (Gujarat).- Journal of the Palaeontological Society of India **23-24**: 71-80; Lucknow.

BARDHAN, S. & DATTA, K. 1987. Biostratigraphy of the Jurassic Chari Formation: a study in Keera Dome, Kutch, Gujarat.- Journal of the Geological Society of India **30**: 121-131; Bangalore.

BISWAS, S. K. 1980. Mesozoic Rock-Stratigraphy of Kutch, Gujarat.- Quarterly Journal, Geological, Mining & Metallurgical Society of India **43**: 1-51; Calcutta.

BISWAS, S. K. 1981. Basin framework, palaeo-environment and depositional history of Mesozoic sediments of Kutch Basin, Western India.- Quarterly Journal, Geological, Mining & Metallurgical Society of India **53**: 56-85; Calcutta.

BISWAS, S. K. 1987. Regional tectonic framework, structure and evolution of the western marginal basins of India.- Tectonophysics **135**: 307-327; Amsterdam.

BISWAS, S. K. 1991. Stratigraphy and sedimentary evolution of the Mesozoic basin of Kutch, western India. In: TONDON, S. K., PANT, C. C. & CASSHYAP, S. M. (eds.) Sedimentary Basins of India. Tectonic Context: 74-103; Nainital (Hyanendra Prakashan).

CALLOMON, J. H. 1993. On *Perisphinctes congener* WAAGEN, 1875, and the age of the Patcham Limestone in the Middle Jurassic of Jumara, Kutch, India.- Geologische Blätter für NO-Bayern **43**: 227-246; Erlangen.

FÜRSICH, F. T. 1977. Corallian (Upper Jurassic) marine benthic associations from England and Normandy.- Palaeontology **20**: 337-385; London.

FÜRSICH, F. T. 1994. Palaeoecology and evolution of Mesozoic salinity-controlled benthic macroinvertebrate associations.- Lethaia **26**: 327-346; Oslo.

FÜRSICH, F. T. & ABERHAN, M. 1990. Significance of time-averaging for palaeocommunity analysis.- Lethaia **23**: 143-152; Oslo.

FÜRSICH, F. T. & OSCHMANN, W. 1993. Shell beds as tools in basin analysis: The Jurassic of Kachchh, western India.- Journal of the Geological Society, London **150**: 169-185; London.

FÜRSICH, F. T. & WERNER, W. 1986. Benthic associations and their environmental significance in the Lusitanian Basin (Upper Jurassic, Portugal).- Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen **172**: 271-329; Stuttgart.

FÜRSICH, F. T., OSCHMANN, W., JAITLY, A. K. & SINGH, I. B. 1991. Faunal response to transgressive-regressive cycles: example from the Jurassic of western India.- Palaeogeography, Palaeoclimatology, Palaeoecology **85**: 149-159; Amsterdam.

FÜRSICH, F. T., OSCHMANN, W., SINGH, I. B. & JAITLY, A. K. 1992. Hardgrounds, reworked concretion levels and condensed horizons in the Jurassic of western India: their significance for basin analysis.- Journal of the Geological Society, London **149**: 313-331; London.

HUCKRIEDE, R. 1967. Molluskenfaunen mit limnischen und brackischen Elementen aus Jura, Serpulit und Wealden NW-Deutschlands und ihre paläogeographische Bedeutung.- Geologisches Jahrbuch, Beihefte **67**: 1-263; Hannover.

JAI KRISHNA & WESTERMANN, G. E. G. 1987. Faunal associations of the Middle Jurassic ammonite genus *Macrocephalites* in Kachchh, western India.- Canadian Journal of Earth Science **24**: 1570-1582; Toronto.

JAI KRISHNA, CARIOU, E. & ENAY, R. 1988. Succession of Macrocephalitinae assemblages as revealed at Keera Dome in Kachchh, Western India.- 2nd International Symposium on Jurassic Stratigraphy: 383-394; Lisboa.

JAITLY, A. K. & SINGH, C. S. P. 1983. Discovery of Late Bajocian *Leptosphinctes* BUCKMAN (Jurassic Ammonitina) from Kachchh, Western India.- Neues Jahrbuch für Geologie und Paläontologie, Monatshefte **1983**: 91-96; Stuttgart.

MITRA, K. C., BARDHAN, S. & BHATTACHARYA, D. 1979. A study of Mesozoic stratigraphy of Kutch, Gujarat with special reference to rock-stratigraphy and biostratigraphy of Keera Dome.- Bulletin of the Indian Geologists' Assocation **12**: 129-143; Chandigarh.

MONGIN, D. 1967. Les mollusques du Bathonien saumatre du Moyen Atlas.- Notes et Mémoires du Service géologique du Maroc **200**: 37-94; Rabat.

PANDEY, D. K. 1983. Biostratigraphical and palaeoecological studies of the Bathonian-Callovian rocks of Khavda-Sadhara area, Pachchham "Island", (Kachchh, Gujarat).- Unpublished Ph.D. Thesis, Banaras Hindu University: 576 pp., 46 pls.; Varanasi.

PANDEY, D. K. & AGRAWAL, S. K. 1984a. On two new species of the Middle Jurassic ammonite genus *Clydoniceras* BLAKE from Kachchh, western India - Neues Jahrbuch für Geologie und Paläontologie, Monatshefte **1984**: 321-326; Stuttgart.

PANDEY, D. K. & AGRAWAL, S. K. 1984b. Bathonian-Callovian molluscs of Gora Dongar, Pachchham "Island" (District Kachchh, Gujarat).- Quarterly Journal, Geological, Mining & Metallurgical Society of India **56**: 176-196; Calcutta.

PANDEY, D. K. & WESTERMANN, G. E. G. 1988. First record of Bathonian *Bullatimorphites* (Jurassic, Ammonitina) from Kachchh, India.- Journal of Paleontology **62**: 148-150; Lawrence.

PANDEY, D. K., SINGH, C. S. P. & AGRAWAL, S. K. 1984. A note on new fossil finds from Gora Dongar, Pachchham "Island", District Kachchh (Gujarat).- The Journal of Scientific Research, Banaras Hindu University **34**: 299-310; Varanasi.

RAI, J. N. 1972. Palaeontological and stratigraphical studies of the Jurassic rocks of Western Bela Island, Kutch, Gujarat.- Unpublished Ph. D. Thesis, Banaras Hindu University; Varanasi.

RAJNATH 1932. A contribution to the stratigraphy of Cutch.- Quarterly Journal, Geological, Mining & Metallurgical Society of India **4**: 161-174; Calcutta.

REINECK, H.-E. & SINGH, I. B. 1980. Depositional sedimentary environments.- 551 pp.; Berlin (Springer).

SINGH, C. S. P., JAITLY, A. K. & PANDEY, D. K. 1982. First report of some Bajocian-Bathonian (Middle Jurassic ammonoids) and the age of oldest sediments from Kachchh, India.- Newsletters on Stratigraphy **11**: 37-40; Berlin.

SINGH, C. S. P., PANDEY, D. K. & JAITLY, A. K. 1983. Discovery of *Clydoniceras* BLAKE and *Gracilisphinctes* BUCKMAN (Bathonian-Middle Jurassic ammonites) in Kachchh, W. India.- Journal of Paleontology **57**: 821-824; Lawrence.

SINGH, C. S. P. & RAI, J. N. 1980. Bathonian-Callovian fauna of Western Bela Island (Kutch). Bivalvia families Cardiidae, Neomiodontidae, Corbulidae.- Journal of the Palaeontological Society of India **23-24** (for 1978-79): 71-80; Lucknow.

SPATH, L. F. 1927-1933. Revision of the Jurassic cephalopod fauna of Kachh (Cutch).- Memoirs of the Geological Survey of India, Palaeontologia Indica, new series 9, Memoir **2**: 945 pp., 130 pls; Calcutta.

WAAGEN, W. 1873-1875. Jurassic fauna of Kutch. The cephalopoda.- Memoirs of the Geological Survey of India, Palaeontologia Indica, new series 9, Volume **1**: 247 pp., 60 pls.; Calcutta.

WESTERMANN, G. E. G. & CALLOMON, J. H. 1988. The Macrocephalitinae and associated Bathonian and Early Callovian (Jurassic) ammonoids of the Sula Islands and New Guinea.- Palaeontographica A **203**: 1-90; Stuttgart.

Plate 1

Fig. 1. Graded shell bed produced by storm processes. Polished cross-section, Goradongar Yellow Flagstone Member (E2); scale bar: 1cm.

Fig. 2. Conglomeratic coarse-grained sandstone interpreted as transgressive lag deposit. Cross-sectional view, Gadagupta Sandstone member (Fa); scale bar: 1 cm.

Fig. 3. Scattered disarticulated shells (*Trigonia* and *Placunopsis*) on bedding plane. Goradongar Yellow Flagstone Member (E2 b); scale bar: 1 cm.

Fig. 4. Detail of storm-produced shell bed. The reworked nature of shells is indicated by the argillaceous-silty matrix attached to them, which contrasts with the fine-sandy matrix of the shell bed. Thin-section, Sadhara Coral Limestone member (A2); scale bar: 1 cm.

Fig. 5. Flat-topped microripples bioturbated by *Rhizocorallium irregulare*. Gadagupta Sandstone Member (F); scale bar: 2 cm.

Fig. 6. Compactionally distorted shell bed from the Lower Yellow Flagstone member (C1 w). Thin-section; scale bar: 0.2 cm.

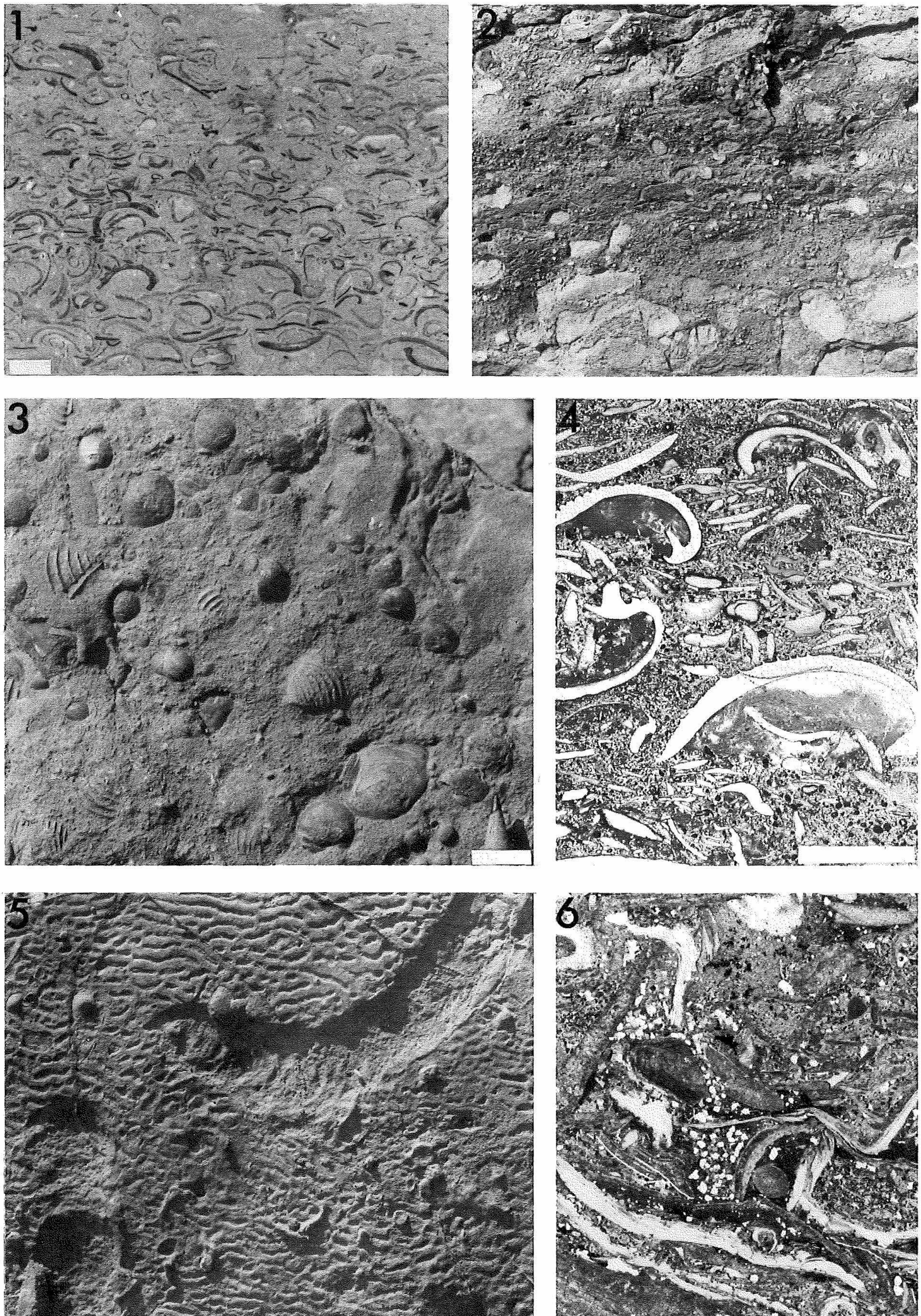

1
2
3
4
5
6

Plate 2

Characteristic Bathonian bivalves at Sadhara

Fig. 1. *Homomya* cf. *hortulana* AGASSIZ (PIW1994 VIII1). Articulated specimen, left valve view; Goradongar Yellow Flagstone Member (E2 b), x1.

Figs. 2-3. *Pholadomya (Bucardiomya) lirata* (J. SOWERBY). Articulated specimens, right valve view; Goradongar Yellow Flagstone Member (E2 b), x1. 2: Specimen PIW1994 VIII2; 3: specimen PIW1994 VIII3.

Fig. 4. *Pholadomya (Pholadomya) inornata* J. DE C. SOWERBY (PIW1994 VIII4). Articulated specimen left valve view; Goradongar Yellow Flagstone Member (E2 b), x1.

Fig. 5. *Protocardia (Protocardia)* sp. A (PIW1994 VIII5). Articulated specimen, right valve view; Eomiodon Red Sandstone member (B2 l: *Eomiodon* level III), x1.

Fig. 6. *Modiolus imbricatus* J. SOWERBY (PIW1994 VIII6). Left valve, Lower Yellow Flagstone member (C1 z: *Eomiodon* level IV), x1.

Figs. 7-8. *Palaeonucula kaoraensis* COX. Articulated specimens; Goradongar Yellow Flagstone Member (E2 b), x1. 7: Specimen PIW1994 VIII7, left valve view. 8: Specimen PIW1994 VIII8; a: dorsal view; b: anterior view; c: right valve view.

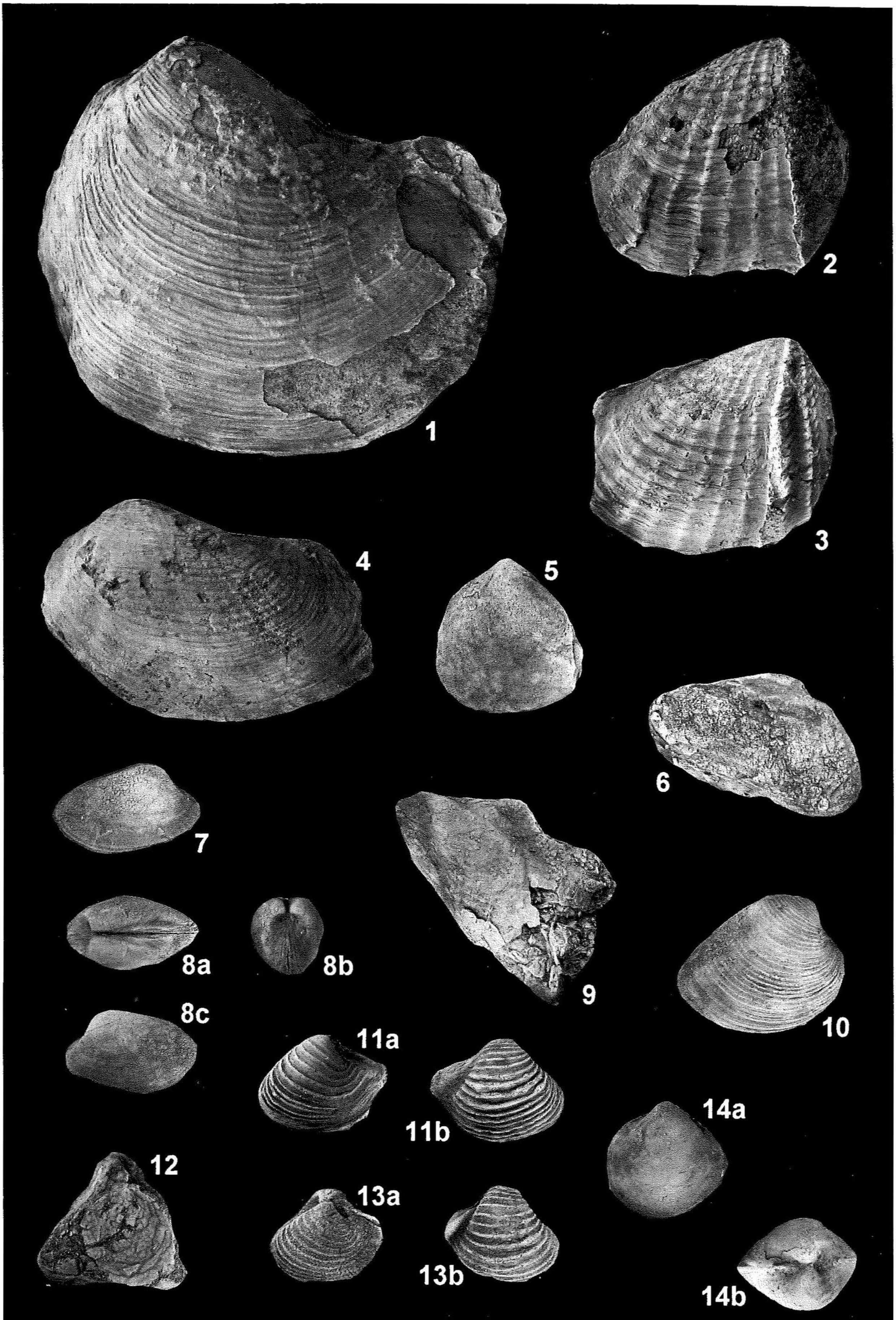
Fig. 9. *Bakevellia waltoni* (LYCETT) (PIW1994 VIII9). Left valve; Lower Yellow Flagstone member (C1 v), x1.

Fig. 10. *Eomiodon indicus* COX (PIW1994 VIII10). Articulated specimen, right valve view; Eomiodon Red Sandstone member (B2 e: *Eomiodon* level II), x1.

Figs. 11, 13. "*Corbula*" *lyrata* J. DE C. SOWERBY. Articulated specimens. Goradongar Yellow Flagstone Member (E2 b), x1.5. 11: Specimen PIW1994 VIII11; a: left valve view; b: right valve view. 13: Specimen PIW1994 VIII12; a: left valve view; b: right valve view.

Fig. 12. *Placunopsis socialis* MORRIS & LYCETT (PIW1994 VIII 13). ?Left valve; Sadhara Coral Limestone member (A2), x1.5.

Fig. 14. *Protocardia (Protocardia)* sp. nov. (PIW1994 VIII14). Articulated specimen; Goradongar Yellow Flagstone Member (E2 b), x1. a: left valve view. b: Dorsal view.


1
2
3
4
5
6
7
8a
8b
8c
9
10
11a
11b
12
13a
13b
14a
14b

Appendix: Litholog of the Jurassic rocks exposed in the Sadhara Dome, Gora Dongar (Pachcham 'Island')

Section westwards from the core of the dome. From below:

Khvada Formation, Sadhara Coral Limestone member (5m+)

A1	Limestone, strongly sandy, hard, well-bedded, flaggy, weathering greyish light brown; barren. With oscillation ripples, small ripple bedding and large-scale low angle crossbedding. Top surface locally with large deformation structures (?dewatering structures). *Planolites* (o). Forming core of the dome, exposed in gullies, seen to		**... 3 m**
	- widespread platform -		
A2	Coral beds: limestones and calcareous sandstones, rubbly, thin-bedded, fossiliferous, exposed in gullies, seen to		**... 2 m**
	-made up as follows:		
	a	micrite, fine-sandy, shelly, with sharp erosive base, scattered coral heads *Melikerona parva*, *Protocardia keerae* (c), *Eomiodon indicus* (c), *Placunopsis* sp. (c), *'Corbula' lyrata* (o), *Modiolus* sp. (o), *Globularia* cf. *aparayensis* (o)	0.1 m
	b	sandstone, fine-grained, calcareous, crossbedded	0.05 m
	c	micrite, fine-sandy, shells (c) *Placunopsis* sp. (c), *Eomiodon indicus* (c), *Nanogyra nana*, *Lopha* sp., *Modiolus* sp., *Cylindrites* sp., cidaroids	0.3 m
	d	sandstone, fine-grained, calcareous, shelly	0.07 m
	e	sandstone, fine-grained, calcareous, weathering light brown	0.2 m
	f	marl, recessive	0.1 m
	g	sandstone, fine-grained, calcareous, top with small wave ripples, bioturbated by *Rhizocorallium jenense*	0.1 m
	h	sandstone, fine-grained, calcareous, bioturbated	0.1 m
	i	sandstone, fine-grained, intraclastic, shelly, grading into sandy calcarenite towards top; base sharp, top bioturbated by *Diplocraterion parallelum* and with scattered coral heads	0.1 m
	j	biosparite, shelly, with large *Thalassinoides*	0.1 m
	k	sandstone, fine-grained, ripple-laminated, bioturbated towards top, *Skolithos* (c)	0.4 m
	l	sandstone, fine-grained, calcareous, shelly, with scattered ooids, sharp base; corals (r), *Lopha*, oyster fragments, *'Corbula'*	0.1-0.25 m
	m	sandstone, fine-grained, calcarenitic, ripple-laminated, *Cylindrichnus concentricus* (c)	0.1 m
	n	calcarenite, fine-sandy, in three beds, *Diplocraterion habichi* (o)	0.15 m

- covered interval, estimated gap 10 m -

Eomiodon Red Sandstone member (35 m)

B1	Sandstone, fine-grained, partly ripple-laminated, partly large-scale trough crossbedded, light-coloured	**... 8 m**

- not exposed for 3 m -

B2	Sandstones, fine to medium-grained, quartzose, pink stained, in cycles, soft poorly cemented and bioturbated units topped by hard resistant beds; rich in paucispecific bivalve assemblages dominated by *Eomiodon*. Together		**... 25 m**
	a	sandstone, fine-grained, poorly cemented, bioturbated	0.4 m
	b	sandstone, fine-grained, hard, laminated; marker	0.2 m
	c	sandstone, fine- to medium-grained, gritty, bioturbated; *Eomiodon* level I: *Eomiodon indicus* (a), *Protocardia (P.)* sp. A (a), '*Corbula*' *lyrata* (o), *Agrawalimya pseudosulcata* (r)	2.6 m
	d	sandstone, fine-grained, laminated, hard cap	0.4 m
	e	sandstone, silty, poorly cemented, shells occurring throughout; *Eomiodon* level II: *Eomiodon indicus* (a), '*Corbula*' *lyrata* (o), *Protocardia (P.)* sp. A (o)	1.6 m
	f	sandstone, fine-grained, clean, hard cap, ripple bedded, top surface rippled	0.1 m
	g	fine sand, silty, crimson red, bioturbated; marker	1.5 m
	h	sandstone, fine-grained, clean, small ripple bedded, hard cap	0.3 m
	i	fine sand, silty, reddish	1.5 m
	j	sandstone, fine-grained, clean, hard, structureless, variegated, *Skolithos* (a) extending from top downwards	0.2 m
	k	sandstone, fine-grained, poorly cemented, reddish	1.1 m
	l	sand, fine-grained, silty, crimson red, shells profuse, scattered and concentrated in 40 cm thick shell bed. *Eomiodon* level III: *Eomiodon indicus* (a), *Protocardia (P.)* sp. A (o), *Protocardia (P.) keerae* (r), '*Corbula*' *lyrata* (r)	1.0 m
	m	sandstone, fine-grained, clean, hard, ripple-bedded	0.15 m
	n	fine sand, silty	0.2 m
	o	sandstone, medium-grained, poorly sorted, poorly cemented, brownish, wood fragments (a)	0.2 m
	p	silt, fine-sandy, argillaceous, variegated, with several cm thick bands of fine sand	3.5 m
	q	sandstone, fine- to medium-grained, clean, ripple bedded, in several beds separated by thin intervals of silty fine sand	1.0 m
	r	sandstone, fine- to medium-grained, hard, in two beds, bases laminated, middle parts ripple bedded, tops bioturbated, *Diplocraterion parallelum* (a)	0.4 m
	s	fine sand, silty, argillaceous, light-grey, uppermost 20 cm with caliche nodules	2.2 m
	t	sandstone, fine-grained, ripple-laminated	0.25 m
	u	sandstone, fine- to medium-grained,in two beds, lower bed gritty, poorly cemented, upper bed hard, trough-crossbedded; marker	0.6 m
	v	sandstone, fine-grained, silty, poorly cemented, bioturbated, pink, with several 10-20 cm thick more strongly indurated layers. 1 m below top with numerous shells. *Eomiodon* level IV:	3.2 m

Eomiodon indicus (c), *Protocardia (P.)* sp. A (a), *Isognomon (M.) patchamensis* (o), *Protocardia (P.) keerae* (r), *'Corbula' lyrata* (r)

w sandstone, medium- to coarse-grained, poorly sorted, ripple-bedded 0.2 m

x sandstone, fine-grained, friable, reddish, alternating with 5-15 cm thick harder layers 1.6 m

y sandstone, fine-grained, ripple-bedded 0.4 m

B3 Sandstones, massive, light-coloured **... 10 m**

a sandstone, fine- to medium-grained, quartzose, massive, large-scale trough crossbeds, white 9.0 m

b sandstone, fine-grained, hard, ripple-bedded 1.0 m

- sharp change of facies -

Lower Yellow Flagstone member (33 m)

C1 Marl, fine-sandy, bioturbated, weathering yellowish-brown, with numerous 5-10 cm thick intercalations of harder, slabby-weathering sandy micrite, graded medium-grained calcarenites, fine-grained sandstone, or bivalve shells **... 26.5 m**

a lower parts not further subdivided 15 m
Modiolus, *'Corbula' lyrata*, *Isognomon (M.) patchamensis*, *Bakevellia waltoni*, near-monospecific pavements of *Eomiodon indicus*

-higher parts:

v micrite, fine-sandy, shelly seen for 2 m
'Corbula' lyrata (a), *Bakevellia waltoni* (c), *Isognomon (M.) patchamensis*, *Placunopsis radiata* (c), *Protocardia* cf. *grandidieri* (c) *Modiolus imbricatus* (o), *Gervillia (Virgellia) sobralensis* (r), *Thracia depressa* (r), *Pronoella* sp. (r), pholadomyoid (r), neritopsid (r)

w micrite, fine-sandy, full of shells, fauna like in (r) 1.5 m

x sandstone, fine-grained, calcareous, ripple-crossbedded, top bioturbated 0.3 m

y poorly exposed, marl, fine-sandy, with several intercalations of calcareous fine-grained sandstone and fine-sandy micrite, partly developed as shell beds and shell pavements 6.2 m

z micrite, fine-sandy, shelly, hard, forming shelf 1.5 m
Modiolus imbricatus (a), *Bakevellia waltoni* (c), *Placunopsis radiata* (o), *Isognomon (M.) patchamensis* (o), *Protocardia* sp. (o), *Nanogyra nana* (r)

C2 Sandstones, fine-grained, calcareous, shelly, soft, in beds 5 to 15 cm thick; some beds highly bioturbated, others laminated; basal 3 m poorly exposed, top 2 m weathering to yellow slabs; fauna as in C1z **... 6.5 m**

- sharp boundary, change in facies -

Middle Sandstone member (93 m)

D1 Sandstones, medium- to coarse-grained, crossbedded, weathering brown to white **...20,6 m**

a sandstone, very coarse-grained, micro-conglomeratic, poorly sorted, with reworked ferruginous pebbles 0.2 m

b sandstone, coarse-grained, ripple-bedded 0.4 m

c sandstone, poorly exposed, in 5-30 cm thick coarse- to medium-grained beds, partly laminated, partly ripple-bedded, alternating with fine-grained softer intervals; capped by a resistant bed 8.0 m

	d	sandstones, as below	10.8 m
	e	sandstone, hard, medium-grained, trough-crossbedded, top with wave ripples; forming a shelf	1.2 m
D2	Sandstones, continued		**...11.0 m**
		not exposed	3.7 m
	b	sandstone, fine-grained, ripple-laminated	0.3 m
	c	sandstone, fine-grained, in places ripple-bedded, poorly exposed, weathering more softly, *Skolithos* (o)	7.5 m
D3	Sandstone, medium- to coarse-grained, quartzose, massive, large-scale trough crossbedded, weathering pink to white forming a prominent ridge		**...11.0 m**
D4	Sandstones, recessive		**...18.1 m**
	a	sandstone, medium-grained, consisting of shallow channels filled with large-scale trough crossbeds, in places strongly ferruginous; thinner, softer interval 2-4 m below top; *Planolites* (o)	9.0 m
	b	top strongly ferruginous, with abundant fossil wood and plant remains, marker; *Skolithos* (c)	
	c	sandstone, fine- to medium-grained, bioturbated, with four 5-30 cm thick intercalations of sandstone, medium- to coarse-grained, hard, laminated or ripple-bedded; topmost 0.5 m gritty, with abundant shells *Protocardia (P.)* cf. *grandidieri* (c), *'Corbula' lyrata* (c), *Bakevellia waltoni* (o), *Modiolus (M.) imbricatus* (r), *Modiolus glendayi* (r), *Nicaniella extensa* (r), *Palaeonucula cuneiformis* (r), *Agrawalimya pseudosulcata* (r)	9.0 m
	d	shell bed, fine- to medium-grained sandstone	0.1 m
D5	Sandstones, continued		**... 32.5 m**
	a	sandstone, fine- to medium-grained, bioturbated, soft, recessive, thin-bedded, with ironstone interbeds, *Planolites* (o); some levels laminated, others with *Skolithos* (a) 2 m above base: 10 cm thick layer of *Eomiodon*; further thin shell beds 4.8 and 6.8 m above base	17.0 m
	b	sandstone, coarse-grained, white, massive, with large-scale trough crossbeds, forming a prominent shelf	15.5 m

- sharp boundary -

Goradongar Yellow Flagstone Member (44 m)

E1	Transition beds: sandstones, fine-grained, calcareous, well-bedded, flaggy		**... 20.5 m**
	a	sandstone, coarse-grained, microconglomeratic, with sandstone pebbles and some shells, sharp base	0.5 m
	b	sandstone, fine-grained, calcareous, well-sorted, partly with low angle trough crossbedding, partly with ripple bedding, shell pavements of *Protocardia* and *'Corbula'* on some foresets; also some 2-3 cm thick shell beds with a micritic sandstone matrix occur	5.0 m
	c	sandstone, fine- to medium-grained, in places ferruginous, with large-scale low angle crossbedding, surfaces with oscillation ripples; scattered shells of *Protocardia* and nuculids 4-5 m below top; some interbeds of white, quartzose, porous coarse-grained sandstones	15.0 m
E2	Thin-bedded, fossiliferous yellow calcareous sandstones, limestones and marl		**... 23.3 m**

	a	micrite, fine-sandy, shelly, very poorly sorted, with quartz and sandstone pebbles up to gravel or cobble conglomerate	0.1 m
	b	marl, fine-sandy, with numerous hard calcareous interbeds, 2-30 cm in thickness, consisting of fine-sandy shelly micrites, some of them laminated; 1.2 m above base: near-monospecific shell bed of *Nicaniella* near top of unit: level of reworked, encrusted and bored concretions; fauna: *'Corbula' lyrata* (a), *Placunopsis radiata* (c), *Palaeonucula cuneiformis* (c), *Nicaniella extensa* (c), *Trigonia (T.) nitida* (c), *Inoperna sowerbyana* (o), *Pholadomya lyrata* (o), *Palaeonucula stoliczkai* (o), trochid gastropod (o), *Camptonectes* sp. (r), *Unicardium aequalis* (r), *Isocyprina leckhamptonensis* (r), *Nanogyra nana* (r), *Pteria polyodon* (r), *Grammatodon jurianus* (r), *Protocardia (Tendagurium) bannesianum* (r), *Ceratomyopsis* sp. (r), *Pseudomelania (P.)* sp. (r), *Pseudomelania (Oonia)* cf. *conica* (r), *Nododelphinula* sp. (r), *Corbulomima* sp. (r) trace fossils: *Rhizocorallium irregulare* (a)	12.0 m
	c	micrite, fine-sandy, marly, bioturbated, fossiliferous, yellow, marker *'Corbula' lyrata* (c), *Homomya hortulana* (c), *Palaeonucula cuneiformis* (c), *Pholadomya (P.) inornata* (c), *Pholadomya (Bucardimya) lirata* (c), *Agrawalimya pseudosulcata* (c), *Protocardia (P.) patchamensis* (c), *Ceratomyopsis striata* (o), *Ceratomya* cf. *concentrica* (o), *Modiolus glendayi* (o), *Catinula sandalina* (o), *Vaughonia (O.)* sp. (o), *Trigonia (T.) nitida* (o), *Pictavia* sp. (o), *Globularia* cf. *eparcyensis* (o), *Plagiostoma complanata* (r), *Nicaniella extensa* (r), *Neocrassina (N.) pandeyi* (r), *Camptonectes* sp. (r), *Chlamys curvivarians* (r), *Isocyprina leckhamptonensis* (r), *'Trochus actaea'* (r), *Neritoma (Neridomus)* sp. (r), *Quadrinervus* cf. *amoenus* (r), corals (r), serpulids (r)	0.25 m
	d	micrite, marly, fine-sandy, shelly, thin-bedded, continued; ammonites *Gracilisphinctes* sp.	2.0 m
	e	sandstone, calcarenitic, forming large slabs; marker, platform *Rhizocorallium irregulare* (r), *Thalassinoides* (o)	0.2 m
	f	micrite, fine-sandy, shell bed	0.1 m
	g	sandstone, fine-grained, calcarenitic, well-sorted, laminated	0.1 m
	h	micrite, fine-sandy, rubbly, bioturbated, shells abundant, with 2 spaced beds of well-sorted micritic fine sand and level with reworked and encrusted concretions *Rhizocorallium irregulare* (a), striated burrows (a); oysters, *'Corbula' lyrata*, ampullinid gastropod, serpulids; ammonites and nautiloids 1.5 m below top: *Gracilisphinctes* sp., *Paracenoceras* cf. *kumagunense*	2.3 m
	i	micrite, fine-sandy, well-sorted, heavily bioturbated, ledge-forming	0.2 m
	j	micrite, fine-sandy, rubbly, highly bioturbated, yellowish, with 2-3 thin intercalations of laminated calcareous fine-grained sandstone topped by oscillation ripples *Rhizocorallium irregulare* (a), *Teichichnus rectus* (a)	6.0 m

- sharp boundary, change of facies -

Gadagupta Sandstone Member (28 m)

F	Sandstones, slabby, but soft, fine-grained, thin-bedded, mostly recessive; some layers calcareous		**... 28.3 m**
	a	sandstone, coarse-grained, conglomeratic, strongly ferruginous to haematitic, large-scale trough-crossbedded, sandstone pebbles up to 15 cm	

		in diameter, quartz pebbles up to 2 cm in diameter, shells (o); upper surface with megaripples; prominent marker	0.4-0.5 m
		section continued south-west of the dome, west of Sadhara village	
	b	marl, fine-sandy, silty, with 5 cm thick band of wave-rippled sandstone in the middle	3.0 m
	c	sandstone, fine- to medium-grained; current-rippled surface 40 cm above base; uppermost 100 cm with large-scale low angle crossbedding	3.0 m
	d	sandstone, medium-grained, ferruginous	0.2 m
	e	sandstone, fine-grained, soft	1.4 m
	f	sandstone, medium-grained, ferruginous	0.4 m
	g	sandstone, fine-grained, partly bioturbated, partly with large-scale low angle crossbeds	2.0 m
		not exposed	3.0 m
	h	sandstone, poorly exposed	6.0 m
	i	sandstone, marly, silty, with interlayered bedding, slightly baked	2.5 m
	j	sandstone, hard, massive	0.4 m
	k	disturbed sequence due to dyke; mainly sandy-silty	6.0 m

- change of facies -

higher beds best seen east of Sadhara village, just east of the dam

Patcham Formation, Raimalro Limestone Member (2-3 m)

G	Limestone, massive but well bedded fine-sandy, bioclastic calcarenites, with faint large-scale low angle crossbedding, lenticles of bivalves and gastropods, and lenticular conglomerate layers consisting of reworked calcarenite pebbles, weathering light buff or brownish-grey; here reduced to only *Macrocephalites* sp., one imprint seen	... **2-3 m**

- sharp boundary -

Chari Formation, Lower Macrocephalus Beds (12 m+)

H1	Sandstones, fine-grained, shaley, interlayered with silt, bioturbated, soft; some intercalations of thin shell beds *M. (Kamptokephalites)* sp.	... **9 m**
H2	Shales, silty, soft, with scattered red ironstone concretions, strongly gypsiferous	seen ... **3 m**

-sharp angular unconformity -

Tertiaries:
Sandstones, quartzose, coarse-grained, light-coloured, lying almost horizontal, lapping on to the southern margin of the dome, forming the flat plain of the Banni running into the Rann, soon covered in superficial sands.