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MARKER BEDS IN THE JURASSIC OF THE KACHCHH BASIN, WESTERN INDIA: THEIR DEPOSITIONAL ENVIRONMENT AND SEQUENCE-STRATIGRAPHIC SIGNIFICANCE

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ABSTRACT

A survey of the Middle Jurassic (Bajocian-Lower Oxfordian) rocks of Kachchh has identified a series of marker beds that aid in the genetic correlation of the sedimentary sequences. Six of these are described here. They are, in ascending order, (1) the Leptosphinctes Pebbly Rudstone (Late Bajocian) of Kala Dongar that can be traced to Gora Dongar and into the Jhura Dome; (2) the Purple Bed (early Late Bathonian) of the Jhura Dome and its equivalents on Pachchham Island and in the Jumara Dome; (3) the top of the Raimalro Limestone Member (Late Bathonian) of the Islands and of the Sponge Limestone member (both Patcham Formation) of Kachchh Mainland; (4) the top part of the lower and upper sandstone bodies of the Ridge Sandstone member (Middle Callovian) of Kachchh Mainland; (5) the Athleta Sandstone (early Late Callovian) of the Jara Dome and equivalent horizons in the Jumara, Jhura and Habo Domes; and (6) the Dhosa Oolite member *sensu stricto* (latest Early Oxfordian) of Kachchh Mainland and Khadir Island. Except in the case of the top Raimalro Limestone Member, which corresponds to a maximum flooding surface, the remaining marker horizons belong to the early TST of depositional sequences, in which sediments of LST are preserved only as palimpsests within transgressive lags.

The pattern of sedimentation in the Jurassic of the Kachchh Basin is cyclic, cycles stacked in hierarchical order, from parasequences to 3rd order sequences and transgressive-regressive facies cycles.

Key words : Jurassic, sequence stratigraphy, correlation, Kachchh, India.

INTRODUCTION

The Kachchh Basin, an E-W oriented rift basin situated on the western margin of the Indian plate (e.g. Biswas, 1982, 1991), is an ideal object for the study of the marine history of the early phases of the opening of the Indian Ocean during the Jurassic. Reasonable exposures (fig. 1) and rich faunas allow us to trace the evolution of the basin from the time it was flooded by the sea. The earliest biostratigraphically dated evidence, a specimen of the ammonite *Leptosphinctes* (Singh, Jaitly and Pandey, 1982; Jaitly and Singh, 1983) from Kala Dongar, Pachchham Island, is of Late Bajocian age, but the earliest evidence of marine influence of any form, marine bivalves and trace fossils, comes from approximately another 250 m below this level. The earliest terrestrial stages of the sedimentary history, which reaches back into the Late Triassic (Koshal, 1984), are not exposed but have been documented in boreholes (e.g. Banni Well 2).

A particularly striking feature of the sediments of the Kachchh Basin is their abundance of macrofossils, both benthic and nektic, which characterise not only the various environments of the basin, but provide also an excellent representation of the so-called Ethiopian Faunal Province that encompassed large areas of the southern margins of the Tethyan Ocean during the Jurassic. It was because of the significance of these benthic macrofaunas that an Indian-German research project was launched in the late 1980s to concentrate on tracing the spatial and temporal distribution patterns of these macrofaunas. It soon became apparent, however, that a major prerequisite for such studies, a detailed biostratigraphic framework, did not yet exist, although several studies in recent years tried to remedy this (e.g. Krishna and Westermann, 1987; Krishna *et al.* 1988; Krishna and Ojha, 1996; Jain and Pandey, 2001). Lithologies, moreover, are laterally highly variable. Thus,

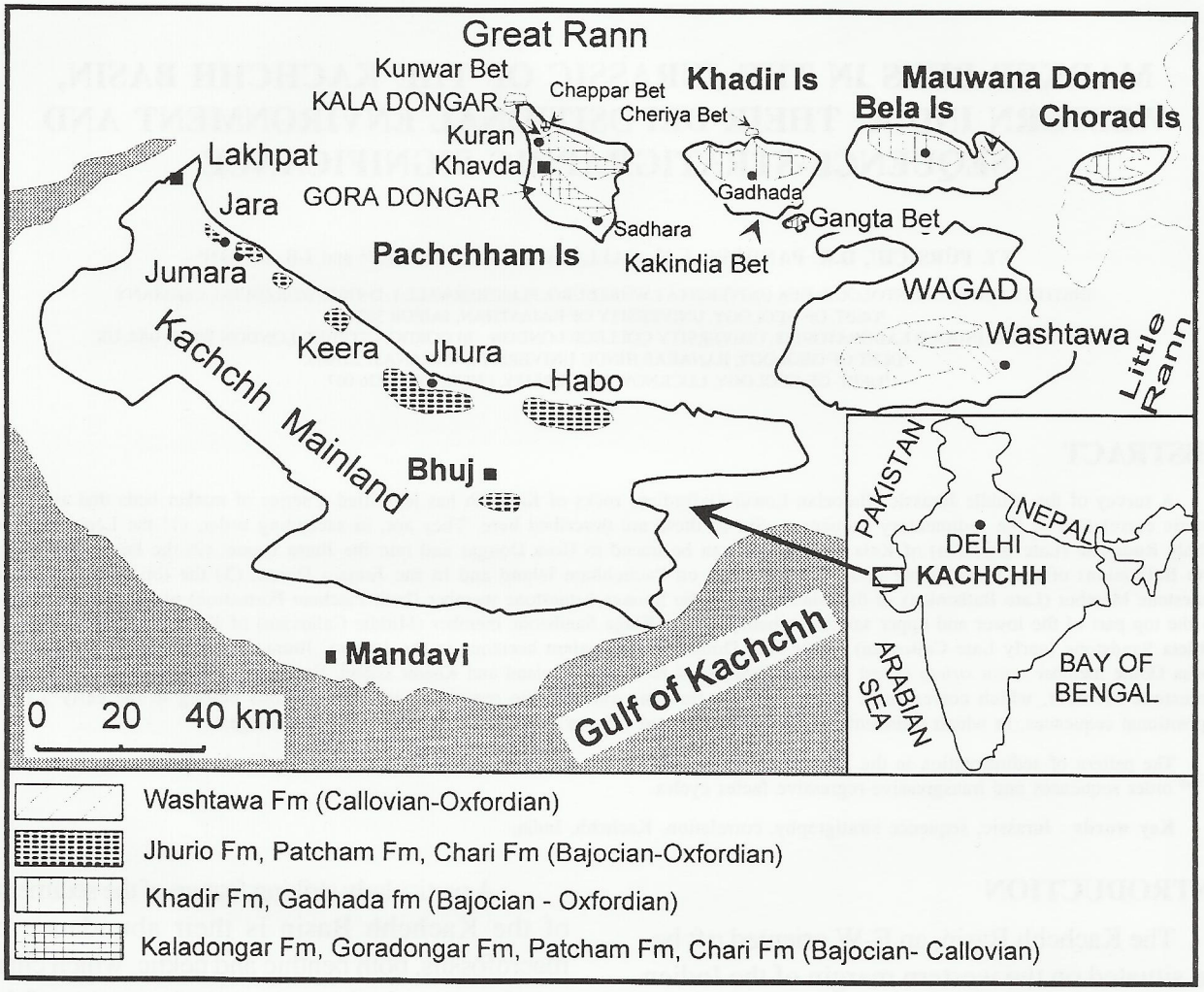

Fig. 1. Locality map.

it was only rarely possible to correlate sedimentary units across the basin with any confidence. We now try to show that there are several marker beds that can be traced across large parts of the basin, thereby facilitating time-correlations and helping to understand the lithostratigraphy, a prerequisite for the sequence-stratigraphic interpretation of the succession. This is particularly important in the lower parts of the exposed sedimentary succession and in the more marginal parts of the basin, because guide-fossils such as ammonites are there extremely rare. Attempts to date the succession with the help of benthic foraminifera (e.g. Pandey and Dave, 1993) must be viewed with caution, as their stratigraphic precision is usually not sufficient.

In shallow seas, the classical three types of systems tracts, i.e. transgressive, highstand, and lowstand (e.g. Van Wagoner *et al.*, 1988), are commonly represented only by the former two because, due to lack of accommodation space, lowstand deposits are generally absent (e.g. Embry, 1993, Holland, 1993, Brett, 1995). As will be shown in this paper, this is generally also the case in the Kachchh Basin. Moreover, in such settings transgressive systems tracts are generally thin or even condensed, consisting mainly of beds rich in biogenic hardparts, so that depositional sequences are highly asymmetric (see also Holland, 1993), a

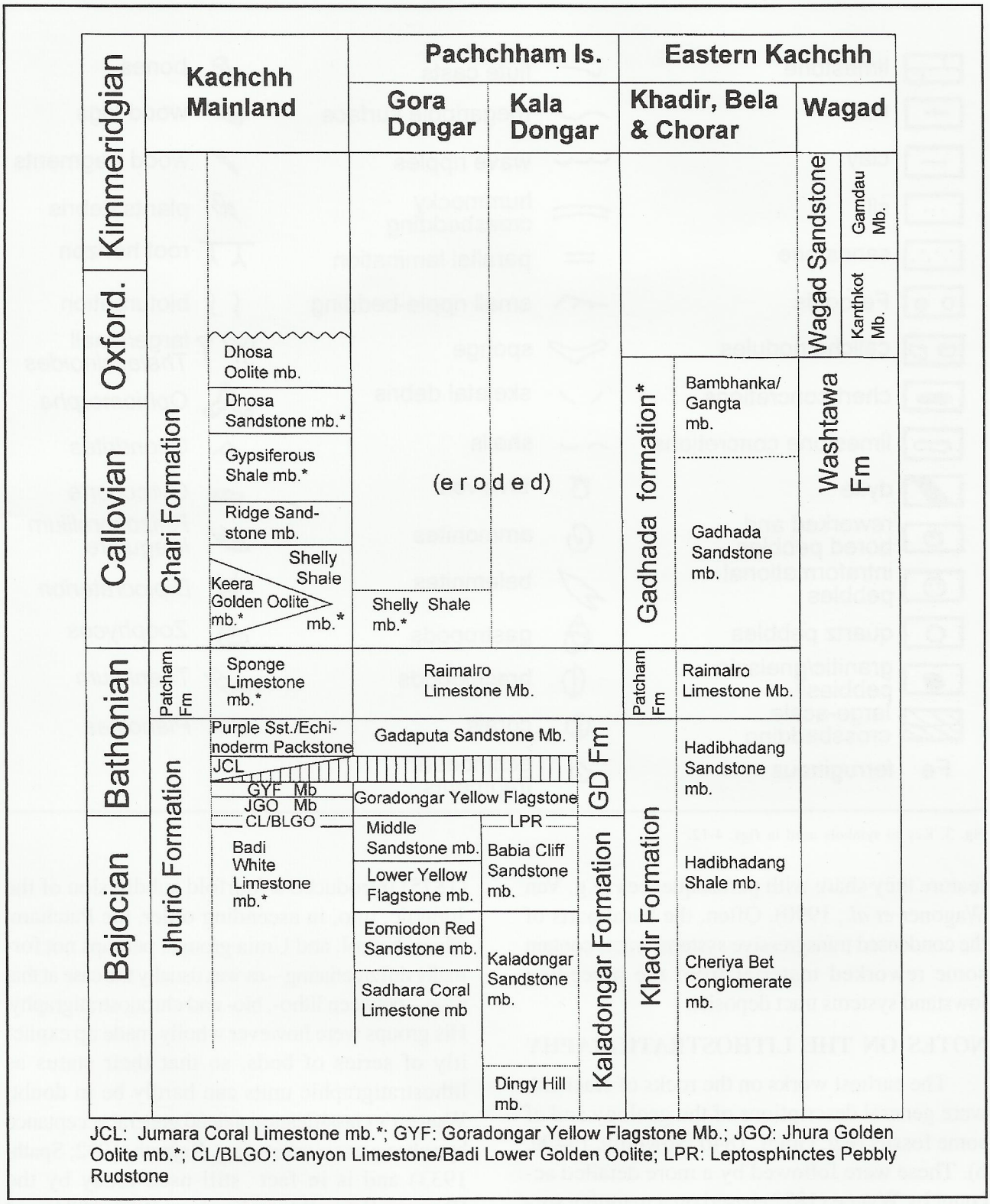

Fig. 2. Lithostratigraphic framework of Middle Jurassic and lower Upper Jurassic rocks of the Kachchh Basin. The lithostratigraphic terms are partly those of Biswas (1980), partly they are the traditional terms introduced by Waagen (1875). Yet other terms (marked with an asterisk) are new and await formal description (Fürsich *et al.*, in prep.).

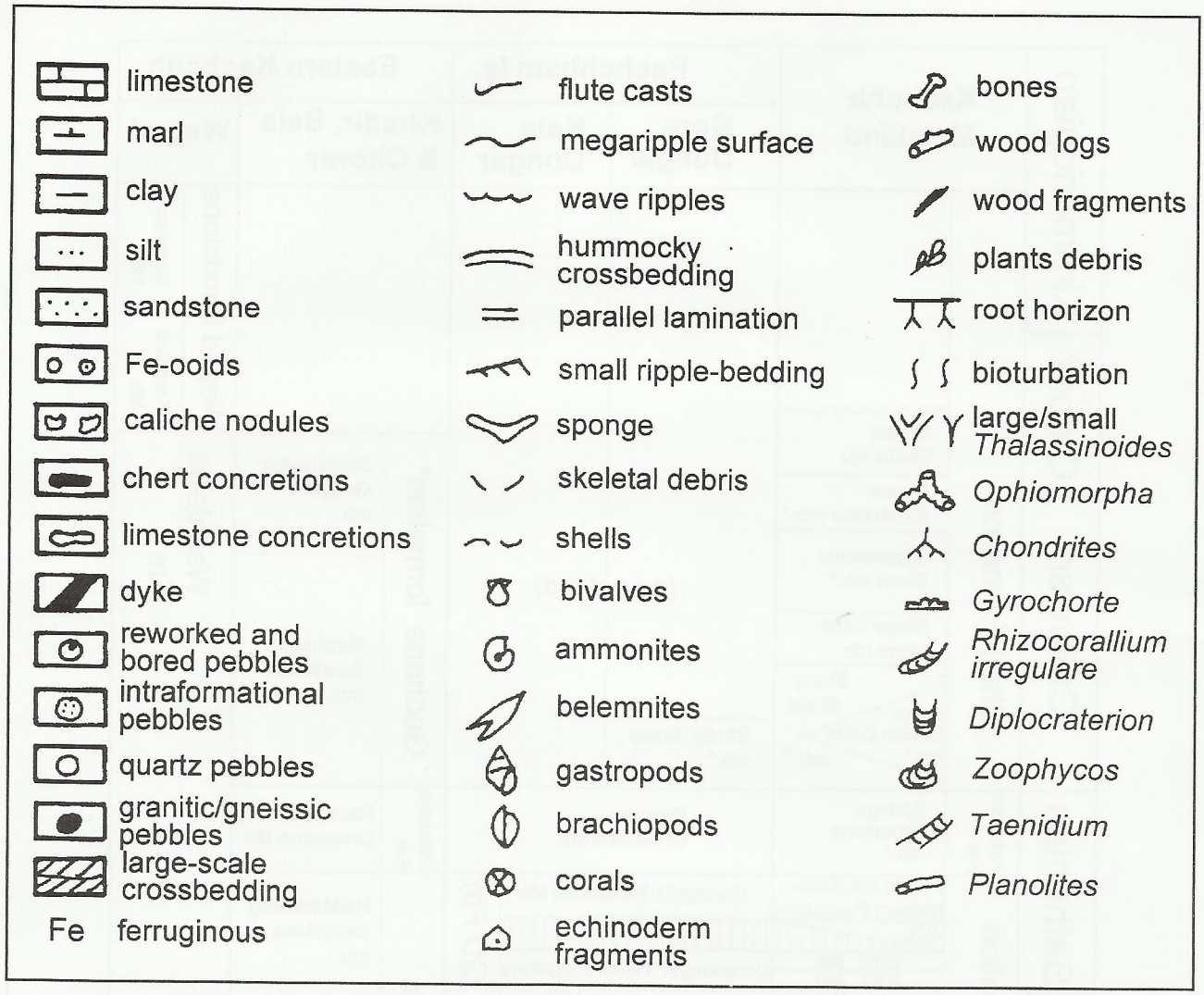

Fig. 3. Key to symbols used in figs. 4-12.

feature they share with parasequences (e.g. Van Wagoner *et al.*, 1990). Often, the basal parts of the condensed transgressive systems tracts contain some reworked material from the preceding lowstand systems tract deposits.

NOTES ON THE LITHOSTRATIGRAPHY

The earliest works on the rocks of Kachchh were general descriptions of the geology and of some fossils (e.g. Grant, 1840, Sowerby, 1840a, b). These were followed by a more detailed account by Wynne (1872) based on a mapping survey in 1867-8. In describing the rich ammonite faunas collected largely by Stoliczka, Waagen (1875) introduced a fourfold subdivision of the Jurassic, into, in ascending order, the Patcham, Chari, Katrol, and Umia groups, perhaps not formally differentiating – as was usually the case at that time – between litho-, bio- and chronostratigraphy. His groups were however wholly made up explicitly of series of beds, so that their status as lithostratigraphic units can hardly be in doubt. Waagen´s classification gained general acceptance by subsequent workers (e.g. Rajnath, 1932; Spath, 1933) and is in fact still used today by the 'Banaras School' (e.g. Krishna, 1983, 1984) and others (e.g. Bardan and Datta 1987; Singh, 1989; Fürsich, Oschmann, Singh and Jaitly 1992; Fürsich

and Oschmann 1993; Fürsich, Pandey, Callomon, Oschmann and Jaitly 1994a; Bhalla, Talibet and Ahmad 1998; Pandey and Fürsich 1998). The work of the Banaras School in the last 40 years has led to a continuous refinement and extention of this classification, often with a separate lithostratigraphic nomenclature for each of the major outcrops, the eroded anticlinal 'Domes' on the 'Mainland' and 'Islands' (fig. 1) (e.g. Fürsich *et al.*, 1994a; Kanjilal, 1978; Pandey, Singh and Agrawal, 1984; Jaitly and Singh, 1983).

Biswas (1971, 1980) presented the first comprehensive modern lithostratigraphic classification for the whole basin; he defined and described type sections and correlated the main lithological units. Reviewing the earlier classifications, he came to the conclusion that most of the terms in use did not qualify as lithostratigraphic units as defined in the *International Stratigraphic Guide* of Hedberg (1976) and proposed a completely new scheme. Laudable as his intentions may have been, his new classification was adopted by only a part of the geological community, Waagen´s scheme being deeply engrained in the literature and also easy to use, at least on Kachchh Mainland. Moreover, Biswas' (1980) descriptions of lithostratigraphic units, in particular his drawings of sections, were very condensed and not always very precise. As a result, many of the units are difficult to recognise in the field. However, previous classifications had not placed much emphasis on the basal deposits below the Patcham Formation, which are widely developed in the island belt, because of lack of knowledge. Biswas (1980) was the first to describe many of these deposits. We propose now to use Biswas´s term Jhurio Formation for all beds on the Mainland below the Patcham Formation (fig.2) and to retain the latter term in a restricted sense on the Mainland for the carbonate succession just below the Chari Formation, and its equivalent, the Raimalro Limestone, on the Islands. We also use the terms Goradongar Formation, Kaladongar Formation and Khadir Formation to describe the mixed carbonate-siliciclastic rocks below the Patcham Formation of the Island belt. We introduce informally the term Gadhada formation for all the sediments on the Islands lying above the Patcham Formation, which had previously been included by Biswas in his comprehensive Khadir Formation. A more comprehensive description of the lithostratigraphic units will be given elsewhere (Fürsich *et al.*, in prep.).

THE MIDDLE JURASSIC SEDIMENTARY SEQUENCE OF KACHCHH

Middle Jurassic sediments of the Kachchh Basin are predominantly siliciclastic in nature, ranging from conglomerates to sandstones and fine silty clays, depending on the stratigraphic level and distance from the palaeoshoreline. Carbonates occur in appreciable quantity only in the Upper Bathonian, particularly in more offshore areas. The sediments - with a total thickness of up to 700 m - record a gradual northeastward transgression and deepening of the sea during the Middle Jurassic, which reached a maximum in the Early Oxfordian as reflected in the highly condensed top beds of the Dhosa Oolite member (Singh, 1989; Fürsich and Oschmann, 1993). Control on sedimentation was complex. An interplay of general subsidence and more regional tectonics associated with the opening of the Indian Ocean (Fürsich *et al.*, 1992), eustatic sea level fluctuations and changes in climate all contributed to the sedimentation pattern, as did tectonic movements in the source area (Fürsich and Oschmann, 1993). In most cases, it is difficult to single out a dominant agent. The combined effect of the various agents resulted in changes of the relative sea level which commonly imprinted a cyclic pattern on the sedimentary package. In many cases, the sedimentary expression of the cycles is in the form of hemicycles, the deepening phase being strongly reduced in thickness and typically represented by pebble lags and shell-concentrations (fig. 12; see also Howard and Singh, 1985; Fürsich, Oschmann, Jaitly and Singh, 1991; Fürsich and Oschmann, 1993).

Sedimentary cycles occur not only in the more distal parts of the basin (e.g. from Ler westward to Jumara and Jara), but also in more nearshore areas exposed on the Islands. For example, north of the village of Taga, Kala Dongar, shallow-water marine sandstones of Middle Jurassic (?Bajocian to Late Bathonian) age exhibit a pattern of strongly asymmetric shallowing-deepening cycles ('third order cycles') that can be interpreted as depositional sequences (fig. 4). The transgressive phase is mainly represented by beds of sediment (Transgressive Systems Tract, TST) reworked from the top of the underlying Highstand Systems Tract (HST), and often incorporating material of the Lowstand Systems Tract (LST) characterized by coarse, pebbly sandstone, poor sorting, a high carbonate content, wood remains, and abundant shells of bivalves, gastropods, corals, and rare nautiloids. Deposits of the LST are not preserved as such, but its sediments were reworked and became incorporated in deposits of the early TST, which are mostly developed as lag deposits. The sequence boundary generally coincides with the transgressive surface, leaving a single surface. In deposits of the regressive phase (HST) grain-size coarsens upwards and the bioturbated, muddy sediments of the lower part are replaced up-section by large-scale trough crossbeds.

Such third-order cycles may, as a component, develop marker-beds that may be traced for tens of kilometres. In what follows, we describe the most important of these: beds whose distinct lithology and composition make them easy to identify, and that can be traced throughout much of the basin. Several other beds that exhibit similar features to the ones described below cannot, however, at present be usefully applied for basin-wide correlations because of their more limited extent.

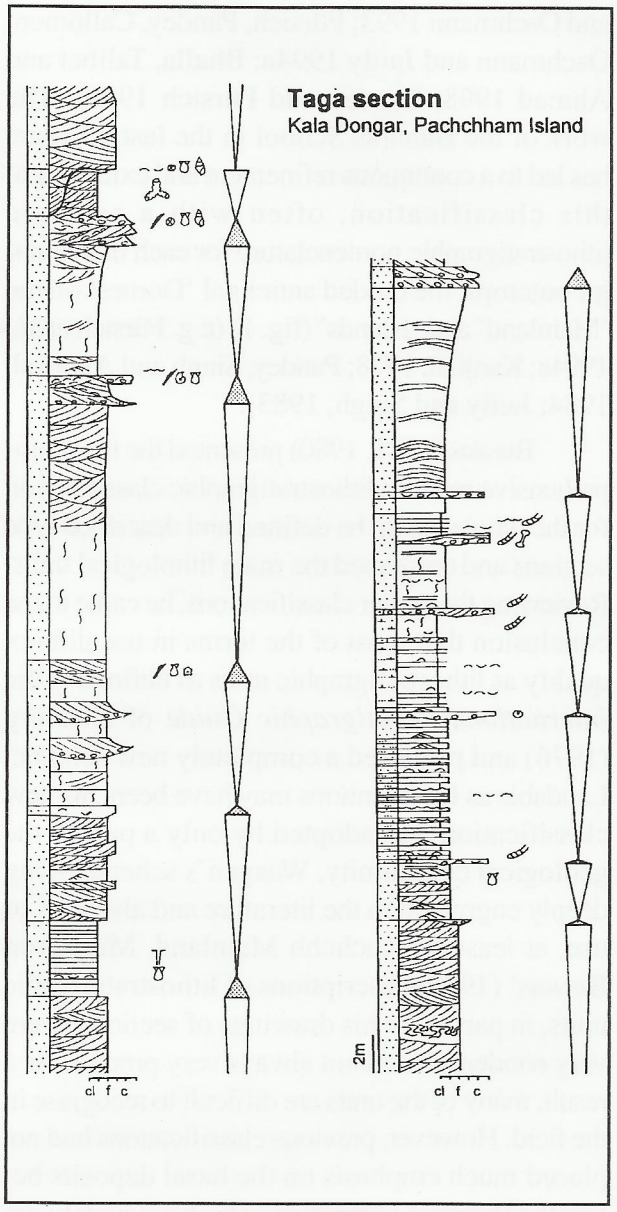

Fig. 4. Strongly asymmetric depositional cycles in the Bajocian-Bathonian rocks of eastern Kala Dongar (N of Taga village), Pachchham Island. Only transgressive systems tracts (dotted arrows) and highstand systems tracts (white arrows) are preserved, the transgressive surface coinciding with the sequence boundary. For key of symbols and abbreviations see figs. 3 and 5.

MARKER BEDS

Six marker-beds have been identified, in descending order as follows:

(6) the Dhosa Oolite Member (late Early Oxfordian);

(5) the *Athleta* Sandstone (early Late Callovian);

(4) the Ridge Sandstone (latest Early Callovian);

(3) the Raimalro Limestone Member, top (late Late Bathonian);

(2) the Purple Bed of the Jhura Dome (Late Bathonian);

(1) the *Leptosphinctes* Pebbly Rudstone of Kala Dongar (late Bajocian).

These are discussed below.

(1) The *Leptosphinctes* Pebbly Rudstone (Late Bajocian) and lateral equivalents

Description: The *Leptosphinctes* Pebbly Rudstone is named after the oldest ammonite found in Kachchh, indicating a Late Bajocian age for the bed in western Kala Dongar on Pachchham Island (Jaitly and Singh, 1983). It can be followed throughout Kala Dongar, forming a distinct ledge and commonly the top of the northern cliff of the island overlying the bulk of the massive Babia Cliff Sandstone member of Biswas (1980). The lower boundary of the bed is rarely visible but apparently is sharp, as is the upper boundary. At the *Leptosphinctes* locality itself, about 2 km east of the village of Kuran (fig. 5C), the bed is underlain by well bedded, strongly calcareous, bioclastic fine- to medium-grained sandstone with occasional layers of intraformational mud clasts, seen for several metres. Incipient ooids are found in some of the beds as is evidence of small ripple cross-bedding, large-scale trough cross-bedding, horizontal lamination, and bioturbation. The *Leptosphinctes* Pebbly Rudstone itself is 8.6 m thick. Its lower unit, 7.1 m thick, is a very hard, ledge-forming, ferruginous bioclastic rudstone with scattered coarse quartz grains, subangular quartz granules (up to 1 cm in diameter), scattered subangular red siltstone clasts (up to 5 cm in diameter), and in places with abundant shell debris. On the top surface, abraded coral heads (*Isastraea* sp.), rounded quartz pebbles up to 2 cm in diameter, sandstone pebbles up to 8 cm in diameter, and occasionally identifiable bivalves such as *Plagiostoma* occur. The unit exhibits large-scale trough cross-bedding. The upper part of the *Leptosphinctes* Pebbly Rudstone is a reddish, ferruginous, sandy, bioclastic rudstone with scattered quartz granules, some limestone clasts and shells that occur in bands.

Overlying the *Leptosphinctes* Pebbly Rudstone is a thinly-bedded sequence of trough-crossbedded or hummocky-crossbedded fine-grained sandstones, bioclastic rudstones, and shell beds (fig. 5C). Abundant plant debris on some foresets and the trace fossils *Rhizocorallium irregulare* and *Ophiomorpha* are characteristic. 20 m above the top of the *Leptosphinctes* Pebbly Rudstone, the ammonites *Clydoniceras* and *Micromphalites* have been recorded, indicative of the Middle Bathonian. This observation is in marked contrast to the reports of Singh *et al.* (1982) and Jaitly and Singh (1983) who recorded a thickness of more than 300 m of sediment between the levels of the Late Bajocian and Middle Bathonian ammonites.

On Pachchhmaipir, 4 km further east, the *Leptosphinctes* Bed equivalent consists of 8.5 m of yellowish, strongly calcareous fine-grained sandstone in beds 20-80 cm thick. In the lower third, thinner units are ripple-bedded or horizontally laminated, thicker ones show large-scale trough crossbedding; and there are thin bioturbated interbeds. The upper two-thirds of the *Leptosphinctes* Pebbly Rudstone are massive, partly medium-grained, with locally large-scale planar crossbedding and some foresets rich in shell hash. The top bed, as well as some levels further down, contains lenses rich in granitic-gneissic and quartz pebbles.

Lateral equivalents: In the Sadhara Dome, eastern Gora Dongar, 30 km SE of the *Leptosphinctes* locality, a unit of large-scale trough crossbedded, coarse-grained sandstone is overlain with sharp base by a 0.5 m thick coarse-grained microconglomeratic sandstone with sandstone pebbles and scattered shells (fig. 5A; Fürsich *et al.*, 1994a). This unit is regarded as the equivalent of the *Leptosphinctes* Bed of Kala Dongar. It is followed by 5 m of well sorted, fine-grained calcareous sandstone, partly large-scale trough crossbedded, partly ripple bedded with thin shell beds and shell concentrations on the foresets.

In the Jhura Dome on the Mainland, some 60 km SSW of Kuran, there are two lithological

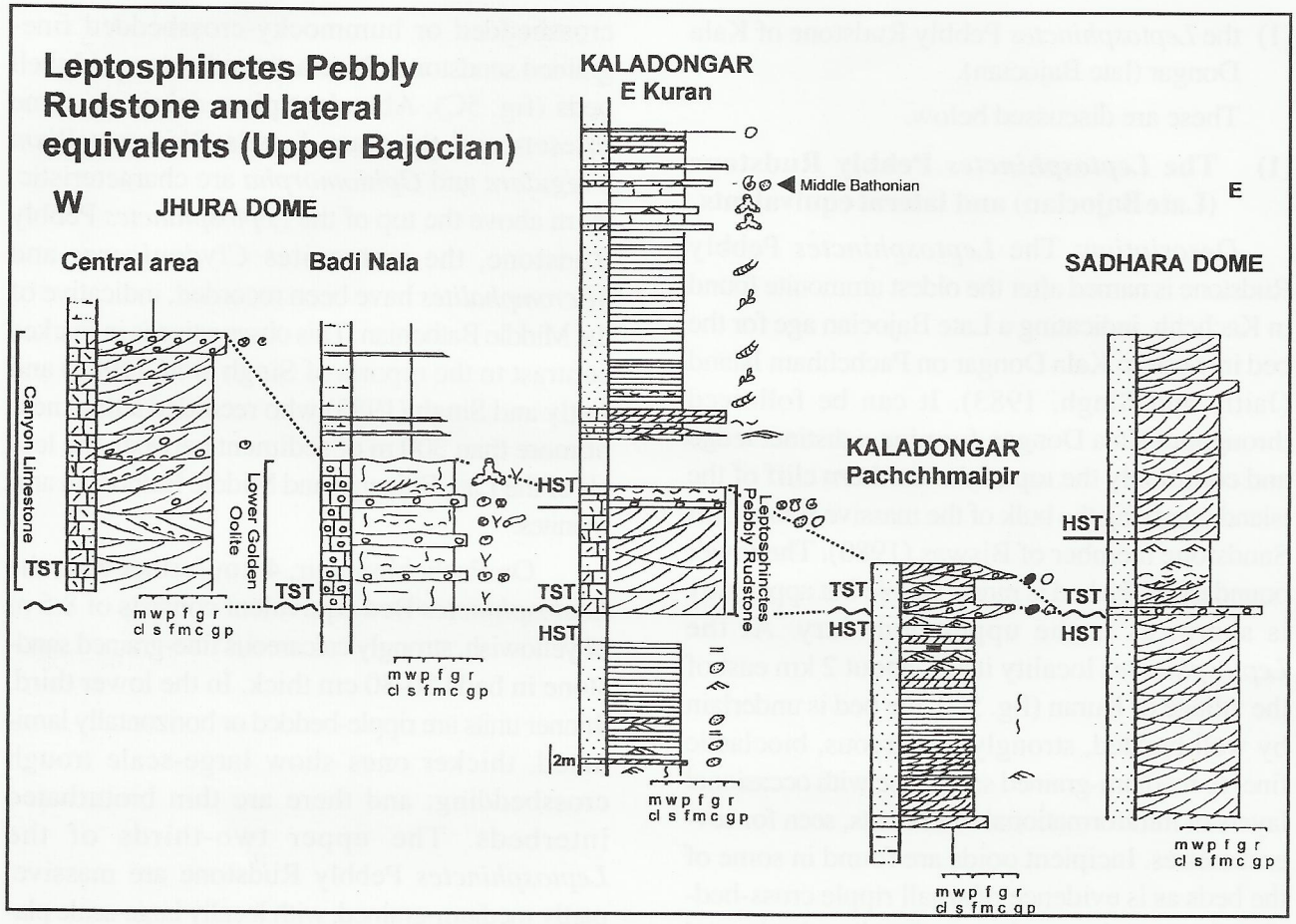

Fig. 5. Correlation and sequence stratigraphic interpretation of the *Leptosphinctes* Pebbly Rudstone and lateral equivalents. TST: transgressive systems tract; HST: highstand systems tract; wavy line: sequence boundary; dotted line: lithological boundaries of the marker bed. m: mudstone; w: wackestone; p: packstone; f: floatstone; g: grainstone; r: rudstone; cl: clay; s: silt; f: fine sand; m: medium sand; c: coarse sand; g: gravel; p: pebble.

units that can again be correlated with the *Leptosphinctes* Bed. In the Badi Nala, in the northern part of the dome, the lower part of the Jurassic sequence exposed in the deeply incised gorge contains two conspicuous units of ferruginous oolite, termed here the Lower and the Upper Badi Golden Oolites. Lithologically the lower one of these units, which we regard as the lateral equivalent of the *Leptosphinctes* Pebbly Rudstone, starts with well bedded, rubbly, Fe-oolitic bioclastic grain- to rudstone, bioturbated by *Planolites*, small *Thalassinoides* and *Ophiomorpha*. Towards the top, it becomes more massive and crossbedded and terminates with a megaripple surface (fig. 5D). Iron-coated shell fragments are common as are lenticular shell layers up to 1 m thick. In places, the rudstone is microconglomeratic. Faunal elements include large oysters, rhynchonellid brachiopods, and scattered coral heads. Layers of sandstone pebbles (up to 5 cm in diameter) occur at several levels. The Lower Badi Golden Oolite is underlain by a very poorly exposed softer and more fine-grained unit that consists to a large extent of silty wacke- and packstones with numerous intercalations of Fe-oolitic grainstones. The Lower Badi Golden Oolite is superseded by about 35 m of bioturbated bioclastic, silty marl with several intercalations of thin (< 10 cm thick) graded grainstones with sharp base, bioturbated partially by *Chondrites* and partially by *Ophiomorpha*.

Towards the east-central area of the Jhura Dome, the Lower Badi Golden Oolite changes its

character, turning into a massive bioclastic rudstone (fig. 5E). termed here the Canyon Limestone, because it forms the vertical walls of a steep valley. The 17 m thick Canyon Limestone is strongly ferruginous but does not contain Fe-ooids. Instead, ferruginised bioclasts are abundant. Conglomeratic lenticles consisting of ferruginous and limestone pebbles occur at several levels. On its top surface lie large overturned coral heads. No lower beds are exposed here, but the beds overlying the Canyon Limestone consist of marly silts with occasional intercalations of thin, graded grainstones and some intercalations of Fe-oolite.

Interpretation : Based on microfacies, sedimentary structures, trace fossils and taphonomic data, the *Leptosphinctes* Pebbly Rudstone and its lateral equivalents in the Sadhara and Jhura domes can be clearly interpreted as sediments deposited in fully marine, high energy, shallow water environments. The presence of intraclast-, basement- and quartz pebbles indicates not only frequent reworking, but the palimpsest nature of the latter two types of pebbles points to erosion and reworking of nearshore or possibly even terrestrial sediments deposited during sea-level lowstand. Thus the *Leptosphinctes* Pebbly Rudstone is interpreted as a transgressive deposit, thinning towards the palaeoshoreline - in this case towards the Sadhara Dome - and changing in character towards the centre of the basin, in the direction of the Jhura Dome. Quartz pebbles, granitic-gneissic clasts and quartz granules are most likely the reworked relicts of fluvial channel or coastal deposits of sea-level lowstand. The ferruginous ooids are thought to be the oxidized relicts of nearshore sediments of low energy embayments, the favourite site of early diagenetic formation of ferruginous ooids during times of sea-level lowstand (e.g. Macquaker and Taylor, 1996). They were reworked and concentrated during the early TST. This interpretation of the marker bed is supported by the presence of the high-energy sandstones and mixed siliciclastic-carbonate sediments that underlie the bed in the more marginal parts of the basin, and by the comparatively low-energy, mixed siliciclastic-carbonate sediments that follow it. In sequence stratigraphic terms, the *Leptosphinctes* Pebbly Rudstone and equivalents represent an early TST, the topmost part corresponding to the maximum flooding surface.

The *Leptosphinctes* Bed is an excellent marker horizon for linking the depositional sequences of the Kachchh Mainland with those of the Islands.

(2) The Purple Bed and lateral equivalents (Early Late Bathonian)

The Purple Bed has been recognised only in the Jhura Dome, where it serves to subdivide the thick carbonate strata occurring in the lower part of the succession. It can be traced from the slopes of Badi Nala in the north of the dome to the central areas, wherever the relevant stratigraphic level is exposed.

Description : In Badi Nala, the Purple Bed is 1.5 m thick and overlies, with a sharp erosional base, the cream-coloured to yellowish, well-bedded limestone-marl alternations of the Goradongar Yellow Flagstone Member that extends from Kala Dongar to Gora Dongar and across to the Jhura Dome. The purplish-brown ferruginous unit consists of several beds of echinodermal detrital packstone with varying amounts of coarse to gravelly quartz grains (fig. 6). 0.75 m above the base is a layer rich in Fe-ooids. The next bed up contains thin lenses of fragmented shells. The top 30 cm contain, apart from scattered, well-rounded quartz granules, pebbles of packstone up to 7 cm in diameter and fragmented oyster shells. The Purple Bed is overlain by well-bedded, cream-coloured to whitish micritic limestone-marl alternations whose members include abundant distal tempestites with occasional demosponges; a unit hence informally called the Sponge Limestone member.

The Purple Bed is fairly uniform in character across most of the Jhura Dome, varying in thick-

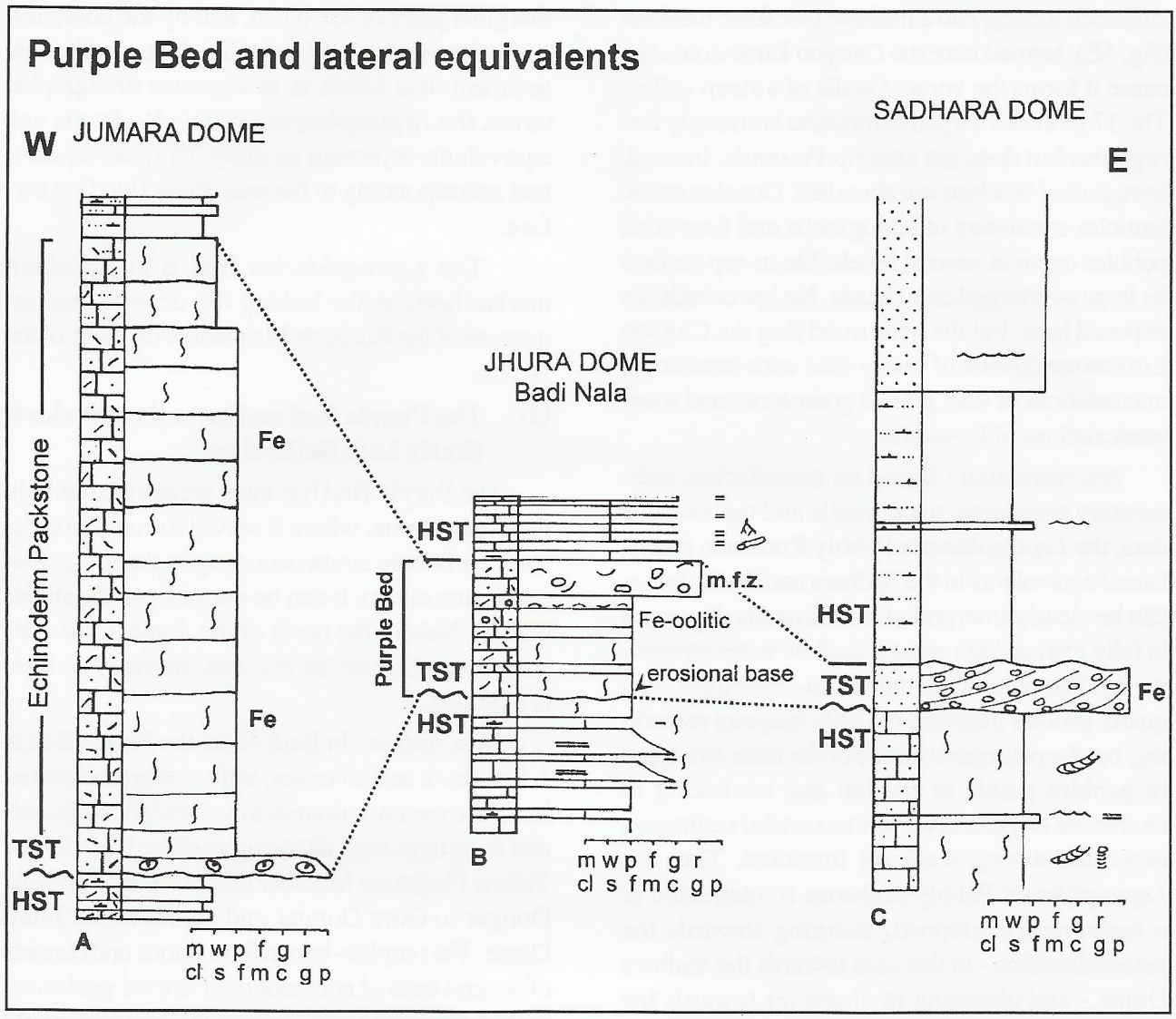

Fig. 6. Correlation and sequence stratigraphic interpretation of the Purple Bed and lateral equivalents. For key of symbols and abbreviations see figs. 3 and 5.

ness between 1 and 2 m. In the southern part of the dome, however, it may thin to as little as 10 cm, being represented there only by the top bed of the succession elsewhere.

Lateral equivalents: In the Sadhara Dome of Gora Dongar, the Gora Dongar Yellow Flagstone Member is overlain with erosional contact by a 0.4-0.5 m thick, strongly ferruginous, conglomeratic, coarse-grained sandstone, forming the base of the Gadaputa Sandstone member (Fürsich *et al.*, 1994a; fig. 6C). The bed shows large-scale trough crossbedding and is topped by a megarippled surface. Pebbles consist of sandstone (up to 15 cm in diameter) and quartz (up to 2 cm). Disarticulated shells occur occasionally. This pebble bed is regarded as the lateral equivalent of the Purple Bed of the Jhura Dome.

Basinward, in the core of the Jumara Dome, the 18 m thick micritic Sponge Limestone member (bed 22 of Rajnath, 1932) is well exposed and contains, as in the case of the Jhura Dome, thin tempestite intercalations. It is underlain with sharp

contact by the 7-11 m thick brownish, ferruginous, sandy, resistant, prominent Echinoderm Packstone (fig. 2; Rajnath's bed 23) that is well bedded, contains thin, softer interbeds, and a scarce fauna of bivalves (e.g. *Plagiostoma*, *Chlamys*, *Eopecten*, *Entolium*), rolled coral heads, and rhynchonellid and terebratulid brachiopods (fig. 6A). Bioturbation (*Planolites*, *Chondrites*) is widespread. The base of the Echinoderm Packstone is sharp, erosional and contains reworked and bored carbonate pebbles; the top 100 cm are gradational, micritic, but still ferruginous. The Echinoderm Packstone is underlain by alternations of well bedded wackestones and marl with thin tempestites, scattered *Bositra* shells and shell pavements of *Eligmus*.

Interpretation: The sharp erosional base of the Purple Bed can be interpreted as representing a sequence boundary, followed by little more than a metre of early TST deposits. The top bed, characterised by an erosional base, poor sorting, presence of quartz granules and pebbles, and ferruginous composition, is interpreted as late TST culminating in the maximum flooding surface. The sequence boundary can be traced palaeo-shorewards to form the base of the Gadaputa Sandstone in the Sadhara Dome, and towards the centre of the basin to form the base of the Echinoderm Packstone of central Jumara Dome. The Packstone is interpreted to have originated as a lowstand deposit which was reworked during transgression (fig. 6C). The HST starts with the Sponge Limestone member seen at the Jhura and Jumara domes. Thus, the Purple Bed is another excellent marker bed linking the depositional succession of the Islands with that of the Kachchh Mainland.

The limestones underlying the Purple Bed of the Jhura Dome and its lateral equivalents, the Echinoderm Packstone of the Jumara Dome and the basal Gadaputa Sandstone of Gora Dongar on Pachchham Island, are shown biostratigraphically to differ in age between the Jumara Dome and the outcrops further east. At the Jumara Dome, ammonites (*Epistrenoceras, Procerites, Oxycerites*: Kayal and Bhardan, 1998 and personal observations) indicate an early Late Bathonian age for the Jumara Coral Limestone member (Rajnath's beds 24-26; Jain, Callomon and Pandey, 1996), whereas the occurrence of *Gracilisphinctes* in the Goradongar Yellow Flagstone Member of the Jhura Dome and, together with *Micromphalites,* at Gora Dongar and Kala Dongar (Pandey and Callomon, 1995), points to a Middle Bathonian age of the member. It appears, therefore, that the time-equivalent sediments of the Jumara Coral Limestone member thins eastwards, perhaps having been removed by erosion during sea-level lowstand that preceded renewed flooding and deposition of the Purple Bed.

(3) Top of the Raimalro Limestone Member and lateral equivalents (Late Bathonian)

The Raimalro Limestone Member (Biswas 1980) marks the top of the Bathonian and also the end of carbonate sedimentation within the Kachchh Basin. On Pachchham Island, the limestone can be followed from Sadhara Dome in the east to Khavda (western Gora Dongar) and along the southern flank of the anticline of Kala Dongar. Lithostratigraphically, it can be correlated with a carbonate complex on Habo Dome ("Black Limestone") and the Sponge Limestone member of the Jhura and Jumara domes (fig. 7). Although its base is most likely diachronous, ammonite evidence suggests that its top is isochronous, most likely even at the easternmost occurrence (Chorad), marking a level at or close to the boundary between the Bathonian and Callovian (Callomon, 1993).

Description: The Raimalro Limestone Member is well exposed near Khavda, western Gora Dongar. On the southwestern flank of the anticline, it measures about 15 m in thickness. The thickly bedded unit consists of large-scale trough-crossbedded, sandy pack- to grainstones with occasional shell lenses and pockets, intraformational pebble layers, and layered chert nodules and bands (fig. 7C). The boundary with the underlying fine-grained sandstone shows no obvious discontinuity.

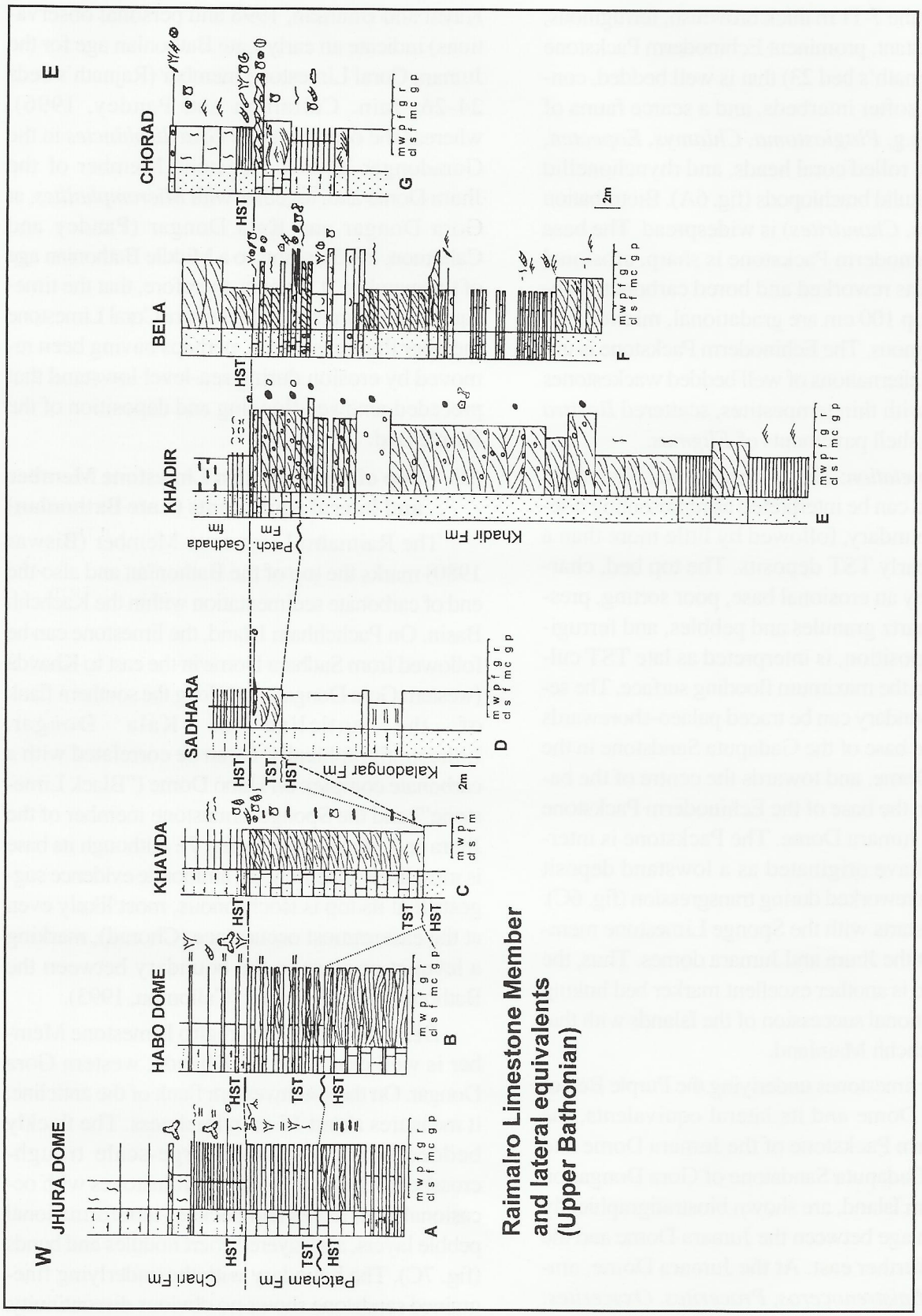

Fig. 7. Correlation and sequence stratigraphic interpretation of the Raimalro Limestone Member and lateral equivalents. For key of symbols see Figs. 3 and 5. Dashed line: lithostratigraphic boundaries; dotted line: sequence stratigraphic boundaries.

The top is sharp, often formed by a megarippled surface, but locally bioturbated and with nests of large shells of the bivalve *Neocrassina*. The overlying sediments of the Chari Formation differ in being fine-sandy marly silts, bioturbated, with thin intercalations of laminated packstones and grainstones.

On western Kala Dongar, the Raimalro Limestone Member measures 5.5-6 m in thickness, both base and top being sharp. The sand content is higher and the faunal content lower than near Khavda; other features (large-scale trough crossbedding, intraformational pebbles, chert nodules) are identical.

Towards the eastern side of Pachchham Island, the thickness of the limestone is strongly reduced. Near Taga, eastern Kala Dongar, it is represented by a less than 1 m thick yellow brownish, strongly calcareous, fine- to medium-grained sandstone with large-scale trough crossbedding. At the Sadhara Dome, on the eastern end of Gora Dongar, the unit consists of 2-3 m of massive but well bedded fine-sandy bioclastic grainstone with lenticles of bivalves and gastropods, intraformational conglomerate layers, and traces of large-scale trough crossbedding (fig. 7D).

Southwards, the Raimalro Limestone reappears in north-eastern part of the Habo Dome, south of the village of Drang. There, a unit of well bedded limestone-marl alternations up to 15 m thick is exposed (fig. 7B). The limestones are 10-80 cm thick, laminated to hummocky crossbedded, occasionally amalgamated grainstones with erosional base. The marly interbeds are 10-20 cm thick. This limestone unit was called the Black Limestone Member of the Habo Formation by Kanjilal (1978), the dark colour being due to a sill that intruded the unit. The boundary to the overlying Chari Formation is sharp, the latter starting with argillaceous silt with occasional sharp-based, laminated grainstone intercalations.

Lateral equivalents: The top of the Raimalro Limestone Member can be correlated with the top of the Sponge Limestone member of the Patcham Formation of the Jhura and Jumara domes (fig. 7A, and see §2 above). This member, a well bedded wackestone-marl alternation with numerous thin intercalations of laminated grainstones, is topped by several flaggy, 20-40 cm thick grainstone beds that are partly laminated, in part hummocky crossbedded, and exhibit flute casts. These White Flagstones are an excellent marker horizon that can be traced across all of Jhura Dome. In some areas of the dome, the contact between the Flagstone and the basal Chari Formation, with its silty marl and occasional intercalations of thin laminated grainstones, is distinct. In others a more gradual change is seen (fig. 7A), the White Flagstones being followed by 4 m of strongly bioturbated, sandy, bioclastic marl with numerous thin intercalations of graded grainstones and occasional burrows of *Ophiomorpha*, and finally by bioturbated silty fine-sandy marl with only rare intercalations of grainstones.

In the Jumara Dome, the transition from the Sponge Limestone Member to the Chari Formation (the boundary between Rajnath's (1932) beds 21 and 22) is not well exposed and is largely covered in alluvium, but coincides again with a change from a more or less pure carbonate regime to a siliciclastic regime.

Going eastwards from Pachchham Island, the Raimalro Limestone Member can be followed to the easternmost Jurassic exposures at Chorad, but its lower boundary becomes increasingly blurred. For example, on Khadir Island (section point: N of Gadhada village; fig. 7E) the member consists of 3.5 m of large-scale trough crossbedded, sandy rudstone with granitic-gneissic clasts, crinoid stems several cm long and shells of bivalves and brachiopods, underlain by strongly calcareous, medium- to coarse-grained sandstone with large-scale trough crossbedding and granitic-gneissic pebbles. The overlying Gadhada Formation (formerly the Gadhada Sandstone and Bambhanka members of Biswas' (1980) Khadir Formation)

starts with silty fine sand containing numerous thin shell beds.

On Bela Island (fig. 7F), the top of the cliffs bordering the Rann of Kachchh consists of a varied sequence of crossbedded, fine-grained, calcareous sandstones, sandy shelly rudstones (some of them with scattered Fe-ooids), coral fragments, subangular granitic-gneissic clasts, rare bone fragments, and abundant shells of the small bivalve *Nanogyra*. The top of this unit can be correlated with the top of the Raimalro Limestone Member. Its base, however, is gradational, calcareous sandstones alternating with thinner, sandy grain- and rudstones.

On Mouwana Dome, the Raimalro Limestone Member is again clearly defined as a 7 m thick unit of rubbly, bioturbated micritic and bioclastic fine-grained sandstone to fine-sandy packstone with thin lenticular shell beds. The topmost 0.9 m is hard, ledge-forming, large-scale trough-crossbedded and contains an internal megarippled surface. At the top, rare coral heads occur. The overlying Gadhada Formation starts with bioturbated fine-grained sandstone containing early Early Callovian ammonites such as *Macrocephalites* cf. *M. verus* or *madagascariensis* (see also Singh, Agrawal and Kacker, 1979, Agrawal and Kacker, 1980).

Finally, at Chorad Dome, between the villages of Jakhotra and Eval, the Raimalro Limestone Member overlies a sequence of non-marine reddish silts and variegated to grey, fine- to coarse-grained friable sandstones (fig. 7G). The carbonate unit starts with a 1 m thick, strongly calcareous, small- to large-scale trough crossbedded sandstone, in places bioturbated. This is followed by thin yellowish flagstones of calcareous fine-grained sandstone interbedded with silty-marly fine sand. The flagstones have a sharp base with tool marks and trace fossils such as *Rhizocorallium irregulare* and *Gyrochorte*. Some bivalve shells (e.g. *Plagiostoma*) occur in the softer interbeds. The following massive, hard, strongly sandy pack- to grainstone is 2 m thick, contains scattered shells (e.g. *Plagiostoma*, *Virgellia*, *Meleagrinella*) and shows small-scale and large-scale trough crossbedding. Towards the top, hummocky crossbedding and convolute bedding are present. This bed is overlain by a 50 cm thick, sharp-based, large-scale planar crossbedded intra- and bioclastic grainstone, locally very shelly (e.g. *Indocorbula*, *Protocardia*, rhynchonellid brachiopods), with echinoid spines, coral heads, and intraformational pebbles up to 10 cm in diameter. The top is formed by asymmetric megaripples, the distance between ripple crests being 50 cm. The following 1.5 m are made up of thinly bedded interbeds of calcareous fine sandstone and marly silt with the trace fossils *Planolites*, *Gyrochorte* and *Rhizocorallium irregulare* and a number of bivalve shells such as *Corbulomima* and *Mesosaccella*. More importantly, the ammonite *Macrocephalites* has been recorded from this level (D.K.P). The overlying units are again more sandy, typically bioturbated, and contain wood fragments, scattered shells and coral heads and occasional calcareous beds, such as bioclastic packstones.

Interpretation: The top of the Raimalro Limestone Member marks a distinct facies change from a carbonate-dominated regime to a siliciclastic regime over the whole of the Kachchh basin. This change, probably reflecting a shift from semi-arid to humid climate, serves as an excellent marker horizon over much of the basin. As one would expect, the character of the carbonates changes on going from a more distal position within the basin, at the Jumara Dome in the west, to more marginal areas, such as the Mouwana and Chorad domes in the east, a distance of roughly 230 km. At the Jumara and Jhura domes, the carbonates are fine-grained, contain distal tempestites, and clearly have been deposited below storm-wave base, revealing evidence only of storm-induced currents. The transition to the overlying silty marls of the Chari Formation is gradual, taking place within 10 m or so (M. Schlirf and S. Schlirf, *personal communica-*

tion), as is to be expected in such a setting. The presence of hummocky crossbedding, thicker beds, and predominance of grainstones several metres below the top in the Jhura Dome suggest the influence of storm waves and a shallowing of the depositional environment. This is followed by laminated carbonate beds indicative of storm-induced currents and thus of deepening. The transition to the siliciclastic Chari Formation is gradual in some areas, in others sharp. Similarly, at Habo most of the carbonates were deposited above storm wave-base, whereas large-scale trough crossbedding, shell lenses, intraformational conglomerates on Pachchham Island point to deposition above fair-weather wave-base. To the east, the sand content of the unit increases - evidence of a more marginal setting – and scattered quartz pebbles and granitic-gneissic clasts indicate a complex history reflecting several transgressive-regressive events. At Chorad, finally, the carbonate unit appears to consist of condensed relicts of several transgressive-regressive episodes spanning much of the Bathonian. More basinwards, these TST and HST carbonates are separated by siliciclastics deposited within a late HST. These siliciclastic sediments bypassed the marginal areas of the basin owing to lack of accommodation space and only relicts are found, in the form of quartz pebbles and granitic-gneissic clasts. In this interpretation, the Patcham Formation of the eastern areas spans a much greater period of time than it does on the Mainland or on Pachchham Island. Thus, the lower boundary is strongly diachronous. Its top, however, appears to be roughly isochronous as macrocephalitid ammonites indicative of earliest Lower Callovian have been found in the basal Gadhada Formation both at the Mouwana Dome (Agrawal and Kacker, 1980) and at Chorad.

Thus, the Raimalro Limestone Member on Pachchham Island can be interpreted as representing sediments of a TST, followed by the basal sediments of the Chari Formation, which belong to the subsequent HST. In the Jhura and Habo Domes, the sequence boundary is placed several metres below the top flagstones of the Sponge Limestone mb and Raimalro Limestone Member respectively, i.e. within the corresponding lithological units: at the change from thick-bedded strongly amalgamated to thinner-bedded hummocky crossbedded and laminated carbonates in the Habo Dome and at the change from hummocky-crossbedded carbonates to bioturbated carbonates with laminated grainstone interbeds in the Jhura Dome. The lower part of the carbonate unit in both domes is then interpreted as part of the HST of the previous sequence. In more nearshore areas (e.g. Khavda, Sadhara Dome) the sequence boundary rests on top of sandstones of the Kaladongar Formation. The lithostratigraphic boundary between the Raimalro Limestone Member and the Chari Formation and between the Sponge Limestone Member and the Chari Formation generally coincides with the maximum flooding surface.

(4) The Ridge Sandstone Member

The Ridge Sandstone member, introduced informally by Biswas (1980) (fig. 10) but still awaiting formal designation, is characteristically developed from the Jara Dome in the West to the Habo Dome in the East. It consists of three successive coarsening-upward sandstone units lying within the generally argillaceous-silty Chari Formation and separating a lower member (Shelly Shale member) and an upper member (Gypsiferous Shale member). This shale-sandstone-shale triplet of the Chari Formation corresponds roughly to the classical *Macrocephalus* Beds-*Anceps* Beds-*Athleta* Beds subdivisions of the older literature. In the present context, the focus is on the top surfaces of the lower and upper of the three sandstone units within the member, which are the excellent marker horizons.

Description: In general, thickness, grain size, trace fossil content and sedimentary structures of the two sandstone bodies change from east to west (fig. 8). In the northeastern Habo Dome, medium- to coarse-grained sandstone with large-scale trough crossbedding and occasional *Diplocraterion*

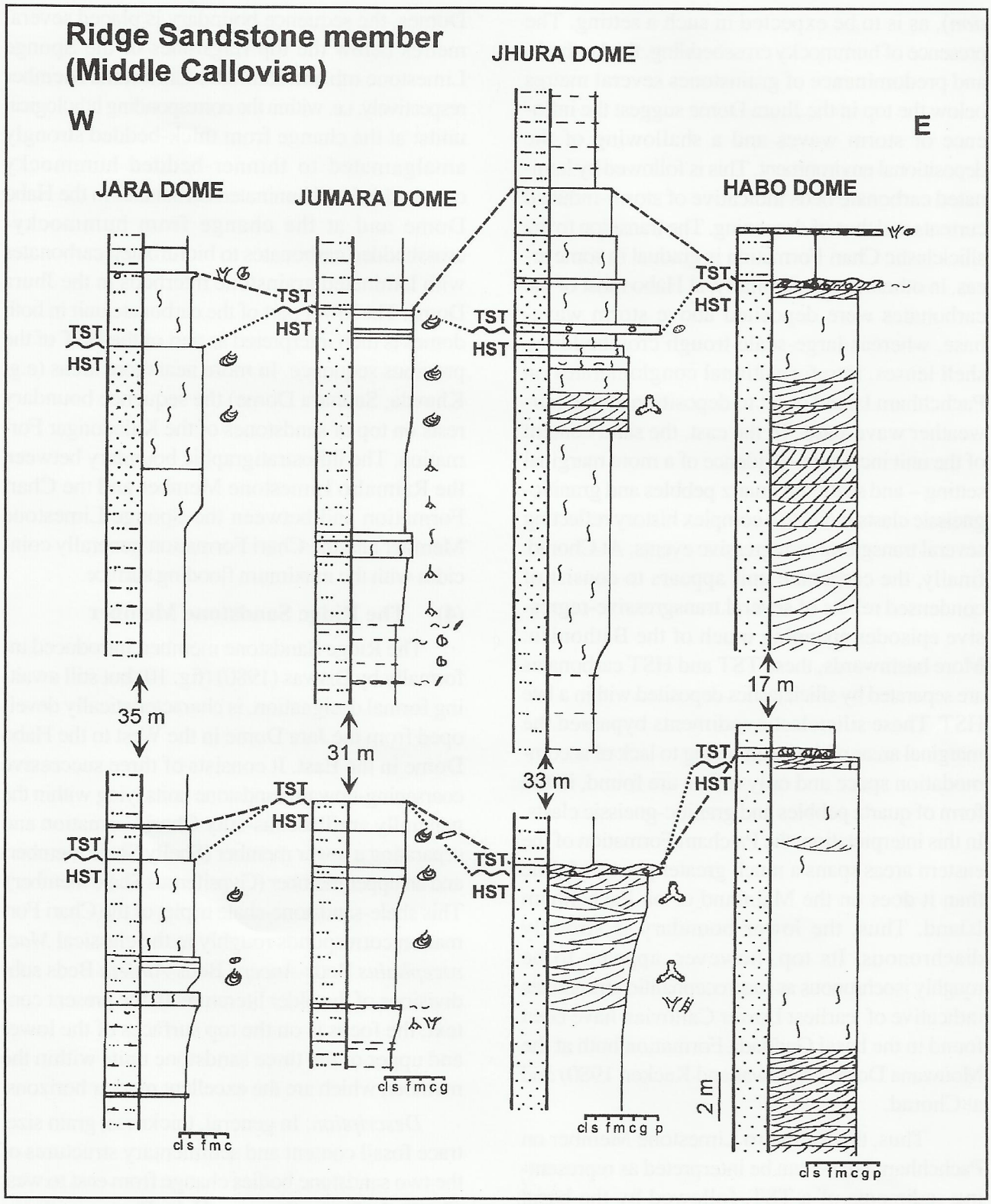

Fig. 8. Correlation and sequence stratigraphic interpretation of the Ridge Sandstone member (Chari Formation). For key of symbols see figs. 3 and 5. Dashed line: lithostratigraphic boundaries; dotted line: sequence stratigraphic boundaries. Between the lower and upper sandstone body a middle sandstone body (occurring in the interval not shown here) is present throughout the area.

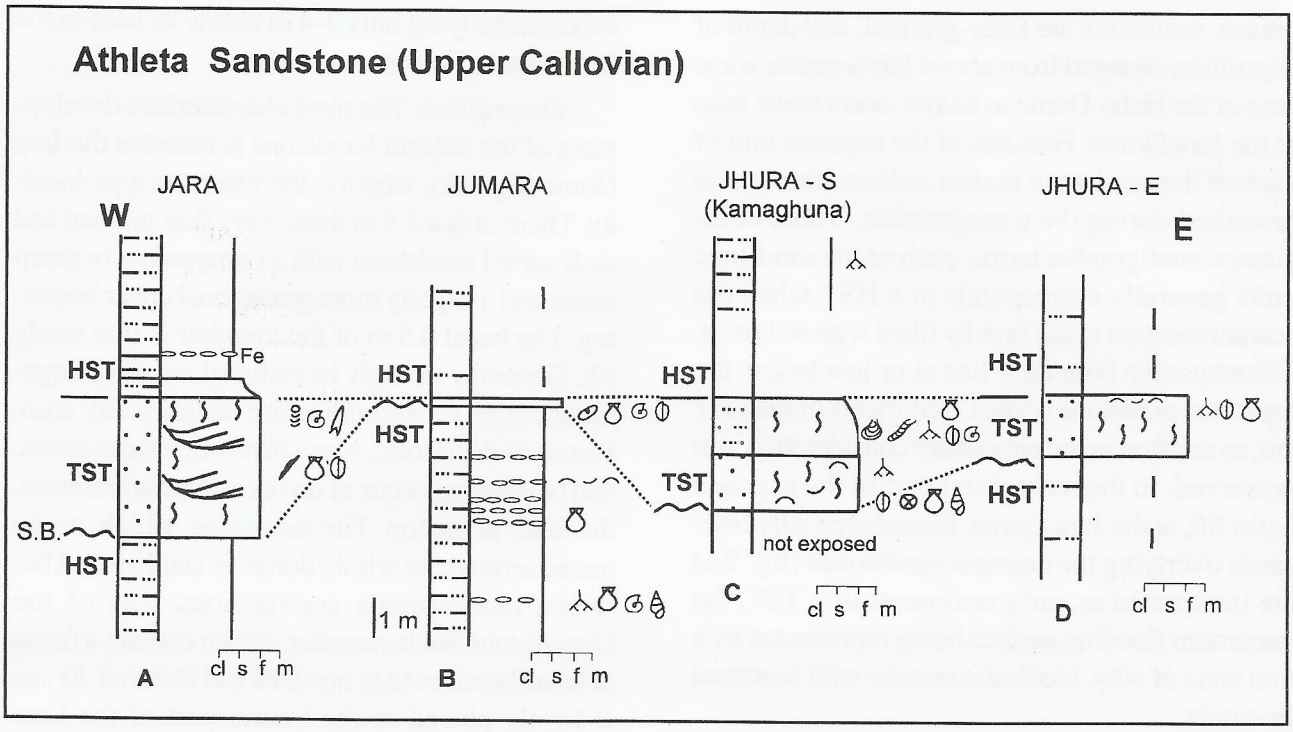

Fig. 9. Correlation and sequence stratigraphic interpretation of the *Athleta* Sandstone (Chari Formation). For key of symbols see figs. 3 and 5.

burrows occurs. At the Jara Dome, the units are thinner, their grain size has changed to silty fine sand, they are thoroughly bioturbated by *Zoophycos* and primary sedimentary structures are absent. The change to the overlying fine-grained sediments is most pronounced in the southern Jhura Dome (Kamaguna section).

At Kamaguna, the coarsening-upward sequence of the lower sandstone is topped by 0.7 m of poorly sorted, gravelly to coarse-grained, large-scale trough crossbedded sandstone with scattered sandstone pebbles. This terminal unit has an erosional base and is topped by a megaripple surface. The change to the overlying argillaceous silts that lead up to the second of the three sandstones is very sharp. At the Habo Dome (Drang section) the top is marked by a coral boulder-bed, the so-called *Amphiastraea piriformis* Bed (Fürsich et al. 1994b). Similar coral assemblages, although *in situ* and not reworked, are found at comparable levels in the Bela Anticline and on the Mouwana Dome, and are probably time-equivalent (Pandey and Fürsich, 2001). At the Jara Dome, the top layer is a 10 cm thick silty ferruginous bioclastic wackestone with scattered Fe-ooids, followed by argillaceous silt.

The upper sandstone, coarse-grained at Habo and Jhura domes, fine-grained to silty in Jumara and Jara domes, shows a similarly sharp boundary to the overlying fine-grained sediments (argillaceous or fine-sandy silt). At the Habo Dome, it is a coarse-grained, large-scale trough crossbedded sandstone with intraformational pebbles of argillaceous siltstone and scattered large shells. The top is a megaripple surface. At the Jara Dome, the top contains scattered Fe-ooids and abundant reineckeiid ammonites.

Interpretation: Ammonites show that the top of each of the two sandstone units is more or less isochronous across the basin. Body- and trace-fossils both indicate that the sandstones are fully marine, coarsening-upward trends pointing to phases of shallowing. With increasing distance from the shore, thicknesses of the sandstones de-

crease, sediments are finer-grained, and depth of deposition changed from above fair-weather wave base at the Habo Dome to below storm wave base at the Jara Dome. Features of the topmost unit of each of the sandstone bodies indicate that it was reworked during the transgression. Thus, in sequence-stratigraphic terms, each of the sandstone units generally corresponds to a HST when the accommodation space rapidly filled with sediment. The sequence boundary lies at or just below the top of the sandstone bodies. Sediments of the LST are, as so often in the area under consideration, not preserved. In the most distal part of the exposed basin fill, at the Jara Dome, bioturbated silty fine-sands overlying the coarsest sandstones (fig. 9A) are interpreted as early sediments of a TST, the maximum flooding surface being represented by a thin band of silty, bioclastic micrite with scattered Fe-ooids.

The coral boulder-bed on top of the lower sandstone unit of the Habo Dome is again part of the TST, the latter starting with a 0.6 m thick, hard, bioturbated calcareous sandstone with remains of crossbedding.

In general, the two sandstones represent strongly asymmetric transgressive-regressive cycles comparable to those discussed in the Bajocian-Bathonian part of the basin fill (§1-2). Although they distinctly change in details of lithology along an onshore-offshore transect, they serve as useful markers for subdividing the Chari Formation and correlating sub-units across the basin.

(5) The *Athleta* Sandstone

This term is introduced here for a relatively thin but prominent, feature-forming bed of well sorted sandstone that makes an excellent marker in the westernmost exposures of the Kachchh Basin, standing out in sharp contrast to the soft, recessive shales of the otherwise fairly uniform Gypsiferous Shale member of the Chari Formation, which it subdivides into two roughly equal parts. It is named after the most sharply time-diagnostic component of a rich ammonite assemblage found in a bed of concretions lying only 3-4 m below its base in the Jara Dome, *Peltoceras athleta*.

Description: The most characteristic development of the *Athleta* Sandstone is found in the Jara Dome (fig. 9A), which is therefore the type-locality. There, it is a 3.5 m thick, very fine-grained and well sorted sandstone with a comparatively sharp lower and a slightly more gradational upper boundary. The basal 0.5 m of the member is fine sandy silt. Generally strongly bioturbated, traces of large-scale trough crossbedding are occasionally seen. Pieces of driftwood, some bivalves, brachiopods, and belemnites occur as do occasional ammonites, the latter at the top. The sandstone, which can be traced around the whole dome, is sandwiched between monotonous argillaceous silts of the Gypsiferous Shale member, which contain a fauna of small bivalves (e.g. nuculids and *Bositra*). Its age is firmly placed in the lowest part of the Late Callovian, lowest Athleta Zone, by the ammonites occurring immediately below it. They include the true *Peltoceras athleta* (Phillips), which, as found here, matches the type material from England in all details over the range of variability, providing an identification with a precision that is unusual over distances such as that separating western Europe from India. The ancillary elements include species of *Reineckeia* that also match European forms well. Yet others differ strongly, belonging to groups that are bioprovincially restricted to the southern palaeohemisphere.

The sandstone is also distinctly developed in Jhura Dome, varying in thickness between 1.5 and 2.8 m (fig. 9B-C). Near Kamaguna, it is fine-grained, strongly bioturbated by *Rhizocorallium irregulare*, *Zoophycos* and *Chondrites*, and richly fossiliferous. Characteristic faunal elements include the coral *Montlivaltia*, several species of rhynchonellid and terebratulid brachiopods, bivalves, and some ammonites. Part of the fauna is preserved in position of growth (*Montlivaltia*, some brachiopods and bivalves). The sandstone is followed by argillaceous silt. In the eastern part of

the Jhura Domes the *Athleta* Sandstone is thinner (1.5 m) than near Kamaguna, is again strongly bioturbated (*Chondrites*), and contains, apart from numerous brachiopods, some bivalves.

Lateral equivalents: Strangely enough, at the Jumara Dome, situated between the Jara and Jhura domes, the sandstone is not developed as such. Instead, it is represented by a ferruginous silty fine sand only 20 cm thick, locally somewhat hardened and standing out from the surrounding soft recessive shales (Rajnath's (1932) bed 2), with reworked and bored concretions, bored ammonites and a fauna consisting of bivalves, brachiopods, and ammonites that show it to be of the same age as the *Athleta* Sandstone at Jara.

In the Habo Dome (Lodai section), it is more difficult to identify the *Athleta* Sandstone, as it is now only one in a series of similar sandy sediments. Using the distance to the top of the Dhosa Oolite member as indicator, as well as ammonites found below and above it, a probable candidate is the base of a 20 cm thick strongly ferruginous, shelly, bioclastic packstone with abundant large and bored pebbles that represent early diagenetically lithified and reworked *Thalassinoides* burrows, prominently exposed on the west side of the road 3 km south of Lodai village.

Interpretation: Sedimentary features, trace fossils such as *Rhizocorallium irregulare*, *Chondrites*, *Teichichnus*, and the benthic fauna

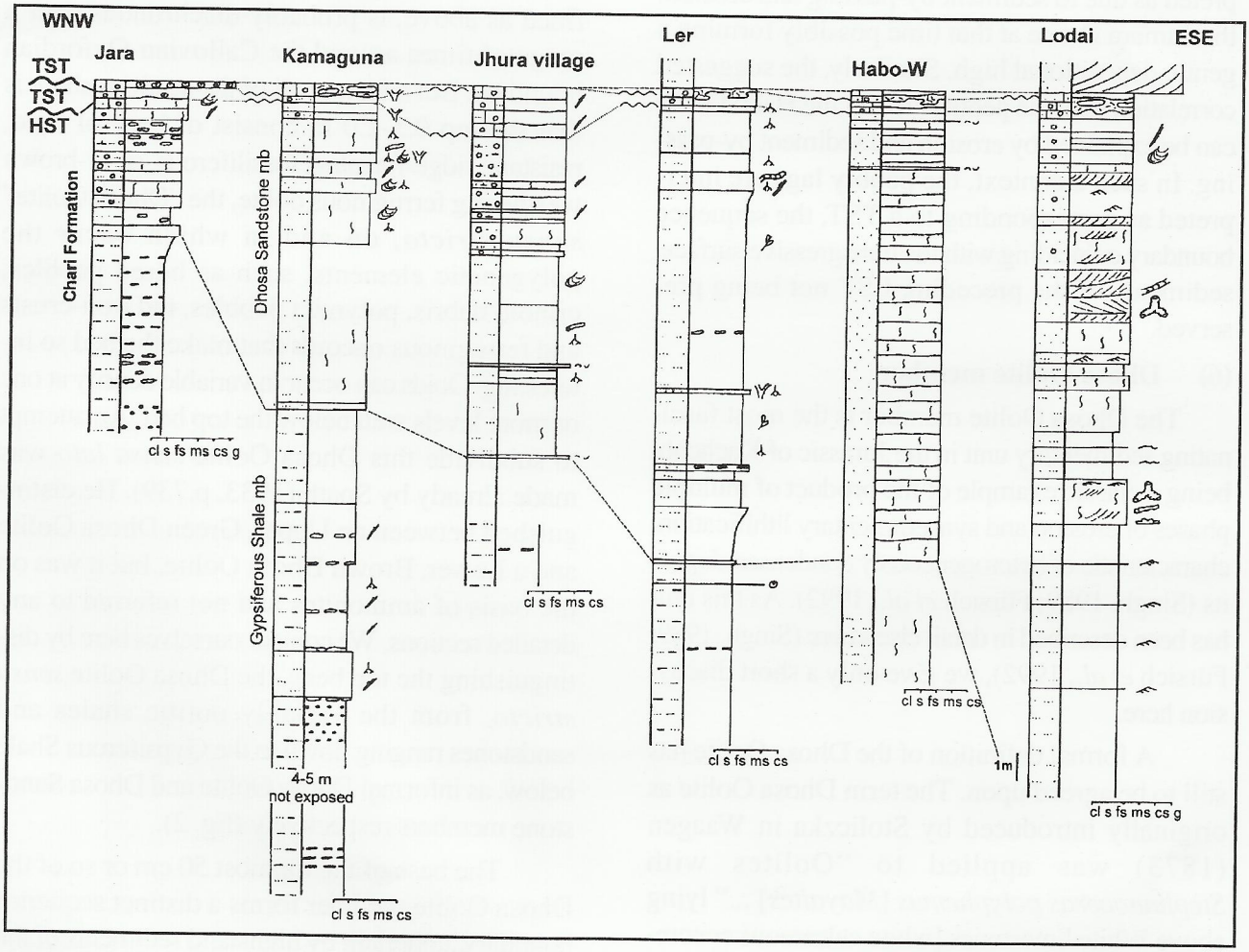

Fig. 10. Correlation and sequence stratigraphic interpretation of the Dhosa Sandstone member and Dhosa Oolite member (Chari Formation). For key to symbols see figs. 3 and 5.

indicate that the *Athleta* Sandstone has been deposited by bedload transport in a generally quiet environment below fair-weather wave base. The sedimentation rate must have been low, providing ample time for bioturbation that destroyed most primary sedimentary structures and accounting for the concentration of fossils at the top of the sandstone. Bivalves, brachiopods, and corals preserved in position of growth also point to little disturbance. The material was most probably introduced into the deeper parts of the basin during storms.

The sharp base of the *Athleta* Sandstone is indicative of a sequence boundary, the sandstone representing sediments of the TST. The thinness of the pebble lag at the Jumara Dome can be interpreted as due to sediment by-passing and erosion, the Jumara Dome at that time possibly forming a gentle depositional high. Similarly, the suggested correlation with the pebble layer at the Habo Dome can be explained by erosion and sediment by-passing. In such a context, the pebbly lags are interpreted as corresponding to a TST, the sequence boundary coinciding with the transgressive surface, sediments of the preceding LST not being preserved.

(6) Dhosa Oolite member

The Dhosa Oolite member is the most fascinating sedimentary unit in the Jurassic of Kachchh, being a classic example of the product of multiple phases of erosion and synsedimentary lithification, characteristic of heterogeneously condensed deposits (Singh, 1989; Fürsich *et al.*, 1992). As this unit has been described in detail elsewhere (Singh, 1989; Fürsich *et al.*, 1992), we give only a short discussion here.

A formal definition of the Dhosa Oolite has still to be agreed upon. The term Dhosa Oolite as originally introduced by Stoliczka in Waagen (1873) was applied to "Oolites with *Stephanoceras polyphemus* [*Mayaites*] ..." lying above White limestones [white calcareous concretions] with *Peltoceras athleta* ... ". Subsequent attempts to refine the definition have had limited success, for the lower boundary may be chosen in various ways, depending e.g. on how much emphasis is put on the presence or absence of ferruginous ooids. The most general definition would make use of a fairly sharp and widely recognizable change of facies at the top of the thick, monotonous, soft, very fine-grained and formerly pyritic shales with white, calcareous reniform concretions now called the Gypsiferous Shale member, to more coarse-grained, silty-sandy sediments, variously structured and variably oolitic. The total thickness of these sediments ranges from 4 m at Ler and 5 m at the Jara Dome, 10 m at the Jhura Dome to 15-20 m in the Habo Dome. Details of the succession vary rapidly from place to place and, to judge by the ammonites, the lower boundary, lithologically defined as above, is probably diachronous over a range of times around the Callovian-Oxfordian boundary. But a feature all of the sections share is that the top 0.5-1.0 m consist of beds of hard, resistant, ridge-forming, fossiliferous, olive-brown weathering ferruginous oolite, the "Dhosa Oolite" *sensu stricto*, on and in which occur the polygenetic elements, such as bored pebbles, crinoid debris, polymict pebbles, red iron-crusts and ferruginous oncoids that make the bed so interesting. Ooids can occur in variable density at one or more levels well below the top bed. An attempt to subdivide this Dhosa Oolite *sensu lato* was made already by Spath (1933, p.739). He distinguished between an Upper, Green Dhosa Oolite and a Lower, Brown Dhosa Oolite, but it was on the basis of ammonites and not referred to any detailed sections. We content ourselves here by distinguishing the top beds, the Dhosa Oolite *sensu stricto,* from the variably oolitic shales and sandstones ranging down to the Gypsiferous Shale below, as informal Dhosa Oolite and Dhosa Sandstone members respectively (fig. 2).

The base of the topmost 50 cm or so of the Dhosa Oolite member forms a distinct sequence boundary, underlain by highstand sediments of the Dhosa Sandstone member (silt to fine sand, e.g. in

Fig. 11. Sections through the Bajocian-Bathonian rocks of the Islands and the Jhura Dome. L: *Leptosphinctes* Pebbly Rudstone; P: Purple Bed; R: Top of the Raimalro Limestone member. For key of other symbols see figs. 3 and 5. Vertical lines on the left side of the section columns indicate carbonates and mixed carbonate-siliciclastic rocks.

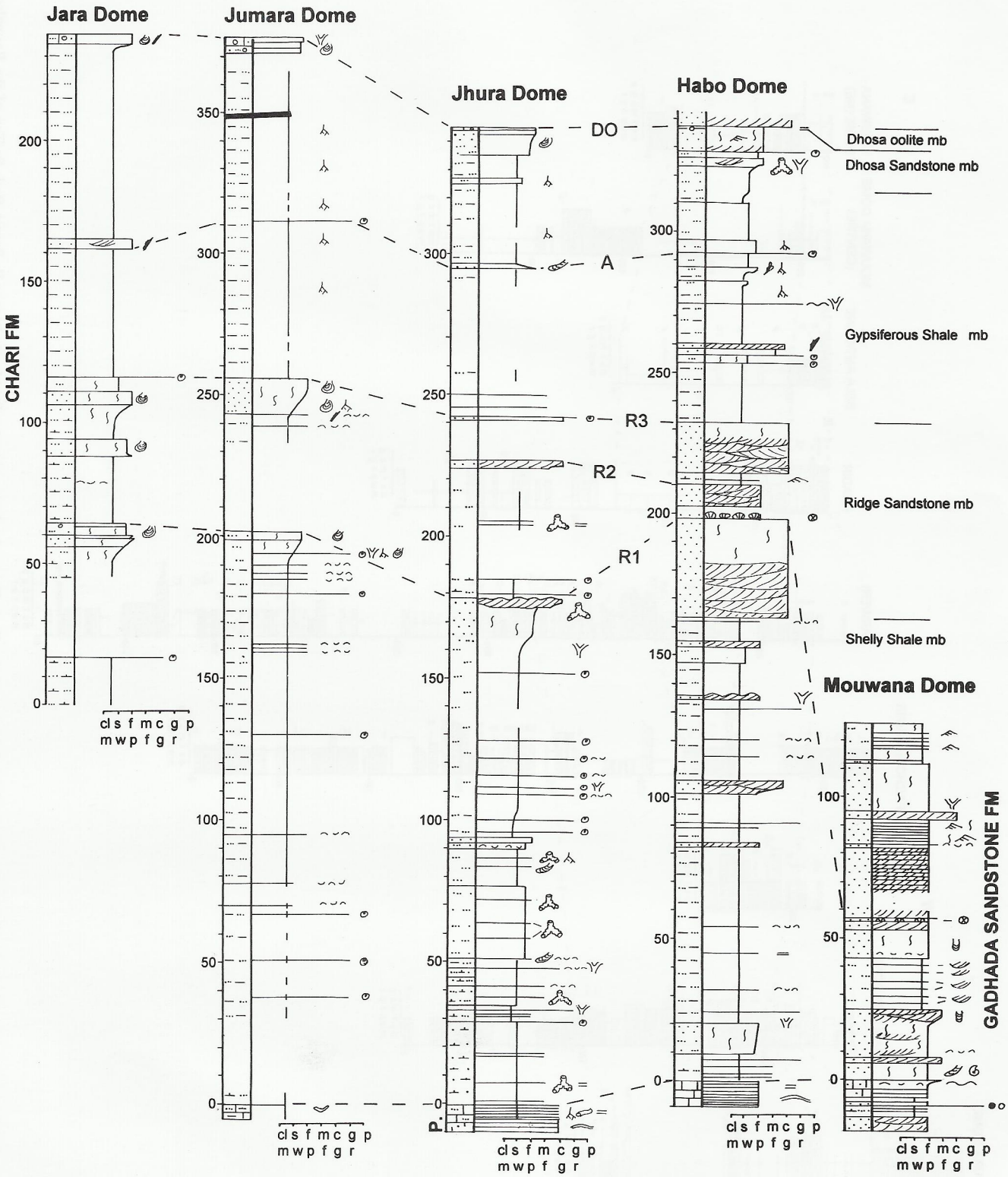

Fig. 12. Sections through the Callovian-Oxfordian rocks of the Kachchh Mainland. R1: Top of lower Ridge Sandstone; R2: top of middle Ridge Sandstone; R3: top of upper Ridge Sandstone; A: *Atʰleta* Sandstone. For key to other symbols see figs. 3 and 5.

the Habo Dome and at Ler, Fe-oolitic silt and marl at most other localities) (fig. 10). The rapid lateral facies change (e.g. between the Kamaghuna and Jhura village sections; fig. 10B-C) may indicate some relief of the sea floor, perhaps caused by synsedimentary fault movements. The complex sedimentary and erosional history of the Dhosa Oolite member indicates that several sequences are telescoped within a few decimetres of sediment. This unit, varying only slightly from place to place, can be traced all over the Kachchh Mainland, thus recording a major sea-level rise. Consequently, it is an excellent genetic as well as lithologic marker horizon. The occurrence at the top everywhere of Lower Oxfordian ammonites, particularly of *Peltoceras semirugosum* Waagen, shows that this marker bed is closely synchronous, and the absence of Middle and Upper Oxfordian ammonites above it points to a major hiatus. This extends over an interval comparable to a whole Stage, as the overlying sandstones of the Katrol Formation are Kimmeridgian in age, and not older than Middle Kimmeridgian at that.

In the Islands, the only one on which beds of equivalent age are still preserved is Khadir, at its southernmost extremity near the village of Bambhanka and on the adjacent islet of Kakindia Bet. The Kakindia Limestone Band of Biswas (1980, p.23, fig. 8) is the undoubted equivalent of the Dhosa Oolite, both lithologically and biostratigraphically as shown by ammonites of late Early Oxfordian age. It is surmounted by a prominent ferruginous pebble-bed, overlain with marked change of facies by a succession of thin-bedded, variably ferruginous sandstones, shales and conglomerates of the upper part of Biswas' Bambhanka Member. These higher beds are only sparsely fossiliferous and it is uncertain, therefore, whether they are equivalent to the basal Katrols that follow the major non-sequence above the Dhosa Oolite on the Mainland or whether they begin to see the incoming of the well-known Middle Oxfordian sediments that fall into the gap on the Wagad Dome to the east, between Bharodia, Tramau and Kanthkot.

CONCLUSIONS

Detailed logging and sedimentological analysis of numerous sections have revealed a number of marker beds that help to correlate the Middle Jurassic sedimentary fill of the Kachchh Basin in a framework of genetic sequence stratigraphy (figs. 11-12). These marker beds are found at the bases of 3rd order cycles. They are invariably rich in marine fauna, contain concentrations of allochthonous clasts and of intraformational pebbles, and are frequently strongly bioturbated. In general terms these horizons represent early deposits of TST with palimpsest sediments of former LST. These marker beds are transgressive lag deposits with sequence boundaries at their bases.

Although a comprehensive sequence-stratigraphic interpretation of the Jurassic rocks is beyond the scope of this paper, it is clear that higher orders of cyclicity can also be widely recognised. For example, the general deepening trend during the deposition of the Callovian Chari Formation culminates in the condensed Early Oxfordian top of the Dhosa Oolite member, which can be interpreted as a maximum flooding surface (see also Fürsich *et al.*, 1993). This coincides roughly with the transgressive-regressive (T-R) facies cycles of Jacquin & Graciansky (1998), who claimed to have recognized a maximum flooding zone in the western Tethys in the Early Oxfordian. Their following T-R facies cycle, however, starting in the Late Oxfordian and reaching its acme in the Late Kimmeridgian, cannot be recognised in Kachchh, as the silty to sandy Middle Kimmeridgian sediments overlying the Dhosa Oolite Member do not suggest a deepening. Biswas (1991) recognised two T-R cycles in the Bajocian-Oxfordian succession of the basin, with transgressive peaks in the Early and Late Callovian respectively, and interpreted the Early Oxfordian top part of the Dhosa Oolite Member as a regressive unit, a view we can-

not support on the evidence of the facies.

At the other end of the scale, parasequences can often be recognised in individual systems tracts. In marginal areas of the basin they are represented by coarsening-upward hemicycles. In more basinal areas, these parasequences are commonly defined by thin conglomerates of reworked concretions and/or shelly lag deposits representing the deepening phases, which alternate with argillaceous silt corresponding to the shallowing phases (see also Fürsich *et al.*, 1993).

These patterns suggest that, during the Middle Jurassic, sedimentation in the Kachchh Basin was in first place determined by fault-controlled subsidence of the basement with which sediment input largely kept pace, giving a cumulative basin-fill of up to 700 m of relatively shallow-water sediments. Superimposed on this were cyclic patterns of sedimentation. These were coupled to changes in relative sea level that were partly eustatic in origin and partly reflections of fluctuations in the history of subsidence arising from extensional tectonics in the graben. In the case of parasequences, the cycles were probably coupled also to changes in climate. However, climatic changes probably controlled in addition some large-scale changes in the sedimentation pattern, such as the major change from carbonate to siliciclastic sedimentation around the Bathonian-Callovian boundary that may reflect a change from semi-arid to humid conditions. This is supported by corresponding changes in faunal diversities and compositions (Fürsich *et al.*, in prep.). A similar climatic change has been proposed, on the evidence of clay mineralogy, to have taken place from the Middle to the Late Jurassic in Madagascar (Uhmann, 1996).

To what extent the 3rd order sedimentary cycles are controlled by changes in eustatic sea level or reflect regional tectonic events (after all, not unusual within a rift basin) is not yet clear.

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