Chapter 2
Mesozoic Stratigraphic Framework in India with Focus on the Jurassic Geological Record in the Kachchh Basin

Abstract It updates the biostratigraphic refinement in the Indian Mesozoics with focus on the Triassic in Spiti, Jurassic in Kachchh, and Cretaceous in Kachchh and Cauvery. As an example, the ammonoid stratigraphic zonation in Kachchh basin inclusive of the new Oxfordian zones, as also the origin of the basin are developed at length. Also are touched upon the salient pre-sequence Paleozoic features as back drop, along with the start and termination of the sequence. State of the art is presented on the integrated high resolution scales for the three periods. The Early-amd Middle Triassic update includes integration of $\sim$35 ammonoid zones to $\sim$15 conodont zones in the lithostratigraphically and splendidly resolved Spiti sections. The Indian Late Triassic to Early Jurassic is largely ammonoid devoid but for scanty Early Jurassic presence at Lamayuru in Ladakh. The Jurassic includes $\sim$35 ammonoid zones, over 50 subzones, and yet more number of Horizons in the Middle and Late in well-resolved Kachchh sections. The Cretaceous update is compositely presented of 18 informal ammonoid zones with ammonoid presence almost in all the 12 stages in some or other Indian basin yet lacking the desired level of lithostratigraphic differentiation.

Keywords Lithostratigraphy · Ammonoids · Lineages · Heterochrony · Range charts · Zones/Subzones/Horizons · Biostratigraphy · Correlation · IEAP · Kachchh · Spiti · Cauvery · Bivalves · Forams · Conodonts · Palynomorphs · Mesozoic · Triassic · Jurassic · Cretaceous

2.1 Origin of the Kachchh Basin

Kachchh is a pericratonic rift basin in the extreme west of India that was proximal and united to NE Madagascar in the erstwhile Gondwana during most of the Mesozoic (Fig. 1.7). Earlier, the intra-Permian origin of the Neotethys witnessed

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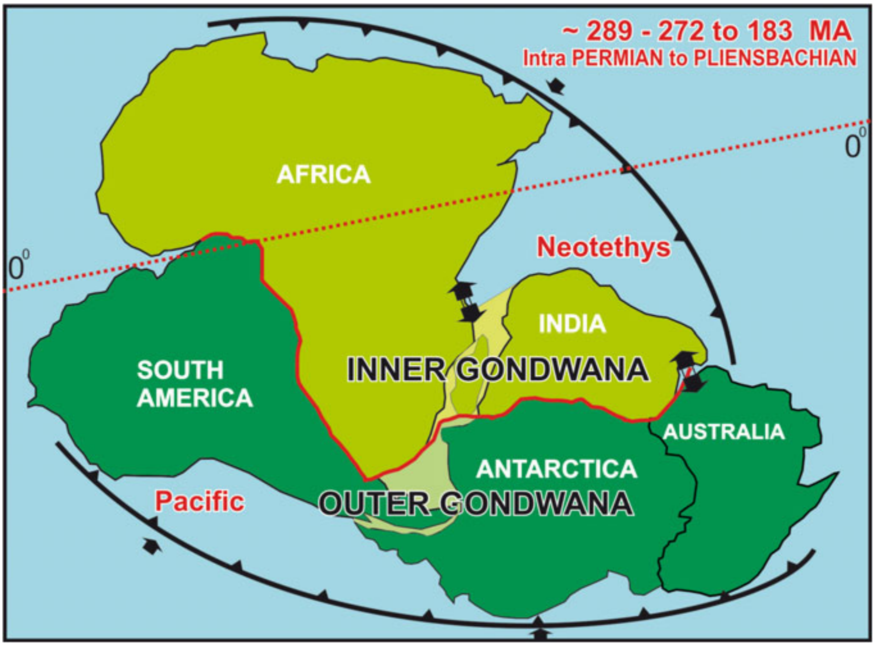


Fig. 2.1 Reorganization of plates and associated rifting on either side of India (inclusive of Madagascar) in India–Africa and India–Australo-Antarctica sectors as possible consequence of compression extented inward from the Neotethyan and Pacific margins of the Gondwana (modified after Geiger and Schweigert 2006)

tilting/subsidence of the just carved new north and northwest margins of India towards the new ocean. The crustal sagging/attenuation/extension/infra-rifting-related progressive subsidence during the Late Permian – Mid-Triassic interval gave rise to number of pericratonic rift basins on India's west, north and east margins inclusive of Kachchh due to reactivation of the faults of the Precambrian times. The mentioned extensional tectonics resulted presumably due to the build-up of threshold level inward radially directed stresses all round the Gondwana (Fig. 2.1).

2.1.1 Reactivation of the Precambrian Weak Zones

The ancient Precambrian weak zones, parallel to the east–west striking Narmada fracture, reactivated in the Kachchh region, which was located north of the mentioned fracture between the Nagarparkar, high in the north and the Saurashtra–Kathiyawar high in the south (Fig. 1.6). The rifting proceeded from north to south in sympathetic consequence of the reactivation of the India–Africa north–south-directed rifting, almost parallel to the future fracture zones of 40°E and

50°E. The mentioned fractures east and west of Madagascar later formed India's west margins in succession, first inclusive of Madagascar and subsequently exclusive of Madagascar.

2.1.2 Infra-rift Sagging

The rifting in the Kachchh region took place in steps, with presumable initiation of the infra-rift sag stage at the start of the Late Permian. The infra-rifting is considered linked to the origin of the Neotethys in the north sector. This interpretation is based on the record of reworked Late Permian palynomorphs in Late Jurassic and Miocene sediments in different parts of Kachchh (Venkatachala 1970). In this context, the record of the reworked Permian palynomorphs in Salt Range north of Kachchh, and in Kerala south of Kachchh, provides credence to the above interpretation in a regional frame. The record of the reworked Late Permian palynomorphs is followed up by the oldest insitu sediments in the Kachchh basin of the Anisian–Pliensbachian age bracket in multiple wells (Koshal 1984).

2.1.3 Intra-Triassic Rift Initiation

The actual/effective origin of the rift basin is interpreted in the MiddleTriassic. In the progression of rifting, each due south step went deeper than the previous one. The Kachchh region sloped due west at the start of the rifting. Thus was developed the resultant southwest sloping basin. The initiation of the mentioned intra-Triassic rifting in Kachchh has been précised near the close of the Mid-Triassic Anisian stage, based on the application of sequence stratigraphy to the Triassic succession of Spiti (Krishna in Bajpai et al. 2012) (discussed in detail in Chap. 3) above the Late Anisian Hollandites Zone–Kellnerites Zone in bed 34 (Krystyn et al. 2004). Small shallow east–west directd non-marine basin/s may have originated with progressive rifting. The presence of non-marine sediments in the Banni and Nirona wells close to the KMU (Kachchh Mainland Uplift) suggests existence either of a ~100 km long east–west striking basin or of two or more basins of smaller sizes. The exercise may have even involved migration of the rift locii in the early phase of the rift basin.

2.1.4 Early Non-marine Phase Prior to the Neotethyan Transgression

The basin in its initial phase escaped inundation by the north–south-directed arm of the Neotethys, and instead received only localized shallow non-marine sediments as evidenced in the Banni and Nirona wells (Fig. 1.5 locality map). It could be transgressed by the Neotethys only in early Early Toarcian as a result of the cumulative effect of the start of sea level rise and tectonically caused submergence near the Pliensbachian–Toarcian boundary. The reworked Late Permian non-marine sediments with possible extension into Early Triassic, subsequently may have been eroded away. The non-marine Late Permian–Early Jurassic phase preceded the initiation of the marine regime in the basin in basal Toarcian. The initial transgression was sudden as evidenced by the widespread presence of the Toarcian–Aalenian coccoliths (Rai and Jain 2012, 2013) almost in the entire exposed sites of the basin, not just in the relatively distal Mainland, but also in the proximal Island belt in the north and Wagad in the east of the exposed margin.

2.2 Salient Features in Brief Prior to the Mesozoic

Significant multifaceted geological transformation occurred immediately prior to the Late Permian–Early Paleogene mega-sequence at the Early/Late Permian boundary on the Paleotethyan East Gondwana margin. Emphasis has been given to the drastic geological changes associated with or without gap, not just in the Indian Mesozoic geological record, but also below the Mesozoic. These are summarized here to provide a backdrop to the present chapter on the current status of the stratigraphic refinement in the Indian Mesozoic geological record.

2.2.1 Intra-Devonian Origin of the Paleotethys

In recent publications (Metcalfe 2011 and others), a widespread interpretation has gained ground of the origin of the Paleotethys out of Paleopacific/Prototethys (Fig. 2.2) as late as intra-Devonian along with the spreading away of Tarim, North China, South China, Indo-China and a few other microcontinents from the north margin of the Indo-Australian plate.

2.2.2 Major, Widespread Gaps in India and Neighbourhood Prior as also During the Late Permian–Early Paleogene Mega-Sequence

Large gaps are known prior to, as also after the commencement of the mega-sequence which provide significant clues to the integrated geodynamic

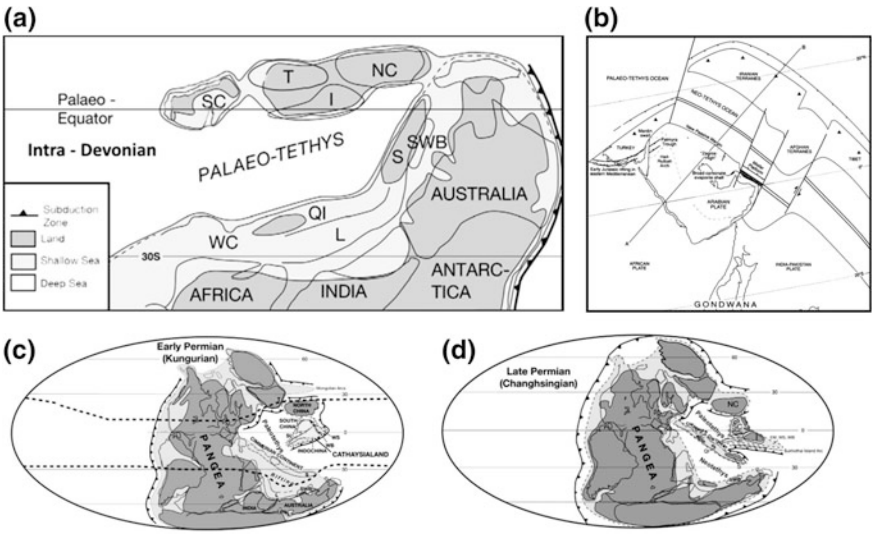


Fig. 2.2 Origin of Paleotethys and Neotethys (**a**, **c**, **d**) (modified after Metcalfe 2011 and **b** modified after Sharland et al. 2001)

evolution. These are invariably subaerial, and are evidenced in the geological record in several Indian basins including the non-marine Gondwana basins. A few such gaps are present even in the GTM basins. The gaps up to the Early Permian are on the Paleotethyan margin, and later ones on the Neotethyan margin. Among such gaps, the most widely spread and one of the largest is the almost continuous one on the proximal Paleotethyan margin from the terminal Precambrian to Carboniferous of more than 240 my in several belts and basins. The Early Permian marked a widespread rifting event in High Himalaya, Lesser Himalaya, Narmada–Son–Damodar belt, and elswhwere. In the Upper Indus basin of Pakistan, the gap is from Cambrian to Carboniferous. In Lesser Himalaya, Assam, and West Rajasthan Bikaner and Nagaur basins, the gap ranges at least from the late Middle Cambrian to the close of Carboniferous. In Ganga basin, it includes gap of most of the Ordovician (Prasad 2011), later part of Devonian and entire Carboniferous. In High Himalaya are present relatively much shorter gaps from late Cambrian to Early Ordovician, from Wenock to Middle Devonian, Middle Permian, Changhsingian to Induan (Bhargava 2008). Smaller gaps are also widely present in Indian basins during the Middle Triassic, Late Jurassic and Late Cretaceous.

In the Indian northeast, the gap extends from the Cambrian up to the close of Mesozoic but for a short transient Early Permian in many basins. In the K-G basin, near continuous Permian to Quaternary succession is present, while the gap is from the Precambrian to Carboniferous. In Cauvery, the gap, but for a short Permian intervention, extends up to late Middle Oxfordian. In West Bengal, the gap is from the Late Precambrian to Carboniferous. In the Gondwana basins, the gap extends from Precambrian to Carboniferous and then again from Toarcian to late Middle Oxfordian.

The mentioned gaps of different durations are probably caused by the tilting down/up of the distal/proximal locations of the basins episodically at important tectonic events, for example, in the distal High Himalaya the gaps are causally associated with tilting down of the plate. Similarly, tilting up of the proximal locations of the submerged part of the Indian plate prompted the gaps in Lesser Himalaya, Vindhyan and Ganga basins. The gaps included in the mega-sequence are discussed and differentiated with regard to their subaerial or submarine character in appropriate context in later chapters.

2.2.3 Widespread Basal Permian Extensional Tectonics, and Glaciation, Followed up Further by Major Transgressive Event

The widespread basal Permian extensional event supposedly reactivated the pre-existing fracture zones. Linear graben/half-graben basins formed along High Himalaya, Lesser Himalaya, Gondwana and a few other localities. One of the all-time major Gondwana events was of widespread glaciation that ranged from the terminal Carboniferous to basal Permian. The glaciation in India occurred in basal Permian, and is evidenced through the basal Talchir boulder and coeval units of explicit glacial impress. As the climate improved and temperatures picked up immediately after the glaciation, the melting of ice prompted the rise of sea level. It in turn resulted in an important and widespread transgression (Fig. 2.3) not only on the Paleotethyan margin but also in West Rajasthan, Bihar, Madhya Pradesh, Orissa, Tamilnadu, Uttarakhand, northeast states and elsewhere, also suspected in Kachchh.

2.2.4 Intra-Permian Origin of the Neotethys

The most important geological event on the GTM has been the intra-Permian origin of the Neotethys. The basal Permian rift developed into spreading at the start of Late Permian, locally even earlier at the Sakmarian/Artinskian boundary as suggested by the start of volcanism around this time (Shellnut et al. 2009). The start of the spreading marks the basal SB of the mega-sequence. A few microplates (Cimmeria continent) broke and spread away due north to subsequently unite with the then Asian congregation, and thus in size grew the Neotethys.

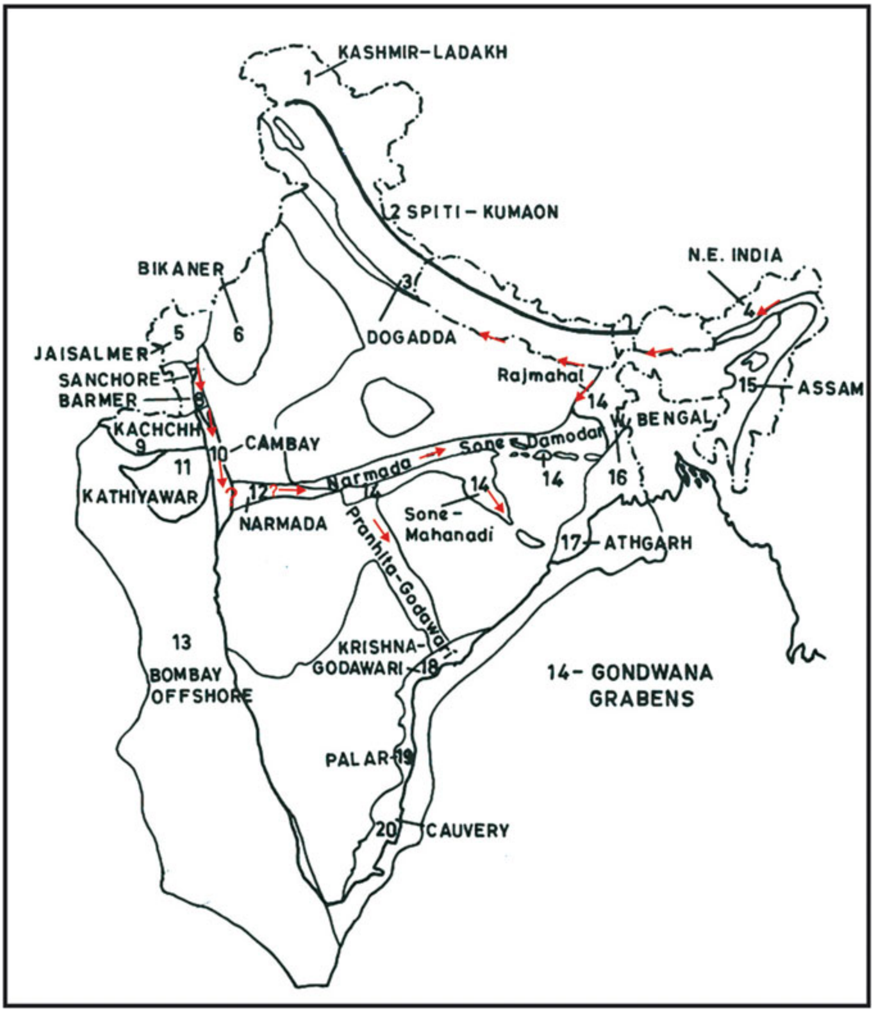


Fig. 2.3 early Early Permian transgression along the Gondwana basins from the east with suspected connection to the west sector through Barmer–Sanchore–Cambay–Narmada (modified after Krishna 1987a)

2.2.5 Wide Spread Early/Late Permian Change in Inland Non-marine Gondwana Basins at the Start of the Mega-Sequence

Widespread lithological and faunal/floral change and stratigraphic break are known between the Barakar and the coeval units below and the Raniganj and the coeval

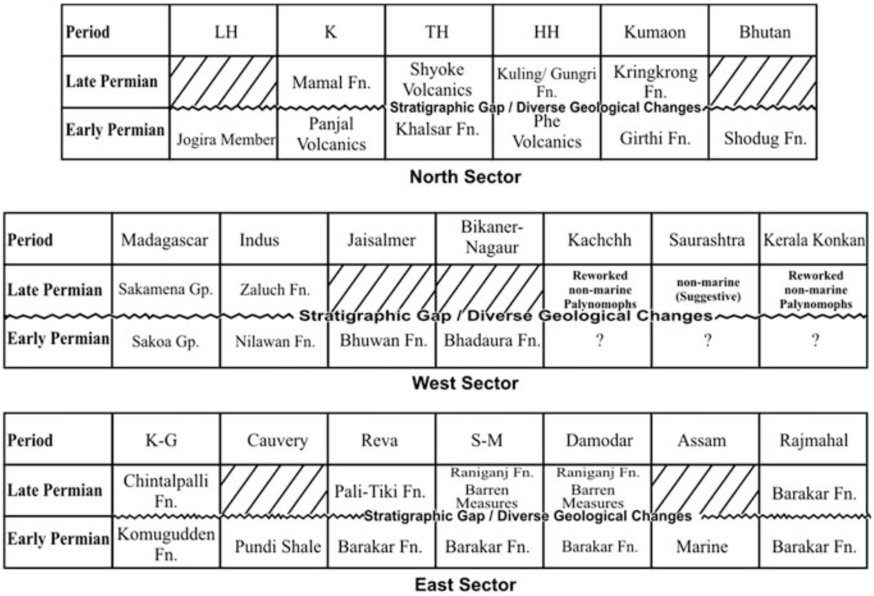


Fig. 2.4 Widespread geological changes with or without stratigraphic gap between Early and Late Permian at the base of the mega-sequence

units above within the intervening Barren Measures. The post Barakar gap is at least of the Middle Permian Wordian stage of the broad D. indicus palynozone in almost all the inland Gondwana (Satpura, S. Rewa, Damodar, Rajmahal and Pranhita–Godavari) basins (Fig. 2.4). The lithostratigraphic succession of the Talchir–Karharbari–Barakar units is nearly identical in all the inland non-marine Gondwana basins. However, the mentioned uniformity is not maintained further up due to a widespread post Barakar event. The Permian is otherwise featured with widespread Gondwanian *Glossopteris* flora which allows easy differentiation of the GTM Permian from the neighbouring Cathyasian and Angaran land assemblies and their diagnostic floral elements.

2.2.6 *Early/Late Permian Change in Marine Basins*

The disconformity between the Early Permian Pundi Shale and the Early Cretaceous sediments in the Cauvery basin well, between the Komuguddem Formation of Early Permian age and Late Permian Chintalpudi Formation in K-G basin in outcrops as also in wells, is well-documented. Similar disconformities are

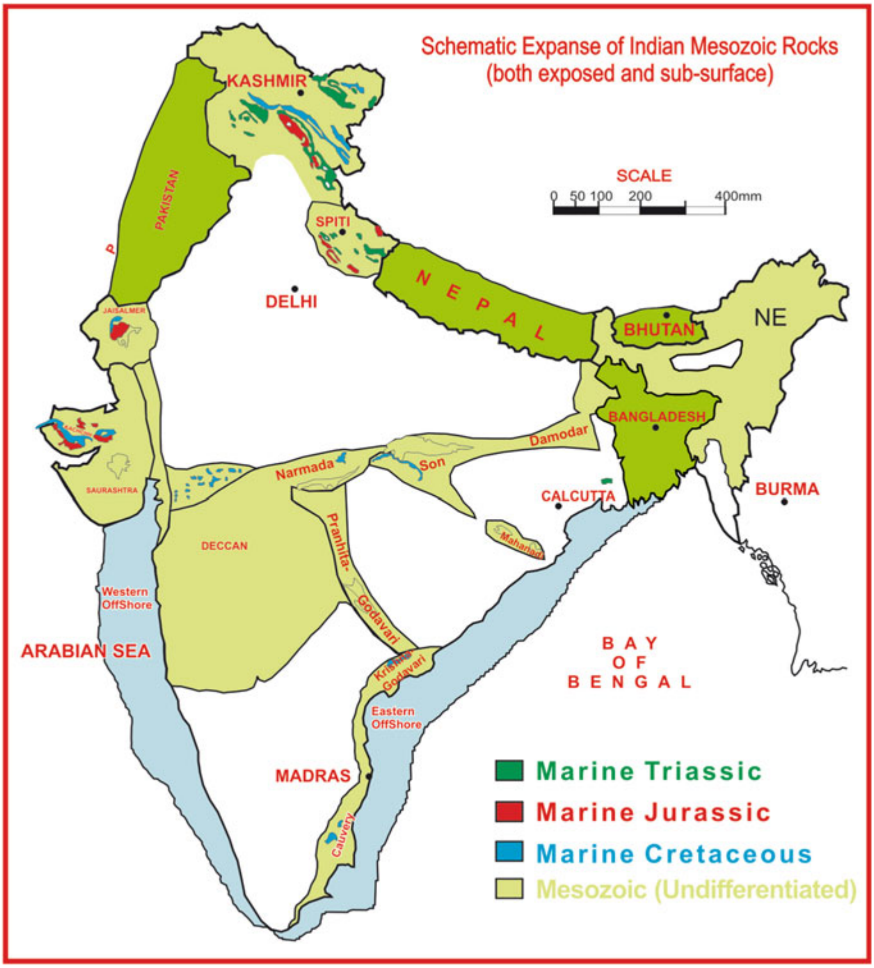


Fig. 2.5 Schematic expanse of Indian Mesozoic sediments (both exposed and subsurface)

recorded in the Palar basin, in the Lesser Himalaya between the marine Early Permian and the younger sediments, also in Shilong (Assam) above the Early Permian, in West Rajasthan above the Early Permiam Bap and Badhaura units. These disconformities are manifestations of a widespread mid/late Permian Pan-Indian event or even Pan IEAP event (Fig. 2.4).

The detailed current status of the Indian Mesozoic stratigraphic distribution (Fig. 2.5) and refinement along with salient geological events.

2.3 Triassic

2.3.1 Triassic System—International and National Status

The Triassic system was so named in 1832 by Alberti in North Germany, in view of its tripartitite division into Bunter, Muschelkalk and Keuper in ascending order. Soon it was realized that the first and third divisions were mostly non-marine, and thus difficult to subdivide and refine further as also correlate to the far located basins. This in turn prompted discovery and description of the exclusively marine ammonoid-rich Triassic in Alps as replacement for the earlier divisions. The Alpine Triassic found ready acceptance among the Triassic stratigraphers of the time. The Triassic is currently organized into a succession of seven stages, two in the Early (Induan and Olenekian), two in the Middle (Anisian and Ladinian) and three in the Late Triassic (Carnian, Norian and Rhaetian). According to the 2012 Geological Time Scale (Gradstein et al. 2012), the Triassic ranges from 252.2 to 201.3 ma with a duration of 50.9 my. The system is defined by the base of its first stage—Induan—and more precisely by the base of its first conodont based Parvus Zone. The system includes a succession of about 45 ammonoid zones with average zonal resolution of 1 my. Conodont studies have also provided a moderately well-resolved parallel scale into ~25 zones.

2.3.2 Development of Triassic in India

Among the best developed and early studied Triassic in the world is held the Triassic of the Indian High Himalaya with best studies to date in the Spiti basin. Apart from High Himalaya, marine Triassic is not exposed any where else in India. On the contrary, non-marine Triassic is well-developed in several Gondwana graben basins. Subsurface Triassic is also encountered in part or full in a few East Coast basins, particularly in K-G and Bengal basins. Subsurface Triassic is also present in the Indian Jaisalmer and Pakistani Indus basins.

2.3.3 Triassic Succession in Spiti

The Spiti basin of High Himalaya includes one of the best developed ammonoid marine Triassic in the world with a gap over the Late Permian. Stoliczka (1866), Hayden (1904) were the earliest workers who investigated the Triassic stratigraphy of Spiti. Srikantia (1981) mapped the area and classified the succession into five formations. Bhargava et al. (2004) have organized the succession into four mappable groups and ten formations, and subdivided them further into member units (Figs. 2.7, 2.8, 2.9, 2.10, 2.11, 2.12, 2.13, 2.14, 2.15, 2.16 and 2.17), along with detailed description of the lithological and paleontological features of the formations and members. The ~1400 m thick Triassic sediments unconformably ovely the Wuchiapingian Gungri unit. In between is a thin ferruginous layer. Changhsingian makes a gap below the Triassic. Mikin Formation—the basal most of the Triassic—is extremely rich in the stratigraphically significant ammonoids, compared to the overlying succession of the Kaga to Kioto units. Other significant fossil groups present are bivalves and conodonts.

2.3.4 Intra-Triassic Interstage Boundaries

In Triassic, the interstage boundary demarcation is possible only in Spiti basin, and is based mostly on Bhargava et al. (2004) and Krystyn et al. (2004) (Figs. 2.6, 2.7, 2.8, 2.9, 2.10, 2.11, 2.12, 2.13, 2.14, 2.15, 2.16 and 2.17).

The base of the Induan stage or for that matter of the Triassic system is best approximated in the Spiti (High Himalaya) stratigraphic sections between the underlying Gungri Formation of the Kuling Group or its coeval units in spite of some gap exclusively on the Permian side of full or part of Changhsingian. The youngest brachiopods of the Gungri Formation are ranged up to Early Changhsingian (Bhargava 2008). The boundary lies in the early part of a normal magnetic polarity chron. The basal *Otoceras* ammonoid bed includes the basal Triassic *Hindeodus parvus* Zone (Krystyn et al. 2004). Immediately underlying is a marker ferruginous layer. In turn underneath the ferruginous layer, is picked up the Europium enrichment event in the youngest black shale (Bhargava 2008). In the non-marine Gondwana basins the P/T boundary is approximately delineated between the Damodar Group/Formation and the Panchet Formation on the basis of the succession of palynoassemblages/events. Vijaya (1997) demonstrated the similarity of the late Permian and Induan palynoassemblages of non-marine Gondwana basins and the Spiti and Niti basins of Higher Himalaya and termed them as the palyno-assemblage/event 4 of Late Permian age and palyno-assemblage/event 5 of the basal Triassic Induan age.

The demarcation of interstage intra-Triassic boundaries is reproduced here as determined by Bhargava et al. (2004) and Krystyn et al. (2004) (Figs. 2.7, 2.8, 2.9, 2.10, 2.11, 2.12, 2.13, 2.14, 2.15, 2.16 and 2.17).

The Induan/Olenekian Boundary is placed between the thick limestone bed 13 and the thinly bedded limestone bed 14 (Fig. 2.7b). It is based on the *Flemingites* bearing beds below and the *Parahedenstroemia* inclusive beds above in several sections of the Spiti basin. On the basis of conodonts, the boundary is placed at the FAD of *Neospathodus waageni* (Fig. 2.7a). An other good level is the FAD of *Rohilla* that marks the base of the beds with *Flemingites* sensu lato. Another possibility is suggested at the FAD of *Flemingites* sensu stricto.

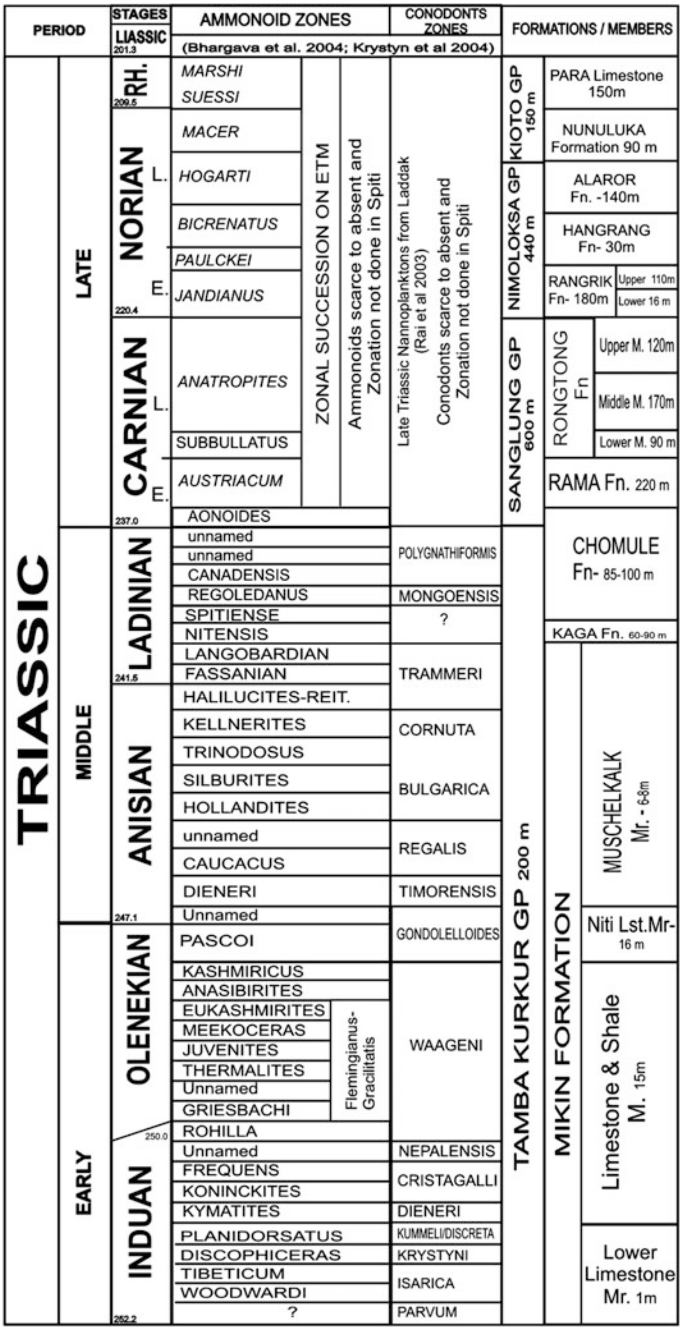


Fig. 2.6 Triassic lithostratigraphic units and ammonoid/conodont zones of Spiti (modified after Bhargava et al. 2004; Krystyn et al. 2004)

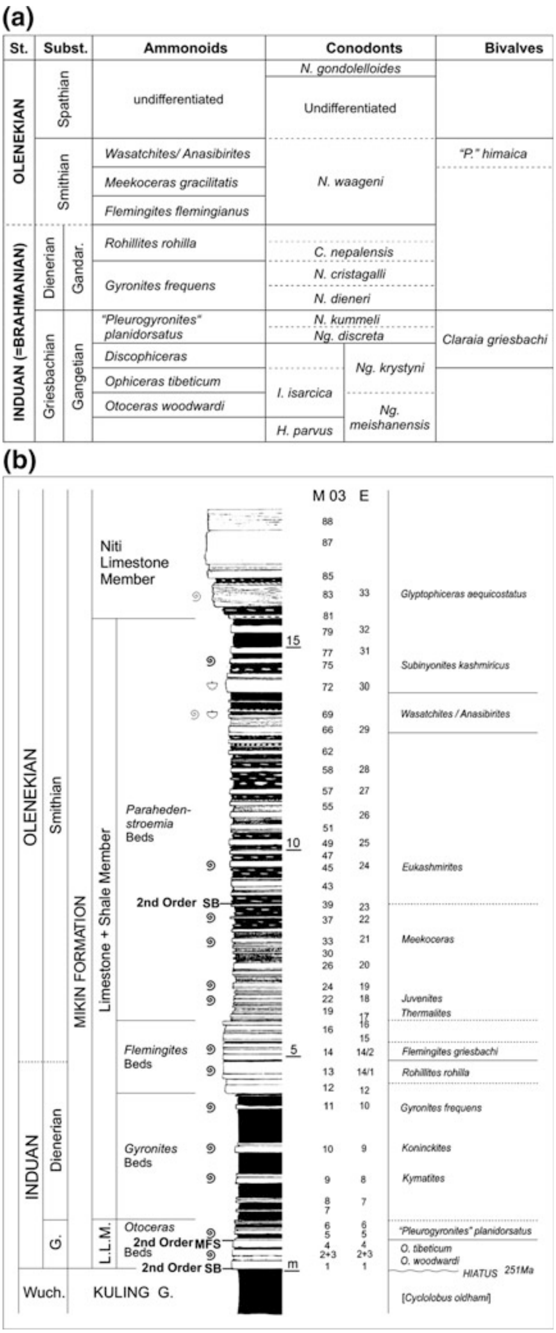


Fig. 2.7 **a** Induan/Olenekian boundry in the Spiti Triassic (after Bhargava et al. 2004; Krystyn et al. 2004). **b** Interstage boundaries along with SBs and MFSs in the Triassic ammonoid zonal framework of Spiti (after Bhargava et al. 2004; Krystyn et al. 2004)

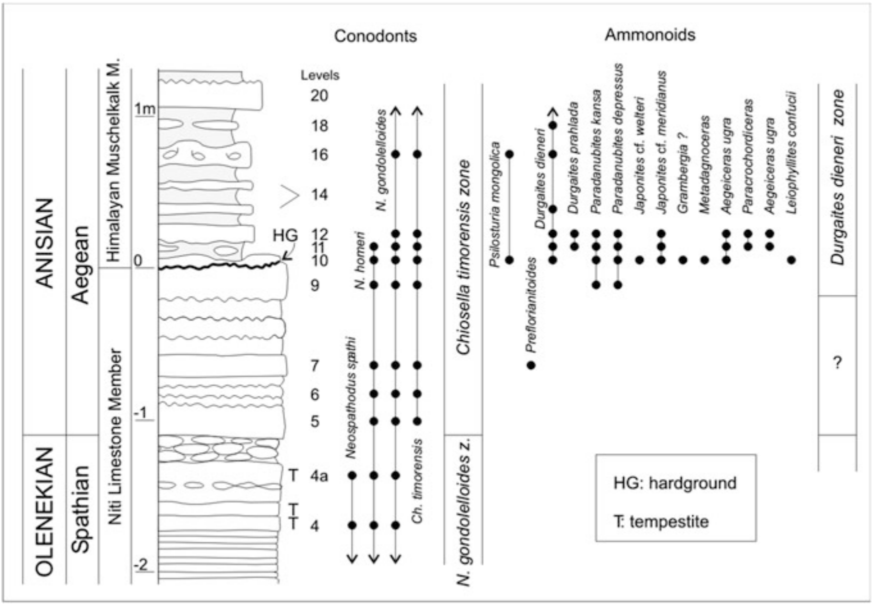


Fig. 2.8 Olenekian–Anisian Boundry at Muth in Spiti Triassic (after Bhargava et al. 2004; Krystyn et al. 2004)

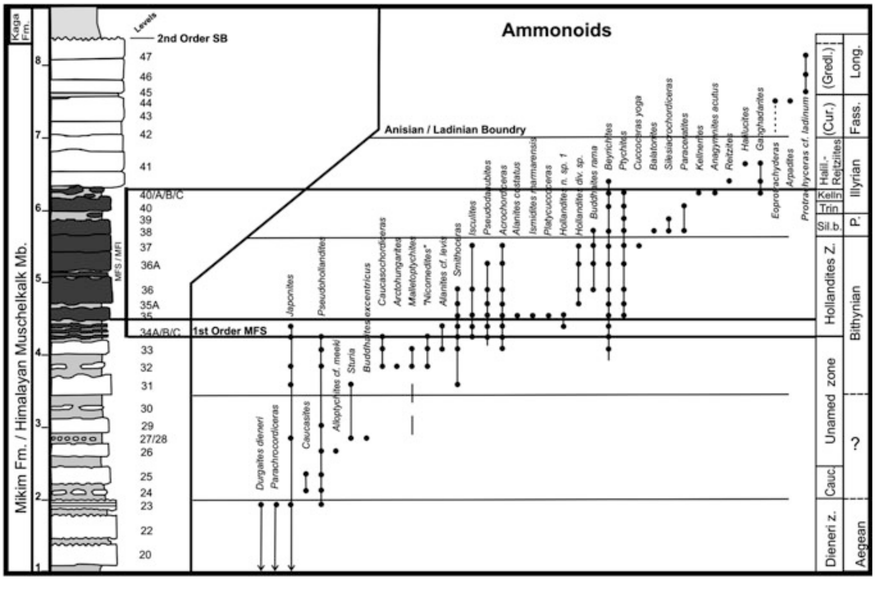


Fig. 2.9 Ammonoid stratigraphy of the Himalayan Muschelkalk with Anisian/Ladinian boundary. Note the strongly reduced thickness in the Late Anisian and the sequence boundary (SB) in the upper part of the section of the Ammonoid stratigraphy in Krystyn et al. (2004)

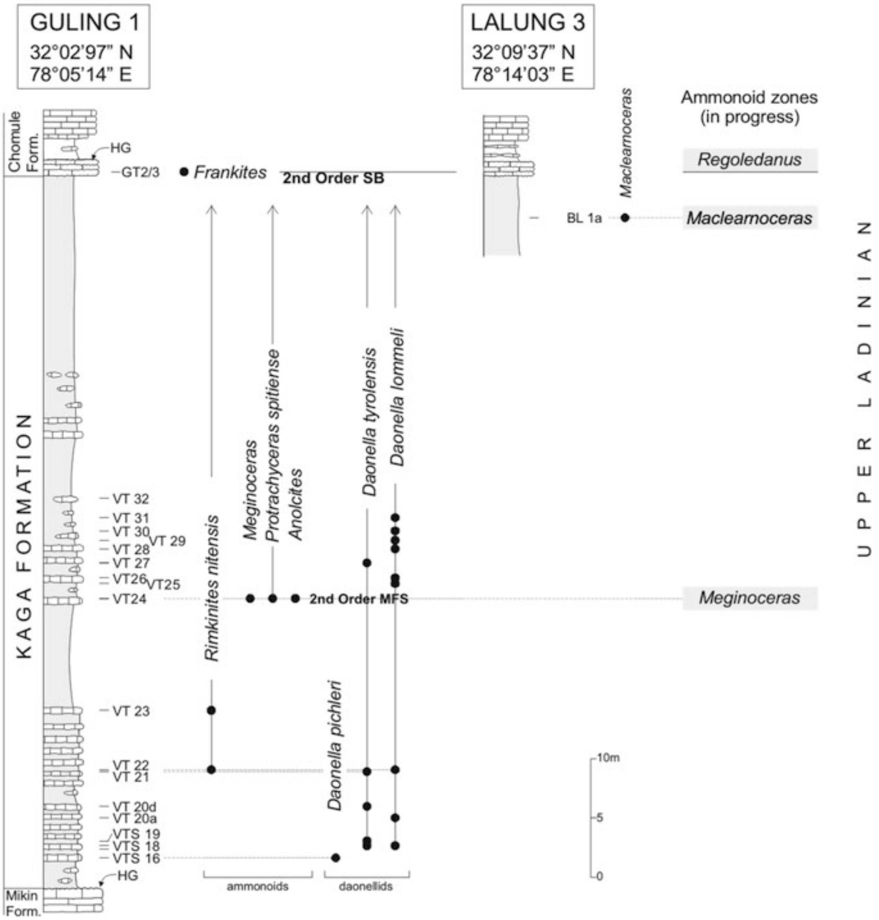


Fig. 2.10 Second-order MFS and SB determined in the stratigraphic log of the Kaga Formation at Guling (after Bhargava et al. 2004; Krystyn et al. 2004)

The Olenekian/Anisian Boundary (also the Early/Middle Triassic boundary) is précised between beds 4 and 5 at the FAD of the conodont *Chiosella timorensis* within the Niti Limestone one m below its top above a marker nodular bed (Fig. 2.8). The interval near the boundary is ammonoid devoid, and the oldest ammonoid found in Anisian is in bed 7–30 cm above the boundary.

The Anisian/Ladinian Boundary is placed between beds 41 and 42 (Fig. 2.9), however, a revised international consensus has favoured the boundary at the FAD of *Protrachyceras* between beds 44 and 45. Formal GSSP is yet to be decided.

The Ladinian/Carnian Boundary (also the Middle/Late Triassic boundary Fig. 2.11) is placed according to one view within one to three m of the base of Chomule Formation. Other views place the same at the LAD of *Frankites*, or at the

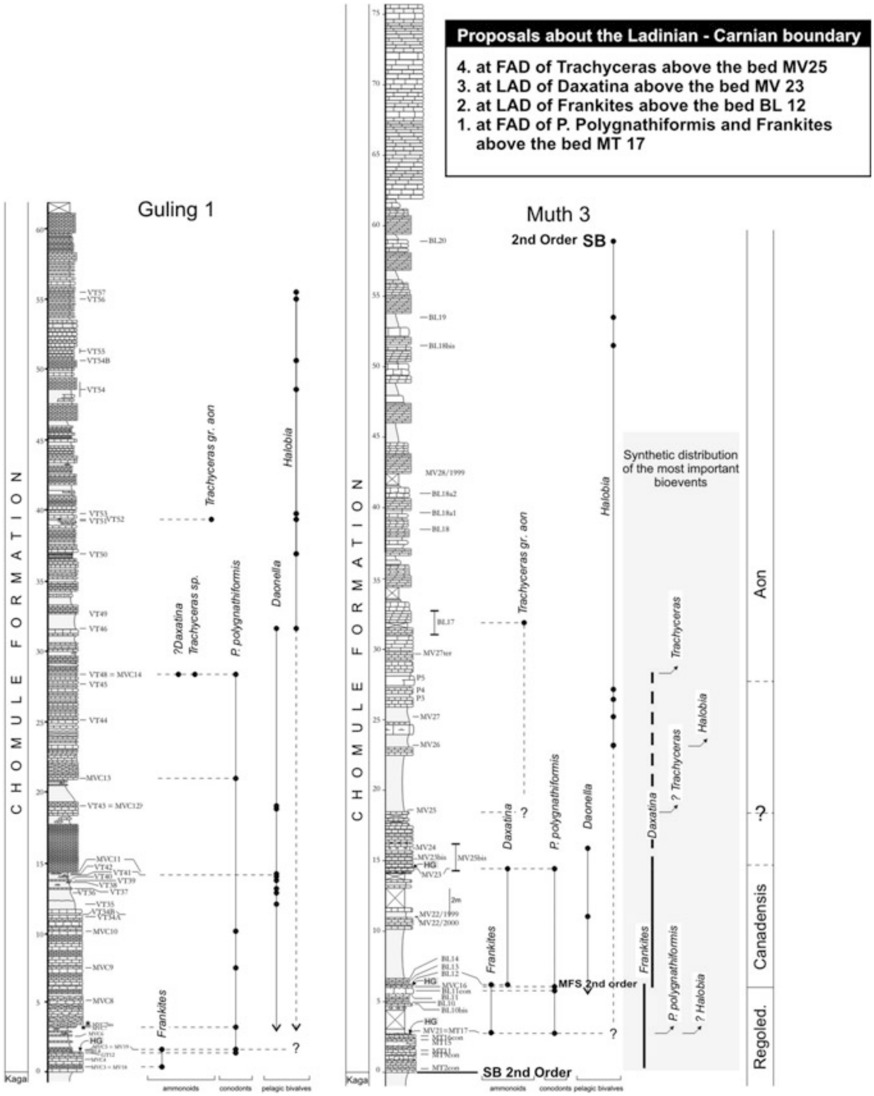


Fig. 2.11 Ladinian–Carnian boundary proposals at guling 1 and muth 3 along with second-order SB and MFS in the Spiti Triassic (after Bhargava et al. 2004; Krystyn et al. 2004)

LAD of *Daxanites*, or at the FAD of *Trachyceras*, or at the FAD of the conodont *P. polygnathiformis*. All these candidates are within the lower half of the Chomule Formation. As per bivalves, the boundary is placed between the LAD of *Daonella* and the FAD of *Halobia*.

The Carnian/Norian Boundary has been only tentatively suggested between the Rongtong Formation and the Rangkrik Formation. That is, between the Nimoloksa

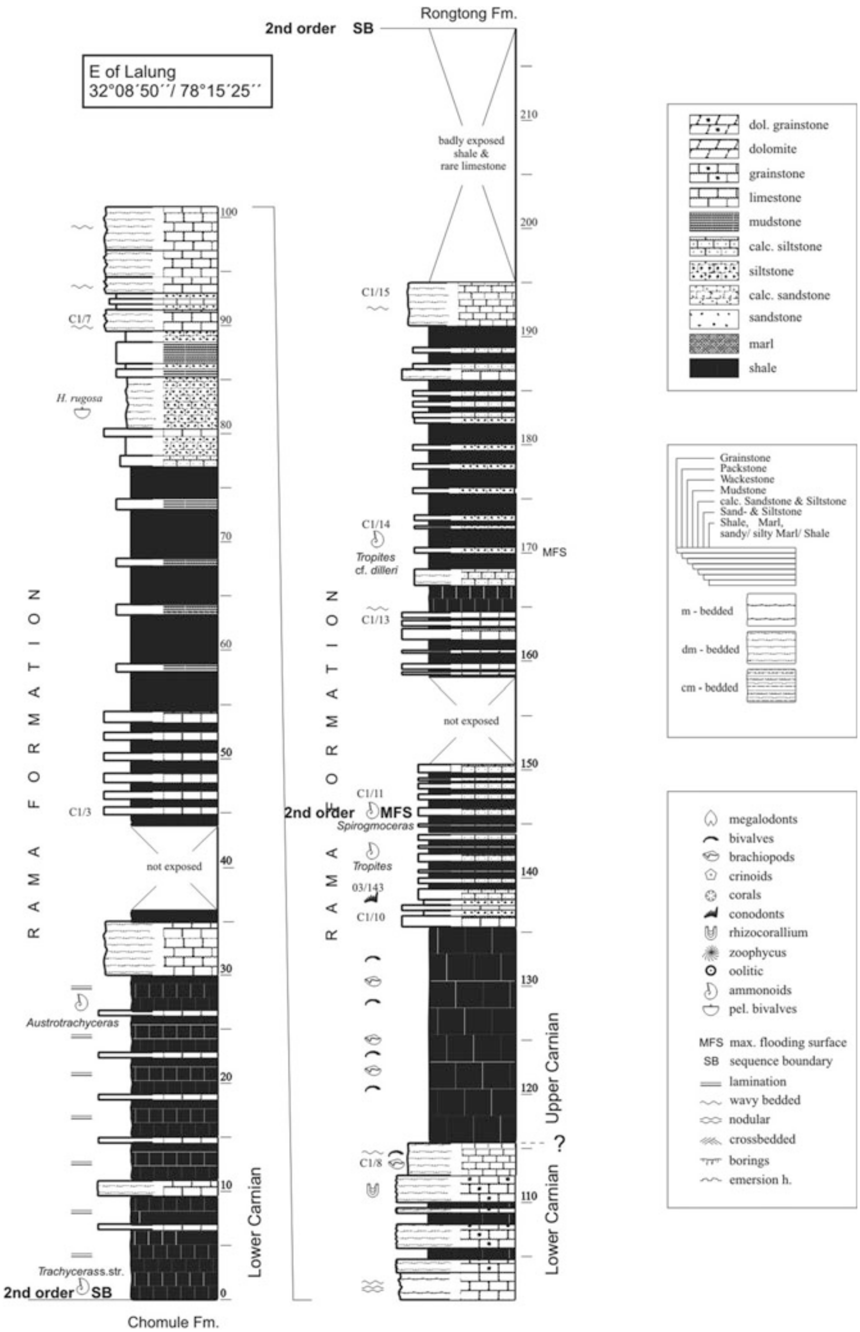
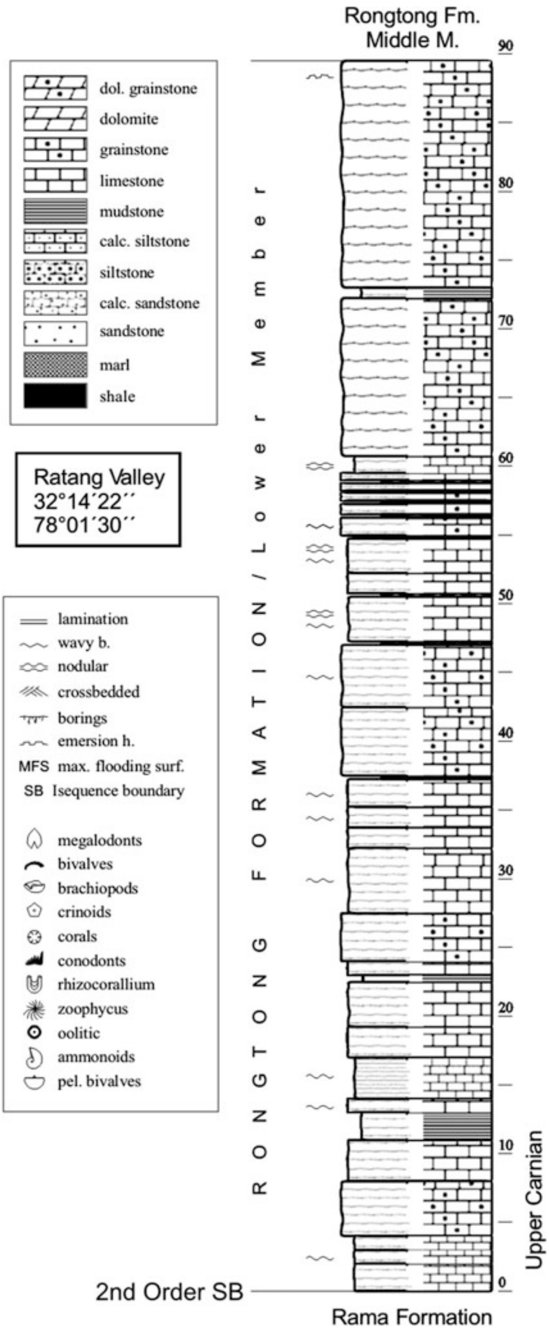


Fig. 2.12 Second-order SBs/MFSs interpreted in the Carnian column (after Bhargava et al. 2004)

Fig. 2.13 Demarcation of second-order intra Carnian SB at the Rama/Rongtong Unit boundary in Spiti Triassic (after Bhargava et al. 2004)



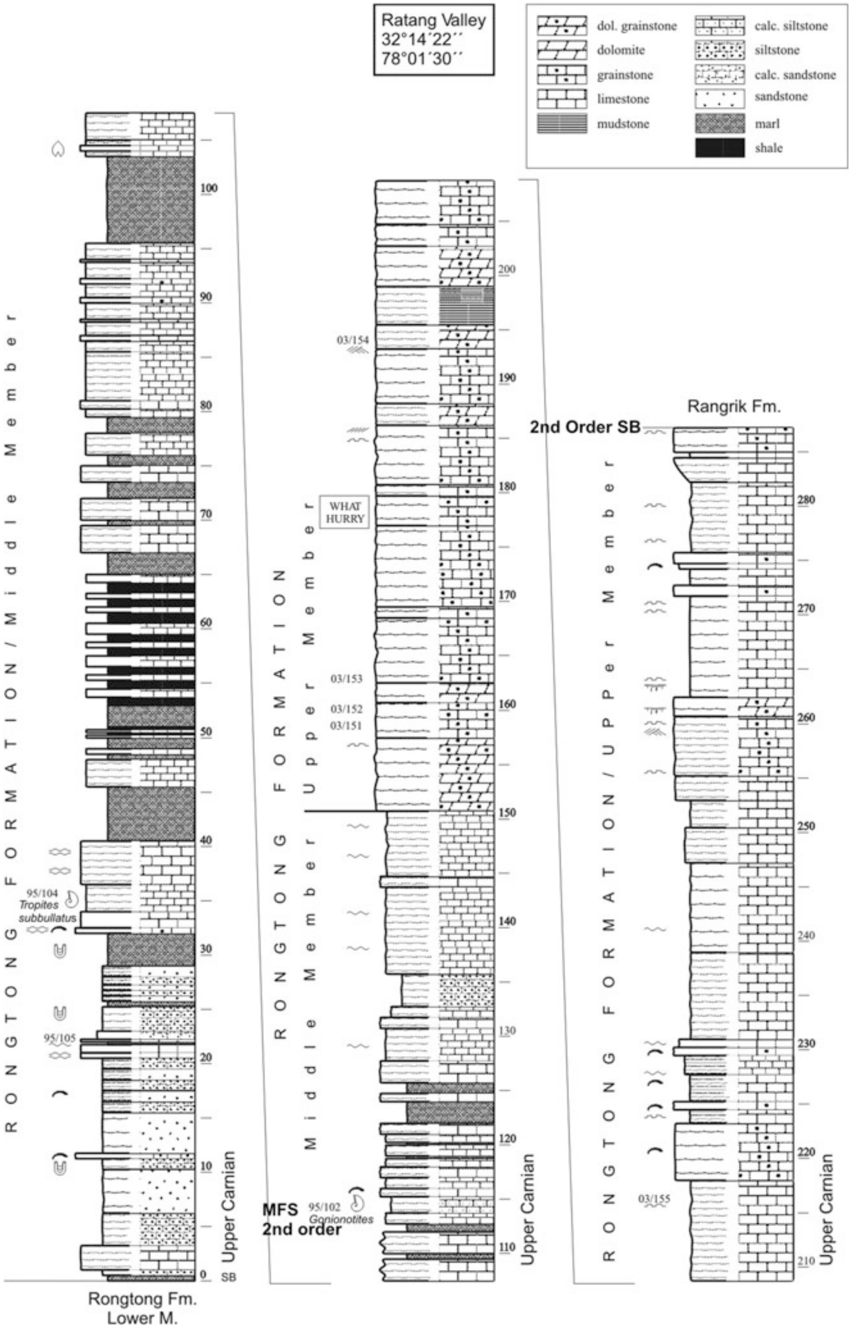


Fig. 2.14 Intra-Carnian second-order SB and MFS determined within the middle member of Rongtong Fn., and SB at the boundary with Rangrik Fn. in Spiti Triassic (modified after Bhargava et al. 2004)

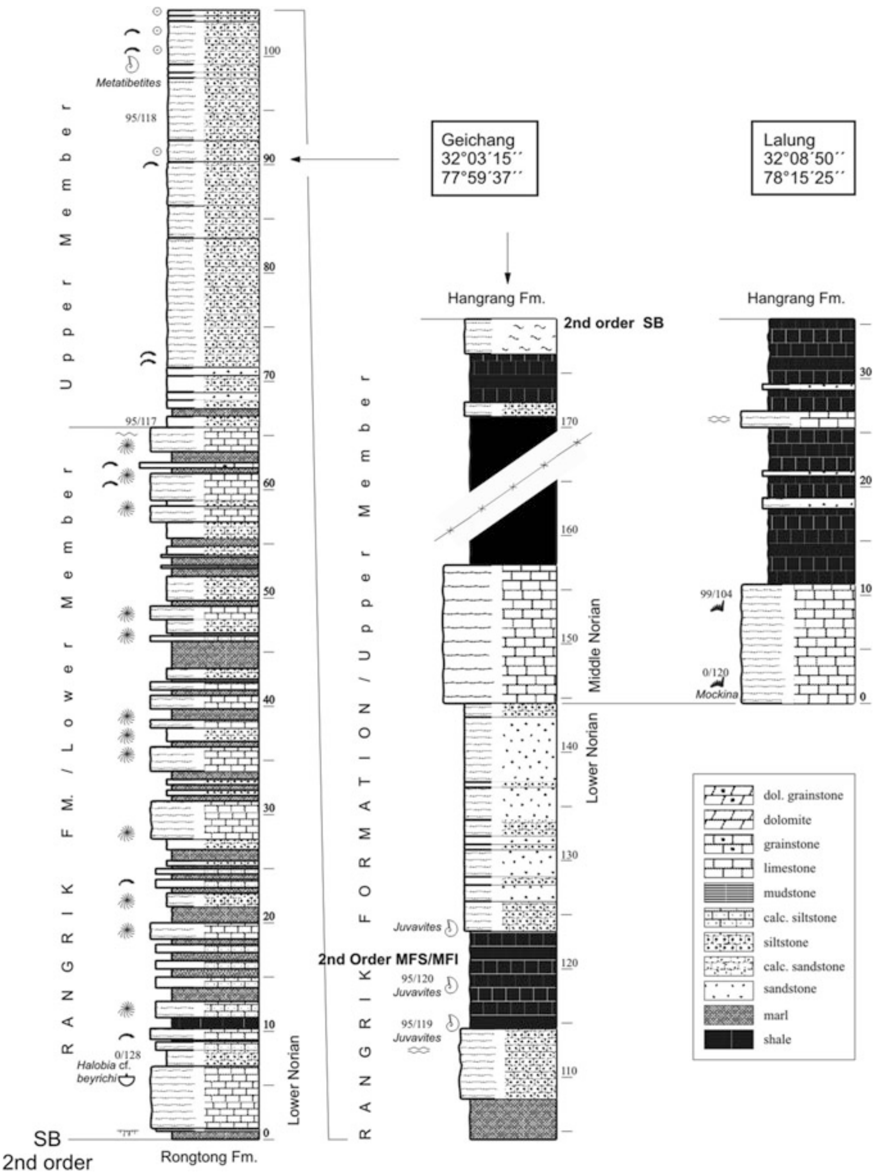


Fig. 2.15 Second-order SBs at the base and top of Rangrik Fn. and MFS/MFI in Juvavites bearing shales in Spiti Triassic (after Bhargava et al. 2004; Krystyn et al. 2004)

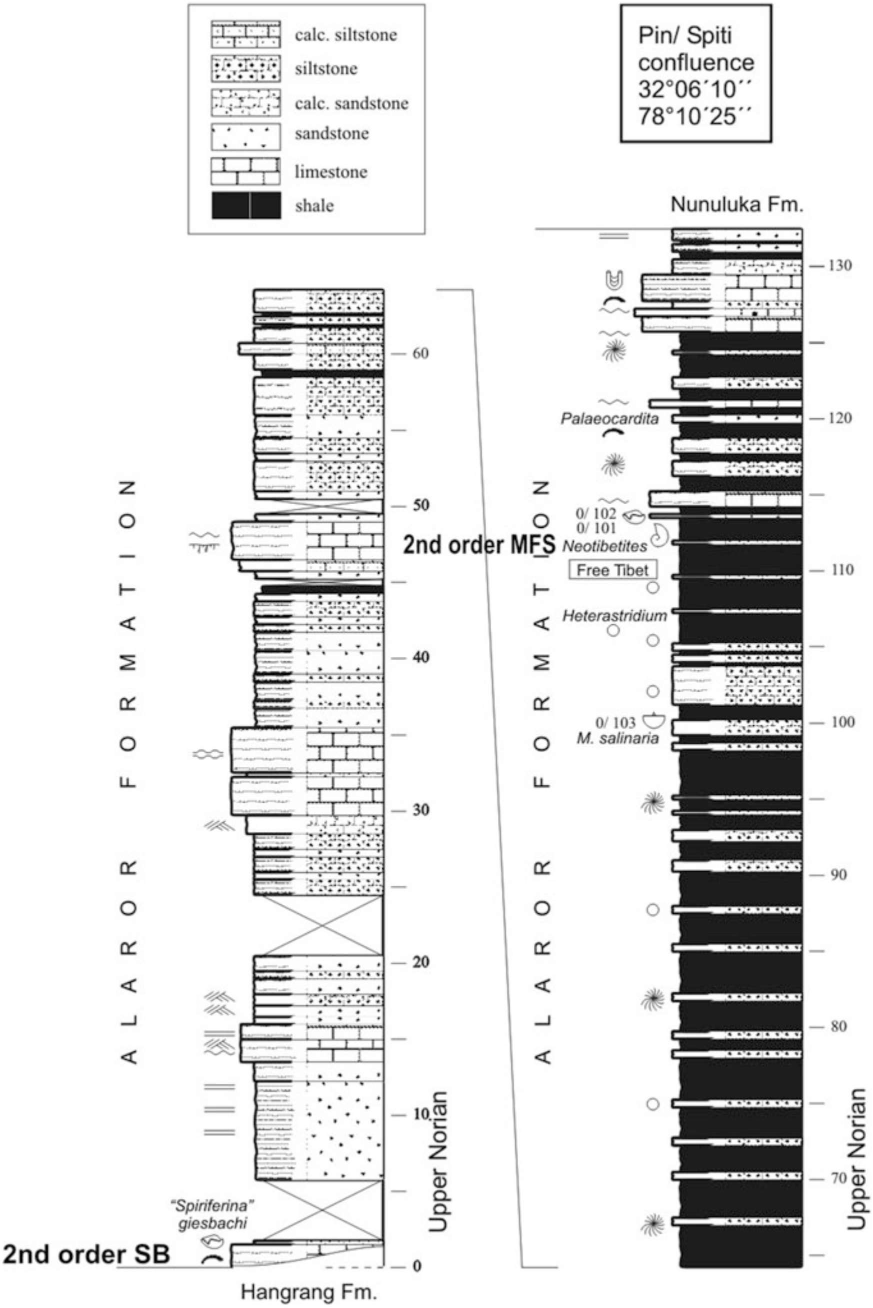


Fig. 2.16 Second-order SB at the base of Alaror Fn. and MFS in the *upper part* of Alaror Fn. above the Neotibetites above the bed 102 (after Bhargava et al. 2004; Krystyn et al. 2004)

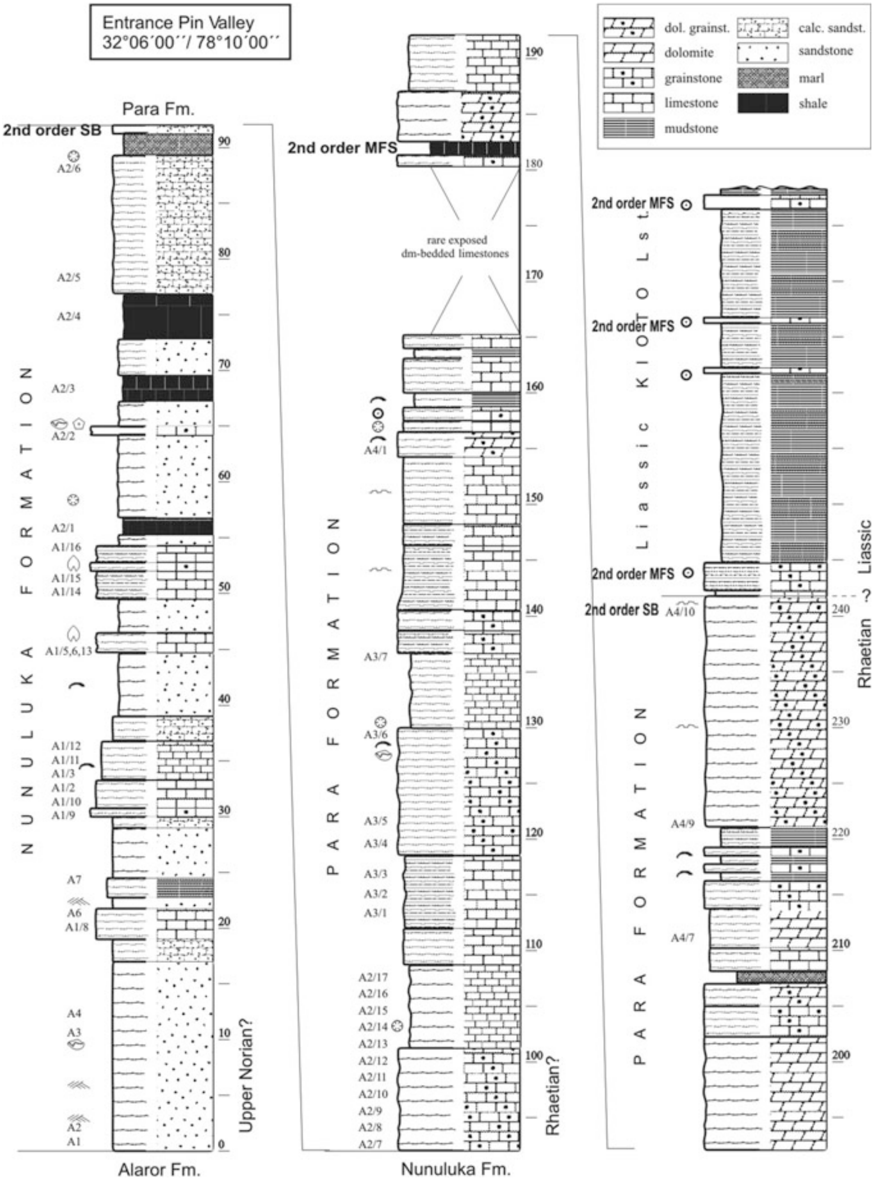


Fig. 2.17 Second-order SB at the base of Para Fn., MFS in the upper part of Para Fn. and Intra Liassic MFSs in the Kioto Limestone of Early Jurassic age in Spiti (after Bhargava et al. 2004; Krystyn et al. 2004)

Group and Alaror Group between *Tropites* beds and *Juvavites* beds at the start of *Zoophycus* rich limestones above the LAD of *Halobia* in the basal limestones of Rangkrik Formation (Fig. 2.12).

The Norian/Rhaetian Stage boundary is tentatively suggested between the Alaror Formation and the Nunuluka Formation. Another placement is between the sands of the early Nunuluka Formation and the overlying grainstones/limestones between beds A2/6 and A2/7 (Fig. 2.13).

The Rhaetian/Liassic boundary is only suggestively placed between the Para Formation and Tagling Formation (Kioto Group) (Fig. 2.17). The latter begins with the thick interval of thinly bedded platy mudstone beds interspersed with thin oolitic limestones.

2.3.5 Paleogeographic Framework at the Start of the Triassic Contextual to Kachchh

Kachchh region until the origin of the basin was a positive peneplained craton since the Precambrian. The Indian plate then occupied the axial/core/central position along with Africa within the Gondwanaland, and included Madagascar as its integral part. This axial/inner Gondwana (Fig. 1.1), comprising India (inclusive of Madagascar) and Africa, was bordered by the outer Gondwana, consisting of Australo-Antarctca in the east and South American continent in the west. There were significant weak divergent ancient tectonic fault zones, particularly on both east and west of the Indian plate. In Kachchh and neighbourhood, there existed east–west striking faults of varying depth parallel to the east–west striking Narmada graben, which were activated, and subsequently exercised control on the Mesozoic geological dynamics in the region. Stresses had been building up for a long time radially inside from the periphery in the region, which triggered the initiation of the rifting, between India and Somalia and in the vicinity of Kachchh and also between India and Australo-Antarctica.

The invasion of the Neoethys later in early Early Toarcian may be related to the deeper somewhat farther south basal Toarcian rift episode. The recently interpreted expanse of the Early Toarcian coccoliths throughout the Kachchh basin (Rai and Jain 2012, 2013) also suggests the near full growth of the Kachchh basin at the onset of the basal Toarcian transgression. The Toarcian ammonoids suggest communication links to Arabia. The Neotethyan invasion advanced from the north at the start of a new first-order sequence. The absence of the benthic ostracods suggests oxygen depleted basins unfavourable to ostracods (Mette 2004). The Gondic shallow marine corridor had yet not evolved and communication farther south to SE Pacific was presumably prevented by the Mozambique ridge (Fig. 1.7).

2.3.6 Suspected Presence of the Late Triassic in the Non-marine Nirona Formation as Encountered in Nirona and Banni Wells of Kachchh

Koshal (1984) recorded Rhaetian–Liassic pollens and spores. It implies an older origin of the basin during a long phase of restrictive, localized and shallow rifting and extension that prolonged for ~45 my. The rifting may have begun much earlier and farther north of the Banni well close to the Nagarparker ridge. The initial intra-Triassic origin of the Kachchh basin may be localized and related to the later Middle Triassic to mid Early Liassic Gondwana rift-framework. Additionally, the record of reworked non-marine Late Permian palynomorphs in younger reworked sediments may extend the localized non-marine sedimentation even as back as Late Permian.

The Late Triassic–Early Jurassic in the small shallow basin/s may have started receiving non-marine sedimentation as evidenced in the Banni and Nirona wells through the study of palynomorphs of Rhaetian–Liassic age in Zone 4 (Koshal 1973) between 1620 and 1760 m immediately above the basement in well Banni 2. In a 1993 0NGC publication, the mentioned Nirona Formation has been assigned to Late Triassic. It may be noted that the initiation of the Kachchh basin occurred immediately south of the Nagarparkar High ~50 km north of the Nirona and Banni wells. Obviously, the non-marine sediments close to the Nagarparker margin of the Kachchh basin are expected to be distinctly older of late Middle and Late Triassic (Ladinian to Norian) stages than the recorded Rhaetian (Koshal 1973) in the Banni and Nirona wells.

2.3.7 Broad Stratigraphic Correlation of the Non-marine Nirona Formation to Non-marine Gondwana Units as also to Spiti Marine Units

In a regional tectono-stratigraphic context, the non-marine Nirona Formation sediments of Banni and Nirona wells correspond broadly to the Mahadeva/Durgpur/Pachmahi/Tikki units of the different Gondwana graben basins, also to the combined nine unit marine succession of Kaga to Kioto units of Spiti, discussed later in Chap. 4.

2.3.8 Marine Triassic in Neighbourhood

In general, the marine Triassic in Pakistan is organized into a succession of three formations; Mianwali Formation, Tredian Fromation and Kingrali Formation, among which Mianwali Formation includes rich ammonoids while the younger two units are ammonoid scarce to devoid (Fatmi 1972). It is disconformable over Permian, and in turn is overlain unconformably by the Jurassic. Thus the ammonoid bearing Mianwali Formation can be best corresponded to the pre bed 40 part of the Mikin Formation of the Induan–Anisian age up to the ammonoid-rich hard grounded part of the Muschelkalk, while the ammonoid devoid Tredian and Kingrali units to the ammonoid scarce part of the Kaga to Kioto units.

2.4 Biostratigraphic Zonation in the Triassic

2.4.1 Ammonoid Zones in the Spiti Triassic

On the GTM, the Triassic is best refined into a succession of ammonoid zones in Spiti (Krystyn et al. 2004), however only Early and Middle Triassic is so zoned. The Late Triassic in Himalaya is mostly ammonoid devoid but for occasional record. There are ~35 zones in the ~15.2 my long Early and early Middle Triassic (Fig. 2.6), which averages to ~400 ky per ammonoid zone.

2.4.2 Conodont Zones in the Triassic of Spiti

Krystyn et al. (2004) provided conodont taxon range charts against detailed Spiti sections up to the close of the Chomule Formation, i.e. approximating to the Ladinian/Carnian or Middle/Late Triassic transition, however, zonation is done exclusively within the Early and Middle Triassic. A succession of 17 conodont zones is developed in the ~15.2 my long Early and early Middle Triassic, which approximates to an average conodont zonal reolution of ~800 ky which is almost half to that of ammonoid zones in the same interval.

2.4.3 Palynozones in the Non-marine Triassic

In the Gondwana non-marine exposed and subsurface basins is developed a succession of seven palynozones (Prasad 2011). Initially, a succession of 4 zones (Prasad et al. 1995) was developed in the Late Schythian to Norian interval. Later one more zone was added for the Early Schythian, while the Fossulatus Zone was presumably subdivided into two zones, and one zone added at the top, thus totaling a succession of seven zones. The first three broadly correspond to Schythian and at least Early Anisian which in turn corresponds to the Panchet Group. The younger four palynozones correspond to the Mahadeva Group of late Anisian to close of

Triassic. The correlation of marine and non-marine biostratigraphic zones has been mutually developed and integrated in Chaps. 3 and 4 with the help of second-order sequence framework.

2.5 Salient Mid-Triassic Features

2.5.1 Biotic and Abiotic Changes Across the Mid-Triassic Anisian/Ladinian Boundary in Spiti

Drastic changes are noticed across the Anisian/Ladinian transition like sudden marked decrease in (i) density, diversity and frequency of ammonoids, (ii) extent and frequency of hard grounds, (iii) carbonate content, (iv) number of concretion/pebble/nodular beds and increase in (i) sedimentation rate, (ii) size of structures, (iii) size of beds, increase in coarseness of texture etc. Quantitatively, there are 34 ammonoid levels in ~13 my long interval up to bed 40 of Muschelkalk Member that correspond to 34 ammonoid levels in in ~38.5 my long post bed 40 part of Spiti Triassic succession. The same amounts threefold decrease in frequency of ammonoids across the Anisian/Ladinian boundary. The pre-Ladinian thickness is ~40 m while post-Anisian thickness is ~1400 m. Thus in context of thickness, the decrease in the frequency of ammonoid is 35-fold. The maximum generic diversity is 10 in bed 34 of the Mikin Formation at or around the boundary (in beds 34–40) which in the post-Anisian Triassic reduces to 3 in the Ladinian Kaga and Chomule units, and to just one in Carnian–Norian interval, and finally absence of ammonoids in the terminal Rhaetian–Plienbachian interval of a major phase of eustatic fall. (detailed discussion on sequence stratigraphy in Chap. 3).

2.5.2 Mid-Triassic Unconformity and Associated Changes in Inland Gondwana Non-marine Basins as also in East and West Sector Coastal Basins

Disconformity with floral and lithological change is observed in K-G basin (Prasad 2011). Mid-Triassic unconformity along with a large stratigraphic gap up to the Pilensbachian or up to the Late Jurassic Kimmeridgian duration is interpreted in the Bengal basin (Vijaya 1997, 2009). Even in Kachchh, the disconformity is present along with a large gap from Late Precambrian to Mid-Triassic until the origin of the Kachchh basin.

2.5.3 Intra-Triassic Localized Rifting/Igneous Event in India

Casshyap and Khan (2000) attribute the profound change in the east–west striking Koel–Damodar, Son–Mahanadi, Rajmahal and Satpura basins to uplift of the source area in the southeast and the resultant non-deposition/deformation and, angular unconformity between the Late Permian–Early Triassic sediments below, and the superposed coarse to very coarse, sandstone, conglomerate, pebbly sandstone above. Evidence is known in West Kashmir of the intercalation of volcanics with Mid-Triassic Muschelkalk and associated sedimentary units (Wadia 1934). Calkins et al. (1975) have made similar observations in north Pakistan. Even the Siberian igneous event had its terminal pulse in the terminal Anisian. Thus, there could be either extended or prolonged Panjal igneous activity or even a separate mid-Triassic event in the Indian north sector as well. The Permian and Early Triassic sediments invariably in all the inland Gondwana basins feature uniform development which is distinctly disturbed by the mid-Triassic event (Krishna 1987a). Mid-Triassic crustal stretching or attenuation has been interpreted in the Spiti High Himalaya (Draganits et al. 2004), so also the origin of the pericratonic rift basins of Kachchh and Saurashtra. In the Spiti sedimentary succession, diverse drastic changes have been inferred within the Middle Triassic.

In Palamau (Bihar) close to the Koel–Auranga Gondwana basin are known Rhyodacite within the Precambrian of K-Ar date of ~217 ma (Sarkar et al. 1996). Also is recorded a ~265 ma intrusive hornblende peridotite dyke at Richguta (Ghose et al. 1973).

2.5.4 Triassic Palyno-Record in the West Sector

In Jaisalmer, in a stratigraphic table (ONGC 1993), the Bhuvan Formation in the Bhuvan well is shown against Triassic period on the basis of palynomorphs present therein. It appears that in the West Indian sector, both Early and Late Triassic sediments are recorded. In Pakistan, there is nearly complete presence of the marine Triassic with ammonoids being restricted to the Early Triassic Mianwali Formation (Shah 1977). The reevaluation of the Banni well palynomorphs can throw more light as to how far back they go in Triassic.

2.6 Jurassic

2.6.1 Jurassic System—International and National Status

The Jurassic system was named in 1829 by Brongniart on a succession in the Jura mountain range of Europe. It is presently organized into 11 stages (4 in Early

Jurassic—also known as Liassic, 4 in Middle Jurassic—also known as Dogger, and 3 in Late Jurassic—also known as Malm). The succession of Jurassic stages in ascending order is Hettangian, Sinemurian, Pliensbachian, Toarcian, Aalenian, Bajocian, Bathonian, Callovian, Oxfordian, Kimmerdgian and Tithonian. According to 2015 time scale (Cohen et al. 2015), it ranges from 201.3 to 145.0 ma with a duration of 56.3 my. Currently, on the basis of succession of the rapidly evolving ammonoids, it is organized into ~65 zones, ~150 subzones and more than 200 horizons. The system is defined by the base of its first stage—Hettangian, more precisely by the base of its first ammonoid zone—the Psiloceras planorbis Zone.

2.6.2 Development in the Indian Subcontinent

There is widespread development of marine Jurassic along the entire High Himalaya (India, Pakistan, Nepal, Bhutan and South Tibet), Kachchh, Jaisalmer, Axial belt and Indus basin of Pakistan with the best development in Kachchh (Fig. 2.18) with continuous late Middle Bathonian–Late Tithonian ammonoid succession. Early Bathonian ammonoids are recorded only recently (Krishna unpublished report 2014; Pandey and Pathak 2015a) However, the ammonoid record in Kachchh is from Bajocian onward of the younger six stages, whereas Hettangian, Sinemurian, Toarcian ammonoids are known from High Himalaya. The Bajocian ammonoid record in Kachchh is extremely poor, but rich in Madagascar, Pakistan, Nepal, and South Tibet. Toarcian ammonoid record is rich in Madagascar and Pakistan. In recent years, important marker coccoliths have also been discovered (Krishna et al. 1983; Rai and Jain 2012, 2013) of Toarcian to Kimmeridgian stages along with reworked taxa of Early Toarcian interval in Kachchh. The presence of terminal Jurassic is also evidenced through the record of the Late Oxfordian–Tithonian palynomorphs in the east coast basins, in particular, in the K-G basin (Prasad 2011).

2.6.3 Outline of the Ammonoid Biogrographic Framework

A distinct IEAP (Indo-East African Province) has been interpreted between Early Toarcian and Late Tithonian on the basis of the ammonoid distribution (Krishna 1983 onward Fig. 2.21). Ammonoid biogeographic reconstruction studies evidenced the availability of the shallow marine Gondic corridor only from late Late Tithonian (Krishna 1983 and in many later papers) from the Neotethyan margin of the Gondwana (GTM) to the SE Pacific margin of the Gondwana. Detailed ammonoid geographical treatment has been made in Chap. 6.

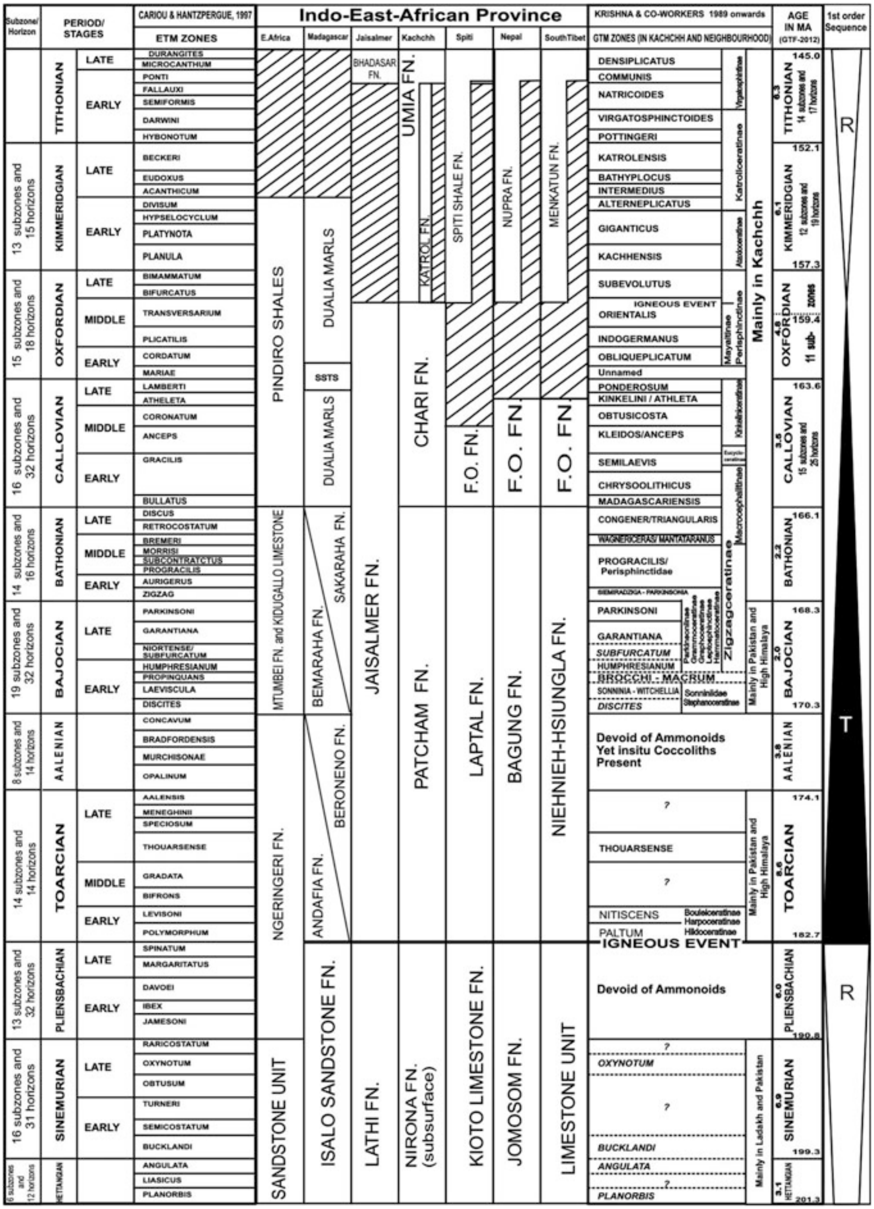


Fig. 2.18 Jurassic units in Indo-East-African Province (modified after Krishna 2002)

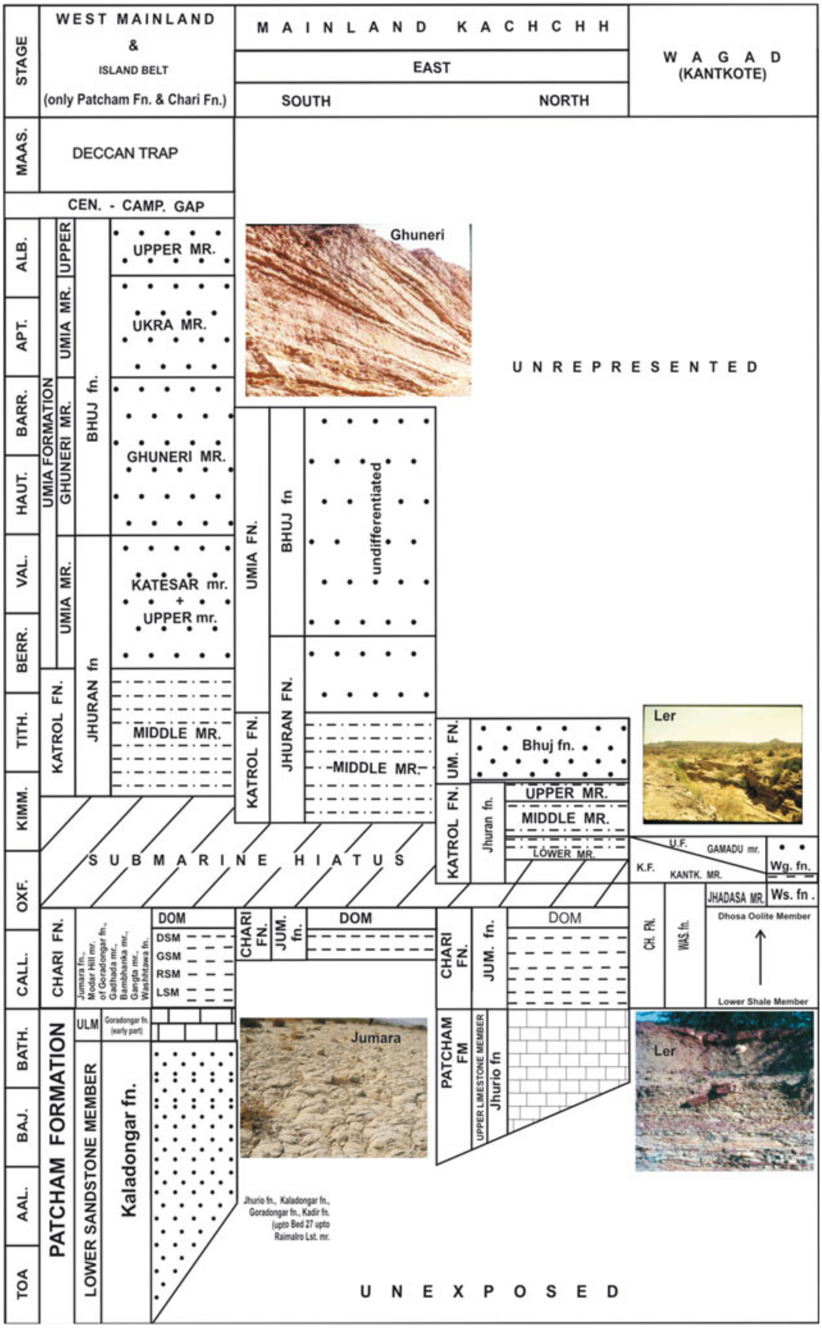


Fig. 2.19 Integration of Biswas (1993) lithostratigraphic units into Stoliczka's units in the Kachchh Mesozoic (modified after Krishna 2002)

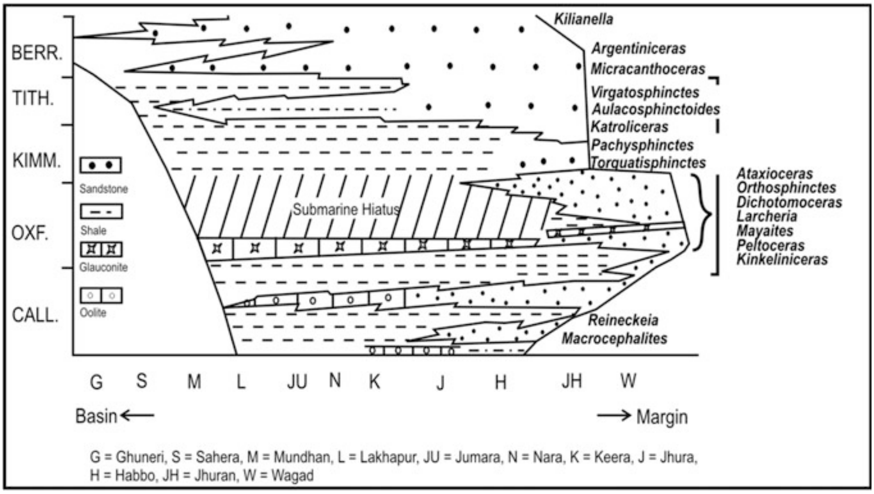


Fig. 2.20 Schemetic chronostratigrapic profile of the Callovian–Berriasian interval in Kachchh between Wagad and Mainland (modified after Krishna 2002)

2.6.4 *Marine Jurassic in Jaisalmer*

As in neigbouring Kachchh, based on the regional context of the Indian subcontinent and GTM, the deposition of marine sediments in Jaisalmer presumably, also, started in Early Toarcian over the non-marine Ladinian–Pliensbachian. The ammonoids are mainly of Callovian and Tithonian stages. A few ammonoids are also known of Late Bathonian, Oxfordian and Kimmeridgian. The Middle Oxfordian to early Early Tithonian makes a gap which has been interpreted as submarine as in Kachchh (Krishna et al. 2011).

2.6.5 *Marine Jurassic in High Himalaya with Focus in Spiti*

The marine Jurassic succession is known to rest conformably over the marine Triassic and in turn is conformably overlain by the marine Cretaceous in Spiti and elsewhere in High Himalaya. At least outer shelf maximum depths are realized in the Late Jurassic. The Middle Oxfordian to at least Early Kimmeridgian interval, if not more, is unrecorded in High Himalaya, and is interpreted as submarine gap. Additional smaller gaps are also present above the Early Bajocian in a few basins. The Hettangian–Pliensbachian record is in carbonate facies, the Toarcian–Bathonian in mixed fine carbonate and clastics, and the Callovian–Tithonian interval in black shales that is rich in nodular concretions. Ammonoids are known of Toarcian, Bajocian, Bathonian, Callovian, Early Oxfordian, Late Kimmeridgian

Photo 2.1 Golden oolitic limestone of Bajocian age from Jhura

Photo 2.2 Late Bathonian nodular limestone of Patcham Formation from Jumara

and Tithonian stages, however, abundant only in Tithonian as nucleii of concretions. Guide dinocysts, mostly of the Tithonian age have also been recovered (Garg et al. 2003) (Photos 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 2.10, 2.11, 2.12, 2.13, 2.14, 2.15 and 2.16).

2.6.6 Brief Summary of the Marine Jurassic in the Neighbouring Pakistan

The Upper Indus basin of Pakistan has been a constituent basin of the large Indus shelf, which is located only few hundred km away from the Kachchh basin. Both

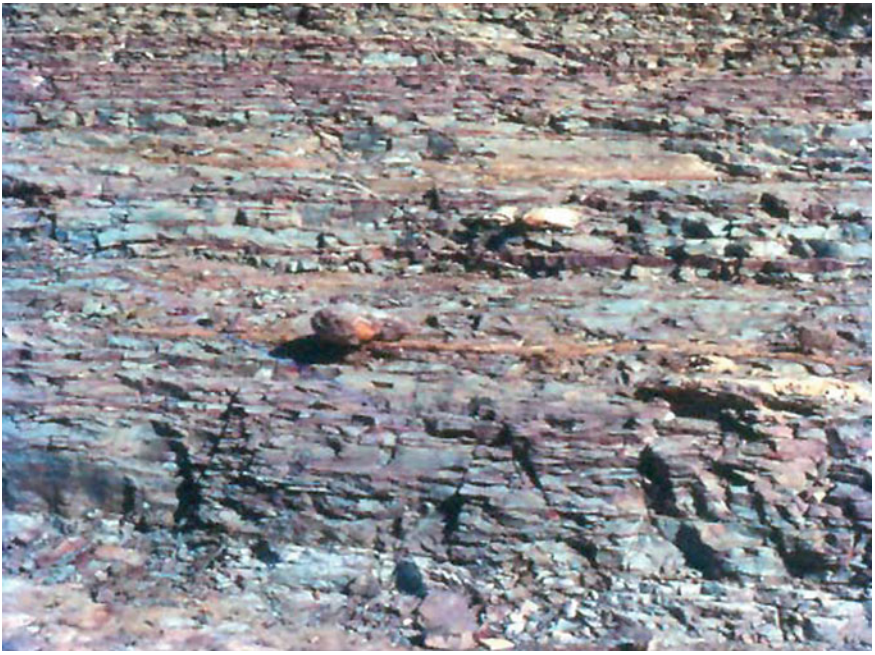


Photo 2.3 Shales of Chari Formation at Ler

Photo 2.4 Dhosa Oolite marker at Ler

Photo 2.5 Dhosa Oolite hard ground at Lakhapur

Photo 2.6 Sandstones of Katrol Formation at Ler

Photo 2.7 Sandstones of Katrol Formation at Ler

Photo 2.8 Sandstones of Umia Formation at Ler

Photo 2.9 Jaisalmer fort on the Fort Member

Photo 2.10 Panaromic view of the Spiti Jurassic–Cretaceous

these basins share similar geological history since the early Early Toarcian initiation of the marine sedimentation in Kachchh. The Upper Indus basin on the other hand includes as well the marine ammonoid scarce Hettangian–Pliensbachian. The Early Bajocian in the Axial belt of Pakistan includes the ammonoid-rich Early Toarcian and Early Bajocian. Thus, Pakistan provides an appropriate Hettangian–Early Bajocian compliment to the Kachchh Late Bajocian–Tithonian ammonoid record. It also makes the record of the marine Jurassic of the Indian subcontinent nearly complete. The ammonoid record however still excludes the Pliensbachian and

Photo 2.11 Giumal Formation at Giumal in Spiti

Photo 2.12 Nodular Limestone Member of Bagh Formation (*courtesy* B. Pandey)

Photo 2.13 Cretaceous in the Narmada basin (*courtesy* B. Pandey)

Photo 2.14 Development of asymmetric sequences in the Karai Formation (*courtesy* B. Pandey)

Photo 2.15 Marker sandstone bed in the Late Albian of the Cauvery Cretaceous (*courtesy* B. Pandey)

Photo 2.16 Transition from the Spiti shales to Guimal sands at Giumal

Aalenian stages, which, though present in High Himalaya marine facies, are neither ammonoid bearing nor even stratigraphically differentiated from the Sinemurian below and the Bajocian above.

2.7 Jurassic in Kachchh

2.7.1 Initiation of the Marine Transgression in Kachchh

The marine transgression that began regionally in early Early Toarcian, is also so interpreted in the Kachchh basin (Krishna and Pathak 1994; Krishna et al. 2010, 2011). At this point of time occurred a regional tectonic event on the entire GTM, with associated igneous expression in all the sectors. The geological signature of this regional event is well-recorded all over the GTM as the major intra-Jurassic first-order SB. In the regional perspective, it is expected that even the non-marine Ladinian to Norian sediments may also be locally present underneath the Rhaetian in the exposed Patcham sediments immediately after the origin of the basin.

2.7.2 Improbability of the Transgression in Early Pliensbachian During the Terminal Phase of Eustatic Fall

Minor transgressions in the terminal part of the first-order RST interval have been suspected in a few Arabo-African basins, e.g. Oman (Rabu 1993) in Early Pliensbachian Ibex Zone MFS. These are based on coccolith and/or other micro-fossil evidence. Any definite Pliensbachian ammonoids have neither been knwon nor any marine incursion otherwise confirmed over the last 100 years in East Africa or Madagascar, or even Indus basin of Pakistan and the Indian Jaisalmer basin, or even in wells. Hardly any one ever interpreted a significant eustatic rise but of a third order in an over all major fall since the Ladinian until the close of Pliensbachian. In the entire neighbourhood, thick unfossiliferous sands are known to make the terminal Sinemurian–Pliensbachian interval. The coccoliths ages are based on ammonoids and not otherwise. In Kachchh, the presence of the reworked Early Plienbachian coccolith mixed with reworked Early Toarcian elements (Rai and Jain 2012, 2013) is difficult to explain. For example in an insitu assemblage, the *C. pliensbachia*, with its LAD within Early Pliensbachian, can not co-occur with *B. finchii* having FAD in Late Pliensbachian. So, also, is impossible the cooccurrence of the *P. liasicus* having LAD within Early Toarcian and *T. tiziense* which appeared first only in Aalenian. These examples demonstrate that either the above cooccurrences are anomalous or the ranges in India are different than those in Europe. Even in Europe the ranges are diachronous from the Boreal to Mediterranean to Submediterranean regions.

At the time of intra-Triassic origin of the Kachchh basin, the Neotethys, in spite of being present in the vicinity through its due south progressing arm, witnessed a major eustatic fall phase (Haq et al. 1987 and others). On the other hand, the infant Kachchh basin most probably was extremely shallow and localized, and hence away from the reach of the Neotethyan arm. During the major eustatic fall phase, the Kachchh basin is interpreted as surrounded by emerged relatively high land conditions and several hundred km away from the Neotethys in spite of the over all due west basinal slope. The surrounding high-lands coupled with shallow localized basin/s did not permit any transgression. Subsequently, the start of eustatic rise combined with significant deepening of the rift in Early Toarcian facilitated the transgression. The flooding of the basin could not have occurred during relatively quieter intervening phase of eustatic fall between the successive rift events of the terminal Anisian and basal Toarcian. Prior to start of the Toarcian, any minor order rise is considered insufficient for the transgression in Kachchh during the preceeding Pliensbachian interval as claimed by Rai and Jain (2013). The published coccolith data lacks decisive evidence. On the same grounds is also contested the pre-Toarcian initiation of transgression in any East African basin.

But for the above anomalies and discrepancies, the Early Plienbachian ingression cannot be totally ruled out in a basin which was undergoing rift-related deepening. It could have been transgressed if the rate of rift-related subsidence exceeded the rate of eustatic fall as an extreme remote possibility. It is also important to evaluate as to which of the two transgressions was stronger in the Kachchh–Early Toarcian or Early Pliensbachian. The answer emphatically is Early Toarcian in a regional context. Doubts also arise since Rai and Jain (2012) reported the assemblage without any mention of reworking, and interpreted the NJ5 to NJ7 Late Pliensbachian–Early Toarcian age. The NJ5 to NJ7 range owerwhelmingly favours Early Toarcian. The same assemblage from the same sample is claimed to be reworked and assigned as well to NJ4 by Rai and Jain (2013) without any explanations about reworking and rvised age assignments. It is here contextual and significant to note that the coccolith based ages have small overlaps/discrepancies with the undisputed ammonoid based ages in Callovian, and has been occasionally found distinctly older to the ammonoid based ages. In this context, it is emphasized that the coccolith ranges are standardized by integrating them with the ammonoid biostratigraphy in the Mesozoic for unreserved age assignment of the ammonoid devoid sediments. The Hettangian–Pliensbachian coccoliths need be explored in High Himalaya Spiti and Ladakh, Axial belt and Lower Indus basins of Pakistan. In spite of the above uncertainties, the date of rifting and concomitant transgression in the Indo-East African province at the start of Toarcian is here maintained.

2.7.3 Oldest Jurassic Ammonoid Evidence

The oldest ammonoid evidence in the exposed geological record since the early 1980s (Jaitly and Singh 1983) has been the single incomplete 'Late Bajocian *Leptosphinctes*' whose taxonomic status and age have been reviewed in the present work. The '*Leptosphinctes*' level is underlain by the ammonoid devoid plus 200 m sediments in Kala Doongar near the north margin of the basin. Another stratigraphic section in the same Patcham region at Gora Doongar, during sampling for magnetochronology yielded a single *Calliyphylloceras* of suggestive Early Bajocian age, if not older (Pandey et al. 2013a) from near the base of that section. This level of tentative correlatibility is underlain by the older sediments of the Dingy Member at Dingy hill and Kuar Bet in the Kala Doongar section.

2.7.4 Oldest Jurassic Nannoplankton Evidence

The older Aalenian and Toarcian stages were always suspected even in the exposed sediments of Kachchh (Krishna and Pathak (1994) and later). Reworked Toarcian nannoplanktons (Rai 2006; Rai and Jain 2012, 2013; Rai et al. 2005) in the Late Callovian non-gypseous shales (collected under guidance of the present author) of Lakhapur/Jara dome of Mainland Kachchh suggested presence of marine Toarcian sediments in Patcham region of the north margin of the basin which later worked as provenance for the Lakhapur Late Callovian sediments (Krishna 2012). The author's so held interpretation was confirmed through the discovery as well of insitu Toarcian–Aalenian coccoliths in the middle part of the Dingy beds at Kuar bet (Rai and Jain 2012) of Lower Sandstone Member (LSM) of Patcham Formation. It substantiated that the marine transgression commenced in Kachchh in Early Toarcian as elsewhere in several basins on the GTM.

2.7.5 Regional Evidence of the Early Toarcian Marine Transgression

There is evidenced major transgression in early Early Toarcian all over the Gondwanian Tethyan Margin (GTM) from Arabia to NW Australia over a regional subaerial gap at the basin margins (Krishna et al. 2011), particularly in Madagscar and Pakistan that were located close to Kachchh in the Jurassic. Even in Tethys Himalaya, is witnessed drowning of the carbonate platform near the Pliensbachian/Toarcian boundary, so dated by the record of Early Toarcian *Alocolytoceras* (Stoliczka 1866) in the marls immediately above the Kioto Limestone in the Spiti basin.

2.7.6 Jurassic Stratigraphic Record of Kachchh and Neighbourhood

Among the three Mesozoic systems in Kachchh, the best developed is Jurassic, also in comparison far better than the overlying Cretaceous, while the Triassic record is meagre as discussed above. Out of the 11 Jurassic stages, the younger six are definitively differentiated in the exposed record through ammonoids. Insitu Toarcian–Aalenian nannoplanktons have been recorded at Kuar bet in Dm, soon after the discovery of reworked Toarcian–Aalenian nannoplanktons in Late Callovian of West Mainland (Rai and Jain 2012). In a regional sratigraphic framework, these two stages had long been anticipated in the exposed basal part that is included in Dm of Patcham Formation at Patcham, which otherwise had been best assigned to Bajocian. The non-marine undifferentiated Liassic is known in the Banni well (Koshal 1973, 1984). The exposed Jurassic stratigraphic sections are of high quality with good over all presence of the stratigraphically significant ammonoids, and their potential has been successfully exploited by the author and associates in developing the high resolution ammonoid based zonal scales in Kachchh for the GTM in the relatively better endowed early Early Bathonian–late Late Tithonian interval. There is developed a well-defined succession of about 27 zones, 50 subzones and 80 plus horizons in the ~26.0 my long late Bajocian–Tithonian interval (Fig. 1.8). The Jurassic development elsewhere in India, even outside in Pakistan and Madagascar, which were part of the erstwhile Tethyan margin of the Indian subcontinent, even of GTM, allowed further recognition of the additional ~20 ETM ammonoid zones on the GTM. To summarize, out of the ~65 zone ETM Jurassic zonal scale ~45 zonal intervals have found differentiation in the Indian subcontinent among which are 25 indigenously developed ammonoid zones together with their subzones/horizons. Among the mentioned 20 ETM zonal intervals, five are differentiated in the Kachchh Bajocian–early Middle Bathonian interval, and rest 15 recognized in the other neighbourly located basins of the erstwhile Indian subcontinent. Excellent stratigraphic sections and the refined scale so developed further allowed us to formulate a highly refined first to third-order sequence framework for the GTM in the Indian subcontinent that is detailed later in Chap. 3. The sequences are mostly developed and differentiated in Kachchh, and then demonstrated elsewhere on GTM as best as possible in spite of severe impediment of the non-availability of the desired level of biostratigraphic refinement in most of the basins.

2.7.7 Lithostratigraphic Framework in the Jurassic of the Kachchh Basin

The succession of Patcham, Chari, Katrol and Umia lithostratigraphic units (2.17–20) developed by Stoliczka in his field diary in 1867 for the exposed Mesozoic

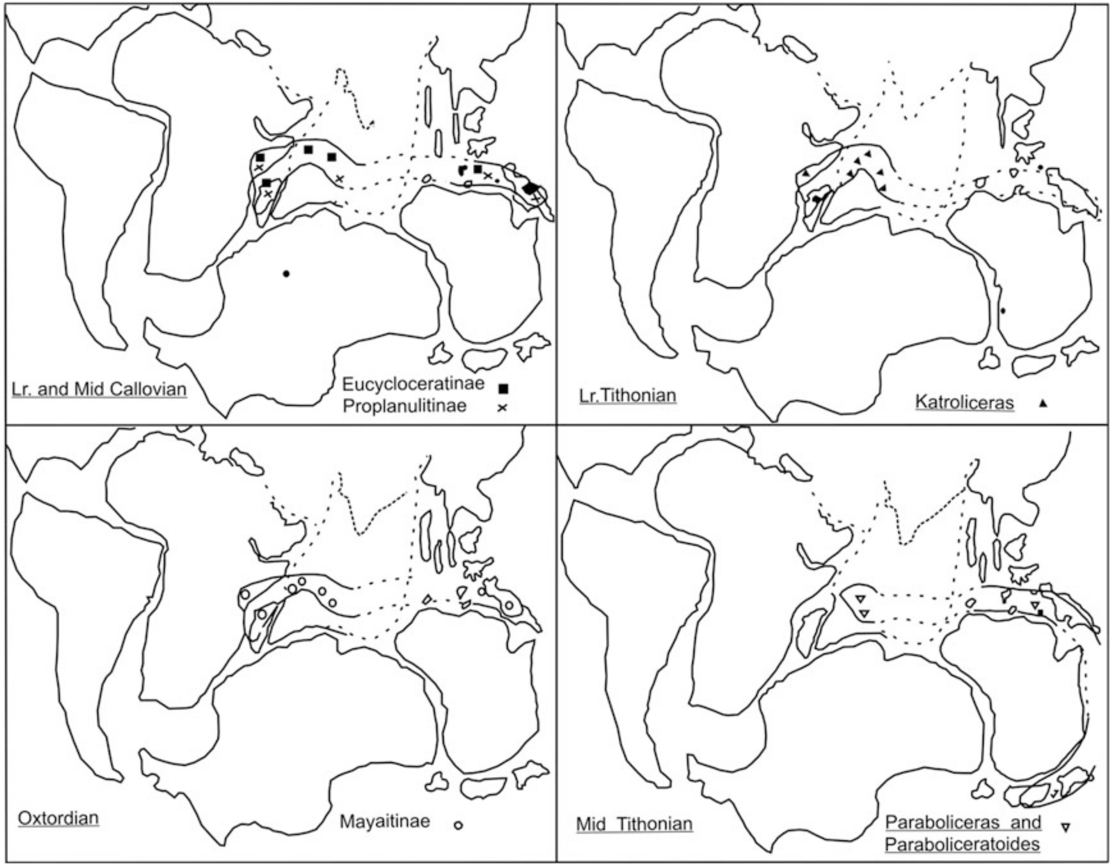


Fig. 2.21 Probable extent of the Indo-East-African Ammonoid Faunal Province (within the Tethyan Realm) for successive stage and substage time intervals (Lower Callovian to Tithonian) (after Krishna 1983)

sediments of the entire Kachchh basin was later published in Waagen (1871), who himself never visited Kachchh. The Stoliczka's scheme was based primarily on Stoliczka's lithostratigraphic considerations that he recorded in his field diary.

Biswas (1977) and a few others misunderstood Stoliczka's units as biostratigraphic and on that pretext coined new lithostratigraphic names. On the contrary, the present author recognized all the four units in the entire basin with emphasis on physical and lithological attributes.

Biswas' Several Unwarranted Objections to Stoliczka's Units Clarified Once Again

1. Stoliczka's units lacked original definitions and were considered biostratigraphic by Biswas.
   Stoliczka—a non-ammonoid field geologist—classified the sequence during his only stay in Kachchh in his field diary on the basis of his field observations. He did not have the opportunity of any taxonomic determinations of the collected fossils even after his return due to his untimely death within a year of his field visit to Kachchh. Such a classification cannot be biostratigraphic. The taxonomic determinations were made later by Waagen (1871) in the same publication in which he included Stoliczka's fourfold classification.
2. Stoliczka's units were not linked to any type sections.
   This was not considered obligatory in the nineteenth century. The very names of the units explicitly implied the type section/locality. Any code for stratigraphic nomenclature did not then exist. Nevertheless, it is clear that the Patcham Group/Formation was named and based on the exposed sedimentary succession in Patcham region up to the contact of the light coloured limestones and relatively darker grey shales, while the Chari Group/Formation was so based in Keera dome up to the top of the marker Dhosa Oolite in the neighbourhood of Chari–Fulae village settlement. It was neither obligatory then nor at all important even at present as to whether Chari village stood on Chari Group sediments or not. Even Biswas could not find a better or alternative differentiation of his Jumara Fromation which only later turned out as a junior synonym of Stoliczka's Chari Formation with the same content and boundaries in another locality.
   Similarly, Stoliczka's Katrol Group/Formation and Umia Group/Formation were based on their respective dominantly shaly and dominantly sandy character, respectively, in the Katrol hill and the Umia region. The base of Umia unit was defined by the base of the green glauconitic sands above the Katrol shale succession in Umia. Krishna could easily recognize the Katrol unit in Ler–Katrol above the Dhosa Oolite.
   To clarify the nomenclatural ambiguities and uncertainties Krishna (1987b, Table 4) published an elaborate framework with stratotype sections, essential physical/lithological features of these units, their lithostratigraphic boundaries, and facies variation from basin to margin.
3. The mappability of Stoliczka's units was never tested, yet lacked mappability.

This is not true. Rajnath mapped and published Stoliczka's units in west Mainland. The applicability of the mentioned units has been demonstrated in the entire basin from east to west and north to south.

4. Stolickzka's units were distinguished by fossil content. This is untrue, as the mentioned units have been primarily recognized and differentiated on gross lithology and marker beds.
5. Boundaries remained disputed and remained untraceable in poorly fossiliferous east Kachchh.
   This is again untrue; the boundaries of Stoliczka's units are tracable in the entire basin on gross lithology and lithological marker beds.
6. Stoliczka's classification and units are ambiguous and defy code of stratigraphic nomenclature.
   There is no such ambiguity found by the present author. No code existed in the nineteenth century. The units as originally implied by Stoliczka and later understood by the present author and numerous other workers are well in tune with all such codes that have come up from time to time.
7. Stoliczka's units had their time ranges, disputed and constantly under revision. This has neither any relevance nor obligation to the validity of the units. Time ranges of lithostratigraphic units are regularly revised as per new information.
8. Stoliczka's units are only applicable to Mainland while correlation problems prevent their extension to other parts of the basin not studied by Stoliczka. The applicability of Stoliczka's units in all parts of the basin has been amply well-demonstrated through new data and vastly improved correlations that have allowed reasonably precise age to every cubic centimetre of sediments through the length and breadth of the basin.

In light of the above, every new worker in any basin needs to honestly stand by the existing unit names irrespective of either lack of minimum or sufficient information or even faulty information. There is always scope of supplementing information towards making them more objective and understandable by fresh crop of workers without changing the names of the units, and thus avoiding possibility of addition to confusion. The science of geology and stratigraphy may soon reach a stable pedestal that it can even do away with plethora of names of lithostratigraphic units, and yet arrive at improved high resolution objective comprehension through event and sequence stratigraphic approach, events and resultant sequences that transcend intrabasinal and interbasinal limitations and instead have regional applicability.

2.7.8 Adoption of the Member Units of Biswas and Others

Stoliczka in his incomplete, rather preliminary, field studies did not attempt member units, and as such member units of Biswas and others in the stratotype localities of Stoliczka's units have been readily and easily incorporated and integrated in

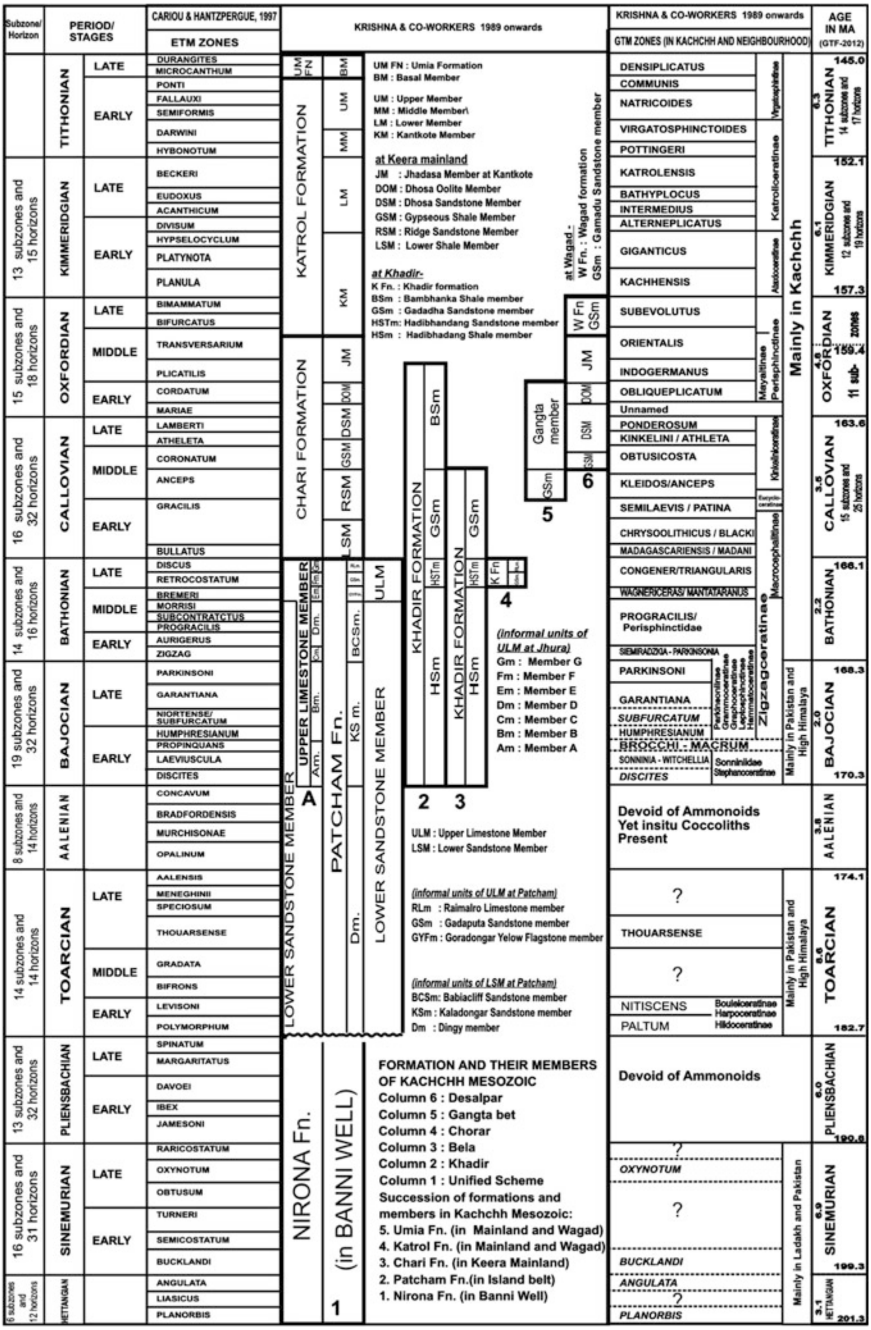


Fig. 2.22 Stoliczka's units demonstrated in the entire kachchh basin

Stoliczka's scheme while 'formations' created later have been abandoned and suppressed as junior synonyms (Krishna 2002, 2005 and later). A few new formal and informal units at member level have been necessitated, and so here introduced. The so integrated and unified lithostratigraphic framework is reproduced here (Fig. 2.22). In the present work, the abandoned members and formations, if and when, informally used are mentioned with suffixes m and fn.

Patcham Formation

The base of the Patcham Formation, i.e. contact with the basement is nowhere exposed in the basin. The marker Raimalro Limestone member and other homotaxial limestones make the top of the Patcham Formation in Mainland and in 'island belt'. The present author has traced the Patcham/Chari lithostratigraphic boundary meticulously. In its stratotype in Patcham region, the Patcham Formation includes two newly introduced members, viz., **Lower Sandstone Member (LSM)** with three informal members of Biswas and **Upper Limestone Member (ULM)** again with three informal members of Biswas in their stratotypes in Patcham. LSM is exclusive to the 'Island belt'. ULM is present both in Mainland (Habo, Jhura, Nara and Jumara localities) and 'Island belt' (Fig. 2.22). The complete ULM is present only in Jhura, yet its base is not exposed there. The contact with the underlying LSM is present all over the 'Island belt'.

Chari Formation

It is incomplete throughout the Mainland where the marker Dhosa Oolite represents its youngest part. Its terminal part is absent all over the Mainland in view of the overlying large significant submarine gap and the associated Chari/Katrol disconformity (Pathak 1989; Krishna and Pathak 1989, 1991 and since then). The terminal part of the Chari Formation is exclusively present in Wagad and in the neighbourhood of Khadir. The best development of the mentioned terminal part is in a ~10 m thick ammonoid abundant hardgrounded succession in the Kantkote section (included in Jhadasa Member), that is well over two ammonoid zones (~2 my) younger to the Dhosa Oolite of the Mainland. But for near absence of oolites, the mentioned 10 m thick succession is physically closest to Dhosa Oolite in its hard grounded, nodular, bumpy, conglomeratic features as also richness in ammonoids (only as visually observable physical features in the field). The Chari Formation includes six members (Fig. 2.22), the first five in Mainland and the sixth member in Wagad. Among the Mainland members, the first four members are created in Biswas (1977), while the younger two members have been created later. The first three members of Biswas are Lower Shale Member (LSM), Ridge Sandstone Member (RSM) and Gypseous Shale Member (GSM). Biswas' 'Dhosa Oolite member' has been further differentiated by Fursich into Dhosa Sandstone Member (DSM) and Dhosa Oolite Member (DOM) inclusive of the youngest conglomerate bed in Mainland. The youngest member—Jhadasa Member (JM)—is created in (Krishna et al. 1998). JM is present exclusively in Wagad, Gangta bet, Khadir and neighbourhood. The older five are present in Mainland, while all the six in Wagad, and Khadir. The younger five are present in Gangta bet. The older two members only are present in Patcham and Bela, while just the oldest member in Chorar.

'Members' created elsewhere are held extensions of the formal members developed in the stratotype. Chari Formation is also incomplete in Patcham, Bela and Chorar uplifts. The base of the youngest member—the Jhadasa Member—is defined at Gangta Bet in GBm (=Gangta Bet Member) above the bed 13 of Biswas while the top is the top of the Chari Formation at Kantkote.

Katrol Formation

The Katrol Formation is also incomplete all over the Mainland. There is absence of its basal part in Mainland because of the inclusion of the corresponding time in the submarine gap at the Chari/Katrol disconformable boundary in Mainland. The basal part of the Katrol unit is present only at Wagad as Basal/Kantkote Member because of the absence of the mentioned submarine gap there at the Chari/Katrol unit boundary.

Katrol Formation includes four members; the basal member is present only in Wagad with Kantkote–Bharodia section as the type locality as Kantkote Member. The younger three members (Lower Member, Middle Member and Upper Member) are developed in Mainland with stratotypes in the Ler–Katrol section on the right flank of the Kukma–Hajipir Road exposed on a small hillock/mond (Photos 2.4, 2.6 and 2.7). The Lower Member includes shales/silts with interbeds of pebbly/nodular/concretionary conglomeratic sandstones in its early part that alternate with shales/clays/silt, while the later part of the laminated and flaggy sandstones up to bed 13 in East Ler. The Middle Member mainly includes sandstones with subordinate shales/siltstones from bed 14 to bed 24, while the Upper Member mainly includes shales/siltstones. The Lower Member and Middle Member combinely are broadly equivalent and lithologically similar to the 'Lower Member of Jhuran Formation' of Biswas at Jhuran as also to early part of the Katrol Formation at Ler–Katrol up to the marker belemnoid bearing marly sands. The Upper Member is lithologically similar and equivalent to the Middle member of the Jhuran Formation of Biswas.

Umia Formation

Krishna (1987b), in absence of the Umia Glauconite marker bed, placed the Katrol/Umia unit boundary in East Mainland and Wagad at the start of the first high ridge forming hard sands (start of the 'Upper Member' of 'Jhuran Formation of Biswas in Mainland and start of the 'Gamadu Sandstone' in Wagad) above the Basal or Kantkote Member of the Katrol Formation (Fig. 2.22). The Umia Formation is observed to rapidly prograde towards the basin. Umia Formation is considered physically undifferentiable in the east into member units that have been recognized and formalized only in the west. Four to Five member units are distinguished—Basal Member, Ghuneri Member, Ukra Member, Upper Member and the Amarsar Member. The youngest member—the rather thin green glauconite bed as an alternative—could be included in the Upper Member, subject to its conformity with the rest of the Upper Member that underlies it. In fact, the sandy facies that typifies the Umia Formation may have conceptually started immediately after the climax of the major transgression in the basin farther east at the margin near Radhanpur. The mentioned sands now may be lying buried under the cover of the post Mesozoic sediments.

2.7.9 Fundamentals of Stratigraphic Refinement and Ammonoid Zonation

The past two centuries witnessed refinement of the geological time to the welfare of the human society through the exploitation of diverse geological resources that are in substantive manner tied to specific geological intervals of the earth's history. Initially, the principle of order of superposition of strata was used. The Geological Time Scale (GTS) primarily evolved between 1820 and 1840 with the enunciation of the principle of faunal and floral successions by William Smith. It allowed correlation of fossiliferous beds of widely separated localities through guide/index fossils. Prior to this, the progress of stratigraphy was extremely slow and limited in geographical extent for a century and half. Smith's discovery made it fast, and organization of the rock successions could be rapidly spread through out Europe into erathems and systems.

The Mesozoic systems were named in Europe between 1822 and 1834. By 1860, the Jurasic and the Cretaceous guide fossil rich successions were already subdivided into stages and zones. The Jurassic in England as early as 1858 was differentiated into 28 ammonoid zones, even many decades earlier to the discovery of the radioactivity by Becqurel in 1894, and subsequent initiation of the radiometric age determinations.

At present, the average zonal resolution in the Phanerozoic systems is of the order of 1–2 my. In the twentieth century, of all the systems, the $\sim$56 my long Jurassic received maximum refinement in Western Europe into 11 stages, 65 zones, 150 subzones (Figs. 2.24, 2.25 and 2.6) and well over 300 horizons with average horizonal resolution of $\sim$200 ky. In recent years, in conjunction with the third and yet finer order sequence stratigraphic data, it has been possible to unearth depositional cycles of about 400, 200, 100, 40 and 20 ky durations in Europe and occasionally even elsewhere inclusive of Kachchh, that are supposedly governed uniformly across the globe by earth's orbital dynamics. Internationally, the refinement of geological time is a high priority research area, and is being actively persued under the aegis of the UNESCO/IUGS through the International Commission of Stratigraphy (ICS) and its sub-commissions for various systems, and stage boundary GSSP working groups.

2.7.10 Lithostratigraphic Differentiation and Guide Fossil Collection in the Field Followed by Systematic, Bio- and Chrono-Stratigraphy in the Laboratory

Detailed field investigations were undertaken only after selection of stratigraphic sections in the basin through literature survey and reconnaissance traverses. Parameters that carried paramount significance in the selection of sections were good nearly continuous frequency and density of guide fossils, fine textured, somewhat slower than moderately deposited sediments under subtidal low energy framework, and also having good potential for parallel microfossil, radiometric, geochemical and magnetochronologic studies.

The first and most essential step after the selection of the sections has been meticulous high resolution lithostratigraphic differentiation, measurement and record of the stratigraphic column, approaching near optimum possible differentiation (Krishna 2004) into say **nl** number of the smallest possible beds/bands/bedules as the smallest order lithostratigraphic units. Even this first step of high resolution lithostratigraphic differentiation has not been adequately accomplished in the Indian geological record in most of the Phanerozoic systems, although good progress has been registered in the last decade. For a Jurassic stage of 5 my average duration **nl** desirably need be of the order of 300 beds in the selected sections.

The next most important exercise has been of the guide fossil collection from as many precise lithostratigraphically differentiated positions as possible, say **np** positions. It is found that **nl** is always way greater than **np**,

$$\mathbf{nl} \quad \gg \quad \mathbf{np} \tag{2.1}$$

since all the beds in any stratigraphic section for environmental and preservational factors do not contain the guide fossils. The collected guide fossils were numbered, carefully packed and safely brought to the laboratory.

Laboratory studies included cleaning and preparation of the collected guide fossils, transfer of field numbers to laboratory numbers to make the material ready for taxonomic determination. Taxonomic studies were followed by heterochronic evolutionary lineage studies with macro and micro trends, preparation of biostratigraphic range charts, and finally establishment of zones, subzones and horizons. Let the number of the smallest order biostratigraphic units realized is **nb**. It is observed that **np** is much larger than **nb** which is expressed as under.

$$\mathbf{np} \quad \gg \quad \mathbf{nb} \tag{2.2}$$

This is so, since even the rapidmost evolutionary rates are slower compared to the durations of the finest individual depositional cycle components. From (2.1) and (2.2), it is easily deduced that

$$\mathbf{nb} \quad \lll \quad \mathbf{nl} \tag{2.3}$$

nb requires to be large for high resolution stratigraphic and chronologic refinement which in turn necessarily requires several fold larger **nl**. This obviously implies hard painstaking patienceful field input.

In this context, a few other parameters like chronologic resolution were also explained and defined. Also, conceptual presentation was included on the desired high quality of lithostratigraphic differentiation within a Jurassic or for that matter Phanerozoic stage of about 60–300 beds towards realizaion of high resolution bio/chrono-stratigrphic refinement. Based on the so-defined parameters, a crude comparison of relative stratigraphic refinement in the different periods of the earth

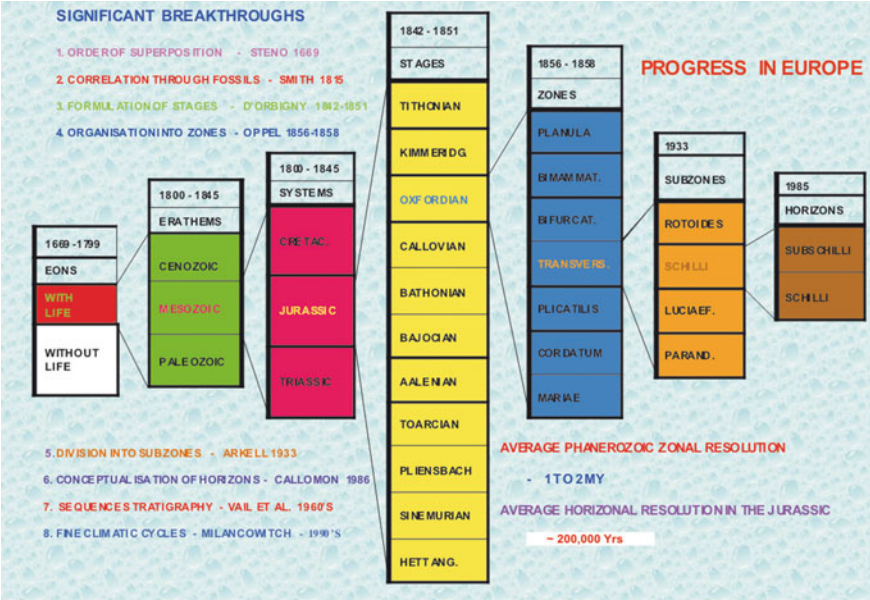


Fig. 2.23 Significant breakthroughs in ammonoid stratigraphic refinement since Smith 1813

AVERAGE DURATION OF A JURASSIC / MESOZOIC / PHANEROZOIC STAGE	55 / 11	OR	175 / 29	OR	540 / 90	=	5 to 6 MY
AVERAGE DURATION OF FINE ORDER CLIMATIC CYCLIC SEQUENCES	= CA 100,000 YRS TO CA 20,000 YRS						
AVERAGE NUMBER OF FINE ORDER CYCLICS IN A STAGE	= 50-60 TO 250-300						
MINIMUM NUMBER OF PHYSICALLY DIFFERENTIABLE UNITS IN EACH FINE SEQUENCE	= 2						
NUMBER OF OPTIMUM SMALLEST ORDER LITHOSTRATIGRAPHIC UNITS	= 100-120 TO 500-600						
MODERATELY GOOD TO VERY GOOD TO EXCELLENT TO OUTSTANDING LITHOSTRATIGRAPHIC DIFFERENTIATION	= 60% AND MORE OF OPTIMUM = 60-72 TO 300 - 360						

Fig. 2.24 Desired lithostratigraphic differentiation for high resolution ammonoid stratigraphy in the Mesozoic

history in international vis-à-vis Indian Mesozoic does not provide a comfortsome picture. Examples are presented of good quality lithostratigraphic differentiation in the Kachchh Mesozoic units. The history of the ammonoid stratigraphic refinement is also traced over the last two centuries from the differentiation of eonthems to the differentiation of horizons in the Jurassic (Figs. 2.23 and 2.24).

Indian Scenario

In contrast to the above progress in Euro-America, the slow progress in India has been frustrating in spite of foundation studies between 1840 and 1940. Nothing to speak of zonal differentiation, even systems and stages are not precisely differentiated in spite of collection of vast amount of geological data since the establishment of the Geological Survey of India way back in 1851. More depressing is the fact, that such studies in India are not allotted priorities. Currently, researchers seem more inclined to instrument based studies hardly involving any sustained painstaking field work.

Author's Strides and Failures of the Past 3 Decades

Such a dismal scenario prompted the author to persue this seemingly lack-lustre area in the Jurassic of Kachchh. The journey has been extremely slow and struggleful involving only occasional strides forward amidst innumerable failures and set-backs. However, in this venture, my long continued association as a member of ISJS and near continuous interaction with colleagues in Europe helped me in substantive manner to realize meaningful progress.

Kachchh Jurassic has been a relatively better and constantly studied area for nearly two centuries. However, the author had to begin almost from scratch. Numerous molluscs and other marine invertebrates were collected without the required level of lithostratigraphic differentiation. Thus only limited lithostratigraphy was possible. Ammonoid stratigraphic range charts could not be developed, for worthwhile objective ammonoid stratigraphy. It was in such backdrop, the author was baptized in the Kachchh Jurassic at the start of 1980s, with the first field excursion in the winter of 1980–1981.

2.8 Ammonoid Stratigraphic Refinement in Kachchh—Principal Results at a Glance

Ammonoid-rich six stages spanning through ~25.0 my are studied. In respective stratotypes, the study included ~900 beds vertically spread through a composite thickness of ~700 m. Ammonoids were collected from over 350 stratigraphically précised positions out of ~900 precisely differentiated beds, as a rare extreme high quality exercise. The high resolution scale so developed included ~27 zones, 50 subzones, and yet greater number of horizons with average horizonal resolution of ~200 ky. The stage wise description is undertaken as under.

2.8.1 Hettangian–Pliensbachian Record (Non-marine)

The early three of the ammonoid devoid five older Jurassic stages are differentiated in Kachchh on the basis of palynomorphs, and have already been discussed earlier. A review of the Nirona and Banni well microflora may in near future allow broad if not precise differentiation of the mentioned three stages from one another as also from the older Late Triassic part from the younger early to mid Early Jurassic part.

2.8.2 Toarcian–Aalenian Record (Largely Marine, yet Ammonoid Devoid)

The presence of Toarcian in the exposed Jurassic sediments of Kachchh based on record of nannoplanktons has been discussed earlier. The $\sim$300 m thick early part of LSM (Dingy member beds 1–36 at Dingy in Patcham of Patcham Formation Figs. 2.25 and 2.26) exposed only in Dingy and Kuar bet localities of Kaladoongar is considered Toarcian–Aalenian in Kachchh. Lithologically, the duration is made up of conglomerates, sandstones and sandy limestones with shale/silt/clay interbeds. The thin calcareous sands/silts are mostly fossiliferous except in the basal part. The mega-invertebrates are present only in a few levels, significantly in the middle part of the member. These are mostly bivalves (corbulids, gervillids, astartids, trigonids, etc.) and corals. In sequence stratigraphic context, detailed in Chap. 3, possibilities have come forth to distinguish the Aalenian from Toarcian below and Bajocian above. It should also be possible to differentiate the Aalenian in High Himalaya. The author's interpretation (Krishna 1987b; Krishna and Pathak 1994) on the initiation of the marine succession in Kachchh in Early Toarcian is validated by insitu record of the Toarcian coccoliths in the Dm at Kuar bet, and regional framework, and detailed in Chap. 3. Beds 37–38 of Dingy Member (Biswas 1977, 1993) are included at the base of the overlying KSm, while Dm is held to comprise beds 1–36 on an unknown unexposed basement (Figs. 2.25 and 2.26). The basement most likely is Precambrian, though there is also a possibility of its being the non-marine Nirona Formation.

Pandey and Dave (1993) speculated without any evidence of the thick marine Aalenian in the Banni well, and created the stage—'Bannian'. In a regional framework, in all probability, the marine Aalenian should be present in the Kachchh wells, as already reported, although undifferentiated, in the exposed sediments in 'Island belt' as Toarcian–Aalenian from the early part of the LSM (Dm) in the Kaladongar section of the Patcham hill at Kuar Bet and Dingy. Biotically, the differentiation of Aalenian has yet not been possible even from any region of the Indian subcontinent, although there is continuous record of the marine Early and Middle Jurassic in neighbouring Pakistan, Madagascar, and High Himalaya. However, the application of sequence stratigraphy has allowed tentative differentiation of the Toarcian from Aalenian in the Dm as a second-order RST of coarse cross-bedded sands near the

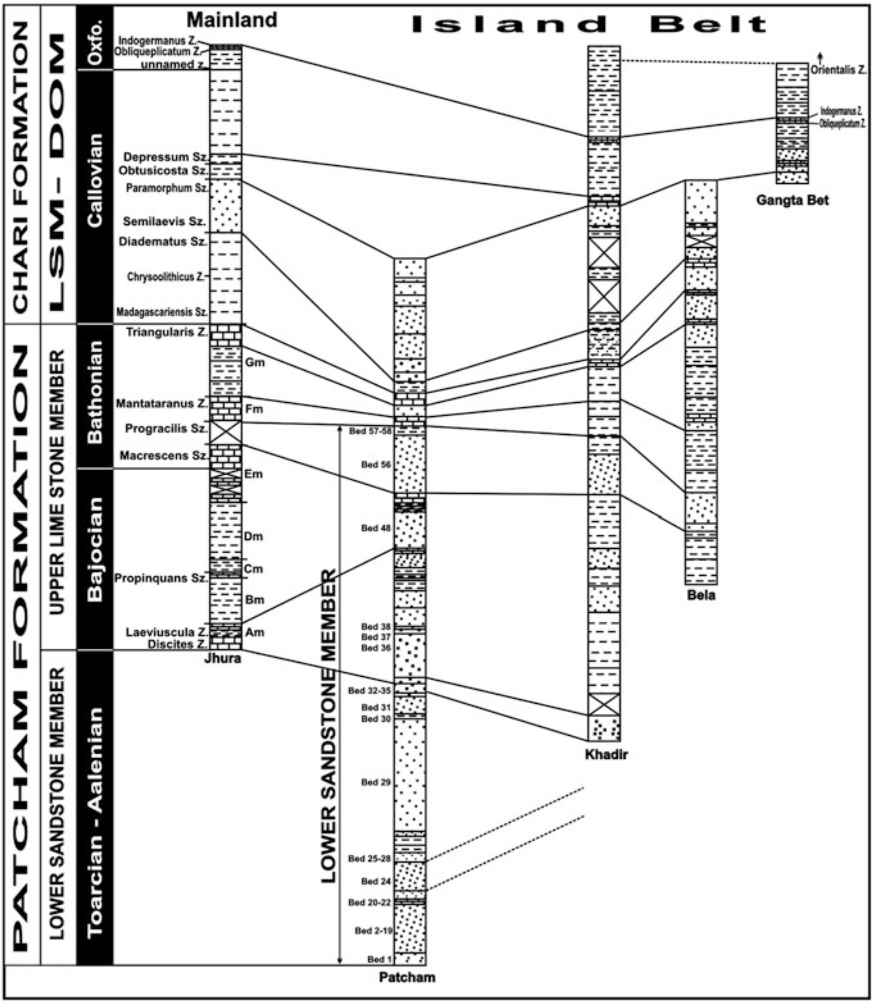


Fig. 2.25 Lower Sandstone Member at Patcham and Upper Limestone Member at Jhura alongwith intrabasinal correlation among Mainland and Island belt in the Kachchh Jurassic in the Toarcian–Middle Oxfordian interval with bed nos. and simplified columns after Biswas (1993)

margin within the Dm, suggestively, from the bed 25 to bed 36 (Figs. 2.25 and 2.26), presumably so also on the margin of other GTM basins.

2.8.3 Bajocian

The exposed Bajocian sediments, ~100 m or less thick, are here suggested to occur widely in 'Island belt' (Kaladongar and Goradongar sections) as the informal middle part of LSM and Mainland (Jhura and Nara) as the early part of the ULM. In 'Island belt', in view of the near margin relatively proximal locations, the Bajocian is expressed almost exclusively in coarse clastics with thin interbeds of fine textured limestones/marls/shales (Figs. 2.25 and 2.26), while in Jhura the Bajocian includes alternations of golden ooltic limestones and shales as Am (mostly golden ooltic limestomes, occasionally also conglomeratic) and Bm (mostly shales). Am consists mostly of the golden oolitic limestones that are formed below normal wave base conditions. In Nara, only, late Bajocian may be present, if so, near the base immediately above the underlying igneous body (Fig. 1.11) in view of the recent discovery of the early Early Bathonian ammonoids in the overlying limestones of the bed 9. The Nara sedimentary succession may be most probably conformably underlain by unknown and unexposed Bajocian–Toarcian sediments over the igneous plug of presumable ~183 ma widely expressed igneous activity already recorded in the Kachchh and Saurashtra wells.

The Late Bajocian sediments included in the BCSm of LSM were claimed from the Kala Doongar section of the Patcham region near Kuran. The claim was based on the discovery of a single incomplete entirely septate ammonoid specimen determined as '*Leptosphinctes*' and assigned to Late Bajocian (Jaitly and Singh 1983). The so called *Leptosphinctes* level is underlain by ammonoid devoid ~150 to 200 m thick sediments. In a few other sections of Patcham hill, both in Kaladoongar and Goradoongar, nearly equally thick sediments underly the levels otherwise considered correlative to the so called *Leptosphinctes* level. In Kaladoongar, the nannoplankton evidence and regional stratigraphic framework extended the succession as far back as Toarcian. In view of the overlying well-dated late Middle to early Late Bathonian ammonoid bearing Goradoongar Yellow Flagstone member (GYFm) in Kaladoongar, the immediately underlying sand dominating Kaladoongar Sandstone member (KSm) and Babia cliff Sandstone member (BCSm) of LSM are here considered as belonging to the Bajocian–mid. Middle Bathonian interval. Similar thick sands in the Goradongar sections are also here assigned to the Bajocian–mid. Middle Bathonian interval below the ULM.

Pandey and Dave (1993) determined the start of Bajocian from the base of GYFm and included the same in the early part of their newly created 'Patchamiam' stage. The base of the GYFm based on enclosed ammonoids is otherwise firmly placed in late Middle Bathonian. Recently, a single septate *Calliphylloceras* has been discovered in Goradoongar in the basal limestones of the middle part of the LSM. The mentioned limestones in sequence stratigraphic context are later in Chap. 3 tentatively assigned best to Early Bajocian. It now becomes the oldest Jurassic as also the sole Bajocian ammonoid of Kachchh. However, it is hoped to find in near future Late Bajocian ammonoids in the Nara section below the newly discovered early Early Bathonian (Pandey and Pathak 2015a).

Ammonoid Zones in the Kachchh Jurassic Stages

The presentation of the recently developed ammonoid zonation in the Kachchh Jurassic stages is preceded by general remarks and summaries of lithostratigraphic framework of each stage. The individual zones are characterized by their

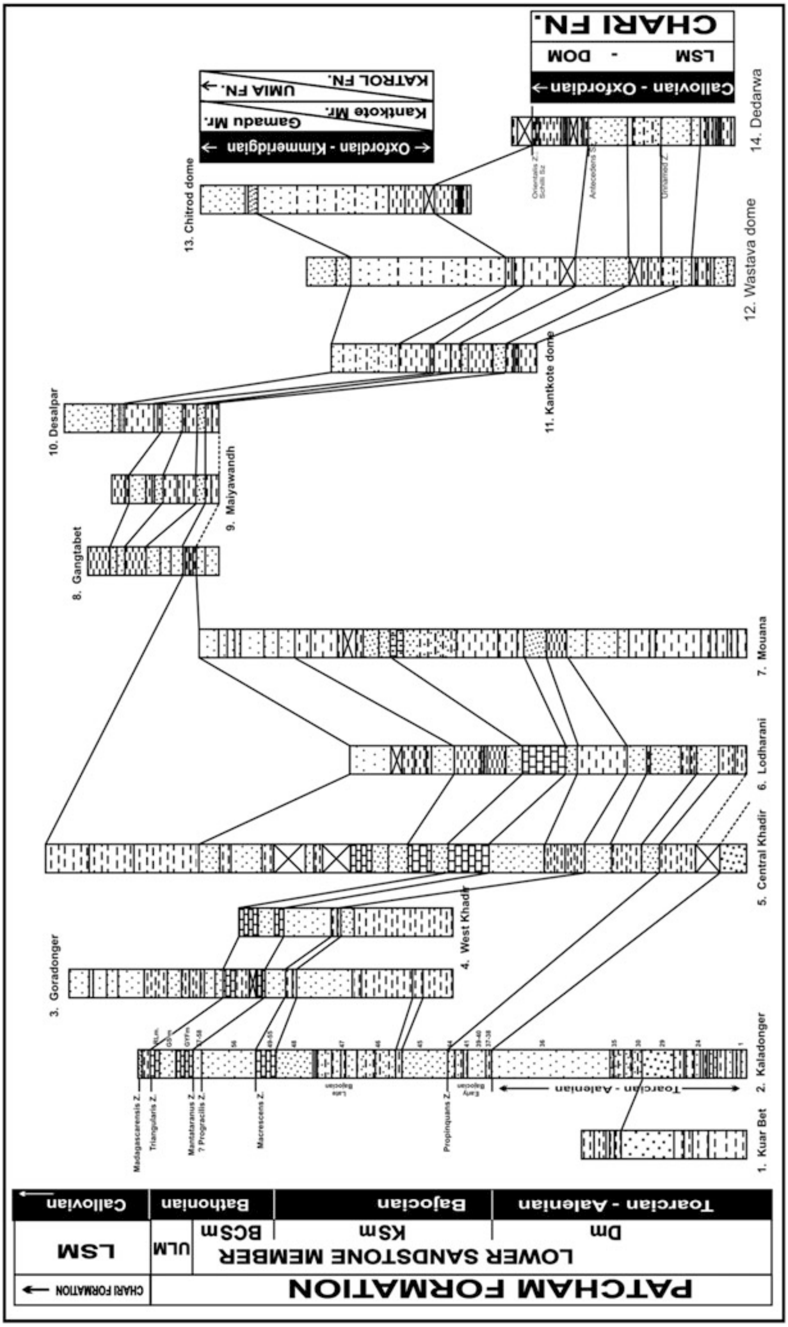


Fig. 2.26 Ammonoid based precise intrabasinal correlations among lithocolumns of Island belt and Wagad region of Kachchh basin during the early Toarcian–early Kimmeridgian Interval with bed nos. and simplified columns after Biswas (1993)

assemblages as a whole. The zones have been named after a characteristic and commonly present species appearing at the base or otherwise significant in the zone. The ammonoid zones, subzones and horizons are based on bed by bed collection under the rigorest possible stratigraphic precision. The successive units are initially developed as biostratigraphic units. It is emphasized that once the ammonoid zonal boundaries are confirmed as time boundaries through intrabasinal and long distance correlations, the mentioned ammonoid based biostratigraphic units, since fulfilling the requirements and definition, were also formalized as chronostratigraphic units. Many taxa of the Kachchh subzones and even horizons are present elsewhere in the Indo-East African province cf. Madagascar, Pakistan and East African countries on GTM, and even in ETM basins.

2.8.4 Bathonian

Recent discovery of the Early Bathonian ammonoid bearing section in Nara
The author's research group recently discovered an ammonoid bearing Early to mid Middle Bathonian section at Nara. The preliminary evaluation yielded a moderately ammonoid-rich ~1.5 m limestone bed ~3.5 m above the exposed base of early Early Bathonian Zigzag Zone Macrescens Subzone (Fig. 1.11—Krishna unpublished report 2014; Pandey and Pathak 2015a). Improved bed-by-bed collection were, subsequently, made in the ~23 m thick column from beds 1 to 15 which yielded ~100 fragmented ammonoid specimens, most from bed 9. These belong to seven families and 13 genera (Pandey and Pathak 2015a). The bed 9 includes *Parkinsonia*, *Siemiradzkia*, *Prohecticoceras*, *Cadomites*, *Berbericeras*, *Zigzagiceras*, *Telermoceras*, *etc*. (Pandey and Pathak 2015a). The presence of *Micromphalites* in bed 15 in context of earlier records from Jhura, Sadhara, and Jumara (Jain 2014) is considered significant for intrabasinal correlation in the exposed Bathonian in the Kachchh basin. Over all, the discovery is very important as the only ammonoid bearing Early and early Middle Bathonian in IEAP, and one of the rare ones on the entire GTM of pre-Macrocephalitinae pre-Morissi Zone age. The ammonoid devoid beds 16–18 above the ammonoid bearing beds 1–15 are considered pre-Morissi Zone in age. Distinct overlapping is evident between the oldest exposed at Jumara and the youngest at Nara of the early Middle Bathonian prior to the Macrocephalitinae bearing succession.

The complete Bathonian in Kachchh is exposed in Patcham, Khadir and Bela in the 'island belt', Nara and Jhura section of East Mainland, where it is underlain by the Bajocian and older sediments. The Jumara section of the West Mainland includes mid/late Middle to latest Bathonian, while the Habo section also includes part of the terminal Bathonian. The Nara section (Fig. 1.11) of West Mainland has only in the last decade yielded Bathonian ammonoids, while the presence of the Early to early Middle Bathonian ammonoids in the Nara section is for the first time determined. As expected, the dominant lithology in the 'Island belt' is of sandstones. Even in Jhura thick sandy limestones are present that are suspected to be of the early part of Bathonian, while the relatively distal Nara and Jumara sections of West Mainland exhibit fine textured shales/marls and limestones. There is noticed large facies variation among the exposed proximal and distal sections. In addition, is observed a marked temporal facies contrast between the Toarcian to mid Middle Bathonian LSM at Island belt, and Bajocian–Bathonian ULM at Goradongar, Jumara, Nara and Jhura. The LSM comprises ammonoid scarce to ammonoid devoid coarse sand dominating sediments, while the ULM includes poorly to richly ammonoid bearing golden oolitic sediments, nodular limestones and shale interbeds. The maximum age range of the ULM is suggested as Bajocian – Bathonian at Jhura and minimum at Habo of only the terminal part of the Late Bathonian. Thus, Bathonian (Figs. 2.25 and 2.26) includes the sand dominating early part (BCSm of LSM) and the limestone/shale dominating later part in the ‘Island belt’ as ULM. The Bathonian in Habo, Jhura, Nara and Jumara exclusively includes the limestone/shale succession as ULM of the Patcham Formation.

2.8.4.1 Early and Early Middle Bathonian

In 2012, under sponsored research, is discovered a limestone/marl/shale succession close to the igneous plug in Nara which included as many as 19 beds (Krishna unpublished project report 2014 Pandey and Pathak 2015a). Ammonoids are present all through, particularly in the middle part of the ~23 m dominantly limestone succession (Fig. 1.11). In total, 10 levels of ammonoids have been differentiated with good density and diversity. The ammonoids collected do not include any Macrocephalitinae that are present in younger beds in another section. Thus, the succession in consideration appears to be of pre-Macrocephalitinae age, i.e. older than mid Middle Bathonian, and includes Early to mid Middle Bathonian, since at least in distal Nara; even subaerial break can not be thought of.

Initially, in absence of the confirmatory evidence, the principles of sequence stratigraphy were utilized. In thick sand dominating sediments at relatively proximally located ‘Island belt’, Washtawa and even East Mainland (close to KMF), the presence of ammonoids is invariably observed in the terminal part of the successive second-order TSTs close to the MFS, e.g. early to mid Early Callovian in Habo, Washtawa, Bela, Mouwana, Khadir and Patcham, late Early Oxfordian in Kakindia limestone, late Middle Oxfordian at Kantkote, in early Late Callovian in Washtawa, Gangta bet, Khadir, in basal Kimmeridgian in Bharodia, early to mid Late Kimmeridgin in Jhuran etc. The mentioned almost invariable observation strengthens the probable anticipation that the bed 9, the richest of all the 10 ammonoid levels devoid of the macrocephalitins at Nara below the late Middle Bathonian Macrocephalitinae bearing sediments in the newly discovered section, should correspond to the early Early Bathonian Zigzag Zone Macrescens Subzone. The sequence stratigraphic interpretations were subsequently confirmed (Pandey and Pathak 2015a) through the record of number of ammonoid genera (*Zigzagiceras*, *Procerozigzag*, *Siemiradzkia*, *Berbericeras*, *Parkinsonia*, *Ebrayiceras*, *Telermoceras*, *Micromphalites*, *Prohecticoceras*, *Procerites*, *Cadomites*, etc.).

The above framework necessitated the reevaluation of the so called *Leptosphinctes* in the terminal part of the BCSm as of early Middle Bathonian Progracilis Zone Progracilis Subzone Perisphinctinae. The taxonomic status of the claimed *Leptosphinctes* may require review since Leptosphinctinae already extincted by the close of the Macrescens Subzone.

The above discussion demonstrates that the Bathonian in Nara and Jumara is ammonoid bearing. It includes a rich succession of relatively less shallow water Macrocephalitinae only from mid/late Middle Bathonian onwards. This faunal assemblage and fine textured carbonate/shale lithology suggests increase in bathymetry from Early to Late Bathonian, and farther up until at least the mid/late Early Callovian boundary.

The ammonoid record from the Bathonian sediments of Kachchh is poor except for Jumara and the newly discovered Nara where the sediments are highly fossiliferous as also rich in ammonoids. Available reports mentioned only a few ammonoid genera/species over the last many decades from a maximum of six ammonoid levels in the ~300 m thick Bathonian sediments exposed in Kachchh. Only occasional stray attempts have been made in recent past (e.g. Roy et al. 2007) towards enlargement of the Bathonian ammonoid stratigraphic record. The lithostratigraphic differentiation in the above work is inadequate and the ranges of the determined genera/species are vague. The attempted zonation does not meet the rigours of precision zonation. The new '*Prohecticoceras majalense*' Horizon has been assigned to the Middle Bathonian based on a new species with no taxonomic details. Unfortunately, the act renders the new species invalid, so also the horizon created after it.

A part of the biostratigraphic study of the Bathonian sediments of Kachchh, is presented as a preliminary biostratigraphic scheme for the sediments exposed at Nara in Mainland that are included here in a new informal member NLm within the ULM. Also included in the discussion here is the '*Leptosphinctes*' bed of Kuran in Kaladongar part of Patcham. In the present preliminary effort, only two zones are proposed as under:

Nara Limestone member (NLm)

1. **Parkinsonia–Siemirdzkia Zone**
   It is based on the co-occurrence of *Parkinsonia* and *Siemiradzkia* at the top of the ~1.5 m thick bed 9 of the newly discovered Late Bajocian–early to mid Middle Bathonian ammonoid inclusive section (Fig. 1.11). The other ammonoid genera have already been listed above (Pandey and Pathak 2015a). The zone is tentatively extended from bed 1 to bed 9, and assigned to Zigzag Zone Macrascens Subzone, however, in view of the presence of *Parkinsonia*, its extension down into late Late Bajocian is not ruled out.
2. **Perisphinctinae Zone**
   It is created tentatively on the revised determination of the earlier claimed *Leptosphinctes* as a Perisphinctinae instead of Leptosphinctinae below the

ammonoid bearing Middle Bathonian above, and correlation of the basal part of the BCSm with ammonoid bearing Early Bathonian at Nara. It may be noted that the claimed *Leptosphinctes* came from the terminal part of BCSm at Kuran ~10.0 m below GYFm. The zone is speculatively assigned to the early Middle Bathonian Progracilis Zone–Subcontractus Zone interval.

2.8.4.2 Late Middle to late Late Bathonian

Good and near continuous presence of ammonoids is noted only in the Jumara section, and hence the same is included in a new informal member JLm of the ULM. The ~51 m thick Bathonian sedimentary succession exposed at Jumara constitutes the later part of the Patcham Formation (Fig. 2.27). Its base is not exposed. The contact with the overlying Chari Formation is conformable. It has been lithostratigraphically differentiated into two distinct sediment intervals I and II having a sharp erosional contact. These two major lithostratigraphic intervals have been further subdivided, respectively, into 24 and 63 beds/bands (Pandey et al. 2013a). The Patcham Formation yielded over 130 ammonoid specimens from 36 levels. The entire Bathonian succession at Jumara exhibits the dominance of the relatively fine textured well-bedded limestone and shale/silt/marl. The sediment interval I of the older ~18 m thick succession largely comprises alternations of relatively thicker yellowish/greenish white, occasionally gypseous shale/marl and yellowish grey to earthy limestone (packstone) packed prolificly with corals (both in variety and number) in multiple relatively harder levels that project out, as also enclosing other diverse invertebrate fauna including ammonites, nautiloids, gastropods, bivalves, brachiopods etc, which correspond (Fig. 2.27) to beds 23–26 of Rajnath (1932). The younger ~33 m thick succession consists of alternations of greyish white/whitish marly limestone and earthy shale/silt which is here corresponded to bed 22 of Rajnath. The characteristic whitish grey nodular limestone makes easy recognition of bed the 22 from distance. Almost all the limestone beds contain ammonoids and other invertebrate fossils. Crinoid stems in lower part and sponges in the upper part are particularly observed at many levels in the sediment interval II. In general, the ammonoid density increases from the older to younger succession and is maximum in bed II-30, subsequently followed up by slow and gradual decrease in ammonoid density between bed II-31 to 53. The overlying succession from the beds II-54 to 63 is the poorest in ammonoids. The limestone/shale Bathonian succession as described above is included in the ULM.

Also, at Jumara Dome based on ranges of seven subfamilies, 10 genera, their many species in the limestone succession of JLm, two ammonoid zones have been created (Pandey et al. 2013a). Among the subfamilies, Macrocephalitinae has had its origin in SW Pacific while the rest arrived on the GTM from ETM. The Macrocephalitinae is thus the indigenous and the dominant GTM element with about 33 % in terms of individuals.

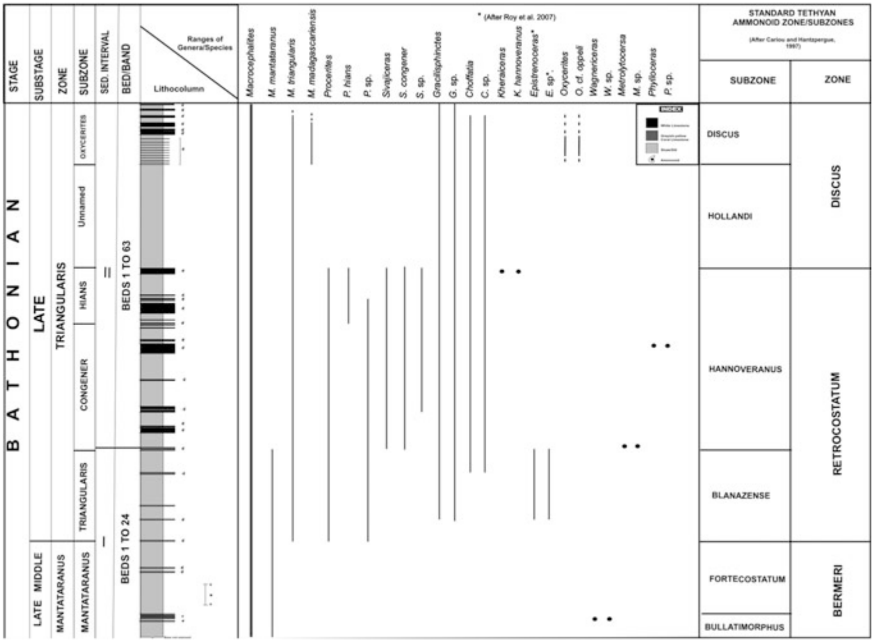


Fig. 2.27 Ammonoid ranges and zones in the later part of Bathonian in Jumara, Kachchh after Pandey et al. (2013a)

The two ammonoid zones are as under:

Jumara Limestone member (JLm)
The JLm, presumably, is confirmably underlain by the unexposed limestone succession of the Early and early Middle Bathonian age.

1. **Mantataranus Zone**
2. **Triangularis Zone** (Spath 1927–33, later emended in Krishna and Westermann 1985, 1987).

These two zones have been further subdivided into six subzones. All the proposed zones/subzones have also been correlated with the Standard Tethyan Scheme developed in Europe (Cariou and Hantzpergue 1997).

Mantataranus Zone/Subzone Pandey, Pathak and Krishna: beds I-01 to I-15 (Fig. 2.27)

This Bathonian ammonoid zone is marked by the first appearance and also dominance of *M*. cf. *mantataranus* Boehm. *Wagnericeras* is also present (Krishna 1994 unpublished report) here. The genus *Wagnericeras* is widely known from Middle Bathonian of NW Germany, Sula Island, New Guinea, (Westermann and Callomon 1988) and India (Krishna and Pathak 1994). Thus the Mantataranus Zone can be safely correlated with Bremeri Zone of the Standard Tethyan scheme developed on the ETM (Cariou and Hantzpergue 1997). The correlation is also strengthened by record of *Epistrenoceras* (Roy et al. 2007) of early Late Bathonian Retrocostatum Zone in the immediately overlying sediments at Jumara. In context of an exclusive Perisphinctidae based Late Bajocian–Late Tithonian ammonoid zonal succession, the zone can be alternatively named *Wagnericeras* Zone.

Triangularis Zone Spath beds I-16 to II-59 (Fig. 2.27)

This Zone is marked by the first appearance of *Macrocephalites triangularis* Spath in bed I-16, and is further differentiated into five subzones as under

Triangularis Subzone beds I-16 to I-23

The base of this subzone is marked by the first appearance of *M. triangularis* Spath with *Procerites* sp. in bed I-16. The genera *Gracilisphinctes* and *Choffatia* also appear in this subzone. The genera *Phylloceras* is also present. *M.* cf. *mantataranus* continued from below. *M. triangularis* Spath has been since long used as the zonal index for the Late Bathonian on GTM (Gondwanian Tethyan Margin) (Krishna and Westermann 1985, 1987; Krishna and Cariou 1993). In context of the Perisphinctidae, this zone alternatively can also be named as Congener Zone.

Congener Subzone beds I-24 to II-16

The base is marked by the first appearance of *Sivajiceras congener* (Waagen). *M.* cf. *mantataranus* Boehm marks its last appearance at the base of the subzone, however, *M. triangularis* Spath, *Gracilisphinctes* and *Choffatia* continue from below. The genus *Phylloceras* is also present.

Hians Subzone The base is marked by the first appearance of the subzonal index in bed II-17. The subzonal index is also restricted within this subzone. *Kheraiceras hannoveranus* (Roemer) is also present. *Gracilisphinctes* and *Choffatia* continue from below. *S. congener* (Waagen) makes its last appearance.

Unnamed Subzone Bed II-31

Oxycerites Subzone beds II-32 to II-63. The base is marked by the first **O**. cf. *arkelli* (Elmi) and *M. madagascariensis* Lemoine at the base in bed II-32. M. *triangularis* Spath, and *Gracilisphinctes*, mark their last appearance in this subzone.

M. triangularis Spath is the zonal index for the Late Bathonian on GTM (Krishna and Westermann 1985, 1987; Krishna and Cariou 1993). Roy et al. (2007, Fig. 2) have recorded *Epistrenoceras* having nearly world wide distribution from the early Late Bathonian Retrecostatum Zone from sediments of Triangularis Subzone (Dietl 1981). The Triangularis Subzone is correlated with the Retrocostatum Zone of the Standard Tethyan scheme (Cariou and Hantzpergue 1997). *K. hannoveranus* (Roemer) is recorded from Hians Subzone here proposed. Thus the Triangularis Subzone–Hians Subzone interval of the proposed scheme can be safely correlated with the ETM Retrecostatum Zone. The superjacent Oxycerites Subzone is easily assigned to late Late Bathonian Discus Zone. The zone can also be named Epistrenoceras Zone.

The age assignments of the GYFm by the Kachchh Jurassic workers in their publications from time to time are reviewed. The GYFm is present only in Patcham and Jhura. Biswas (1977, 1993) placed the unit in Callovian. Fursich et al. (2013, Table 4, p. 33, and also in several other earlier publications) have repetitively over the last two decades in their tables indicated the unit in Early to Middle Bathonian while in the accompanying texts assigned it to Middle Bathonian. Similarly, coral rich limestone of Jumara in the table is indicated in Middle Bathonian, in the text on p. 127 ranged from Middle to Late Bathonian, and on the same page again assigned to Progracilis Zone and Triangularis Zone. Progracilis Zone is an early Middle Bathonian zone while Triangularis Zone is exclusively Late Bathonian, and the two are separated by a large interval of three ammonoid zones—Subcontractus Zone, Morrisi Zone and Bremeri Zone—all of Middle Bathonian. Thus, the coral rich limestone of Jumara can be assigned if at all either to the Progracilis Zone of the early Middle Bathonian or to the Triangularis Zone of Late Bathonian, and not in any way to both the mentioned zones as done by Pandey and Callomon (1995). Several such multidimensional age discrepancies are exampled in Chap. 4. The unit in Patcham and Jhura is known to exclusively include the late Middle to early Late Bathonian ammonoid bearing limestones, and Krishna and coworkers have consistently ranged it from late Middle to early Late Bathonian. The recent discovery of Early Bathonian ammonoids (Krishna 2014 unpublished; Pandey and Pathak 2015a) in Nara below the first Macrocephalitnae in Nara or for that matter even elsewhere in Kachchh clinches the age of the GYFm as late Middle to early Late Bathonian. There is also the issue of additional inclusion of $\sim$25 m of immediately underlying sands in the GYFm by Fursich et al. (2013) which instead may be included in the underlying BCSm of the LSM. The coeval upper BCSm sands below the GYFm in Kaladongar are assigned to Late Bajocian (Jaitley and Singh 1983 to Fursich et al. 2013). Having no possibility of a subaerial gap, the mentioned sands are indirectly considered early and mid Middle Bathonian, without inclusion of any part of Early Bathonian, nothing to speak of Late Bajocian.

2.8.5 Callovian

Development of Callovian in Kachchh

The Callovian span of time is included in the Chari Formation, and is widely exposed through out the basin, in Mainland, ‘island belt’ and Wagad. The sediments are mostly fine textured shale/silt/clay with not so thick sand interbeds in the relatively distally located Mainland sections west of the median high. In the proximal sections east of the median high, ‘island belt’ and Wagad, much thicker sand intervals are present in addition of the shales. The early part in the Keera section locally includes golden oolitic limestones cyclically alternating with shales. The distally located Callovian sedimentary columns west of the median high profusely enclose ammonoids and other marine mega-invertebrates in pebble/concretion/nodular beds. The Keera sedimentary succession overlies the unexposed basement probably of ULM as in Jumara.

The proposition of a high resolution ammonoid chronologic scheme of 7 zones, 13 subzones and 25 horizons for the Callovian stage in Keera section of Kachchh (Ojha 1996a, b; Krishna and Ojha 1996, 2000; Krishna et al. 1993) is noteworthy. One of the significant features of the study is the initial lithostratigraphic differentiation of the Callovian at Keera into ~400 beds. The Keera section is the stratotype of the Chari Formation, so chosen by Stoliczka, as also the Indian stratotype for the Callovian stage. It is one of the several isolated block-faulted and domally uplifted Jurassic localities in the Kachchh Mainland, about 70 km north-east of Bhuj, bounded by longitudes 69° 14′ 15″ to 69° 14′ 33″ E and 23° 35′ 13″ to 23° 35′ 05″ N. The Chari Formation is well-exposed in an elliptical outcrop with Dhosa Oolite as its youngest member there.

Lithostratigraphic Framework (Figs. 2.28, 2.29 and 2.30)

A summary of the Callovian sedimentary succession (from base to top) belonging to the Chari Formation is given below, and the vertical ranges of the ammonoid taxa are indicated in Figs. 2.28, 2.29 and 2.30. The succession is easily differentiable into its members; LSM (sediment intervals 0 and I), RSM (sediment intervals II to VI), GSM (sediment intervals VII, VIII and IX), and DSM (early part of sediment interval X up to bed 392).

Sediment Interval 0 (Beds 1–32, 15 m): Alternation of shelly limestones, ferruginous calcareous sandstones and shales, scarcely fossiliferous.
Sediment Interval I (Beds 33–92, 55 m): Golden oolitic limestones intercalated with shales, highly fossiliferous.
Sediment Interval II (Beds 93–118, 25.59 m): Alternation of variegated limestones and gypseous shales, fossiliferous.
Sediment Interval III (Beds 119–130, 06.60 m): Alternation of variegated soft muddy, somewhat oolitic sandy limestones and shales/siltstones, highly fossiliferous.
Sediment Interval IV (Beds 131–160, 05 m): Alternation of white marly/pebbly bands and shales or maroon fractured marly bands and shales, highly fossiliferous.
Sediment Interval V (Beds 161–192, 25 m): Variegated, hard, jointed, pebbly calcareous sandstones intercalated with shales/siltstones, highly fossiliferous.
Sediment Interval VI (Beds 193–218 as here revised of reduced thickness of 25.5 m): Variegated, fractured, marly to pebbly hard bands capped by fossiliferous sandy limestones, highly fossiliferous.
Sediment Interval VII (Beds 219–334 as here revised with increased thickness of 35.4 m): Maroon to white pebbly fractured bands intercalated with gypseous shales, highly fossiliferous.
Sediment Interval VIII (Beds 335–336, 0.37 m): Whitish maroon limestone intercalated with yellowish brown shale, highly fossiliferous.
Sediment Interval IX (Beds 337–372, 11.5 m): White to maroon, marly to pebbly, somewhat fractured shelly bands alternating with yellowish brown gypseous shale, highly fossiliferous.
Sediment interval X (Beds 373–392, 4.0 m)
Zones, subzones and horizons and correlations with ETM

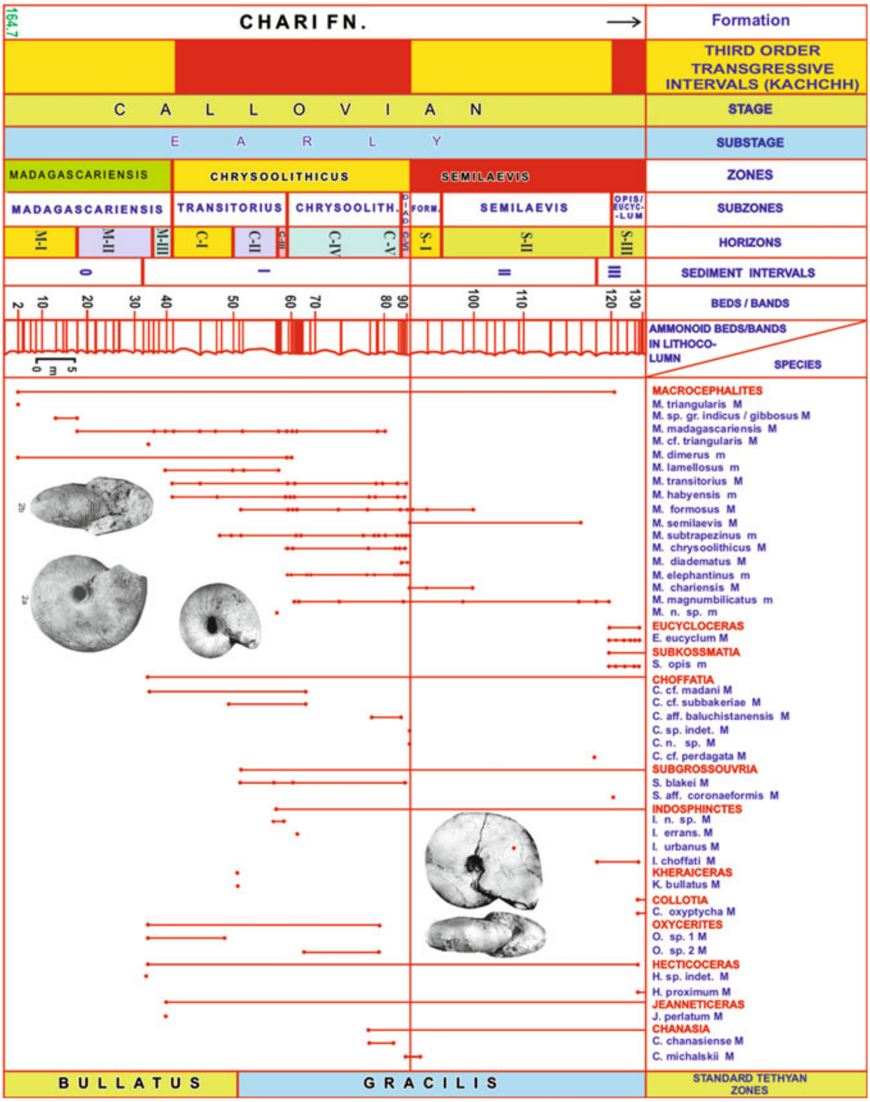


Fig. 2.28 The stratigraphic occurrence, ranges of the ammonoid species and third-order sequences in the Early Callovian of Kachchh (modified after Ojha 1996a, b)

Early Callovian

This interval includes 3 zones, 6 subzones and 12 horizons as under:

Lower Shale Member (LSM)

Madagascariensis Zone Krishna and Cariou (1990): Used first as assemblage by Krishna and Westermann (1987) and formalized later as a zone in Krishna and

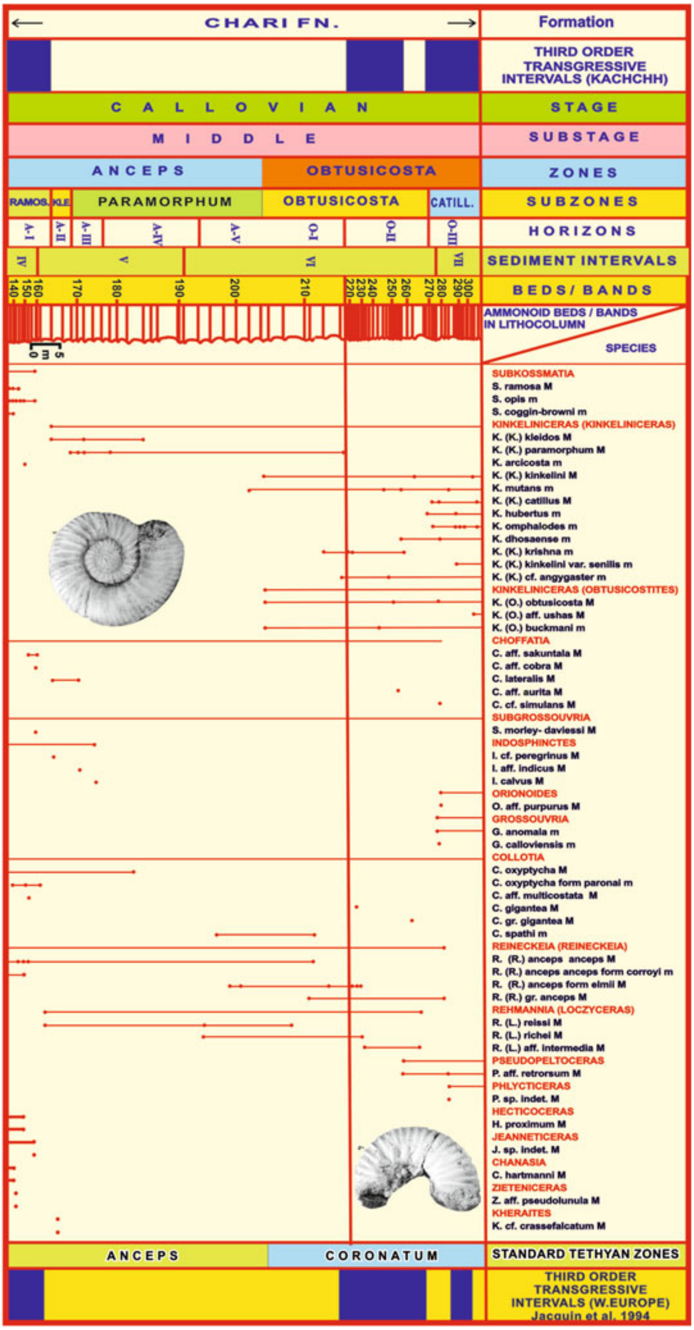


Fig. 2.29 The stratigraphic occurrence and ranges of the ammonoid species vis-a-vis third-order sequence in the Middle Callovian of Kachchh (modified after Ojha 1996a, b)

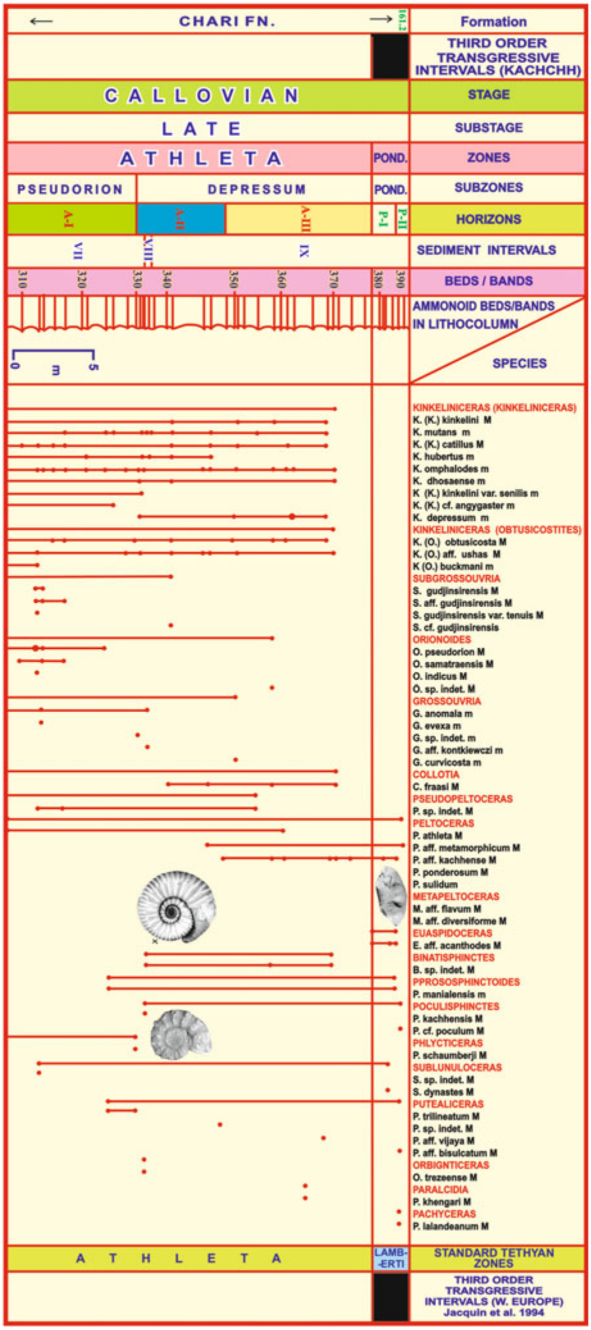


Fig. 2.30 The stratigraphic occurrence and ranges of the ammonoid species vis-a-vis third-order sequence in the Late Callovian of Kachchh (modified after Ojha 1996a, b)

Cariou (1990). It is characterized by the dominance of the zonal index *M. madagascariensis* Lemoine M with exclusion of *M. transitorius* (Spath) M.

M-I Horizon Krishna and Ojha (1996) (beds 1–17): It is indicated by scarce yet near exclusive *Macrocephalites* in Keera, e.g. *M.* cf. *madagascariensis* Lemoine M, *M.* cf. *triangularis* Spath M and *M.* gr. *gibbosus/indicus* (Spath) M, the last species with thick, blunt and sparser primaries.

M-II Horizon Krishna and Ojha (1996) (beds 18–35): It is indicated by the first *M. madagascariensis* Lemoine M morph I exclusive of the morph II of the species. Rare compressed nuclei of *M.* cf. *triangularis* Spath M continue from below.

M-III Horizon Krishna and Ojha (1996) (beds 36–41): It is indicated by the first *Choffatia* gr. *madani* Spath M and *Oxycerites* sp. indet. M in association with *M. madagascariensis* Lemoine M continuing from below. *M. madagascariensis* Lemoine M, the nominal and the most significant species of the Madagascariensis Zone is considered morphologically very close to the European *M. verus* Buckman of the Keppleri Subzone, basal Herveyi Zone (Callomon et al. 1989) and could be a coeval provincial subspecies. Thus is allowed precise subzonal correlation.

Chrysoolithicus Zone Krishna and Cariou (1990): Used first as an assemblage by Krishna and Westermann (1987) and later formalized as a zone in Krishna and Cariou (1990), considerably emended by Krishna and Ojha (1996). The base is defined (Ojha 1996a, b, Krishna and Ojha 1996) by the first *M. transitorius* (Spath) M and its possible dimorph *M. habyensis* (Spath) m. *M. chrysoolithicus* (Waagen) M is the dominant species in this zone along with its dimorph *M. elephantinus* (Sowerby) m.

Transitorius Subzone Krishna and Ojha (1996):
Its base is defined as for the zone. It includes two horizons

C-I Horizon Krishna and Ojha (1996) (beds 42–49): It is indicated by the first transient morph I of *M. transitorius* (Spath) M while *M. madagascariensis* Lemoine M continues.

C-II Horizon Krishna and Ojha (1996) (beds 50–55): It is characterized by *Kheraiceras bullatus* (d' Orbigny) M and its successor smaller variant with the first *Subgrossouvria* (gr. *blakei* Spath) M. *Choffatia* aff. *subbackeriae* (d' Orbigny) M is also present. The *Kheraiceras* provides good basis of correlation with Bullatus (uppermost part) and Prahecquense Horizons of France (Cariou 1984).

C-III Horizon Krishna and Ojha (1996) (beds 56–57): It is characterized by the first *Indosphinctes*. It is significant to note that the first *Indosphinctes* in France occurs in Laugieri Horizon, permitting correlation of the respective horizons of Kachchh and France.

Chrysoolithicus Subzone Krishna and Cariou (1990), emended (Krishna and Ojha 1996): Its base is defined by the first *M. chrysoolithicus* (Waagen) M along with its dimorph *M. elephantinus* (Sowerby) m. It includes two horizons

C-IV Horizon Krishna and Ojha (1996) (beds 58–75): It is marked by the presence of *Indosphinctes errans* Spath M.

C-V Horizon Krishna and Ojha (1996) (beds 76–87): It is marked by the presence of *Hecticoceras chanaziense* Parona and Bonarelli M common in the

Michalskii Horizon of France for correlation. *Choffatia* cf. *baluchistanensis* (Noetling) M is also present.

Diadematus Subzone Krishna and Cariou (1990): It is defined by significant *M. diadematus* (Waagen) and includes only one horizon.

C-VI Horizon Krishna and Ojha (1996) (beds 88–91): It is indicated by the last extremely inflated *M. diadematus* (Waagen) M. This horizon corresponds to the Subboreal Galillaeii Horizon near the top of the Koenigi Zone, which also includes similarly inflated *Macrocephalites*.

Ridge Sandstone Member (RSM)

Semilaevis Zone Krishna and Cariou (1990): Its base is defined by the first *M. semilaevis* (Waagen) M and acme of *M. formosus* (Sowerby) M.

Formosus Subzone Krishna and Cariou (1990) emended (Krishna and Ojha 1996): Its base is defined as for the Semilaevis Zone. It includes just one horizon.

S-I Horizon Krishna and Ojha (1996) (beds 92–95): It is marked by the acme of *M. formosus* (Sowerby) M and its dimorph *M. subtrapezinus* (Waagen) m together with *M. chariensis* (Waagen) M, the latter being exclusive to this horizon. *H. michalskii* Lew provides correlation with Michalskii Horizon of France.

S-II Horizon Krishna and Ojha (1996) (beds 96–119): It is marked by near exclusive *M. semilaevis* (Waagen) M, *Indosphinctes urbanus* Spath M and *I. choffati* Spath M, suggesting correlation with Michalskii and Proximum Horizons of France.

Eucyclum Subzone Krishna and Ojha (1996): It is characterized by the fist *Eucycloceras eucyclum* (Waagen) M and *Subkossmatia opis* (Sowerby) m, and includes only one horizon. Eucycloceratinae is a geographically restricted subfamily, and the associated ETM elements are indecisive about the firm age of its oldest subzone—the Eucyclum Subzone. The Eucyclum Subzone thus alternatively can also be included at the base of Middle Callovian, thereby including the entire subfamily at the base of Middle Callovian. Nevertheless, it is a mere suggestion, and for the present, the Eucyclum Subzone is maintained as the terminal subzone of the Early Callovian.

S-III Horizon Krishna and Ojha (1996) (beds 120–131): It is characterized by the abundance of *Eucycloceras eucyclum* (Waagen) M and *S. opis* (Sowerby) m. *H. proximum* Elmi M and*Collotia oxyptycha* (Neumayr) M in common between Kachchh and France.

Middle Callovian

This interval includes 2 zones, 5 subzones and 8 horizons

Anceps Zone Oppel: It is indicated by significant *Reineckeia anceps* (Reinecke) M, while the endemic *Subkossmatia ramosa* Spath M, *Kinkeliniceras kleidos* (Spath) M and *K. paramorphum* (Waagen) M are also significant in the early part.

Ramosa Subzone Krishna and Ojha (1996): It is characterized by *S. ramosa* Spath M with *R. anceps* (Reinecke) M, and includes one horizon.

A-I Horizon Krishna and Ojha (1996) (beds 132–163): It is defined by significant *Reineckeia anceps* (Reinecke) M, *S. ramosa* Spath M and single *Chanasia* *hartmanni* Zeiss M, the latter providing correlation with Bannense Horizon of France.

Kleidos Subzone Krishna and Ojha (1996): It is defined by the first *Kinkeliniceras kleidos* (Spath) M at the base, and includes one horizon.

A-II Horizon Krishna and Ojha (1996) (beds 164–167): It is characterized by the first *Kinkeliniceras kleidos* (Spath) M and *Choffatia lateralis* Spath M. *Indosphinctes* aff. *peregrinus* Spath M is exclusive to this horizon. The common *I.* cf. *peregrinus* Spath M suggests correlation of Kleidos Subzone with the Bannense and Medea Horizons of France.

Paramorphum Subzone Krishna and Ojha (1996): It is defined by the first *Kinkeliniceras paramorphum* (Waagen) M at the base, and includes three horizons.

A-III Horizon Krishna and Ojha (1996) (beds 168–175): It is characterized by the first *K. paramorphum* (Waagen) M at the base. *Indosphinctes* aff. *indicus* (Siemeradzki) M. *I. calvus* (Sowerby) M is exclusive to this horizon.

A-IV Horizon Krishna and Ojha (1996) (beds 176–193): It is characterized by the last *K. kleidos* (Spath) M with the significant exclusion of *Indosphinctes*.

A-V Horizon Krishna and Ojha (1996) (beds 194–203): It is characterized by the first *Reineckeia (Loczyceras) richei* (Roman) M and *Collotia spathi*, providing correlation with Jason Horizon of France.

The Paramorphum Subzone, on the strength of common *R. (L.) richei* (Roman), M and *C. spathi,* correlates well with the Jason Subzone of France.

Obtusicosta Zone Krishna and Ojha (1996): It is defined by the FAD and significant presence of the zonal index *Kinkeliniceras (Obtusicostites) obtusicosta* (Waagen) M. *K. paramprphum* (Waagen) continues. It includes two subzones

Obtusicosta Subzone Krishna and Ojha (1996): The base is defined as for the Obtusicosta Zone. *R. (L.) richei* (Roman) M is still present while *R. (L.)* aff. *intermedia* m is ecxclusive to the subzone. *Collotia gigantea* Bourquin M is also present. *Pseudopeltoceras* marks its FAD in this subzone, so also *K. dhosaeinse* m. It includes two horizons.

O-I Horizon Krishna and Ojha (1996): (beds 204–217): It is indicated by the first *K. (O.) obtusicosta* (Waagen) M. *R. (L.) richei* (Roman) M continues. *R (L) reissi* becomes extinct in this horizon.

Gypseous Shale Member (GSM)

O-II Horizon Krishna and Ojha (1996) (beds 218–269): It is indicated by *C. gigantea* Bourquin M and *R. (L.) intermedia* (Bourquin) M, the latter being exclusive to this horizon.

Catillus Subzone Krishna and Ojha (1996): It is marked by first *Kinkeliniceras catillus* (Waagen) M and *Orionoides*. It includes just one horizon

O-III Horizon Krishna and Ojha (1996) (beds 270–307): It is marked by the first *K. catillus* (Waagen) M, *K. hubertus* m and *K. omphalodes* m, also first *Orionoides*, providing correlation with Rota Horizon of France.

Late Callovian

This interval includes 2 zones, 2 subzones and 5 horizons

Athleta Zone It is indicated by the first scarce *Peltoceras* through *Peltoceras athleta* (Phillips) M and first *Orionoides pseudorion* (Waagen) M at the base. *Binatisphinctes* is exclusive to this zone, while *Poculisphinctes* registers its first occurrence in this zone. The last *Subgrossouvria* occurs in this zone. It includes two subzones

Pseudorion Subzone Krishna and Ojha (1996): Its base is defined as for the Athleta Zone. It includes one horizon

A-I Horizon Krishna and Ojha (1996) (beds 308–331): It is marked by the first *P. athleta* (Phillips) M and *O. pseudorion* (Waagen) M. *Subgrossouvria* gr. *gudjinsirensis* Spath M is also significant.

Depressum Subzone Krishna and Ojha (1996): Its base is defined by the first *Kinkeliniceras depressum* Krishna and Ojha m. It includes two horizons:

A-II Horizon Krishna and Ojha (1996) (beds 332–347): It is indicated by the first *K. depressum* Krishna and Ojha m, *Binatisphinctes* and *Poculisphinctes* and the last *Subgrossouvria*.

A-III Horizon Krishna and Ojha (1996) (beds 348–377): It is marked by the first *Peltoceras* aff. *kachhensis* Spath M, the last kinkeliniceratins, the last *Binatisphinctes*, the last *Orionoides* as also the last *P. athleta* (Phillips) M along with solitary *Paralcidia* cf. *khengari* Spath M.

The Depressum Subzone is correlated with the French Collotiformis Subzone in view of common *Collotia fraasi* (Oppel) M, *P. metamorphicum* Spath M, *P. vijaya* Spath M, and morphologically close *Binatisphinctes* and *Paralcidia*.

Dhosa Sandstone Member (DSM)

It in fact begins in the terminal part of Depressum Zone from bed 373.

Ponderosum Zone Krishna and Ojha (1996): It is defined by the first *Peltoceras ponderosum* (Waagen) M. It includes two horizons

P-I Horizon Krishna and Ojha (1996) (beds 378–385): It is indicated by the first *P. ponderosum* (Waagen) M, the first *Euaspidoceras*, the first *Metapeltoceras* and the first *P. solidum* Spath M, suggesting good correlation with the Subtense Horizon of France.

P-II Horizon Krishna and Ojha (1996) (beds 386–390): It is indicated by the first *Pachyceras llandeanum* (d' Orbigny) M, *Prososphinctoides manialensis* Spath m, and single *Poculisphinctes* cf. *poculum* (Lackenby) M which suggest correlation with the Athletoides Horizon of France.

The Ponderosum Zone neither includes any Early Oxfordian pandemic Perisphinctinae, nor the Mayaitinae, nor the Kinkeliniceratinae that are geographically restricted to GTM. It is instead featured by the diverse ETM elements of Mediterranean origin, e.g. Peltoceratinae, Aspidoceratinae and Pachyceratinae. It is interpreted that the Kinkeliniceratins underwent near extinction to drastic reduction near the second-order MFS at the close of the ammonoid-rich gypsiferous clays. The change from the ammonoid-rich gypsiferous clays to the ammonoid devoid/scarce non-gypseous silt/sand is also easily picked up in the well logs, and is interpreted to mark the start of the second-order RST. The ammonoid assemblage in the Horizon P-II in general suggests a small third-order transgression which is in

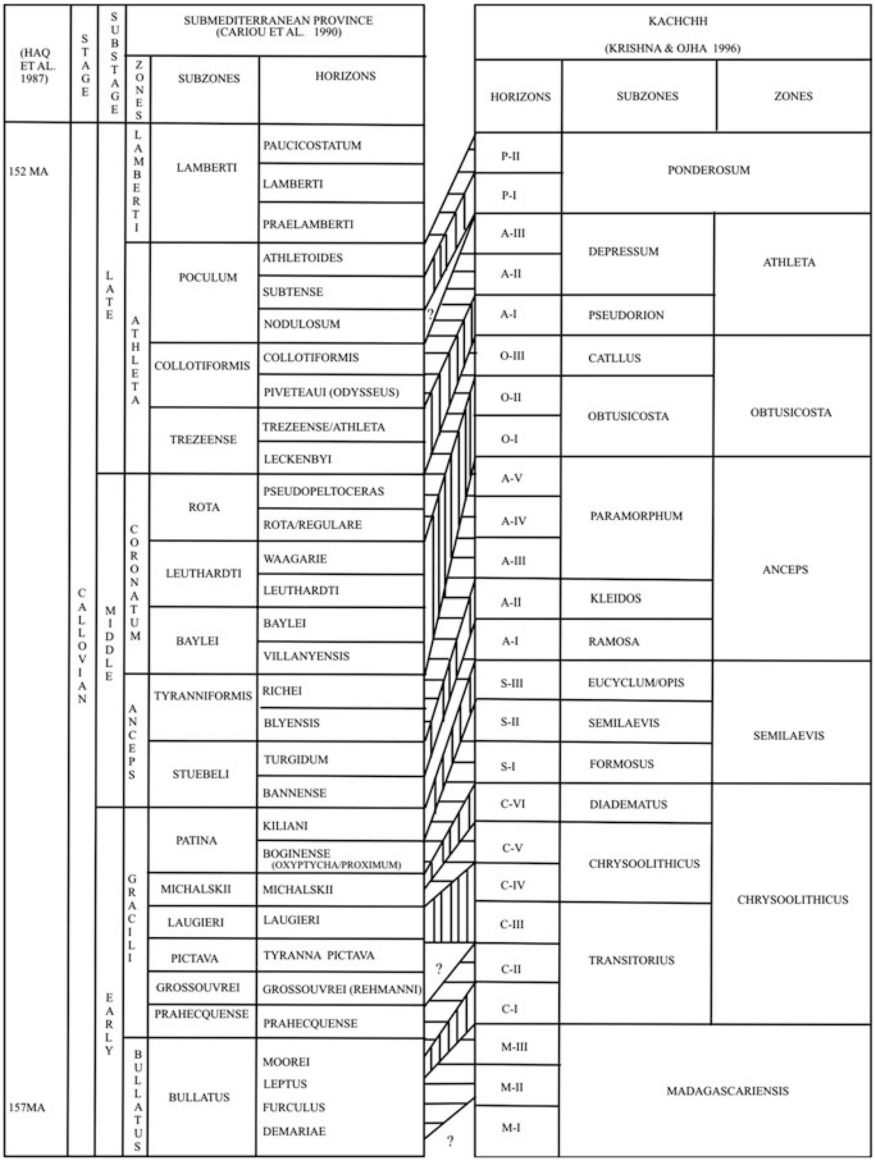


Fig. 2.31 The correlation of the Kachchh Callovian Horizons with the ETM standard (modified after Krishna and Cariou 1990)

turn followed up by the early Early Oxfordian ammonoid devoid thick sand/silt present throughout the basin from Mainland Kachchh to Wagad and Khadir. Such sands are even found in different basal Oxfordian sections in Madagascar of probable Mariae Zone age that are deposited in the regressive phase. The possibility of a small subzonal subaerial gap above the ammonoid devoid non-gypseous sands is discounted in view of the location of Keera a good distance away from the margin, however, the presence of such a gap is not ruled out in proximal sections in East Mainland, Khadir, Gangta bet and Wagad. High resolution precise correlation with the Submediterranean province of ETM is indicated in Fig. 2.31. The entire DSM could also be included in the terminal most Late Callovian.

2.8.6 Oxfordian

Development of the Oxfordian in Kachchh
Zonal correspondence with ETM

The development of the Oxfordian (s. l.) on the Gondwanian Tethyan Margin (GTM) between Arabia and Australia is invariably incomplete. Also, almost all over the GTM, it is expressed in the moderately to highly condensed oolitic facies, particularly, in the Early and early Middle Oxfordian in proximal locations. Such characteristic features are on account of the inclusion of the first-order Jurassic MFS on the GTM in the Middle Oxfordian along with the accompanying submarine stratigraphic gap at sedimentation sites away from the margin. The GTM Oxfordian interval is more interesting and significant than on the ETM (European Tethyan Margin) since the intra-Jurassic first-order MFS on the ETM instead of falling in the Oxfordian is included in the Kimmeridgian stage. In spite of the features of incompleteness and condensation, it has been all the more desirable to refine the ammonoid stratigraphy and zonation in the Oxfordian of the GTM. The prospects of progress in the Oxfordian ammonoid zonation improved in context of the recent discovery of uninterrupted, moderately to rapidly sedimented, complete Oxfordian in the proximal part of the Kachchh basin at Gangta Bet and Kantkote in Wagad (Krishna et al. 1994a, c, 1995a, 1996a, b, 1998, 2000 and later). The ammonoid-rich Early Oxfordian has been already known since the classic monographs of Waagen (1873–75) and Spath (1927–33). Almost all the ETM Oxfordian zonal intervals are found recognizable in Kachchh (except the doubtful nearly ammonoid devoid equivalent of the early Early Oxfordian Mariae Zone) those of Early to early Middle Oxfordian throughout the basin, while the Middle and Late Oxfordian exclusively in proximal Kantkote and Gangta Bet. Here, the author proposes a preliminary tentative succession of ammonoid zones in the Oxfordian of Kachchh as the first such effort anywhere on the Gondwanian Tethyan Margin. The Oxfordian sediments invariably are conformably underlain by the exposed Callovian sediments.

The Oxfordian duration includes two highly contrasting stratigraphic intervals of unequal duration in Kachchh (Krishna et al. 1998, 2000). The older is present all over the exposed basin from the distal-most Lakhapur in the west to proximal-most Wagad in the east, also in Khadir of ‘Island belt’ while the younger is exclusive to Wagad (Figs. 2.32 and 2.33) and Khadir. The older interval is ~2.6 my long up to the early Middle Oxfordian Vertebrale Subzone of the Plicatilis Zone of the ETM inclusive of the terminal part of the DSM, and the DOM. It is ~12–18 m thick (thickness increasing towards the margin), mostly fine textured, slow to extremely slow sedimented, ammonoid and other body fossil rich, irregularly based, nodular, boxworked, hardened to hard grounded, pebbly/nodular/bumpy/conglomeratic, densely oolitic limestone (in the distal relatively deeper sites to much less oolitic and less calcareous beds in the proximal sites). The dominantly oolitic succession although present in the ~300 km wide exposed shelf, is best characterized in the western half of the Mainland Kachchh, west of the MH (Median High). The coeval Early and basal Middle Oxfordian part is also included in Wagad and Khadir, which is overlain by the younger mid Middle to latest Late Oxfordian. The mid Middle to Late Oxfordian is exclusive to Wagad and Khadir on the east and north margins outside the Mainland Kachchh. It is ~140 m thick of ~3.6 my duration, and is compositely best developed in Khadir, Gangta Bet, Desalpar and Kantkote–Bharodia stratigraphic sections. It includes the terminal part of the DSM and the full JM of the Chari Formation up to the late Middle Oxfordian. The Chari Formation is conformably superposed by Katrol Formation in Wagad.

Lithostratigraphic Framework

Among the several Oxfordian sections studied, only three are detailed here (1. Lakhapur section as representative of the Mainland Kachchh, coeval sediments of Early and early Middle ages are also present particularly in Khadir, Gangta bet, and Kakindia, however, mid Middle to Latest Oxfordian sediments are absent on the Mainland, 2. Gangta bet section and 3. Kantkote–Bharodia, i.e. the K–B section of Wagad). These account for the first tentative, yet, independent ammonoid zonal formulation for the Kachchh Oxfordian in Particular, and for the GTM in general.

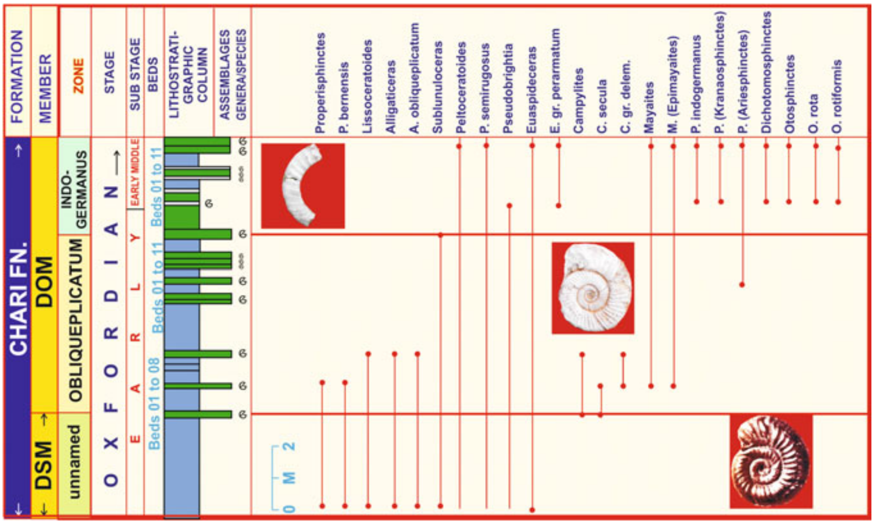


Fig. 2.32 Ammonoid zones in the Early and early Middle Oxfordian of Kachchh in Lakhapur section

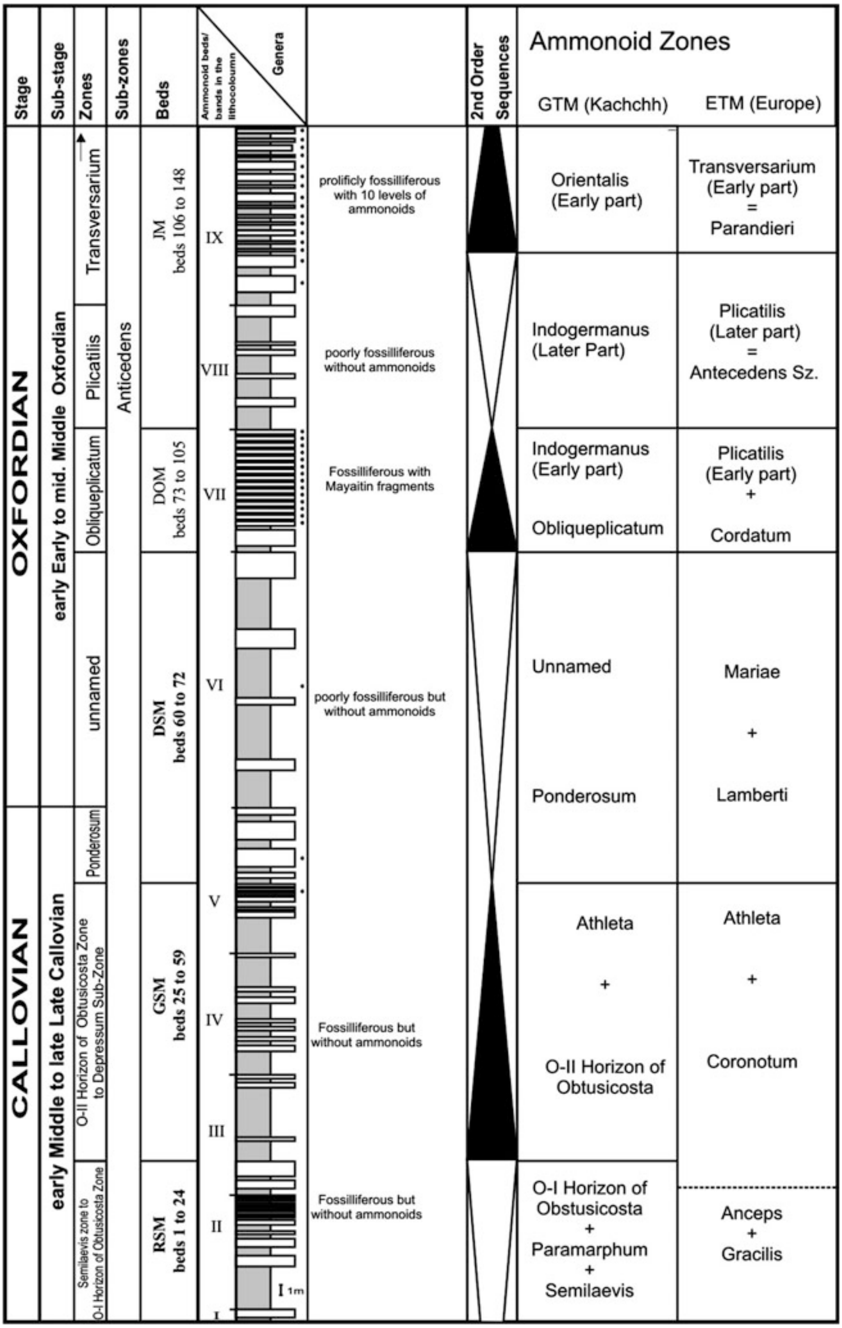


Fig. 2.33 Preliminary zonation in the newly discovered Callovian–Oxfordian stratigraphic column at Gangtabet vis-a-vis second-order sequences

The Oxfordian sediments all over the basin are conformably underlain by the exposed Callovian sediments.

These sections are

Lakhapur Stratigraphic Section

The stratigraphic section is organized into three sediment intervals (LI to LIII) which are further differentiated into a succession of 30 beds (LI-beds 01–08, LII-beds 01–11 and LIII-beds 01–11) with 15 ammonoid levels at the distal most exposed part of the basin (Early and early Middle part of Oxfordian representing the younger part of Chari Formation which is followed by a large submarine stratigraphic gap up to the early Early Kimmeridgian Hypselocyclum Zone (Krishna et al. 1998).

Sediment Interval LI (Beds 01–08): 5.30 m thick, earthy non-gypseous shale with maroon to greenish maroon, medium to fine grained, pebbly, marly, fractured, calcareous, fossiliferous, sandstone bands, yielding ammonoids from 3 different levels.

Sediment Interval LII (Beds 01–11): 3.80 m thick, earthy shales intercalated with yellow to greenish maroon, pebbly, nodular, fractured, very hard, occasionally oolitic, sandy limestone bands, highly fossiliferous, yielding ammonoids from six different levels.

Sediment Interval LIII (Beds 01–11): 2.90 m thick, earthy to yellowish green shale/siltstone, occasionally enclosing nodules, alternating with medium to fine grained, hard, compact, blocky, jointed, pebbly, nodular, yellowish to greenish yellow, ammonoid-rich, highly fossiliferous, sandy limestone bands, yielding ammonoids from six different levels.

It may be noted that the coeval sediments are also studied at Gangta Bet, Kakindia bet, Khadir and Wagad outside the Mainland Kachchh where the thickness is distinctly greater, ooilte presence minimal and ammonoid density and diversity substantively reduced in view of their proximal locations.

Gangta Bet Section

It is organized in nine sediment intervals which are further differentiated into 64 beds with at least 25 ammonoid levels in the proximal-most exposed part of the basin of Early to late Middle Oxfordian age. The first five sediment intervals belong to the Callovian while the younger four to the Oxfordian (Fig. 2.33). The mentioned Oxfordian up to the early Middle Oxfordian is underlain by at least Middle to Late Callovian. The entire late Middle Callovian to Middle Oxfordian included earier in the column of the abandoned 'Gangta bet member' is unambiguous extension of the Chari Formation in Gangta bet.

Sediment interval I—0.80 m hard, medium to fine grained, maroon to brown, highly jointed pebbly sandstone.

Sediment interval II—10.80 m earthy yellow shale alternating with thick (50 cm to 1.00 m thick) hard medium to fine grained, brown concretionary sandstone bands in the lower part and with thin (15–20 cm thick) ash-maroon to maroon, box worked nodular concretionary sandstone bands.

The above two sediment intervals correspond to the later part of RSM.

Sediment interval III—12 m ochre yellow to earthy shale alternating with hard medium to coarse grained cross-bedded nodular fractured box worked reddish to yellowish maroon thick (40–1.5 m thick) sandstone/sandy limestone bands, highly fossiliferous in younger levels with numerous shell fragments, yet no ammonoids.

Sediment interval IV—12 m earthy shale alternating with hard medium to fine grained greenish yellow to ash-maroon and even reddish grey (40–60 cm thick) sandy limestone bands with numerous shell fragments, yet without ammonoids.

Sediment interval V—14.80 m earthy yellow shale alternating with hard medium to fine and even coarse grained, occasionally flaky and jointed, greenish grey, yellowish maroon to even reddish sandstone/sandy limestone bands, fossiliferous with occasional or rich in shell fragments, and two levels of rare ammonoids.

Sediment intervals III–V are broadly correlated to GSM with two levels of Kinkeliniceratinae ammonoids in sediment interval V of Depressum Subzone.

Sediment interval VI—24.60 m grey to earthy yellow shale alternating with hard and compact, yellowish to greenish maroon, medium to fine, even coarse grained, box worked, pointed to blocky with occasional concretions and nodules sandstone, sandy limestone bands, mostly poorly fossiliferous while a 2 m thick medium grained friable variegated sandstone at the top with a marker conglomerate in the middle. Ammonoids as yet not collected in this interval.

Sediment interval VII—11.40 m earthy shale alternating with hard fractured medium to fine maroon 10–20 cm thick sandstone bands with indeterminate perisphinctin and mayaitin fragments in upper part while a 1.6 m thick very hard compact coarse grained grey coloured jointed blocky sandstone bed in the lower part. This is perhaps the correlative of the marker Kakindia Limestone of Kakindia bet (beds 8–12 of Gangta bet and bed 36 of Khadir).

Sediment interval VIII—11.20 m earthy shale alternating with hard grey to maroon medium to fine sandstone bands (20–60 cm thick) capped by 1.60 m thick medium grained very hard and compact poorly fossiliferous sandstone.

Sediment interval IX—17.00 m thick earthy shale with hard coarse even gritty, occasionally friable pebbly nodular fractured jointed blocky yellowish to yellowish maroon or even grey calcareous 20–80 cm thick sandstone bands, highly fossiliferous yielding ammonoids from at least 16 ammonoid-rich levels. This is perhaps the famous ammonoid-rich Gangta ammonoid bed.

Kantkote–Bharodia (K–B) Stratigraphic Section (Figs. 2.34 and 2.35): It is located at the proximal-most part of the basin from Kantkote to Bharodia in Wagad (late Middle Oxfordian to early Early Kimmeridgian in age representing the youngest part of the Chari Formation and the Basal (Kantkote) Member of the Katrol Formation exclusively present in Wagad). It may be noted that the sediment intervals III to VII of the Fig. 2.5 after Krishna et al. (2009) correspond to the sediment intervals IV to VIII in the here updated Fig. 2.34.

Sediment Interval K–B I (Beds 01–05 of K–B I & II): 24.50 m thick, earthy shale alternating with medium to fine sandstone bands in the lower part capped with hard, medium to coarse grained, rippled and nodular sandstones, yielding ammonoids from two levels.

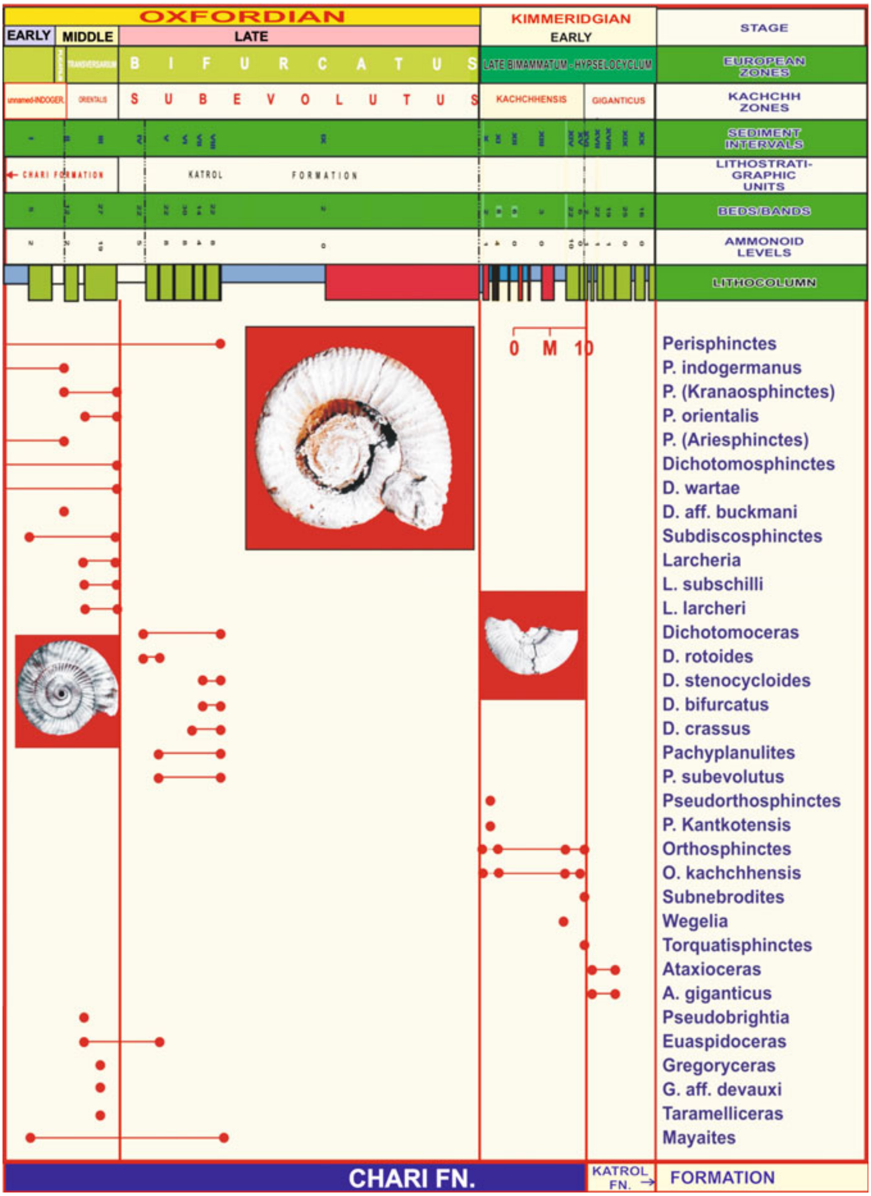


Fig. 2.34 The stratigraphic occurrence and ranges of the ammonoid species in the Middle and Late Oxfordian–Early Kimmeridgian of Kachchh in Kantkote–Bharodia section

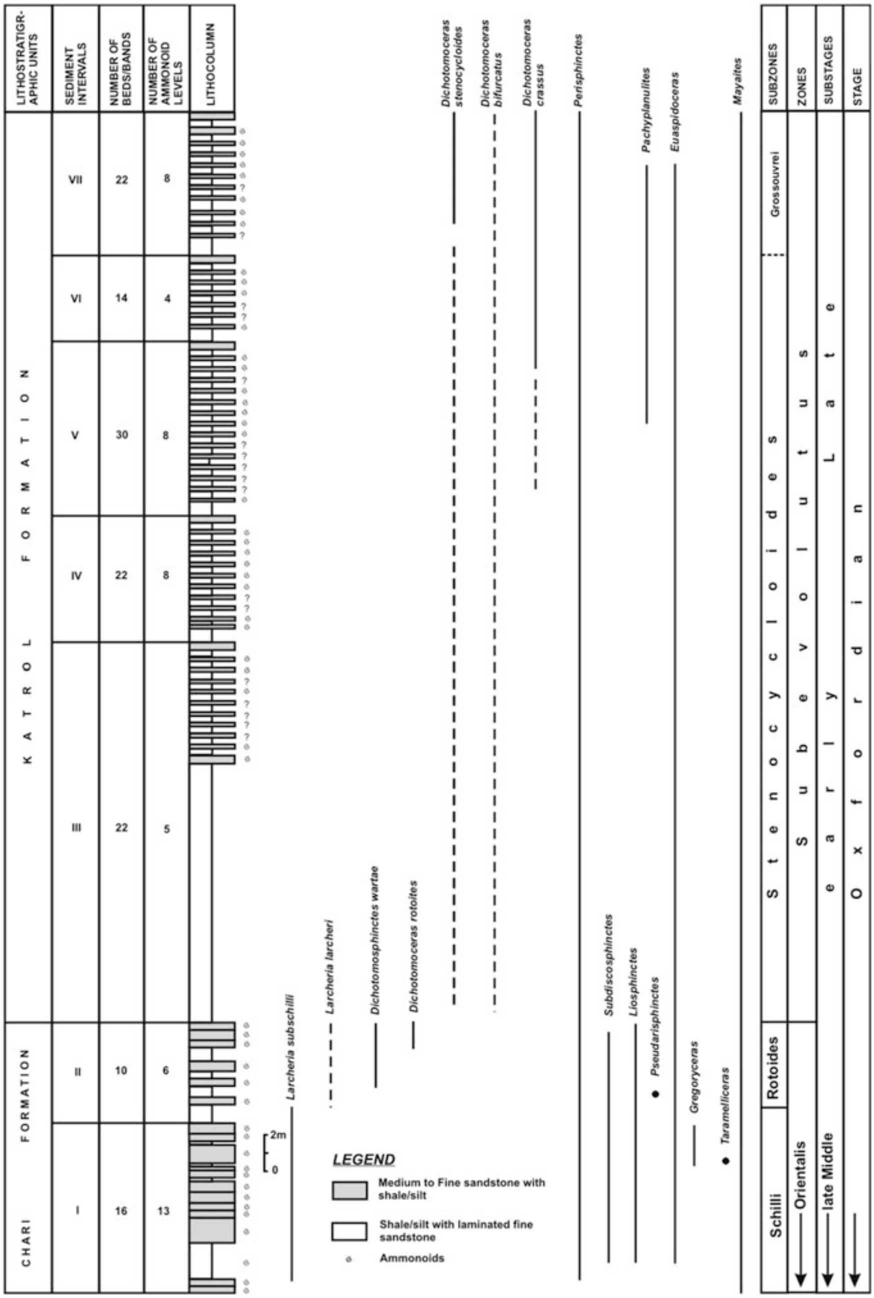


Fig. 2.35 Ammonoid zones in the late Middle Oxfordian–Early Kimmeridgian column of Kantkote–Bharodia section after Krishna et al. (2009)

Sediment Interval K–B II (Beds 01–12 of K–B I & II): 13.50 m thick, earthy gypseous shale alternated with nodular, sometimes bioturbated sandstone bands, poor in ammonoids (only two levels).

Sediment Interval K–B III (Beds 01–27) m thick, shale with maroon to brick red, medium to fine grained, hard, nodular sandstone, highly fossiliferous with plenty of ammonoids (19 different levels), frequent wood and belemnites.

Sediment Interval K–B IV (Beds 01–22): 22.0 m thick, earthy-grey gypseous silty shale with several thin, variegated, nodular, flaky sandstone bands in the lower part and shale alternating with maroon to yellowish maroon, medium to fine grained, pebbly, fractured bands in the middle part, capped with (50–70 cm thick) massive, jointed, blocky, hard and compact, grey, medium to fine grained sandstones, poorly fossiliferous, yielding ammonoids only from five different levels.

Sediment Interval K–B V (Beds 01–22): 9.0 m thick, earthy-grey silty shales intercalated with several thin bands of sandstone and topped with the massive, jointed and blocky sandstone giving similar physical and lithological appearance as that of Sediment Interval IV as above, yielding ammonoids from eight different levels.

Sediment Interval K–B VI (Beds 01–30): 10.0 m thick, earthy-grey silty shale and thin sandstone bands having similar lithological appearance as that of Sediment Intervals IV and V and yielding ammonoids from eight different levels. (lower portion) to hard and compact, yellowish to maroon coloured, occasionally bioturbated, variegated calcareous sandstone with belemnites, ammonoids, woods and other fossil shell fragments.

Sediment Interval K–B VII (Beds 01–14): 6.0 m thick, repetition of similar lithology as that of Sediment Intervals IV, V and VI, yielding ammonoids from four ammonoid levels.

Sediment Interval K–B VIII (Beds 01–22): 8.0 m thick, sedimentary succession of the same physical and lithological appearance as that of Sediment Intervals IV, V, VI and VII, yielding ammonoids from eight different levels.

Sediment Interval K–B IX (Beds 01–02): 34 m thick, variegated shale alternating with thin sandstone bands (lower 54 m part), capped with massive, cross-bedded, medium to coarse grained, friable to hard, variegated sandstone (80 m upper part), unfossiliferous.

Dhosa Sandstone Member (DSM)
The terminal part of DSM may include the unnamed zone of early Early Oxfordian.

Ammonoid zones and Correlation
Early and early Middle Oxfordian (Mainland Kachchh at Lakhapur Section)
early Early Oxfordian (unnamed zone = Mariae Zone of the ETM): There is determined a third-order TST within the sediment interval VI near the top in a marker conglomerate bed. Applying isochroneity of the third-order sequence surfaces across the world, this marker conglomerate bed may be assigned to the early part of the early Early Oxfordian Mariae Zone. This marker conglomerate is otherwise age-constrained between the *Kinkeliniceras* bearing sediment interval V of the early part of early Late Callovian Athleta Zone below and *Mayaites* bearing

sediment interval VII of late Early Oxfordian Obliqueplicatum Zone above. Thus, the major part of the Sediment interval VI underlying the transgressive marker Conglomerate bed is suggestively corresponded to the Dhosa Sandstone Member, while the Callovian/Oxfordian boundary in Kachchh may be suggested within the sediment interval VI below its youngest marker sandstone bed. Alternatively, the sediment interval VI could also exclusively belong to terminal Late Callovian, which is farther up disconformably superposed by late Early Oxfordian ammonoid bearing sediment interval VII. Any ammonoids as such have not been discovered in the mentioned conglomerate or sandstone bed, which could be due to shallowing of the basin followed up by possible transient emergence. The absence of ammonoids does not permit any formal name to this terminal Callovian/basal Oxfordian zone. The mentioned marker conglomerate presumably is the bed 6 of Biswas.

Dhosa Oolite Member (DOM)
Obliqueplicatum Zone (new) (Sediment Interval LI, Beds 02 to LII bed 11, Fig. 2.32) (equal to Cordatum Zone): The zone is indicated by the first Mayaitinae, first *Alligaticeras* through *A. obliqueplicatum* (Waagen) and other species, first *Properisphinctes* through *P. bernensis* (de Lor.) and associated other *Properisphinctes* in the sediment interval LI, beds 02–08 of the Lakhapur section in association with Hecticoceratinae and Peltoceratinae. It is tentatively correlated to the Claromontanus Zone of Europe on the basis of the common *Properisphinctes bernensis* (de Lor.) in Claromontanus Zone (Cariou and Hantzpergue 1997) and Kachchh, which in turn, is correlated with the Bukowskii Subzone of the Cordatum Zone. The morphologically similar *Peltoceratoides* and *Alligaticeras* suggest the duration of the zone up to the Cordatum Subzone of the Cordatum Zone of the ETM. There is possibility of even further differentiation into at least two subzones based on the first *Properisphinctes* and the first *Alligaticeras* in the early part of the bed 01, and the first *Mayaites* in the bed 04.

The early Early Oxfordian interval of the Mariae Zone is unknown. Any clue to that is not picked up even in the sequence stratigraphic context. There could even be a subaerial break particularly in the proximal sections of Gangta bet, Habo and Jhura at the second-order SB between the Dhosa sand/silt and Dhosa Oolite. Whatever, be the reason, neither the latest Late Callovian nor the earliest Early Oxfordian subzones are yet differentiated through ammonoids in Kachchh. However, in the Nara section Kanjilal and Singh (2012) suggested the presence of the latest Late Callovian Lamberti Zone through a rare not easily explainable record of the cold water boreal *Quenstedtoceras* cf. *lamberti* in the middle part of the DSM. This in turn could relate to the widespread transient cooling phase near the Middle/Late Jurassic transition as in Europe of Dromart et al. (2003), also discussed later elsewhere. At present, in the absence of the early Early Oxfordian ammonoids, using isochroneity of the third-order TSTs between the GTM and the ETM, there is determined a thin oolitic, conglomeratic slow sedimented bivalve bearing bed (bed 6 of Biswas) as a third-order TST, and assigned to early Early Oxfordian in the Gangta bet section less than ~10 m below the Mayaitinae bearing Kakindia Limestone marker of definite late Early Oxfordian Obliqueplicatum Zone age.

Biswas (1993) correlated the mentioned conglomeratic sandstone to an ammonoid bearing bed of the Khadir section, although the present author did not find any. May be later searches yield in the mentioned bed ammonoids of the early part of early Early Oxfordian. Which may allow naming of this zone as also confirm its being of the early part of early Early Oxfordian.

Indogermanus Zone (new) (Sediment Interval LIII, Beds 02 to 11—upper limit not exposed in Lakhapur section but determined in the Gangta Bet section, Fig. 2.33) (time equivalent of the ETM Plicatilis Zone): The base is indicated by the first appearance of *Perisphinctes indogermanus* (Waagen) in sediment interval LIII, bed 02 in Lakhapur stratigraphic section in association with Peltoceratinae, Mayaitinae and Haploceratinae. It is correlatable to the Plicatilis Zone of Europe (Cariou and Hantzpergue 1997) on the basis of morphologically close Perisphinctinae and Peltoceratinae. Only the early part of this zone, that is suggestively equivalent to Vertebrale Subzone, is present in the Mainland Kachchh on account of a large submarine stratigraphic gap above. The later part of this zone is recognized recently in the Gangta Bet section up to the top of sediment interval G—VIII, and beds 11–13 of Biswas with ammonoids of the Antecedens Subzone.

Jhadasa Member (JM)

Mid. Middle to Late Oxfordian at Kantkote–Bharodia section of Wagad

Orientalis Zone (new) (at Kantkote–Bharodia Section at Wagad) (Figs. 2.34 and 2.35) (time equivalent of the late Middle Oxfordian Transversarium Zone of ETM): The Orientalis Zone is exclusively developed at Wagad in the Kantkote, Khadir and Gangtabet sections. The precise base is determined in the Gangta Bet section at the base of the sediment interval G—IX through rich *Dichotomosphinctes* cf. *buckmani*. The single and septate example of *Dichotomosphinctes* aff. *buckmani* in sediment interval K–B II, bed 04 (Fig. 2.34) at Kantkote, also, suggests the base of the Orientalis Zone. In Biswas, the base is indicated at the base of bed 13 at Gangta bet and also includes bed 15. Bed 13 includes *D*. gr. *buckmani* of Parandieri Subzone of the ETM. It is the most abundantly ammonoid bearing zone in the entire Kachchh Jurassic and named after the most common Perisphinctinae species found in this interval. It is correlatable with the Transversarium Zone of Europe (Cariou and Hantzpergue 1997) on the basis of the presence of rich *Larcheria*, particularly the species *Larcheria subschilli* (Lee) and a few *Gregoryceras* aff. *devauxi* (Bert and Enay), and *Dichotomoceras rotoides* (Ronch.) in later part of the zone in sediment interval K–B III, beds 05–27 (Figs. 2.34 and 2.35). It is further differentiable in several subzones as on ETM based on the ranges of *D*. cf./aff. *buckmani*, *D*. *lucaeformis* (Krishna et al. unpublished), *Larcheria schilli* and, *Dichotomoceras rotoides* (Krishna et al. 2000, at the Gangta Bet and Kantkote–Bharodia sections, which shall be formalized at a later stage.

Informal Patasar Shale Member of Kantkote Member (KM)

It starts at the lithostratigraphic contact of the JM of the Chari Formation below and the KM of the Katrol Formation at the ammonoid stratigraphic Schilli Subzone/Rotoides Subzone boundary within the Orientalis Zone. It makes the basal part of the KM in the Kantkote section.

Subevolutus Zone (new) (K–B IV, bed 02–K–B IX, bed 02, Fig. 2.35): The base is indicated by *Pachyplanulites pagri* Spath and *P. subevolutus* (Waagen) in sediment interval K–B IV, bed 02 in association with the significant presence of species of *Dichotomoceras* like *D. bifurcatus*, *D. crassus*, *D. stenocycloides* which otherwise characterize the Bifurcatus Zone in Europe (Cariou and Hantzpergue 1997) and hence, the correlation with the European Bifurcatus Zone. This zone is quite thick and ammonoid scarce with large indeterminate varicostate Perisphinctinae fragments. Though the terminal few metres are completely devoid of ammonoids, yet are tentatively included in the terminal Oxfordian Subevolutus Zone, prior to the onset of Kimmeridgian through the first Ataxioceratinae *Orthosphinctes*. The revised Oxfordian/Kimmeridgian boundary suggests tentative correspondence of the upper boundary of the mentioned zone to the early part of Bimammatum Zone.

2.8.7 Kimmeridgian

Develoment of the Kimmeridgian in Kachchh

The Kimmeridgian ammonoid bearing succession is best represented in the Kachchh Mainland (Fig. 2.1). Six different sections have been studied (Figs. 2.34, 2.36 and 2.37), which from the margin to the basin are: (i) Bharodia that includes early and mid. Kimmeridgian. (ii) Jawahar Nagar (iii) Southeast Ler (iv) Southwest Ler (v) Walakhawas and (vi) Lakhapur. Sections (ii) to (vi) include late Early and Late Kimmeridgian. The Kimmeridgian all through the Mainland is unconformably underlain by the exposed Early and early Middle Oxfordian sediments.

The Kimmeridgian is not present in the island belt on account of the complete withdrawl of the sea from that region even prior to the close of the Middle Oxfordian. Also, only early and mid Early Kimmeridgian is known through ammonoid bearing sediments belonging to the genera *Orthosphinctes* and *Ataxioceras* presumably of Planula–Hypselocyclum suprazonal interval at Bharodia in the informal Adhoi member of the Kantkote Member of Katrol Formation in Wagad. It may incidently be the youngest Jurassic ammonoid bearing geological record of the Kachchh basin outside the Kachchh Mainland. The immediately superjacent ammonoid devoid, rapidly deposited sands could also be included in the Hypselocyclum Zone. Thus the Wagad succession is not younger than the Early Kimmeridgian. The Early Kimmerdgian in Wagad is underlain conformably by the Late Oxfordian sediments.

Lithostratigraphic Framework

At Bharodia

The Bharodia section of early and middle Early Kimmeridgian age is described below:

Sediment Interval K–B X (Beds 01–02): 5.0 m thick, shale with very hard and compact, jointed, yellowish, medium to fine grained, calcareous sandstone band with shell fragments, rare ammonoids.

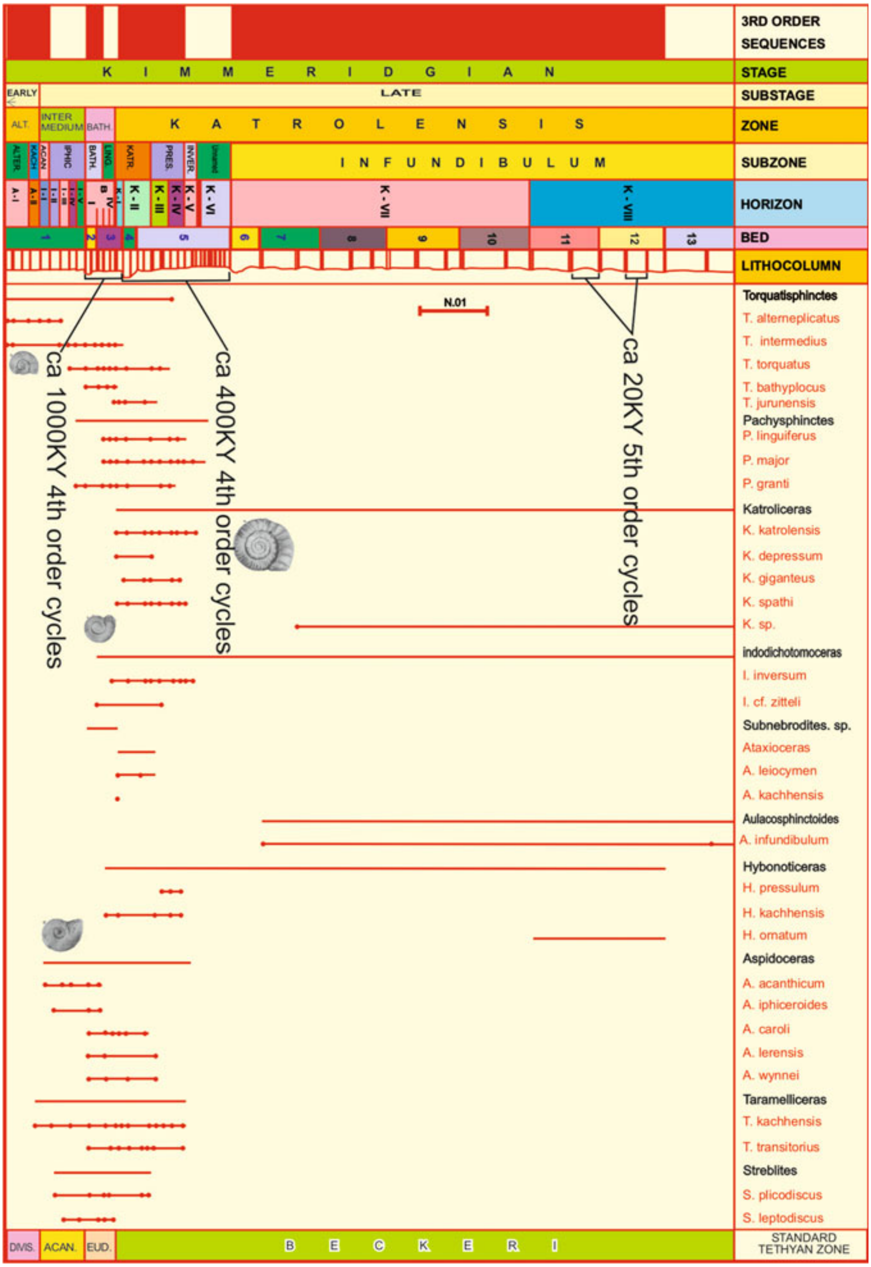


Fig. 2.36 The stratigraphic occurrence, ranges of the ammonoid species and third-order sequences in the Kimmeridgian of Southwest Ler, Kachchh after Krishna et al. (1995b)

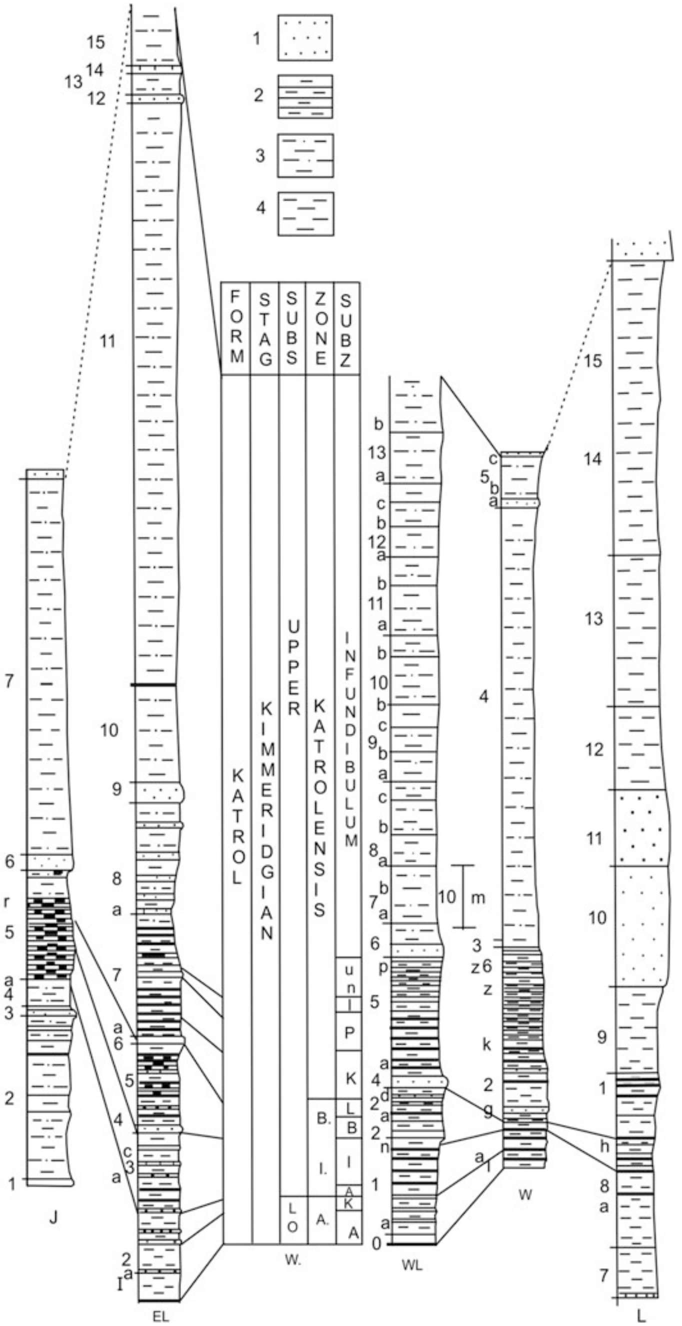


Fig. 2.37 Correlation in the Mainland Kachchh during the Kimmeridgian interval; 1–4 stand, respectively, for sandstone, shale/sandstone alternation, siltstone/shale and shale; J,WL, W and L abbreviate, respectively, for Jawahar Nagar, East Ler, West Ler, Walakhawas and Lakhapur localities after Krishna et al. (1995b)

Sediment Interval K–B XII (Beds 01–02 of K–B XI and XII): About 36.0 m thick sedimentary succession of yellowish shale intercalated with coarse grained, gritty, hard, maroon colored vertically burrowed sandstone with rare wood, belemnites and very rare indeterminate ammonoids, frequent shell fragments. Sediment Interval K–B XIII (Beds 01–03): 15 m thick shale with variegated, massive, occasionally cross-bedded, coarse grained, friable sandstone, capped by highly ferruginous, bioturbated, maroon colored, unfossiliferous sandstone.

Sediment Interval K–B XIV (Beds 01–22 of K–B XIV & XVIII): 14.0 m thick, shale alternating with hard, nodular, fractured, maroon, ash-maroon to yellowish maroon sandstone bands, fossiliferous, yielding ammonoids from 10 different levels.

Sediment Interval K–B XV (Beds 01–06 of K–B XIV & XVIII): 2.30 m thick, gypseous shale intercalated with medium grained, flaky sandstone bands.

Sediment Interval K–B XVI (Beds 01–02 of K–B XIV & XVIII): 1.80 m thick, shale, capped with yellowish maroon, highly fossiliferous, medium grained, densely packed with trigonids and rare ammonoids.

Sediment–B XVII (Beds 01–22 of K–B XIV & XVIII): 8.30 m thick, gypseous silty shale with variegated sandstone bands, poorly fossiliferous, ammonoids scarce.

Sediment Interval K–B XVIII (Beds 01–19 of K–B XIV & XVIII): 6.80 m thick, shale with several hard and compact, coarse grained, calcareous, fossiliferous, trigonid bands, ammonoids rare.

Sediment Interval K–B XIX (Beds 01–25): 8.30 m thick, shale with variegated sandstone bands, poorly fossiliferous.

Sediment Interval XX (Beds 01–16): 11.80 m thick unfossiliferous shale with thin, occasionally massive, variegated sandstone bands.

At Ler

The basal 100–150 m part of the Katrol Formation represents the Kimmeridgian in the Mainland Kachchh. It disconformably overlies the Chari Formation. The contact is distinctively marked by a hard persistent oolitic bed (Dhosa Oolite Member) representing the top of the Chari Formation (Callovian–early Middle Oxfordian) of early Indogermanus Zone age.

The late Early and Late Kimmeridgian ammonoid successiosn is best developed in Southeast and Southwest Ler. In the latter section, ammonoids have been collected from 37 levels within the thickness of ca 110 m (subdivided into 13 beds), while in Southeast Ler the Kimmeridgian ammonoids come from 41 levels in ca 150 m thick succession (split up into 15 beds).

Adhoi member of Kantkote Member (KM)

Ammonoid Zones

The interval includes two zones Kachchensis Zone and Gignaticus Zone based on new species which are here described prior to the introduction of the mentioned new zones.

Genus: ***Orthosphinctes*** **Schindewolf 1925**
Ammonites tiziani **Oppel 1863**
Species: ***Orthosphinctes kachchhensis*** **n. sp.**
(Figures 1–3, plate 8)
Material: Three specimens, fragmented, moderately preserved.
tirely septate.
Locality: Kantkote–Bharodia section, Wagad, Kachchh, India.
Measurement:

S. No.	Types	D	H	W	U	H/W %	P/2	S/2	Remarks about body chamber
1.	Holotype	124.0	44.0	36.0	51.0	122	26	–	Septate
		92.0	32.0	28.0	38.0	114	–	–	
		70.0	23.0	21.0	30.0	110	23	–	
2.	Paratype	106.0	32.0	29.0	50.0	110	27	–	Septate
		80.0	26.0	24.0	36.0	108	–	–	
		60.0	20.0	19.0	27.0	105	26	–	
3.	Paratype	110.0	38.0	37.0	49.0	102	27		Septate
		84.0	29.0	28.0	38.0	103	–		
		65.0	21.0	23.0	30.0	91	26		

Diagnosis: Size moderate to large, entirely septate, compressed, whorl section quadrate to subquadrate, evolute, umbilicus wide, umbilical wall almost vertical, umbilical shoulder curved, laterals slightly convex to nearly flat, venter rounded, primaries from near the base of umbilical wall, slightly concave forward around umbilical shoulder, prorsiradiate on laterals, sharp, distinct, well-spaced, coarseness and spacing gradually increasing with diameter, sescondaries from near the middle of the whorl height or slightly above, mostly biplicate with occasional single ribs up to 105–110 mm D, triplication appearing somewhere between 90–110 mm D, first triplicate rib at 93 mm D, thereafter 2–3 biplicate ribs between two successive triplicate ribs until the preserved end of 124 mm D, slightly projected forward and uninterrupted on venter, suture distinct but undecipherable.

Remarks: It is comparable to *Orthosphinctes* (*Orthosphinctes*) *polygyratus* (Quenstedt) in its prorsiradiate ribbing pattern. *Orthosphinctes* (*Praeataxioceras*) sp. gr. *laufenensis* (Siemiradzki) differs from the present Kachchh species in its distinctly smaller size, more compressed whorl section and almost radiating pattern of ribbing.

Stratigraphic Horizon: Kachchhensis Zone (Sediment Interval K–B X, bed 01 to Sediment Interval K–B XV, bed 06).

Age: Kachchhensis Zone.

Genus–*Ataxioceras* Fontannes 1879

Perisphinctes hypselocyclum Schindewolf 1925

***Ataxioceras giganticus* n sp**

(Figure 4, plate 8)

Material: One specimen made up of several small fragments.

Locality: Bharodia in Wagad, Kachchh.

Size and Remarks: The specimen has an unusually large size of 500 mm among the known species of *Ataxioceras*, and hence the creation and naming of the new species as *A. giganticus*. The specimen is compressed, moderately evolute, and featured by typical ataxioceratid twice bifurcated ribs, first at the mid lateral and later near the ventrolateral shoulder. The preserved bodywhorl is characterized by strong sharp cuniform primaries.

Stratigraphic Horizon: KB XVI to KB XVIII

Age: **Giganticus Zone**

Ammonoid zones, subzones and horizons

(Bharodia)

Kachchensis Zone (new) Krishna (KB-XIV beds 01–22 and KB-XV beds 01–06) (time equivalent of Planula Zone of ETM): The base of the zone is indicated by the first Ataxioceratinae through moderate *Orthosphinctes kachchensis* n. sp. In bed 02. Single fragment of *Wegelea* aff. g*redingensis* (Wegele) and again single nucleus of *Subnebrodites* cf. *minutum* (Dietrich) are present in bed 22 which have prompted correspondence of this zone to collective interval of Haufianum Subzone of Bimammatum Zone and Planula Zone of ETM. Fursich et al. (2013) have placed the early red/maroon part of this zone for the terminal ammonoid-rich part of Chari Formation in the Kantkote river section, and assigned to the late Middle to mid Late Oxfordian instead of early Early Kimmeridgian, which is contrary to our findings. Their indentification of *Orthosphinctes as Larcheria* and *Dichotomoceras* and farther in the section, the determination of *Orthosphinctes* and *Ataxioceras* as species of *Torquatisphinctes* occurring within the younger *Astarte–Gryphaea* interval as Late Kimmeidgian is negated. The gap of the entire Late Oxfordian–Early Kimmeridgian ~5 my between the underlying early Early Kimmeridgian red beds of Kachchhensis Zone and the conformably overlying younger *Astarte–Gryphaea* bearing sands of mid Early Kimmeridgian Giganticus Zone proposed by Fursich et al. (2013) is non-existent.

Giganticus Zone (new) (KB-XVI to XVIII) (time equivalent of the collective interval of Platynota Zone and Hypselocyclum Zone of ETM): The zone is featured by rare *Ataxioceras* at three levels. The youngest level includes a new species of relatively large size (*A. giganticus* n. sp.). Further up to the top of sediment interval KB-XVIII, only, the lag bivalve astartid–trigonid assemblage is observed. This zone on the basis of *Ataxioceras* is tentatively corresponded to the collective interval of Platynota Zone and Hypselocyclum Zone of ETM.

Lower Katrol Member (LKM)

Ammonoid zones/subzones/horizins

All the undermentioned zones and most subzones were first defined by Krishna and Pathak (1991, 1993) while 3 subzones and 19 horizons were introduced for the first time in Pandey (1993 unpublished) and Krishna et al. (1995b, 1996c) with minor revision in a few zones.

The ammonoid zonation at Ler is based on a sedimentary succession, which unconformably overlies the early Middle Oxfordian Indogermanus Zone (Fig. 2.36). In absence of common ammonoids, it is not possible to establish any correspondence between the oldest late Early Kimmeridgian Alterneplicatus Zone of Ler to the youngest Kimmeridgian Giganticus Zone developed in Wagad. However, in view of the suggested correlations with the ETM zonation scheme, it is surmised that the Alterneplicatus Zone follows the Giganticus Zone without any significant gap, not exceeding a subzone or so.

Alterneplicatus Zone Krishna and Pathak (1991) (beds 0–1c)

Alterneplicatus Subzone Krishna and Pathak (1991)

A-I Horizons Krishna et al. (1995b) (beds 0–1b): Its base is marked by the first appearance of the index *Torquatisphinctes alterneplicatus* M.

Kachhensis Subzone Krishna and Pathak (1991)

A-II Horizons Krishna et al. (1995b) (bed 1c): It is marked by the first appearance of *Taramelliceras kachhensis* (Waagen) M.

Intermedius Zone Krishna and Pathak (1991) (beds 1d–1h)

Acanthicum Subzone Krishna and Pathak (1991)

I-I Horizon Krishna et al. (1995b) (bed 1d): This horizon is marked by first *Aspidoceras acanthicum* (Oppel) M.

Iphiceroides Subzone Krishna and Pathak (1991)

I-II Horizon Krishna et al. (1995b) (bed 1e): This horizon is marked by the first appearance of *Aspidoceras iphiceroides* (Waagen) m and *Streblites plicodiscus* (Waagen) M.

I-III Horizon Krishna et al. (1995b) (bed 1f): It is indicated by the first appearance of *Streblites leptodiscus* Spath M.

I-IV Horizon Krishna et al. (1995b) (bed 1g): This horizon is marked by first appearance of *Torquatisphinctes torquatus* (Sowerby) m.

I-V Horizon Krishna et al. (1995b) (bed 1h): It is marked by first appearance of *Pachysphinctes granti* Spath M.

Bathyplocus Zone Krishna and Pathak (1991) (beds 2–3c): In the present work this zone has been divided into two subzones, namely Bathyplocus Subzone and Linguiferus Subzone. It includes four horizons (B-I to B-IV Horizons). B-I and B-II Horizons correspond to the Bathyplocus Subzone, while B-III and B-IV Horizons correspond to the Linguiferus Subzone. These horizons are based on the four successive transient morphs (morph I, morph II, morph III and morph IV) within the stratigraphic range of *T. bathyplocus* (Waagen) m. These informal/quasiformal stratigraphically differentiated morphs of *T. bathyplocus* (Waagen) m are based on the clearly expressed distinct microevolutionary unidirectional centripetal extension (hypermorphic peramorphosis) with time in the position of the initiation of triplicate ribbing on the body chamber from the last quarter to near the start of the body chamber.

Bathyplocus Subzone Krishna et al. (1995b) (beds 2–3a): The base of this subzone is marked by the first appearance of the zonal index *Torquatisphinctes bathyplocus* (Waagen) m (genetic assignment here transferred from *Pachysphinctes* to *Torquatisphinctes*) and *Aspidoceras caroli* Spath *M*. *Torquatisphinctes intermedius* Spath m, *Torquatisphinctes torquatus* (Sowerby) m, *Pachysphinctes granti* Spath M, *Taramelliceras kachchhensis* (Waagen) M, *Streblites plicodiscus* (Waagen) M, *Streblites leptodiscus* Spath M, *Holcophylloceras mesolcum* (Dietrich) M, *Aspidoceras acanthicum* (Oppel) M and *Aspidoceras iphiceroides* (Waagen) m continue from bellow. *Indodichotomoceras* cf. *zitteli* Spath m and *A. lerensis* Spath m & M mark their first appearance within this subzone.

B-I Horizon Krishna et al. (1995b) (bed 2): It is marked by the first appearance of morph I of *T. bathyplocus* (Waagen) m in which the first triplicate rib appears in the last quarter of the body chamber.

B-II Horizon Krishna et al. (1995b) (bed 3a): It is marked by the first appearance of morph II of *T. bathyplocus* (Waagen) m in which the first triplicate rib appears at the end of the second quarter of the body chamber. *Aspidoceras lerensis* Spath m & M also starts in this horizon.

Linguiferus Subzone Krishna et al. (1995b) (beds 3b–3c): The base of this subzone is marked by the first appearance of *Pachysphinctes linguiferus* Spath m as also of the first appearance of morph III of *T. bathyplocus* (Waagen) m. *Torquatisphinctes intermedius* Spath m, *Torquatisphinctes toquatus* (Sowerby) m, *Torquatisphinctes bathyplocus* (Waagen) m, *Pachysphinctes granti* Spath M, *Indodichotomoceras* cf. *zitteli* Spath m, *Taramelliceras kachhensis* (Waagen) M, *Streblites plicodiscus* Waagen m, *Aspidoceras caroli* Spath M, *Aspidoceras lerensis* Spath m & M, *Holcophylloceras mesolcum* (Dietrich) M, *Streblites leptodiscus* Spath M continue from below. *Torquatisphinctes jurunensis* Spath M, *Pachysphinctes major* Spath M, *Indodichotomoceras inversum* (Spath) M, *Indodichotomoceras* sp. m, *Taramelliceras transitorius* Spath M and *Aspidoceras wynne*i Waagen M also mark their first appearance in this subzone.

B-III Horizon Krishna et al. (1995b) (bed 3b): It is indicated by the first *P. linguiferus* Spath m as also of morph III of *T. bathyplocus* (Waagen) m in which the first triplicate rib appears in the beginning of the second quarter of the body chamber.

B-IV Horizon Krishna et al. (1995b) (bed 3c): Its base is marked by the first appearance of *T. transitorius* Spath M as also of morph IV of *T. bathyplocus* Waagen m in which the first triplicate rib appears in the first quarter of the body chamber.

Katrolensis Zone Krishna and Pathak (1991) (beds 3d–13b): The Katrolensis Zone has been revised to include Infundibulum Zone, earlier placed at the base of the Hybonotum Zone. This zone includes five subzones, namely Katrolensis Subzone, Pressulum Subzone, Inversum Subzone, Unnamed Subzone and Infundibulum Subzone. These have been further subdivided into eight horizons (K-I to K-VIII Horizons). Among these, K-I and K-II Horizons correspond to the Katrolensis Subzone, K-III to K-IV Horizons correspond to the Pressulum Subzone.

K-V and K-VI Horizons belong to the Inversum Subzone and the unnamed subzone and K-VII to K-VIII to Infundibulum Subzone, respectively. Horizons of the Katrolensis Subzone and Pressulum Subzone are developed/strengthened with the first appearance of the successive four transient morphs (morphs I–IV) of *Katroliceras katrolensis* (Waagen) m within a part of its stratigraphic range. These informal/quasiformal stratigraphically differentiated morphs of *K. katrolensis* (Waagen) m are based on the clearly expressed distinctly unidirectional microevolutionary centripetal extension with time in the position of the first appearance of the abruptly modified (cuniform) primary ribs from the last quarter to the start of the body chamber in the successively younging morphs (hypermorphic peramorphosis). There is also observed size increase in successively younging morphs with stratigraphic age upto the level of morph IV. On the other hand, K-V horizon is based on the sudden reduction in size of *K. katrolensis* (Waagen) m. K-VI Horizonal interval is devoid of determinable ammonoids although fossil wood and belemnoids are present. Horizons K-VII and K-III are based, respectively, on the first *Aulacosphinctoides* and *H. ornatum* Spath m (Fig. 2.36).

Katrolensis Subzone Krishna and Pathak (1991) (beds 3d–5b)

K-I Horizon Krishna et al. (1995b) (bed 3d): It is marked by the first appearance of morph I of *K. katrolensis* (Waagen) m in which the first abruptly modified (cuniform) primary rib appears in the last quarter of the body chamber.

K-II Horizon Krishna et al. (1995b) (beds 4–5b): Its base is marked by the first appearance of the morph II of *K. katrolensis* (Waagen) m, in which the first abruptly modified (cuniform) primary rib appears in the middle of the second quarter of the body chamber.

Pressulum Subzone Krishna and Pathak (1991) (beds 5c–5f): The base of this subzone marked by the first appearance of the zonal index *Hybonoticeras pressulum* (Neumayr) m and is additionally strengthened by the first morph III of *K. katrolensis* (Waagen) m. It is also correlatable to Early Beckeri Zone Subeumela Subzone Horizon II of ETM (Schweigert et al 1996).

K-III Horizons Krishna et al. (1995b) (beds 5e–5d): Its base is marked by the first appearance of the morph III of *K. katrolensis* (Waagen) m in which the first abruptly modified rib appears in the beginning of the second or at the end of the first quarter of the body chamber, in addition of the first *H. pressulum* (Neumayr) m.

K-IV Horizon Krishna et al. (1995b) (beds 5e–5f): Its base is marked by the first appearance of the morph IV of *K. katrolensis* (Waagen) m, in which the first abruptly modified rib appears between the start and the middle of the first quarter of the body chamber. It is suggestively correlatable to Subeumela Subzone Horizon III.

Inversum Subzone Krishna and Pathak (1991) (beds 5g–5h)

K-V Horizon Krishna et al. (1995b) (beds 5g–5h): In addition to the significant presence of *I. inversum* (Spath) m, this horizon is marked by the sudden decrease in size of *K. katrolensis* (Waagen) m.

Unnamed Subzone Krishna et al. (1995b) (beds 5i–5p): It includes only K-VI Horizone which is marked by the presence of scarce indeterminate virgatosphinctin

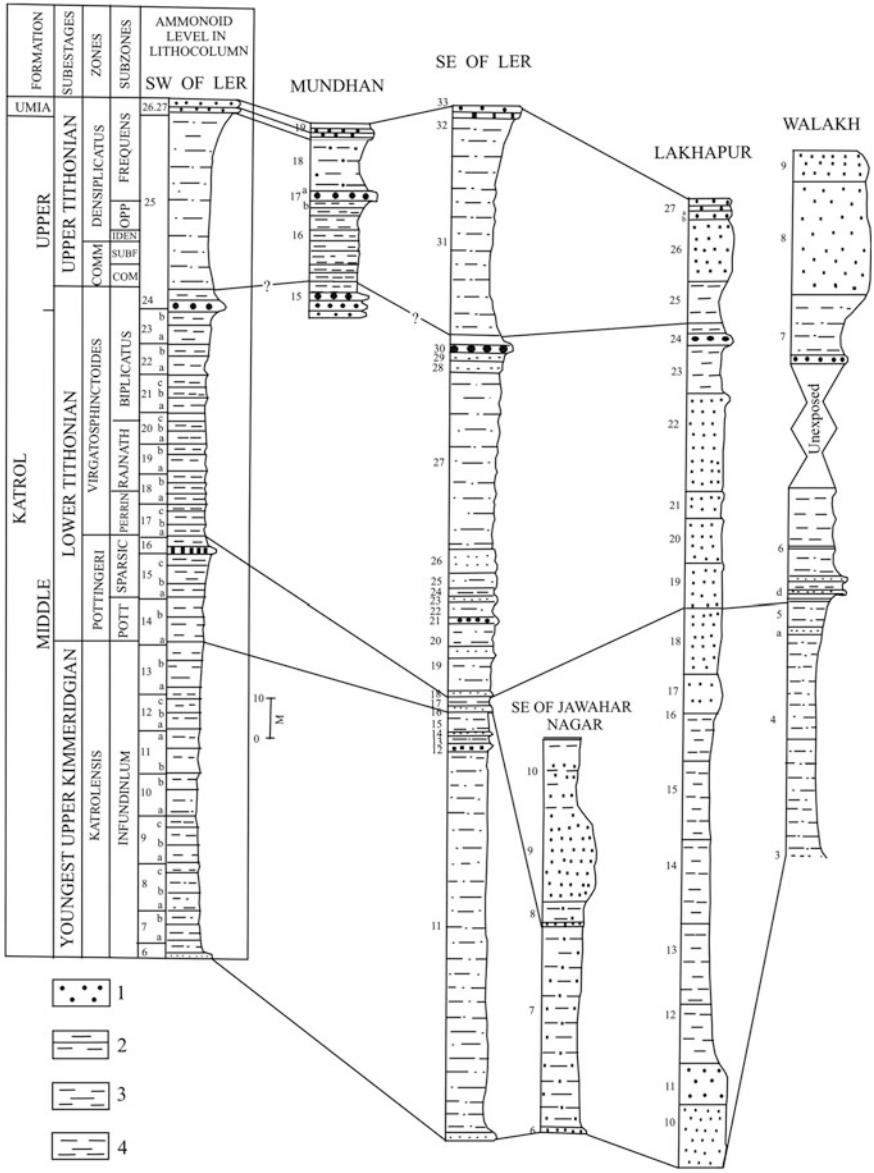


Fig. 2.38 Correlation in the Mainland Kachchh during the youngest Upper Kimmeridgian–Tithonian interval; 1–4 stand, respectively, for sandstone, shale/sandstone alternation, siltstone/shale and shale after Krishna et al. (1995b)

ammonoids. *K. katrolensis* (Waagen) m seems to have become extinct. Fossil wood and belemnoids are present.

Infundibulum Subzone Krishna and Pathak (1991) (beds 6–13b)

K-VII Horizon Krishna et al. (1995b) (beds 6–10 b): Its base is marked by the first *Aulacosphinctoides* with *A. infundibulum* (Uhlig) m.

K-VIII Horizon (beds 11a–13b): Its base is marked by the first *H. ornatum* Spath m which is also restricted in this horizon. Here, it is correlated to mid Setatum Subzone of Beckeri Zone.

In the above scheme, the Kimmeridgian/Tithonian boundary is revised and raised from the earlier (within bed 7) to the top of bed 13 in Southeast Ler to additionally include the Inversum Subzone, Unnamed Subzone and Infundibulum Subzone. This became necessary in view of the revised taxonomic affiliation of *H. ornatum* Spath m to *H.* gr. *beckeri* (Neum.) m instead with *H.* gr. *hybonotum* (Oppel) m as thought earlier (Krishna and Pathak 1993). Thus, in all the sections the occurrence of *H. ornatum* Spath m are now included in the Kimmeridgian.

The Kimmeridgian/Tithonian boundary is revised to the base of Pottingeri Zone at the level of the first *K. pottingeri* (Sowerby) m between the youngest Kimmeridgian Infundibulum Subzone and the oldest Tithonian Pottingeri zone. However, alternatively, bed 13 could still represent either the youngest part of Setatum Subzone exclusively or even be inclusive of the Ulmense Subzone. The Ulmense Subzone is either absent or represented by the early part of the Pottingeri Zone. In that case, the Kimmeridgian/Tithonian may be included within the Pottingeri Zone. In sequence stratigraphic context, the K/T boundary marks the start of a third-order TST which imparts better candidature of bed13/14 boundary as K/T boundary, so also in context of the heterochronic evolutionary cut between *K. katrolensis* and *K. pottingeri*.

2.8.8 Tithonian

Development of Tithonian in Kachchh

The ammonoid bearing Tithonian stage is fairly well-developed in the Mainland Kachchh (Figs. 2.39 and 2.40). In spite of some good sections, the Tithonian biochronology has remained much less known in comparison to the pre-Tithonian part. In India, after the early works (Waagen 1871, 1873–75; Uhlig 1903–10; Spath 1927–33). Krishna and Pathak (1993) established a scheme of four zones and five subzones in the Early Tithonian at Southeast Ler in the eastern part of the Mainland Kachchh. The Tithonian in the East Mainland is invariably underlain conformably by the Late Kimmeridgian sediments, while in the West Mainland it is either conformable over the Late Kimmeridgian or uncoformable over the Early and early Middle Oxfordian sediments.

Six different sections were studied. These are: Jawahar Nagar, Southeast Ler, Southwest Ler, Walakhawas, Lakhapur and North Mundhan (Figs. 2.38, 2.39 and 2.40). Among these, the Early Tithonian ammonoid succession is best developed in Ler, while the Late Tithonian at Lakhapur and Mundhan. The collection includes 27–48 successive levels of ammonoids in the Tithonian within the ~130 m thick succession, which has been organized into 14 beds. All the Early Tithonian zones and subzones of Krishna and Pathak (1993) were later confirmed in the principal section at Southwest Ler (Pandey 1993 unpublished, Krishna et al. 1995b, 1996b) with slight reorganization and further refinement in to horizons. However, the first ever zonation was realized yet later (Krishna et al. 1995b) in the Late Tithonian at Mundhan. An integrated zonation scheme with 5 zones, 14 subzones and 17 horizons in Tithonian is presented here.

Lithostratigraphic Remarks The Tithonian stage broadly corresponds to the major part of Katrol Formation (Middle Member and Upper Member) and basal part of Umia Formation. The Katrol Formation is further organized in to four members namely, Kantkote Member, Lower Member, Middle Member and Upper Member. The ~36–51 m thick Lower Member (mostly Kimmeridgian) characteristically comprises alternation of hard, highly fractured, deep brown to maroon coloured, highly fossiliferous, fine to medium grained sandstone bands and gypsiferous to sandy shale with occasional concretions. The overlying ~166–222 m thick Middle Member (mostly Early Tithonian) is separated from the Lower Member by a massive, hard and compact, dark brown, fine to medium grained, persistant sandstone at the base. The Middle Member mainly comprises alternation of maroon, calcareous sandstone bands and siltstone/shale. The lower part of this Member (~70–90 m thick) is relatively very poorly fossiliferous in comparison to the ~40–50 m thick upper part. The ~45–62 m thick Upper Member mainly consists of sandy shale/siltstone intercalated with occasional thin, maroon, fractured sandstone bands and concretions. Its contact with Umia Formation appears structurally disturbed.

Middle Katrol Member (MKM)
Ammonoid zones

The Kimmeridgian/Tithonian boundary placement in Kachchh (Pathak 1989 unpublished, Pandey 1993 unpublished, Krishna and Pathak 1993) is revised (Krishna et al. 1995b, 1996b). The Infundibulum Zone characterized by the presence of *A. infundibulum* (Uhlig) m and *H. ornatum* Spath m is now included as the youngest Kimmeridgian. In comparative studies undertaken with the European type material (Schweigert et al. 1996), *H. ornatum* Spath m was found closest to *H.* gr. *beckeri* (Neumayr) m instead of *H. hybonotum* (Oppel) m as previously considered (Kishna and Pathak 1993). The revised base of the Tithonian stage in Kachchh is now marked at the base of the Pottengeri Zone with the first *K. pottingeri* (Sowerby) m. The proposed scheme (Krishna et al. 1995b, 1996b) now includes

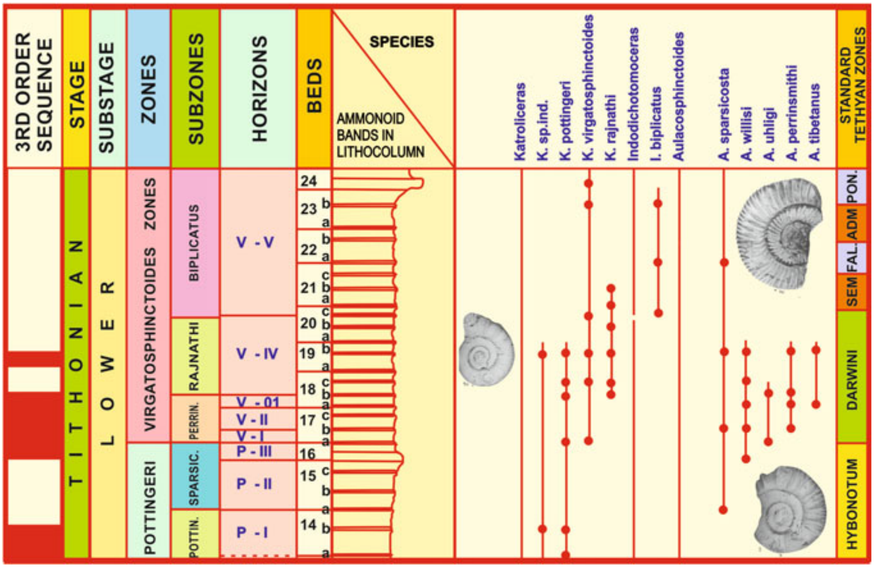


Fig. 2.39 The stratigraphic occurrence, ranges of the ammonoid species and third-order sequences in the Early Tithonian of Southwest Ler, Kachchh (modified after Krishna et al. 1995b)

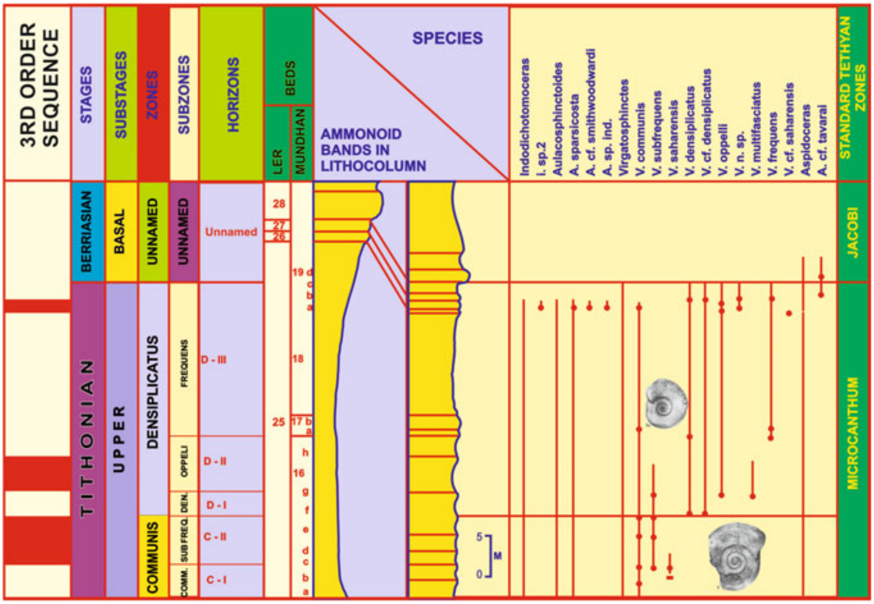


Fig. 2.40 The stratigraphic occurrence, ranges of the ammonoid species and third-order sequences in the Late Tithonian of Southwest Ler, Kachchh (modified after Krishna et al. 1995b)

two zones, five subzones and eight horizons in the Early Tithonian and two zones, five subzones and five horizons in the Late Tithonian. The resolution realized is of the order of 500,000 years. The horizons are either marked on the basis of the first appearance of a species or distinct evolutionary morphological change in the species in successive stratigraphic levels.

Zones, Subzones and Horizons

Early Tithonian (At Southwest Ler)

Pottingeri Zone Krishna and Pathak (1993)

Pottingeri Subzone Krishna and Pathak (1993)

P-I Horizon Krishna et al. (1995b) (beds 14a–14b): The base of this horizon is indicated by the first *K. pottingeri* (Sowerby) m as for the zone.

Sparsicosta Subzone Krishna et al. (1995b) (beds 15a–16): The base of this subzone is marked by the first *A. sparsicosta* (Uhlig) m. *K. pottingeri* (Sowerby) m and *Katroliceras* sp. indet. M continue from below, while *A. willisi* (Uhlig) m appears first within this subzone.

P-II Horizon Krishna et al. (1995b) (beds 15a–15c): Its base is marked by the first appearance of *Aulacosphinctoides sparsicosta* (Uhlig) m.

P-III Horizon Krishna et al. (1995b) (bed 16): Its base is marked by the first appearance of *Aulacosphinctoides willisi* (Uhlig) m.

Virgatosphinctoides Zone Krishna and Pathak (1993) (beds 17a–24): In its revised definition, it also includes the Rajnathi Zone of Krishna and Pathak (1993). Its base is marked by the first appearance of the zonal index *Katroliceras virgatosphinctoides* Krishna and Pathak m and *Aulacosphinctoides uhligi* Spath m which are also restricted within this zone. *Indodichotomoceras* and *Aulacosphinctoides* continue from below while *Katroliceras* marks its last occurrence within this zone.

Perrinsmithi Subzone Krishna et al. (1995b) (beds 17a–18a): Its base is marked by the first appearance of *Aulacosphinctoides uhligi* Spath m and *K. virgatosphinctoides* Krishna and Pathak m. *Aulacosphinctoides perrinsmithi* (Uhlig) m is the most significant/abundant species within this subzone. *Katroliceras* sp. indet. M, *Katroliceras pottingeri* (Sowerby) m, *Aulacosphinctoides willisi* (Uhlig) m and *Aulacosphinctoides sparsicosta* (Uhlig) m continue from below. *Aulacosphinctoides perrinsmithi* (Uhlig) m and *Aulacosphinctoides tibetanus* (Uhlig) m mark their first appearance within this subzone.

V-I Horizon Krishna et al. (1995b) (bed 17a): Its base is marked by the first appearance of *Aulacosphinctoides uhligi* Spath m and *Katroliceras virgatosphinctoides* Krishna and Pathak m.

V-II Horizon Krishna et al. (1995b) (beds 17b–17c): Its base is marked by the first appearance of *Aulacosphinctoides perrinsmithi* (Uhlig) m.

V-III Horizon Krishna et al. (1995b) (bed 18a): Its base is marked by the first appearance of the nominal species *Aulacosphinctoides tibetanus* (Uhlig) m.

Rajnathi Subzone Krishna and Pathak (1993): In view of additional data, this zone of Krishna and Pathak (1993) is here emended as a subzone. In its emended definition, the base is indicated by the first appearance of the subzonal index *Katroliceras rajnathi* Krishna and Pathak m. *Katroliceras virgatosphinctoides* Krishna and Pathak m and *Aulacosphinctoides sparsicosta* (Uhlig) m continue from below. *Katroliceras* sp. indet. M, *Katroliceras pottingeri* (Sowerby) m, *Aulacosphinctoides uhligi* Spath m, *Aulacosphinctoides perrinsmithi* (Uhlig) m and *Aulacosphinctoides tibetanus* (Uhlig) m mark their last occurrence within this subzone.

V-IV Horizon Krishna et al. (1995b) (beds 18b–20b): The base of this horizon is defined as that of the Rajnathi Subzone.

Biplicatus Subzone Krishna et al. (1995b).

V-V Horizon Krishna et al. (1995b) (beds 20c–24): Its base, as also of the Biplicatus Subzone, is marked by the first *appearance of Indodichotomoceras biplicatus (Uhlig) m*. Katroliceras virgatosphinctoides Krishna and Pathak m and *Aulacosphinctoides sparsicosta* (Uhlig) m continue from below. *Katroliceras rajnathi* Krishna and Pathak m marks its last appearance.

Natricoides Zone Pandey and Krishna (2002) (beds 2d–21 at Jaisamer) (Fig. 3.00): This zone was introduced in the Indian Tithonian by Pandey and Krishna (2002) in Jaisalmer between Virgatosphinctoides Zone below and Communis Zone above in Early Tithonian, thus increasing the ammonoid zones in Early Tithonian from 3 to 4. Lithologically, the c 6.0 m thick strata include alternation of gypseous shale/silt and ferruginous maroon to deep brown medium to fine grained, concretionary, nodular, pebbly, boxworked and bioturbated sands. The interval is rather the richest of the entire c 56.0 m succession. Belemnoids and fossil wood also show significant presence. The base is marked by the first *Aulacosphinctoides natricoides* (Uhlig). *Hildoglochiceras latistrigatum* (Uhlig), *H. kobelli* (Oppel), *A. doghlaensis* (Fatmi), *A. linoptychus* (Uhlig), *A. hyderi* (Fatmi), *Virgatosphinctes pumpeckji* (Uhlig), *V. krsafti* (Uhlig), *Haploceras* cf *elimatum* (Oppel) and *Holcophylloceras mesolcum* (Dietrich) also have their FAD in this zone. Pandey and Krishna (2002) have suggested best possible correlation of Natricoides Zone to ETM Semiforme Zone.

It is further organized into four subzones/horizons as under:

Natricoides Subzone/N-I Horizon (beds 2d–2f): The base is indicated by the zonal index along with the first *H. latistrigatum* (Uhlig).

Doghlaensis Subzone/N-II Horizon (beds 2g–2h): The base is marked by the FAD of the subzonal index. *A. natricoides* (Uhlig) and *H. latistrigatum* (Oppel) continue from below.

Pumpeckji Subzone/N-III Horizon (beds 2i–2j): The base is indicated by the first subzonal index. *A. natricoides* (Uhlig), *A. doghlaensis* (Fatmi), *H. latistrigatum* (Oppel) continue from below.

Krafti Subzone/N-IV Horizon (beds 2k–2l): The base is marked by the first appearance of the subzonal index, first *A. linoptychus* (Uhlig) and *H. mesolcum* (Dietrich). *H. kobelli* (Oppel), *H.* cf *elimatum* (Oppel) and *A. hyderi* Fatmi also make their first presence in this subzone. *A. natricoides* (Uhlig), *A. doghlaenis* Fatmi and *V. pumpeckji* (Uhlig) continue from below.

Late Tithonian (At Mundhan Fig. 2.40)
The succession at Sahera, Mundhan and Katesar is rather quite similar. The long known Umia green glauconitic ammonoid beds in quick succession comprise ammonoid-rich maroon to brown ferruginous pebbly/nodular/concretionary glauconitic somewhat conglomeratic, at places even bioturbated sands and muds. Bivalves, brachiopods, belemnoids are also present. More than one Gryphaea bands have also been noticed. The J/C boundary is determined even in Ler section, where the pre-boundary strata are characteristically medium to coarse grained and cross-bedded

Communis Zone Krishna et al. (1995b): The base of this zone is marked by the first appearance of the zonal index *Virgatosphinctes communis* Spath M. It also indicates the first appearance of the genus *Virgatosphinctes*. The genera *Indodichotomoceras* and *Aulacosphinctoides* continue from below. This zone includes two subzones.

Upper Katrol Member (UKM)
Communis Subzone Krishna et al. (1995b)
C-I Horizon Krishna et al. (1995b) (beds 16a–16b): Its base as also of the Communis Subzone is marked by the first appearance of *Virgatosphinctes communis* Spath M.
Subfrequens Subzone Krishna et al. (1995b)
C-II Horizon Krishna et al. (1995b) (beds 16c–16e): Its base as also of the Subfrequens Subzone is marked by the first appearance of *Virgatosphinctes subfrequens* Uhlig m and *Virgatosphinctes saharensis* Spath m. The latter is also restricted within this subzone. *V. communis* Spath M continues from below.
Densiplicatus Zone Krishna et al. (1995b): Its base is marked by the first appearance of the zonal index *Virgatosphinctes densiplicatus* (Waagen) m and *V.* cf. *densiplicatus* (Waagen) m which are also restricted within this zone. The genera *Indodichotomoceras* and *Aulacosphinctoides* continue from below. This zone includes three subzones. Ammonoids have been collected from 6–8 close levels (beds 17a–19 d). Besides Virgatosphinctinae found as the principal elements, *Aspidoceras*, *Argentiniceras*, *Micracanthoceras*, *Blanfordiceras*, *Corongoceras*, *Aulacosphinctes*, *Himalayites* have also been found in the youngest Tithonian level in the last but one green bed.
Densiplicatus Subzone Krishna et al. (1995b)
D-I Horizon Krishna et al. (1995b) (bed 16f): Its base as also of the Densiplicatus Subzone is marked by the first appearance of *Virgatosphinctes densiplicatus* (Waagen) m and *V.* cf. *densiplicatus* (Waagen) m.
Oppeli Subzone Krishna et al. (1995b) D-II Horizon Krishna et al. (1996a, b, c) (beds 16g–16h): Its base as also of the Oppeli Subzone is marked by the first appearance of *Virgatosphinctes oppeli* Spath M and *V. multifasciatus* (Uhlig) m. The latter species is also restricted within this subzone. *V. communis* Spath M, *V. densiplicatus* (Waagen) m and *V.* cf. *densiplicatus* (Waagen) m continue from below.

Basal Member of Umia Formation

Frequens Subzone Krishna et al. (1995b)

D-III Horizon Krishna et al. (1995b) (beds 17a–19c): Its base as also of the Frequens Subzone is marked by the first appearance of *Virgatosphinctes frequens* (Oppel) M which is also restricted within this unit. *V. communis* Spath M, *V. densiplicatus* (Waagen) m, *V.* cf. ***densiplicatus*** (Waagen) m and *V. oppeli* Spath M mark their last occurrence while *Aulacosphinctoides sparsicosta* (Uhlig) m, *Aulacosphinctoides* sp. indet. m, *Aulacosphinctoides* cf. *smithwoodwardi* (Uhlig) m, *Virgatosphinctes* n. sp. m and *Virgatosphinctes* cf. *saharensis* Spath m are restricted within this unit.

The comments made by Enay (2009), and Enay and Cariou (1999) on the Tithonian ammonoid zonal succession in Kachchh of Krishna et al. (1996b), Pathak (1989 unpublished thesis) and Pandey (1993 unpublished thesis) are subjetive and unsubstantiated, hence unwarranted, and uncalled for. The Tithonian ammonoid stratigraphic studies in Nepal and Tibet Himalaya by Enay are not based on precise bed by bed collection and lack adequate lithostratigraphic differentiation and ammonoid stratigraphic range charts in comparison to the studies in Kachchh, Jaisalmer and Spiti Himalaya. Enay and others have ammonoid collections from just seven imprecise levels from a highly generalized lithostratigraphic section without any bed numbers (Fig. 5 on p. 673) compared to 42 stratigraphically précised ammonoid levels in Kachchh from a section differentiated in great detail into 70 beds or their subdivisions along with precise range charts of a large number of ammonoid taxa. The High Himalaya species have been determined by us in Kachchh after actual comparison with their types stored in GSI Museum at Calcutta. Enay's surmise that these forms are either microconchs of large Katroliceratinae or inner whorls or juvenile individuals is far fetched. The mentioned species of *Aualcosphinctoides* from Kachchh are mostly from stratigraphically higher levels than those of large Katrloiceratinae (Krishna and Pathak 1991). The large Katroliceratinae are invariably restricted to pre-Beckeri Zone part of Kimmeridgian that either became extinct or drastically reduced in density, frequency and diversity. *A. infundibulum* is found in the terminal Kimmeridgian and based on cooccurrence with *Hybonoticeras ornatum* common between ETM and GTM is firmly assigned to late Late Kimmeridgian Setatum Subzone of ETM (Schweigert et al. 1996). Other determined species are *A. sparsicosta*, *A. willsi*, *A. uhligi and Tibetanus* again do not occur together with large Katroliceratinae (Fig. 2.36). These taxa are stratigraphically well-constrained in the Virgatosphinctoides Zone of early to mid Early Tithonian after the extinction of *A. infundibulum*. *A. sparsicosta* ranges long from base to close of Tithonian. There emerges an explicit succession of *Aulacosphinctoides* from late Late Kimmeridgian to late Late Ttihonian of 1. *A. infundibulum* (Katrolensis Zone = Beckeri Zone), 2. *A. sparsicosta* of early Early Pottingeri Zone (=to ETM Hybonotum Zone), 3. *A. perrinsmithi*. *A. uhligi*, *A. willisi*, *A. tibetanus* within the early part of Virgatosphinctoides Zone which in spite of absence of any common elements with ETM has been convincingly dated as of early to mid early Tithonian, thus indirectly age-constrained with well-correlated terminal Beckeri Zone below and mid to late

Early Natricoides Zone above, and 4. *A. natricoides*, *A. doghlensis*, *A. linoptychus and A. hyderi* of GTM Natricoides Zone in turn tentatively correlated to ETM Semiforme Zone of mid Early Tithonian below the relatively better dated and well-defined terminal or late Early Tithonian Commuis Zone. The correlation of GTM Natricoides Zone to ETM Semiforme Zone is based on common *Haplophylloceras strigale*. The above succession of *Aulacosphinctoides* in a limted measure is present in Tibet through *A. infundibulum and A. tibetanus* and only tentatively placed in early to mid Ealy Tithonian. Their co-occurence instead of presence in succession is on account of condensed section owing to slow sedimentation after a submarine gap in which the authors failed to differentiate between the underlying terminal Kimmeridgian from Early Tithonian. Enay has similarly found *V. densiplicatus* and *V. frequens* together and placed them in the late Early Tithonian instead of early Late Tithonian. Thus there is unanimity regarding the succession of species of *Aulacosphinctoides and Virgatosphinctes* arrived at by Krishna and coworkers and Enay (2009), though the ages assigned to these species by these authors are different. In Kachchh and Jaisalmer *V. frequens* begins later than *V. densiplicatus*, yet occur together in the Frequens Subzone of the Densiplicatus Zone. Enay and associates have the last *V. densiplicatus* in early Late Tithonian, while Krishna and associates extend the same up to close of Tithonian in view of its last occurrence together with *M. micracanthum*, *Corongoceras* and *Blanfordiceras* in Kachchh, Jaisalmer and Spiti which again does not conflict with the ages given to *Corngoceras* and *M. micracanthum* by Enay and associates. The dispute is only with regard to presence of *V. densiplicatus* in terminal Tithonian Micracanthum Zone (inclusive of undifferentiated *Durangite*s fauna) at the top of Tithonian.

For reasons stated above, the top of the Densiplicatus Zone with *Corongoceras*, *M. micracanthum* and *Blanfordiceras* is inclusive of the undifferentiated *Durangites* fauna, and at present makes the best candidate for the top of Tithonian in India. Citation of Madagascar zones and ammonoid occurrences is hardly of any biostratigraphic significance, since not a single ammonoid there was collected with any precision by Collignon's troops. *Aspidoceras tavarae* in its Spanish stratotype ranges from terminal Tithonian to basal Berriasian, and accordingly its occurrence together with *V. densiplicatus* marks terminal Tithonian and its younger presence without *V. densiplicatus* suggests basal Berriasian. There is absolutely no contradiction about the ranges of *Aspidoceras tavarae* in Spain and Kachchh. Thus the succession of species of *Aulacosphinctoides*, *Virgatosphinctes Aspidoceras*, *Corongoceras*, *Micracanthoceras*, *Blanfordiceras*, *Himalayites*, *Spiticeras* and others have as expected same ranges on GTM in Kachchh, Jaisalmer, Tibet, Pakistan and Madagascar and ETM in France, Spain etc. The apparent differences and discrepancies are on account of condensation, starvation and difficulties of precision collection in High Himalaya. The studies in Kachchh and Jaisalmer have provided an incotrovertible ammonoid succession of GTM not just in Tithonian but almost in the entire Jurassic on the whole of GTM. Fursich et al. (2013) also comment that the J/C boundary can not be fixed needs reconsideration. The youngest Tithonian late Densiplicatus Zone Frequens Subzone ammonoids in

Kachchh, Jaisalmer, Spiti and Malla-Johar, as discussed above are identical and at present make the best parameter for the J/C boundary in IEAP.

Uniqueness of the Kachchh Jurassic Ammonoid Zonal Scale
Unlike the scale developed on ETM which is based on genera/species of several ammonoid families, the ~22 m IEAP scale is near exclusively based on a single superfamily—the Perisphincticeae (Fig. 1.8)—except for the basal Macrocephalitinae based late Middle to Late Bathonian part. Even the succession of zones based on Macrocephalitinae species, also, have alternative Perisphinctinae taxa as names of the mentioned zones. Also, the scale is uniquely developed in a single basin with continuos and splendid outcrops/sections. The IEAP scale has its zonal/subzonal/horizontal boundaries precisely determined in Kachchh, and most of the ammonoid zones well-correlated to those of ETM. The Kachchh ammonoid zones are also found applicable on GTM in spite of invariable absence of the development of ammonoid zonal successions in most basins.

2.8.9 Intra-Jurassic Interstage Boundaries

Triassic/Jurassic system boundary The only Indian locality where basal Hettangian ammonoids (*Psiloceras* and others) are found is Lamayuru in Ladakh close to the Indus suture on the Indian side (Krishna et al. 1997). In High Himalaya in Spiti only a broad surmise is possible above with Triassic. In subsurface Rhaetian/Liassic palynomorphs are known from Banni well, though no clue to demarcate the boundary has as yet come forth. Same situation exists in Jaisalmer wells. The author in sequence stratigraphic context suggests possibility of the tentative boundary in Gondwana non-marine successions.

Hettangian/Sinemurian boundary can be tried in the exposed Lathi Formation of Jaisalmer, also in Kachchh subsurface. In Spiti, it could be explored through microfossil studies in Kioto Limestone.

Sinemurian/Pliensbachian boundary may also be explored in the exposed Jaisalmer sediments and Kachchh subsurface besides Spiti in Himalaya through study of microfossils, particularly coccoliths.

Pliensbachian/Toarcian boundary may be broadly understood at the base of LSM in Dingy and Kuar bet sections of Kaladongar of 'Island belt' in Kachchh. In Spiti and Nepal and other places in High Himalaya, the mentioned boundary is placed at the contact of Kioto Limestone and coeval units and Bagung/Laptal and coeval units.

Toarcian/Aalenian boundary may again be explored in LSM and its coeval fine textured sediments in distally located well sections. The first broad sequence stratigraphy based differentiation in Kachchh is discussed in Chap. 3.

Aalenian/Bajocian boundary is for present suggested at the base of Am in Jhura and at the base of basal limestones at Sadhara, and near the revised KSm/BCSm transition in Kaladongar.

Bajocian/Bathonian boundary is for the present best suggested at the base of bed 3d of Nara immediately underlying the Early Bathonian Macrescens Subzone second-order MFS. In Jhura, it can be placed between Bm below and the massive golden oolitic limestone bearing Cm above. In Kaladongar and Goradongar section, it is placed, respectively, between KSm and BCSm, and between RSm below and LFm above.

Bathonian/Callovian boundary is much better understood in several 'Island belt' and Mainland sections between the youngest light coloured limestone bed of RLm of ULM of Patcham Formation and basal dark-coloured grey shales of LSM of Chari Formation.

Callovian/Oxfordian boundary requires refinement within the topmost sand/silt beds of DSM of Chari Formation in West Mainland sections, above the midLate Ponderosum Zone, however, the obstacle to this so far has been absence of Mariae Zone ammonoid fauna. The boundary has been recently also suggested in sequence stratigraphic context in Khadir and Gangta bet at the top of a fossiliferous yet ammonoid devoid conglomeratic sand bed which is interpreted as a third-order MFS. It is suggestively assigned basal Oxfordian basal part of Mariae Zone age in between the immediately overlying Obliqueplicatum Zone of late Early Oxfordian and the underlying early Late Callovian Athleta Zone which are firmly based on enclosed ammonoids. Thus, the boundary can be placed within or immediately below the mentioned conglomerate bed in Khadir and Gangta bet.

Oxfordian/Kimmeridgian boundary is best demarcated at the base of Am in Bharodia section based on first *Orthosphnctes*.

Kimmeridgian/Tithonian boundary is best placed in Ler section at the base of *K. pottingeri* bearing beds above the largely unfossiliferous laminated sand between beds 13 and 14. Bed 12 includes the last *H. ornatum* and bed 14 starts with first *K. pottingeri*.

Jurassic/Cretaceous boundary is best placed in West Mainland and Ler sections above the beds with late Late Tithonian Densiplicatus Zone ammonoids. Possibilities also exist in east coast well sections between Late Tithonian and Early Berriasian palynoassemblages.

Applicability of the Kachchh scale in the Indo-East-African faunal province and GTM The so developed Jurassic ammonoid zonal scale is the first such effort on GTM, and until this independent indigenous formulation the ETM zones were tentatively extended to GTM. The Kachchh scale is the best and fully applicable to IEAP region in view of the unrestricted geographical spread of IEAP ammonoid subfamilies in the region. Good correlations, mostly at zonal level have been demonstrated with ETM. In Arabia and SW Pacific part of GTM, workable correlation has been managed partly based on common ETM elements, and partly based on common IEAP ammonoid elements.

2.9 Cretaceous

2.9.1 International Status

The system was established in 1822 by a Belgian geologist d'Halloy on a chalk bearing succession in the Vocontian basin of France, and was so named after the dominant chalky lithology there. It is the longest of the three Mesozoic systems, distinctly longer than the other two. Also, it is globally among the most eventful not only of Mesozoic but of the entire Phanerozoic. Its eventfulness in Indian context is noteworthy. It is defined by its basal stage Berriasian, more precisely, by the basal Berriasian ammonoid zone Berriasella Jacobi Zone. It includes 12 stages, 6 each in its Early and Late divisions. The stages are of highly varying duration, Santonian being the shortest of ~ 2.7 my and Aptian being the longest of ~ 13.3 my duration. It is classically organized into ammonoid zones, yet providing, the highest stratigraphic resolution, however, micro-planktons (foraminifers, dinocysts and coccoliths) have come up fast with closely comparable resolutions, particularly during the Late Cretaceous.

2.9.2 Development in India

The Cretaceous system has had much larger development in India than either the Jurassic or Triassic with marine, non-marine and igneous expressions all round the Indian plate as also in inland Gondwana basins. Over the past three decades, maximum hydrocarbon reserves globally have been located in the Jurassic–Cretaceous sequences, and the Indian Cretaceous is being increasingly investigated. Yet the stratigraphic refinement both in surface and subsurface record inclusive of offshore wells leaves much to be desired in terms of zonal differentiation and correlation, stages, and international stage boundaries.

2.9.3 On the Local/Regional Stages in the Indian Cretaceous

In a recent review (Raju 2011), a succession of 8 Cretaceous regional stages is included. These stages have been created by ONGC scientists in recent decades in Indian east coast exposed and subsurface well sections. Among these eight stages, the younger five stages are based in the exposed Cauvery basin sections. These holostratotype sections have hardly ever been adequately lithostratigraphically diffrerentiated and described, in spite of such description of stratotypes being an essential prerequisite to the proposition of the stages. Stages or for that matter any chronostratigraphic unit essentially comprise and refer to the column of sediments which requires to be measured and described in detail with respect at least to its field observable lithological features, physical and biogenic structures, as also body fossil content. It may also be emphasized that guide fossil taxa included in the column of sediments are only used to define the basal time plane of the mentioned stage. It is the column of sediments which makes the stage not the guide fossils included in the column of sediments which merely serve the important purpose of defining the basal time plane. Any taxon range chart of the planktonic foraminifera used as guide fossils either have not been published either in adequately differentiated exposed lithostratigraphic columns or have escaped the present author's notice. ~30 microfossil taxa are indicated in a table against the succession of 12 international stages, 12 planktic foraminifera based biochrons have been introduced in the ~32.5 my Late Cretaceous Cenomanian–Maestrichtian interval in comparison to ~70 international planktic foraminiferal datums in the entire Cretaceous, most of which have been picked up in some other basin with deeper neritic to bathyal signatures. The eight regional stages based on relatively deeper water planktic foraminfera are hardly usful in the study of the shallow marine exposed Indian Cretaceous successions. The best studied are the Cauvery and K-G subsurface well Cretaceous sections. Subsurface Cretaceous has also been studied for dinocysts, coccoliths, pollen and spores also mostly by the ONGC and the BSIP scientists. Composite presence of as many as 18 international or internationally correlatable ammonoid zones is realized in Kachchh (seven zones) and Cauvery (thirteen zones).

Much unlike the older Triassic and Jurassic systems, high resolution ammonoid based zonation could not be developed in the Cretaceous system of India. Even the international inter/intrastage boundaries are not precisely differentiated. Instead, a succession of local/regional stages has been created by the ONGC scientists. Parallel zonations have been published based on planktonic foraminifera/dinoflagellates/coccoliths and pollen/spores without integration.

2.9.4 Integrated Indian Cretaceous Ammonoid Zonal Succession

In Kachchh, only three Early Cretaceous stages are expressed through ammonoids which are Berriasian, Aptian, and Albian. Maximum of eight stages are expressed through ammonoids in Cauvery basin which are the younger ones from Aptian to Maestrichtian. The integration of the two principal Indian Cretaceous basins of Cauvery and Kachchh indicates presence of ammonoids in as many as nine of the twelve stages. Ammonoids of Turonian and Coniacian stages are also known from Narmada basin. In High Himalaya, e.g. in Spiti, almost complete succession of marine Cretaceous is present, however, ammonoids are present in Berriasian and Valanginian at the start, and then again in Aptian and Albian, thus found restricted to the mentioned four stages of Early Cretaceous. Taking the entire Indian Cretaceous, the stages which so far have not yielded any ammonoids are Hauterivian and Barremian, although unconfirmed suggestions have been made in the east coast basins. The ammonoid presence in the Indian Cretaceous is for the first time organized into an integrated succession of at least ~18 ammonoid assemblages without precise differentiation of stage and zonal boundaries. In this context Ayyasami (2011), on the basis of ammonoids has provided tentative demarcation of a few interstage boundaries in the Cauvery basin. The integrated succession of the ammonoid assemblages is produced here (Fig. 2.42) as under

1. Basal Berriasian Aspidoceras tavarae/Argentiniceras loncochensis Zone, 2. Late Berriasian Kilianella Zone, 3. Early Late Valanginian Olcostephanus verrucosum Zone, 4. Early Aptian Deshayesites deshayesi Zone, 5. Late Aptian Australiceras jacki Zone, 6. Early Albian Douvilleiceras mammilatus Zone, 7. Early Middle Albian Hamites rotundus Zone, 8. Late Albian Mortoniceras rostratum Zone, 9. Early Cenomanian Mantelliceras vicinale Zone, 10. Middle Cenomanian Calycoceras asiaticum Zone, 11. Late Cenomanian Eucalycoceras pentagonum Zone, 12. Early Turonian Pseudoaspidoceras footeanum Zone, 13. Early Middle Turonian Romaniceras ornatissimum Zone, 14. Late Middle Turonian Romaniceras deverianum Zone, 15. Coniacian Kossmaticeras theobaldianum Zone, 16. Latest Santonian Texanites roemeri Zone, 17. Campanian Karapadites karapadense Zone, and 18. Maestrichtian Pachydicus otacodensis Zone. In addition, ammonoid presence is also suspected in the Hauterivian–Barremian sediments in Spiti (Pandey and Pathak 2015b; Pandey et al. 2013c; Cauvery and K-G; Spath 1927–33)

Among the above 18 zones, 1 and 2 are in Kachchh; 3 in Spiti; 4, 5, 6 and 7 in Kachchh/Jaisalmer; and 8–18 in Cauvery basin.

2.9.5 Exposed Cretaceous record in Kachchh and Jaisalmer

There is evidenced in Kachchh and Jaisalmer substantive record of the exposed Cretaceous sediments at least west of the median high of Early and early Late Cretaceous age recorded in detail under ONGC sponsored project (Fig. 2.41 Krishna 1987b; Krishna 1994; Dubey 1992; Singh 2006; Singh et al. 2000). The Kachchh Cretaceous includes extremely sparsed and rare presence of ammonoids of Berriasian through *Argentiniceras*, *Negreliceras*, *Groebericeras*, *Kilianella*, *Ducaliceras*, *Aspidoceras*, etc. Aptian through *Deshayesites*, *Dufreynia*, *Epicheloniceras*, *Australiceras*, *Tropaeum* etc., and Albian through *Lemuroceras* (Krishna 1980,

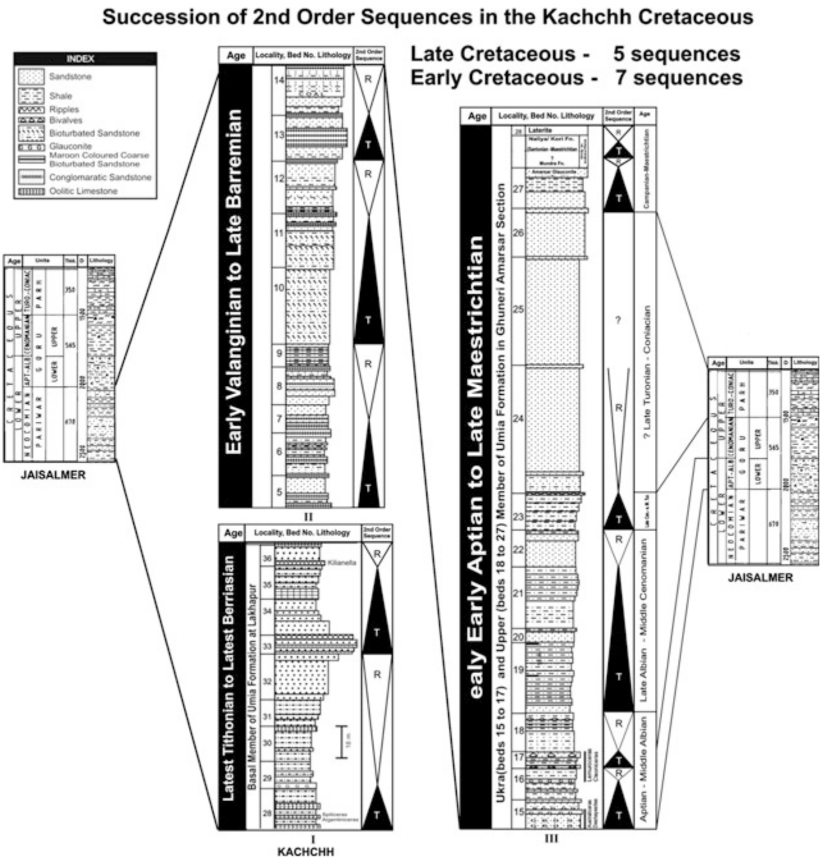


Fig. 2.41 Stratigraphic correlation in the Cretaceous between Kachchh (modified after Krishna 1994 unpublished report, Dubey 1992) and Jaisalmer (modified after Singh 2006) columns vis-a-vis second-order sequences

1983, 2002, 2012 and unpublished). The Kachchh Cretaceous also includes the youngest Cretaceous exposed marine sedimentary unit through relatively thin glauconitic green shale bed underlying the Traps in the Ghuneri–Amarsar section of probable Middle Turonian or Santonian/Campanian age. The non-marine intertrappeans in East Kachchh are assigned Maestrichtian age (ONGC 1993), so also the Deccan Trap themselves. Thus, almost the entire Cretaceous seems present and well-exposed in Kachchh.

2.9.6 Subsurface and Offshore Record

In subsurface and offshore wells (sp-1-1 and K1-1A), respectively, located aout 80 and 150 km in the dip direction from the thin glauconite bed locality, presence of inner to outer shelf sediments (Naliya Fn. in SP-1-1 about 80 km and Kori Fn. About 150 km away) has been interpreted on the basis of planktonic foraminifera and coccoliths of Coniacian–Maestrichtian interval (ONGC 1993).

2.9.7 Early Vis-à-Vis Late Cretaceous in Kachchh

The exposed Early Cretaceous record in Kachchh basin is marine, continuous and confirmed only up to Albian, while the marine Cenomainan to Santonian/Campanian is suggested on broad foraminifer, radiometry, and sequence stratigraphic interpretations. As such, the Albian/Cenomanian or Cenomanian/Turonian stage boundaries can not be differentiated. In context of the equivalent Early Cretaceous record in other Indian basins as also in the Indian subcontinent, the Kachchh Early Cretaceous is better measured and recorded, as also stratigraphically evaluated. In comparison, the Kachchh Late Cretaceous record inclusive of onshore/offshore wells is much less known, and is somewhat discontinuous, scattered and fragmentary. Reliable datable elements merely include microfossils, mostly foraminifers and palynomorphs, which have to some degree facilitated the progress of the Indian Cretaceous stratigraphy.

2.9.8 Interstage Cretaceous Boundaries

Tithonian/Berriasian Boundary This boundary can be placed in Kachchh between the last *Virgatosphinctes* in bed 27 below and bed 28 above with basal Berriasian ammonoids in Ler–Katrol transect as also in West Mainland sections of Umia, Lakhapur, Sahera and Mundhan (Krishna et al. 1994b, 1996b; Dubey and Chatterjee 1997). In the K-G basin, the Bapatala Sandstone and its facies variant Nellore Claystone include most of the Berriasian, and late Tithonian, if present, should be included in the lower ~200 m. Thus, the best tentative suggestion to this boundary is between the shale dominated lower part and sand dominated middle part of the Bapatla Sandstone.

Berriasian/Valanginian Boundary The best suggestion to this boundary in east coast basins is the lithostratigraphic contact between Bapatala Sandstone and Penner Shale in the KS-A-4 well of the K-G basin. In Kachchh, it may be best placed above the *Kilianella* bearing beds in the West Mainland Sahera and Mundhan sections. In Spiti, the best possibilities exist above the Late Berriasian and below the Early Valanginian ammonoid bearing black shales. This boundary may also be explored in east coast well sections. Ammonoid studies under much better stratigraphic control are in progress, which in near future should provide precise determination of the Tithonian/Berriasian, and the Berriasian/Valanginian boundary, as also ammonoid zonation in the mentioned stages.

Valanginian/Hautervian Boundary In the K-G subsurface wells, this boundary is suggested above the Penner Shale or at the contact of Penner Shale and the overlying Golapille Formation. In Kachchh, the best possibilities exist in the early part of the Ghuneri Member sands. In Spiti, this boundary may be best expored between the early Late Verrucosum Zone beds below and basal Aptian ammonoid bearing beds above.

Hauterivian/Barremian Boundary It is the most difficult to approximate in any basin of India due to complete absence of ammonoids or other guide fossils. The best places are east coast well sections. The thin wedge shaped occurrence of the lagoonal coal in the Ghuneri section of Kachchh on composite indirect evidence is best assigned to Late Barremian.

Barremian/Aptian Boundary It is approximated widely in the Indian subcontinent between Pariwar Formation and Abur Frmation in view of start of the Abur Formation little above the Barremian/Aptian boundary in the second oldest Aptian Deshayesites Zone. The above approximated Barremian/Aptian boundary can be extended to the Ghuneri Member/Ukra Member boundary in Kachchh, between Sivaganga Formation and Dalmiapuram Formation in Cauvery basin, within the Andimadam Formation below the level of *Australiceras jacki*, below the level of *Dufreynia/Australiceras* between the Golapille Formation and the Raghavapuram Formation, within the Guimal Formation above the youngest ammonoid devoid sands and *Deshayesites* bearing marl (Pandey et al. 2013b, c). In regional stratigraphic context the boundary in the Narmada basin may be explored between the principal non-calcareous early part of the sandstones below and the overlying bivalve bearing calcareous sands above of the Nimar Formation. However, there are no clues to the actual ages of the older non-calcareous and younger calcareous sands. Jafar (1982) has recorded Turonian coccoliths from the thin fine textured intercalations of the younger calcareous unit of the Nimar Formation. There could even be a large subaerial gap between the lower and upper units of the Nimar Formation allowing the calcareous sands of the upper part to be as young as Turonian. In the neighbouring Kachchh basin, also elsewhere in the Indian

Cretaceous successions, the thick non-calcareous pre-Turonian sands are mostly of the Hauterivian–Barremian age of Ghuneri Member of Umia Fn in Kachchh and its coeval units in many other Indian basins. However, similar sands are also of the younger Late Albian–Early Cenomanian age of the Upper Member of Umia Formation in Kachchh with the marine slow sedimented ammonoid bearing Ukra Member in between the Ghuneri and Upper units. The younger bivalve bearing calcareous sandstone unit in the Narmada basin could even be in part shallower near coast facies variant of the overlying Nodular Limestone Member of Bagh Formation/Group. This boundary can also be strengthened with FAD of charlottae.

Aptian/Albian Boundary It is tentatively placed between the Late Aptian *Epicheloniceras* and Early to early Middle Albian *Douvilleiceras* in the Kuchri–Habur traverse in Jaisalmer, while in subsurface below the FAD of Roberti. The mentioned boundary is included in the early part of Karai Formation in view of the recent determination of the Mammilatum Zone (Gautam et al. 2015).

Albian/Cenomanian Boundary Ayyasami (2011) placed the Albian/Cenomanian boundary in a rather rare but good section east of the Uttatur village in the otherwise badland country within the Karai Shale Formation suggestively in the middle of the unit between the levels repectively of late Late Albian *Mortoniceras rostratum* and early Early Cenomanian *Mantelliceras mantelli* (fig/map, GSITI, Course Material pp. 4–5).

Cenomanian/Turonian Boundary Ayyasami and Bannerjee (1984) and Ayyasami (2011) determined this boundary east of the Odium village within the Karai Shale around the middle of its Kunnam Member below the ~30 m interval of shales with calcareous nodules between the levels, respectively, of late Late Cenomanian *Eucalycoceras pentagonum* below and early Early Turonian *Pseudoaspidoceras footeanum* above (fig./map GSITI, Course Material, pp. 6–7). However, in the section near Kullakalnuttam village, Early Turonian ammonoids seem absent, and the Karai Formation succession not extending into Turonian.

Turonian/Coniacian Boundary Ayyasami (2011) placed this boundary in the gully north of the Andur and Varagur villages above the ~50 m shales with calcareous nodules near the top of the Alundalippar Formation of Trichinopoly Group. It is near the contact of Alundalippar Formation below and Varagur Formation above between the levels repectively of the early Middle Turonian *Lewesiceras anapadense* and early Early Coniacian *Proplacenticeras tamulicum*. The contact of the units is disconformable, and a gap is evident of late Middle to Late Turonian.

Coniacian/Santonian Boundary This boundary can only be tentatively suggested immediately above the Anaipadi Formation of Coniacian age, since the Early and Middle Santonian mark a stratigraphic gap.

Santonian/Campanian Boundary Ayyasami (2011) have suggested this boundary north of the Melmattur village on the basis of the levels, respectively, of Late

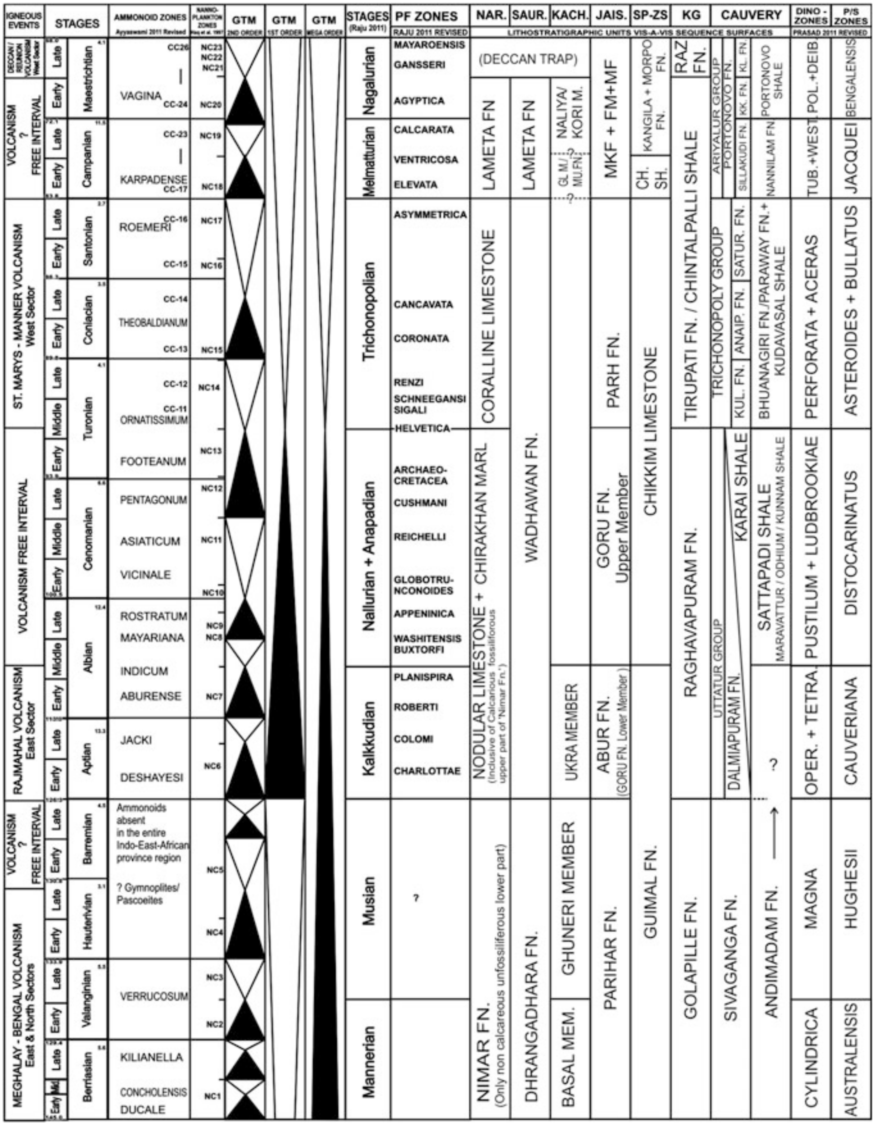


Fig. 2.42 Indian cretaceous lithostratigraphic units vis-a-vis second-order sequences, planktonic, dinoflagellate, pollen–spore zones

Santonian *Inoceramus balitus* below and of Early Campanain forams above. The boundary can also be explored in the east coast well sections.

Campanian/Maestrichtian Boundary Ayyasami (2011) placed this boundary in a gully section north of the Ariyalur–Vilangudi road near Periyanagalur below the first occurrence of *Eubaculites vagina* and the other Early Maestichtian heteromorph ammonoids. The boundary again may be explored in the east coast well sections (Fig. 2.42).

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