Proc Indian natn Sci Acad **78** No. 3 September 2012 pp. 445-455

Status Report

Recent Advances on Phanerozoic Biodiversity, Bioevents and Climate in India

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In the present write up, a synthesis of the research done in the last four years in vertebrate palaeontology, palynology, ammonoid biostratigraphy and stable isotope geochemistry is presented. SB and GVR discuss the issues relating to Cretaceous-Palaeogene (K-Pg) boundary bioevents in India and their linkage to Deccan volcanism, Jurassic and Cretaceous diversity of dinosaurs and elasmobranchs-origin and evolution of archaic mammals of Cretaceous - Early Eocene age during the northward flight of India, their biogeographic relationships, evolution of whales and Neogene mammals. In a related discussion, VP discusses on the time of origin of grass family Poaceae and rice tribe Oryzeae based on the analysis of late Cretaceous dinosaur coprolites and sediments bioevents at the K-Pg boundary in Um Sohryngkew River section in Meghalaya, NE India and the effects of environmental stress from Deccan volcanism on Palaeogene flora presently restricted to Western Ghats, the role of dinoflagellates in dating the highly diversified mammal-bearing levels within the Vastan lignite mine, and the presence of dipterocarp angiosperm trees in the Early Eocene of India and thus supporting the "out of India Dispersal" hypothesis for this group of plants. JK presents a comprehensive picture on the refined Triassic and Jurassic ammonoid biozonation in the Himalayan and western Indian regions, respectively, sequence stratigraphic framework of Mesozoic marine sequences of India, and the relationship between major tectonic events of the Indian ocean and sea level changes. AS discusses the relevance of isotopic studies across Permo-Triassic boundary and Eocene/Oligocene boundary in understanding the extinction of plants and the role of silicate weathering in the Himalaya, respectively, forced regressive event in the Palaeogene of the Himalayan foreland basin linked to the early phases of Himalayan uplift, development of palaeosols with the expansion of C4 vegetation in Ganga-Brahmaputra delta plain during the last glacial maximum (LGM), and different episodes of monsoon intensification that coincide with major pulses in the Himalayan uplift based on hydrogen isotopic studies of Quaternary Siwalik palaeosols.

Key Words: **Cretaceous-palaeogave Boundary; Biodiversity; Palaeogeography; Deccan Volcanism; Ammonoid Biozonation; Stable Isotope; Palaeoclimate**

Introduction

In recent years, the Indian subcontinent has received focused attention from the geoscientific community across the world because of the hypothesized link between Deccan flood basalt volcanism and mass extinctions at the Cretaceous -Palaeogene (K-Pg) boundary and the proposal that some extant Asian biotic elements had actually originated in the former Gondwanaland and later dispersed out of India, which served as a Noah's Ark during its northward flight. Thus India was suggested as a centre of origin for early evolution for certain major graphs of organisms during its northward journey as is evident from recent works from the Late Cretaceous and Early Eocene of India (Bajpai *et al*., 2005, 2008; Prasad *et al*., 2005; Prasad *et al*., 2010). Considerable work was also done on Triassic and Jurassic ammonoid biostratigraphy of Kachchh and Himalayan regions which helped us in refining the chronostratigraphy and sequence stratigraphy of these Mesozoic sequences (Krishna, 2010, 2011). Isotope systematics have also been used in understanding the Phanerozoic bioevents of India and their relationship to climate and major tectonic events (Bera *et al*., 2008; Sarkar *et al*., 2003a; 2009).

Deccan Traps and the Cretaceous-Palaeogene Extinctions

A recent finding of global significance is the recognition that the Deccan volcanic eruptions of peninsular India played a critical role in causing mass extinctions at the

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Cretaceous-Palaeogene (K-Pg) boundary at 65Ma (Keller *et al*., 2008, 2009a,b). Recent data suggest three major pulses of this massive volcanism, with the first phase at 67.5Ma followed by a 2m.y. period of quiescence. The second phase marked the main Deccan volcanic eruptions during Chron 29R near the end of the Cretaceous and accounts for 80% of the entire Deccan lava pile. The last, a relatively minor phase, coincided with the early Paleocene Chron 29R/Chron 29N transition and also witnessed some of the longest lava flows in Earth's history.

Further data from 10 deep wells in the Krishna-Godavari Basin revealed two separate volcanic phases with the major phase-2 in C29R prior to KTB, created the world's largest lava flows, spanning >1500 km across India and into the Gulf of Bengal (Keller *et al*., 2011). These studies strongly suggest that the biotic and environmental effects of Deccan volcanism at K-Pg may have been vastly underrated in the past. In order to assess the climatic and environmental consequences of Deccan phase-2 volcanism, a combined study of geochemistry and planktonic foraminifera on K-Pg sequence known from India exposed along the Urn Sohryngkew River in Meghalaya, NE India was carried out (Gertsch *et al*., 2011). The Um Sohryngkew section, located 800-1000 km from the Deccan volcanic province, is one of the most complete marine K-Pg sections worldwide (comparable to those in Tunisia, Texas, Spain) with all defining and supporting criteria present: mass extinction of planktonic foraminifera, first appearance of Danian species, $\delta^{13}C$ shift, Ir anomaly (12 ppb) and KTB red layer (Gertsch *et al*., 2011). This study suggests that the periodic acid rains associated with pulsed Deccan eruptions and strong continental weathering during latest Maastrichtian resulted in carbonate dissolution causing super-stressed environmental condition in marine system. This would have led to the demise of nearly all planktic foraminiferal species and >95% blooms of the disaster opportunist *Guembelitria cretacea*.

Another major advance, also from the Deccan volcanic province, is the discovery of planktic foraminifers in the main part of the province (Keller *et al*., 2008), indicating that a seaway existed in central India around the Cretaceous-Paleocene (K-Pg) transition. Along the proposed seaway along the Narmada, a rich and diverse fauna of dinosaurs and associated vertebrates flourished during the Late Cretaceous. The decline and eventual extinction of this fauna may now be evaluated in the context of this major trans-Deccan seaway and the killing effects of the main phase of Deccan volcanism near the end of the Cretaceous (Keller *et al*. 2009b; Bajpai 2009).

Cretaceous-Neogene Vertebrate Finds

In another major advance, it has been shown that the Indian subcontinent was the centre of origin/early evolution of several major orders of modern mammals including adapisoriculid insectivore mammals, whales, sea-cows, primates and hoofed mammals such as horses. India is the only Gondwanan landmass that yielded definitive eutherian mammals of Late Cretaceous age. Ankle-bone morphology of these mammals represented by the genus *Deccanolestes* favoured an euarchontan affinity (Prasad and Godinot, 1994; Smith *et al*., 2010; Boyer *et al*., 2010) whereas dental morphology indicated basal eutherian grade of evolution (Wible *et al*., 2007). Assigning *Deccanolestes* to a stem euarchontan will imply that basal primates (hence placental mammals) had originated prior to the Cretaceous-Tertiary (K/T) boundary in a Gondwanan landmass. This would confirm the molecular hypotheses favouring Gondwanan landmasses as centre/s for primate origins. However, recent morphological studies (Prasad *et al*., 2010) and phylogenetic analysis that combined both dental and postcranial characters (Goswami *et al*., 2011) of the Late Cretaceous mammals from the Deccan volcano-sedimentary sequences of peninsular India have demonstrated that these mammals have sister group relationship with adapisoriculid mammals *Afrodonchleuhi* from the Late Palaeocene of Africa (Gheerbrant, 1988), *Afrodongheerbranti* and *Bustylus* from the Early Palaeocene of Belgium (Smith *et al*., 2011), and *A. germanicus* from the Late Palaeocene of Germany (Rusell, 1964) and adapisoriculid mammals occupy a much basal position in eutherian phylogeny (Goswami *et al*., 2011). The new finding reiterated that placental mammals were not present before K/T boundary. Since *Deccanolestes* represents the oldest occurrence of the family Adapisoriculidae, India was interpreted as a possible centre of origin for this group of mammals and the younger taxa from Africa and Belgium possibly dispersed from India some time close to the Cretaceous-Tertiary boundary (Prasad *et al*., 2010; Goswami *et al*., 2011, Smith *et al*., 2011). These findings have important implications for the evolution of eutherian mammals in the former Gondwanaland and Late Cretaceous palaeobiogeography of India and Africa as these two landmasses were separated by a wide stretch of ocean at the end of Cretaceous.

Dinosaur fossils have been poorly documented from the Indian subcontinent with only two mounted skeletons known from the Lower Jurassic Kota Formation and several isolated skull and postcranial bones described from the Upper Cretaceous Lameta Formation. The latest report of several partial skeletons of basal sauropodomorph dinosaurs named as *Lamplughsauradharmaramensis* and *Pradhaniagracilis* from the Lower Jurassic Upper Dharmaram Formation has substantially improved the diversity of dinosaurs from India (Kutty *et al*., 2007). From the Late Cretaceous, a very important finding of a snake skeleton in association with dinosaur egg clutch has come to light from the Lameta Formation of Balasinor limestone quarry in Kheda district of Gujarat (Wilson *et al*., 2010). Here a partial skeleton of a madtsoid snake named as *Sanajehindicus*Wilson *et al*. 2010 was found coiled around a sauropod egg and close to hatchling sauropod dinosaur bones. This co-occurrence of wide-gaped snake and hatchling dinosaur remains offered important clues to feeding habits of Cretaceous snakes and how sauropod hatchlings had to face the danger of predation from non-dinosaur reptiles.

Until recently, Late Cretaceous vertebrate fossils have been documented from the Deccan Volcanic Province only. Though marine Cretaceous rocks spanning Albian to Late Maastrichtian are exposed in the Cauvery basin, south India, very few vertebrate fossils have been described from this region. However, latest field explorations in the Cauvery basin led to the discovery of ichthyosaur reptilian remains (*Platypterygius indicus*) after a gap of 140 years and eight species of piscivorous shark species from the Late Albian-Turonian Karai Formation exposed near the village Garudamangalam in Ariyalur district, Tamil Nadu. These shark taxa were not known previously from India. Most of the shark genera reported from the Karai Formation are known from high palaeolatitudes suggesting antitropical Early Cretaceous distribution and cool-water palaeoenvironmental conditions during the deposition of Karai Formation (Underwood *et al*., 2011). The recent discovery of *Ptychodus decurrens*, a durophagous elasmobranch from the Karai Formation further supports cold water environment of deposition as most of *P. decurrens* yielding sites are located in high palaeolatitudes in both hemispheres (Verma *et al*., 2012).

During the Cenozoic, the origin of whales from a four-footed land animal, a classic example of biological evolution that involved a drastic transition from land to sea, has been documented on the basis of a diverse assemblage of well preserved fossils discovered in the Eocene sections of Kutch (Gujarat) and the Himalayas (Bajpai and Gingerich, 1998; Bajpai *et al*. 1998; Thewissen *et al*., 2007; Bajpai *et al*., 2009, 2011; Thewissen and Bajpai, 2009; Ravikant and Bajpai, 2010). Another globally significant discovery is that of a basal Eocene terrestrial vertebrate fauna from a lignite mine at Vastan, western India (e.g. Bajpai *et al*., 2005, 2008). This fauna, now considered to be nearly contemporaneous with the India-Asia collision at 55 Ma (Clementz *et al*., 2010), represents the oldest record of Cenozoic terrestrial fauna in South Asia. It comprises primitive members of a large number of placental mammal orders including artiodactyls, perissodactyls and primates. In recent years, the vertebrate diversity of Cambay Shale Formation has increased substantially with the discovery of frogs, lizards, birds, avians, and lagomorphs, tillodonts and primates among mammals (Bajpai and Kapur, 2008; Prasad and Bajpai, 2008; Bajpai *et al*., 2008; Rose *et al*., 2009; Mayr *et al*., 2010). Interestingly, many of the Vastan mammalian orders appeared almost simultaneously across the northern continents during the intense warming interval around the Paleocene-Eocene boundary. Many of these taxa exhibit Laurasian affinities implying a terrestrial connection between India and Eurasia by Early Eocene. The Vastan assemblage dates the earliest Cenozoic faunal exchanges between India and Eurasia, providing independent evidence that a subaerial contact was established between these landmasses by at least 54 Ma. The Vastan fossil data also raises the possibility of an Indian origin and subsequent migration to northern continents for some of the modern faunas. Based on recent molecular phylogenetic studies of extant acrodont lizards (Macey *et al*., 2000) and ranid frogs (Bossuyt and Milinkovitch, 2001) it has been suggested that these vertebrate groups may have originated in India or other Gondwanan landmasses such as Africa and were carried on the rafting Indian plate as on a Noah's Ark and finally dispersed into Asia following the collision between India and Asia. Widely known as the "Out-of-India" dispersal hypothesis, this has received some support with the recent fossil discoveries of ranoid frogs (Bajpai and Kapur, 2008) and agamid lizards (Prasad and Bajpai, 2008) from the Early Eocene Cambay Shale, Vastan Lignite Mine, Gujarat. Similarly, based on the occurrence of palynofossils and chemistry of the Vastan resin, it has been suggested that dipterocarp plants may have dispersed out of India into Southeast Asia (Dutta *et al*., 2011).

The Neogene is marked by two major finds that have recently put India on the world map. The first of these is a remarkable new terrestrial vertebrate fauna of Early Miocene age (~17 Ma) from the Kutch region of western India (Bhandari *et al*., 2010). The new finds include perissodactyls, artiodactyls, proboscideans and rodents. Overall, the Kutch assemblage documents the Out-of-Africa proboscidean dispersal event with no major barriers to dispersal between India, northern Africa and mid-latitude Eurasia around the end of early Miocene, and comparable palaeoclimatic conditions in the three regions at this time. Secondly, from nearly coeval marine sections in Kachchh, a major adaptive radiation of sea-cows (dugonginesirenians) has been brought to light based on the discovery of exceptionally well-preserved fossil material, especially skulls (Bajpai *et al*., 2010; Thewissen *et al*., 2009). This record of dugongine diversity will be essential to future understanding of the evolutionary history of sea grass communities worldwide.

Evolution of Plants During India's Northward Drift

The separation of Indian landmass from Gondwanaland, its latitudinal displacement and final collision with Asia

(~90-55 Ma) resulted in large-scale continental plate reorganization, palaeoceanographic and paleoclimatic changes. The period witnessed evolution and dispersal of floral entities.

Evolutionary pattern and major diversification amongst flowering plants (angiosperms) during the Cretaceous initiated fundamental changes in terrestrial ecosystems and set in motion processes that generated most of the extant plant diversity. Presence of grass phytoliths in dinosaur coprolites from the late Cretaceous Deccan intertrappean locality near Pisdura, India age provided evidence of early evolution and diversification pattern in grass family Poaceae (Prasad *et al*., 2005). The study showed that, by the latest Cretaceous (65 Ma), the grass family (Poaceae) consisted of members of the modern grass subclades PACMAD (Panicoideae-Aristidoideae-Chloridoideae-Micrairoideae-Arundinoideae Danthonioideae) and BEP (Bambusoideae-Ehrhartoideae-Pooideae). In continuation, recent discovery of fossil cuticular remains from dinosaur coprolites and sediment succession of latest Cretaceous (65 Ma) from the same locality enriched earlier evidence regarding early evolution of Poaceae (Prasad *et al*., 2011). Based on phylogenetic analyses that combined molecular genetic data and epidermal and phytolith features across the Poaceae, these new fossil forms can be assigned to the rice tribe, Oryzeae, of grass subfamily Ehrhartoideae (Prasad *et al*., 2011). The new Oryzeae fossils from India suggest substantial diversification within Ehrhartoideae by the late Cretaceous. This discovery not only pushes the clock back on the evolution of rice family but also suggests that India could be the place of its origin more than 65 million years ago.

Recent palaeobotanical studies also include those on fossile resins Fossil resins from the Cretaceous sediments of Meghalaya, India and Kachin, Myanmar (Burma). These resins were analysed using Curie point pyrolysis-gas chromatography-mass spectrometry and thermochemolysis gas chromatography-mass spectrometry to help elucidate their botanical source. The study showed the exclusive presence of both labdane and abietane diterpenoids and the lack of phenolic terpenoids suggests that the studied Cretaceous resins were derived from Pinaceae (pine family) conifers instead of angiosperm (Dutta *et al*., 2011). In another important study, the molecular structure of an Eocene fossil resin retrieved from Vastan lignite mine and Matanomadh lignite mine has been investigated with complimentary spectroscopic techniques (Mallick *et al.*, 2009). The FTIR spectrum shows cadalene based bicyclic sesquiterpenoids including some bicadinenes and bicadinanes. The polycadinane products confirm the fossil material as an angiosperm dammar resin, usually associated from Dipterocarp tropical rain forests (Mallick *et al*., 2009; Dutta *et al*., 2011).

After the KTB mass extinction event a relatively brief climatic amelioration was followed by profound change in the global climate during early paleogene. The early Paleogene climate encompasses several long and short term events of global warming. During its northward journey till its eventual collision with Eurasia, the Indian subcontinent lay within the equatorial zone at the time of Paleocene-Eocene transition (55.5Ma) (Prasad *et al*., 2009; Clementz *et al*., 2010). Equatorial positioning coupled with global warm climate resulted in the evolution of various tropical biological entities that are well preserved in marine and terrestrial rocks exposed in the northeastern and western margins of the Indian subcontinent (Prasad *et al*., 2009; Clementz *et al*., 2010). Carbonaceous shale, coal and lignite deposits of Palaeogene age (~55.5-52 Ma) all along the western and northeastern margins of the Indian subcontinent are rich in their fossil content.

In recent years, palynofloras and other plant remains from several of these lignite deposits have been studied, such as those from the Akli Formation in the Barmer Basin of Rajasthan (Tripathi *et al*., 2009). The assemblage is dominated by angiospermic pollen and specimens showing affinity with the mangrove palm *Nypa.* Preponderance on these pollen taxa indicates that the sediments were deposited in a coastal swamp surrounded by thick, *Nypa*-dominated mangrove vegetation.

An important recent investigation has brought to light a rich assemblage of dinoflagellate cysts from the Vastan lignite deposit of Gujarat. This assemblage includes several age-diagnostic taxa that indicate an age ranging from Ilerdian to basal Cuisian, ~55-52 Ma) for the Vastan sequence. Supported by the $^{87}Sr/^{86}Sr$ ages and a prominent ^{13}C excursion (Clementz *et al*., 2010), the dinocyst assemblage has helped fix a fairly precise age for the mammal-bearing levels at Vastan.

Another interesting find is that of fossil fruits from the Cambay Shale at Vastan lignite mine (Singh, *et al*., 2010). Recently, a small assemblage of macro- and micro floral remains comprising fossil leaf impressions, silicified wood, spores, and pollen grains has been reported from the Palaeocene-lower Eocene Vagadkhol Formation (Olpad Formation) exposed around Vagadkhol village in the Bharuch District of Gujarat, Western India.

An attempt has been made recently to track the affinities of the pollen flora of the endemic plants of Western Ghats area with the fossil palynoflora of late Palaeocene-early Eocene (~55–50 Ma) coal and lignite deposits of western and northeastern Indian region. The study shows striking similarity of extant pollen with twenty eight most common fossil pollen taxa of the early Palaeogene. The data revealed that highly diversified equatorial rain forest vegetation once widespread in the Indian subcontinent during early Palaeogene times, are now restricted in a small area as a refugia in the southernmost part of the Western Ghats area. The studies indicate that present day high diversity of the Western Ghats area is a legacy of globally warm interval of the early Palaeogene when the tropical diversity was much higher than the present day and widespread over a greater part of the Indian subcontinent. High precipitation and low seasonality in the low latitude equatorial region during warm Palaeogene was the key factor in widespread distribution of the tropical rain forest community in the Indian subcontinent (Prasad *et al*., 2009).

In a recent study, the molecular structure of an Eocene fossil resin retrieved from Vastan lignite mine and Matanomadh lignite mine has been investigated with complimentary spectroscopic techniques. The polycadinane products confirm the fossil material as an Angiosperm dammar resin, usually associated from Dipterocarp tropical rain forests (Mallick *et al*., 2009; Dutta *et al*., 2011).

The Dipterocarpaceae, a well known and economically important family of trees of the tropical rain forests of Asia, comprise over 470 species. A definitive record of dipterocarp from 53 Ma old sediments from Western India based on fossil resin chemistry and palynological data demonstrate that the Asian dipterocarps must have originated in Gondwana and dispersed from India into Asia once the land connection between the Indian and Asian plate was well established during the middle Eocene (49-41 Ma). This underlines support for the current 'Out of India' Hypothesis (Dutta *et al*., 2011).

The development of mycorrhizal associations is considered a key innovation that enabled vascular plants to extensively colonize terrestrial habitats. Ectomycorrhiza occurs symbiotically with many roots of tropical rain forest plants and helps in the uptake of nutrient from the soil. Fossil ectomycorrhizae were recorded for the first time from 52 million-yr-old piece of amber from the Tadkeshwar Lignite Mine of Gujarat State, Western India (Beimforde *et al*., 2011).

Marine Mesozoic Stratigraphy

Progress made over the past five years has led to a significant improvement in our understanding of depositional sequences including major stratigraphic gaps in the preserved marine Mesozoic record in India. The three MFSs are represented by the intra-Triassic late Middle Anisian *Trinodosus* Zone determined in Spiti, the intra-Jurassic late Middle Oxfordian Schilli Subzone of the *Transversarium* Zone in Kachchh, and the intra-Cretaceous early Middle Turonian Turonainse Zone in the Cauvery basin. The two SBs are intra-Jurassic early Early Toarcian *Nitiscens* Zone determined by Madagascar and Pakistan, and the intra-Createaceous early Early Aptain *Deshayesi* Zone determined in Kachchh and Jaisalmer. The Indian Triassic record is restricted to Higher Himalaya, that of exposed marine Jurassic to Western peninsular India and Higher Himalaya, while the Cretaceous record is much more widespread, almost all around the Indian plate.

Mega/First Order Mesozoic Sequnce Stratigraphic-Framework

The mega/super sequence representing the Indian Mesozoic encompasses the interval from the intra-Permian origin of Neotethys to its intra-Palaeogene closure (Krishna *et al*., 2010, 2011). It includes three 1st order sequences punctuated by three Maximum Flooding Surfaces (MFSs) and two Sequence Boundaries (SBs). The precise instants of geological times of the five 1st order sequence surfaces are included either in subaerial gaps at the basin margin or in submarine gaps in distal sites of the basins. All of the five sequence surfaces are resultants of significant multiple geological events. The first two sequences were developed when India was part of the Gonwanaland in the southern hemisphere, with Madagascar and Africa lying to its west, Australo-Antarctica in the east and the Tethys in the north and northwest. Following its separation from Australo-Antarctica, India, together with Madagascar, drifted northwards until the early Middle Turonian, with Africa in the proximity. Subsequently, around mid-Middle Turonian, India broke away from Madagascar and was oceanically isolated during its rapid northward drift until the end of the Cretaceous. The mega and its three 1st order sequences are net-controlled by regional tectonics and so uniformly expressed in a broad tectonically homogeneous region inclusive of all the basins of the Indian subcontinent.

Dave (2011) emphasized on different 1st order sequence development in different Indian basins. He interpreted the Jurassic-Early Cretaceous sedimentary record in Kachchh and K-G basins as one single 1st order sequence. Dave (op.cit) also considered the following successions to be the 1st order sequences: Early Cretaceous of the Mahanadi and Assam basins; Early Cretaceous through the earliest part of the Late Cretaceous of the Kerala-Konkan basin; Late Jurassic to Late Albian of the Cauvery basin, and the Permian to Late Eocene of the Jaisalmer basin. The remainder of the Cretaceous in Kachchh, K-G, Cauvery, Mahanadi and Kerala-Konkan basins was interpreted by Dave (op.cit) as being part of the next 1st order sequence. The varying remainder of the Cretaceous in Kachchh, K-G Cauvery, Mahanadi and Kerala-Konkan basins made the early part of the next 1st order sequence. There is a mention of further differentiation in some basins into 2nd and 3rd order sequences. However, in this summary Dave did not elaborate on SBs and MFSs of any order.

Triassic Ammonoid Stratigraphic Refinement and Sequence Framework

Continued progress over the past five years has led to differentiation of the ammonoid rich early and Middle Triassic record in Spiti into 27 zones (Bhargava *et al*., 2004; Krystyn *et al*., 2004). Their (Bhargava and Krystyn) proposal for the Induan/Olenekian GSSP in Spiti is receiving serious discussion and consideration by the concerned Stage Boundary Working Group and the Subcommission on Stratigraphy. Krishna (2008, 2010, 2011) based on detailed ammonoid stratigraphic work by Krystyn *et al*. (2004), determined the major intra-Triassic 1^{st}order MFS/MFI between beds 34 and 40 in the Lalung section of Muschelkalk Member of Mikir Formation in Spiti basin, and assigned the same to late Middle Anisian *Trinodosus* Zone.

Jurassic Ammonoid Stratigraphic Refinement

The Jurassic has been one of the best-developed and studied systems in India, specially the globally famed ammonoid rich Jurassic in the Kachchh basin. Ammonoids of nine out of eleven Jurassic stages are known in some or other Indian basin, Kachchh alone recording ammonoids of six Jurassic stages. Compared to the 65 zone stratigraphic refinement on ETM, the Indian subcontinent also distinguishes 45 (Krishna *et al*. 2010, 2011) of which as many as 27 are new and developed in Kachchh (Krishna 2010, 2011), with zonal resolution of 800 ky, and subzonal resolution of 400 ky.

Rai (2011) recorded the presence of Toarcian-Aalenian marine sediments in Kachchh thereby further enlarging the Kachchh exposed Jurassic geological record from the exsting six to eight stages.

Prasad (2011) in a recent review included four standard spore-pollen zones in the Jurassic, however, he has interpreted absence of any Jurassic in the Gondwana grabens. Non-marine Rhaetic and Liassic palynomorphs in Banni well of Kachchh basin have long been known (Koshal 1975, 1983). Narsimha (2006) recorded Late Jurassic (Oxfordian to Tithonian) dincysts in Ariyalur locality of Cauvery basin, below which Raju has interpreted a subaerial stratigraphic gap of the entire Triassic and Early to Middle Jurassic. Late Jurassic marine sediments have also been unearthed in K-G basin well sections (Prasad, 2011).

Sequence Framework

1^{st} to 3^{rd} order sequence stratigraphic framework in the erstwhile Gondwanian Tethyan Margin (GTM) from Arabia to Australia has been developed in the Kachchh basin (Krishna 2009, 2012; Krishna *et al*., 2010, 2012) of the former Indian subcontinent that also included Madagascar in the Jurassic. It includes a complete 1^{st} order TST of c. 25 my duration, constrained a major subaerial gap at its start in basin margins and a major submarine gap at its top in distal sites of the basins all through from Arabia to Australia (Krishna 2011). The interpreted submarine gap since long has been considered a subaerial and is still maintained like that (Biswas, 2001, 2012). The basal SB of the so differentiated TST is near the Pliensbachian/ Toarcian boundary as delineated in Pakistan and Madagascar, and the MFS at the top determined above the late Middle Oxfordian Transversarium Zone Schilli Subzone bed 3-08 in the Kantkote section of Wagad in the Kachchh basin (Krishna *et al*. 2009). The TST is preceded below by the later part of a 1^{st} order HST of the preceding 1^{st} order sequence and followed above by the early part of the 1^{st} order HST of the same 1^{st} order sequence. The Jurassic is further differentiated into 10 plus 2^{nd} order sequences. The basal most 2^{nd} order sequence is recognized in Ladakh, one 2^{nd} order sequence in Pakistan, while nine 2^{nd} order sequences are defined in Kachchh with precise delineation in several margin to basin sections and dating of all the sequence surfaces. These are further differentiated into thirty-four 3^{rd} order sequences (Krishna, 2009). The larger duration mega/1^{st}/2^{nd} order longer than 2.4 my are net-controlled by regional tectonics while the 3^{rd} and yet finer sequences shorter than 2.4 my have global applicability in view of governance by Earth's orbital dynamics. In rapidly deposited and expanded 3^{rd} order HSTs eccentricity and precession based c. 100 ky and c. 20 ky sequences are also recognized (Krishna *et al*., 1996). Another significant demonstration in this context has been control of regional tectonics on the origin and extinction of ammonoid lineages. Each successive 2^{nd} order sequence marks the origin as well as extinction of one indigenous ammonoid subfamily (Krishna, 2009). Mega to 2^{nd} order sequence frameworks differ significantly on GTM and ETM, and the corresponding sequence surfaces are not isochronous. Thus dominant/indigenous ammonoid subfamilies on ETM and GTM indicate their respective origin/extinction at their respective sequence surfaces instead of being isochronous on the two Tethyan margins.

Cretaceous

In a review Prasad (2011) included 7 pollen-spore zones and 14 dinoflagellate zones in the Indian marine Cretaceous. Many of these zones have their either boundaries in between the standard stages, which does not conform to the fundamentals of biozonation. The widely present Cretaceous in Indian basins has registered significant progress, particularly in Cauvery basin. Raju (2011) in a review highlighted the salient features of this progress. He has indicated 6 transgressions in the Cauvery Cretaceous, while 21 fine cycles are noted in Early

Cretaceous. Nagendra *et al*. (2010) based on integrated studies interpreted 4 sea-level cycles in the Cauvery Cretaceous. Ramkumar (2004) has earlier recognised 14 fine cycles and 8 unconformities in the Cauvery Late Cretaceous geological record where as Govindan and Ravindran (1996) interpreted 7 MFSs in the Albian – Maestrichtian duration. Raju (op. cit) interpreted 8 sequences in K-G Cretaceous with maximum sea level in Cauvery and Jaisalmer in Cenomanian and a major sea-leve high during Late Turonian – Early Coniacian in K-G and Cauvery basins. According to Krishna *et al*. (2010, 2011), the Indian Cretaceous geological record includes a major 1st order TST of mid Early Aptian to early Middle Turonian duration which is so constrained by significant subaerial gap at the margin of the basins around Barremian – Aptian transition e.g. between Sivaganga Formation and Uttatur Formation. A less probable Turonian submarine gap between the Bibat Formation below and Mundhra/Kori/Naliya Formation above in the distally located Kachchh off-shore wells has also been interpreted. These authors believe in a uniform sequence stratigraphic framework in all the Indian basins along with precise intra-plate correlatability of the sequence SBs and MFSs. The said 1st order TST is preceded by the later part of HST of the preceding sequence, while followed upward by the early part of the HST of the same sequence.

Krishna (2012) has differentiated in the exposed Berriasian-Turonian records of Kachchh a succession of more than nine 2nd order and twenty-five 3rd order sequences, again with delineation of all the sequence surface in several margin-to-basin precisely recorded sections along with precise dating of all the involved sequence surfaces.

Precision Chronicle of Mesozoic Tectonic Events

According to Raju (2011), few tectonic events have been dated viz. 1. break-up, start of spreading between India and Australo-Antarctica, and origin of Indian ocean during Late Valanginian/Early Hauterivian, 2. Rapid thermal subsidence and opening of new basins during Late Aptian/Albian, 3. Break-up of Madagascar from India around 90 ma. According to Krishna (2012) the 1st order sequence stratigraphic surfaces (SBs and MFSs), in view of being consequences of tectonic events, provide precise ages of the tectonic events. As such the 1st order intra-Triassic late Middle Anisian (c. 241 ma) MFS dates the origin of the Kachchh basin. It also throws light on the age of the Mid. Triassic gap in Gondwana basins, and the crustal attenuation in the Higher Himalaya. The 1st order intra-Jurassic SB (183 ma) dates the start of marine transgression in Kachchh, so also the drowning of the carbonate platform in High Himalaya and many other events. The 1st order late Middle Oxfordian MFS (158.5 ma) contains the climaxing and abortion of rifting in Kachchh, tilting down due east of the Indian plate along. This is accompanied by reversal of palaeocurrent/slope/drainage from due west and northwest to due east and southeast, and initiation of rifting in the India/Australo-Antarctica sector leading to the formation of of graben basins. The intra-Cretaceous major mid.-Early Aptian SB (121 ma) precisely dates the break-up unconformity and beginning of spreading between India and Australo-Antarctica, and initiation of rifting between India and Madagascar. The intra-Cretaceous early Middle Turonian major MFS (91.7 ma) dates the start of rift-volcanics and spreading between India and Madagascar in the western sector. It also given information on litho/faunal/floral changes in other Indian basins. The intra-Cretaceous Rajmahal and terminal Cretaceous igneous events are interpreted here as hot spot related events instead of their linkage to tectonism. However, the older ages (c.120 Ma prior to Rajmahal or 90 Ma prior to Deccan events) of the rift-volcanism related intrusives match with the ages of the sequence surfaces that are genetically related to rift-tectonics.

Proterozoic Bio-climatic Event

Sulphur isotope compositions in sedimentary pyrites from the major Proterozoic basins like Vindhyan, Chattisgarh and Cuddapah support the hypothesized global Proterozoic sulphidic anoxic ocean. Such extreme environmental conditions were possibly responsible for the delayed oxygenation of the biosphere and retarded evolution of multicellular life (Sarkar *et al*., 2009).

Phanerozoic Bio-climatic Events

Carbon isotope and geochemical studies across a continental Permo/Triassic boundary indicated a common causative mechanism for extinction of land plants and disappearance of coal (Sarkar *et al*., 2003a). Isotopic study across the Eocene/Oligocene boundary (time of first polar ice cap development) of western India showed dramatic ocean cooling and decrease in pCO_2 in ocean-atmosphere system possibly resulting from enhanced silicate weathering in rising Himalayas (Sarkar *et al*., 2003b). The geochemical work indicated O_2-poor condition of the ocean during this time (Sarkar *et al*., 2003c). Sedimentological studies in Himalayan foreland demonstrated large-scale presence of basinal turbidites in response to progressive uplift of the basin margin during the earliest phase of Himalayan uplift. This caused a major forced regression that resulted in a total turnaround from a marine to a continental alluvial system coinciding with a major change in provenance (Bera *et al*., 2008, 2010a). Studies on foreland soil carbonates suggest a change in atmospheric CO_2 (Bera *et al*., 2010b). These geological and climatic changes had a dramatic effect on biota recording a change over from arid to humid floral elements in the foreland.

Quaternary Bio-climatic Events

Studies of Ganges-Brahmaputra (GB) delta plain sediments indicate widespread development of palaeosols with vast expansion of C4 vegetation and incised valleys during the last glacial maximum (LGM) when both monsoonal rainfall and sea level were low. Earliest Holocene in the GB delta experienced rapid sea-level rise that pushed the coastline and mangrove front ~100 km inland. Simultaneous intensification of monsoon and very high sediment discharge (~4-8 times than modern) caused a rapid aggradation of both floodplain and estuarine valley-fill deposits. The present Hoogli River was possibly acting as the palaeo-Ganges when C3 vegetation replaced the glacial biomes. The terrestrial vegetation change was modulated by changes in depositional environment, specific ecological niches and climate rather than pCO_2 (Sarkar *et al*., 2009).

Hydrogen isotope studies of Quaternary Siwalik palaeosols from the Himalayas indicates three episodes of monsoon intensification at ~11 Ma, 6 Ma and 3 Ma coinciding with major pulses of tectonic uplift in the Himalayas suggesting causal link between monsoon intensity and uplift. The study also indicated that the appearance of C4 plants during the late Miocene was locally asynchronous (by ~3 Ma), similar to what is seen on a global scale and possibly indicate a combined effect of microclimate (e.g. varying monsoon intensity) and habitat disturbance (e.g. forest fire; Sanyal *et al*., 2010). Stable isotopic studies of soil carbonate and organic matter from the Ganga Plain provided a first quantitative estimation of past rainfall over Indian sub-continent. Decrease of ~20% in rainfall intensity is inferred during the LGM. The change in vegetations over the Ganga Plain during the last 100 ka was mainly driven by variations in monsoonal rainfall (Agarwal *et al*., 2011).

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