Journal of the Palaeontological Society of India
Volume, 53(1), June 2008: 37-49

ISSN 0522-9630

BIOTIC RESPONSE TO CRETACEOUS-EOCENE TECTONIC EVENTS AT THE NORTHERN MARGIN OF THE INDIAN PLATE AND THE INDUS-TSANGPO SUTURE ZONE, LADAKH HIMALAYA, INDIA

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ABSTRACT

The Cretaceous-Eocene successions of the Indus-Tsangpo Suture Zone (ITSZ) and the Zanskar Tethyan Zone (ZTZ) of the Ladakh Himalaya were laid down during progress of the India-Asia collision and have well preserved imprints of the event. In the ITSZ, the northward drift of the Indian Plate during the Early Cretaceous led to subduction of its oceanic crust under the Asian Plate leading to the creation of the Nindam forearc basin, in which was deposited the Nindam Formation with planktic foraminifers and radiolarians in its lower part and larger foraminifers in the upper. The contact of the oceanic crust of the Indian Plate with that of the Asian Plate towards the end of Cretaceous created the Indus Basin, which received sediments of the Danian-Cuisian Indus Formation with shallow marine biota in its lower part and fluvial-brackish in the upper part as well as of the overlying middle-late Eocene Hemis Formation with fluvial biota. In the ZTZ, the deposition of the Giumal Formation with shallow marine biotas occurred after the deep marine sedimentation of the Spiti Shales. The subduction of oceanic crust of the Indian Plate under the Asian Plate steepened the Zanskar shelf, creating deep marine conditions during the deposition of the Cenomanian-Turonian Chikkim/ Shillakong formations with planktic foraminifers. Similar conditions persisted in North Zanskar during the deposition of the Goma Formation with planktic foraminifers up to early Thanetian, whereas in South Zanskar its coeval Kangi La-Marpo-Stumpata succession with deep to shallow marine biotas witnessed gradual shallowing due to contact of Indian oceanic crust with the Asian Plate. The marine conditions continued up to Cuisian when the Dibling/ Lingshet-Kong succession with shallow marine biotas was deposited. Afterwards, the region was uplifted due to the India-Asia collision, leading to deposition of the Chulung La Formation under continental conditions.

Keywords: Cretaceous-Eocene, Biotic response, India-Asia collision, Indus-Tsangpo Suture Zone, Zanskar Tethyan Zone

INTRODUCTION

In the Himalayan region, the marine Cretaceous-Eocene succession is best developed at the northern margin of the Indian Plate and along the Indus-Tsangpo-Suture Zone (ITSZ), which is a major crustal lineament between the Himalayan Range and Tibet and is considered the boundary between the Indian and Asian plates (Figs. 1-2). A major rifting episode on the Gondwanaland assembly towards the end of Palaeozoic, when India (Palaeo-India) was still a part of it, resulted in separation of its northern microplate fringe including the Karakoram and South Tibet (Lhasa) blocks and opening of the Neo-Tethys Sea that represented the future site of the ITSZ (Dewey *et al.*, 1989; Gaetani and Garzanti, 1991; Thakur, 1992; Sinha, 1997). The Karakoram and Lhasa blocks collided with the Asian Plate along the Bangong Nujiang Suture (BNS) closing the older Tethys (Palaeo-Tethys) Sea in the Early Cretaceous (Allègre *et al.*, 1984; Kearey and Vine, 1990; Sinha and Mishra, 1997). Gondwanaland, the archaic southern supercontinent, began disintegrating during the Late Jurassic, and India broke away from it in the Early Cretaceous to set out on a long journey northwards, which resulted in its collision with the Asian Plate along the ITSZ and the closure of the Neo-Tethys during the early Eocene (Fig. 3). The sediments of the Zanskar Tethyan Zone (ZTZ) were deposited at the northern margin of the Indian Plate on the continental shelf and a north facing slope of the Neo-Tethys (Fuchs and Willems, 1990; Upadhyay and Sinha, 1998). The Upper Jurassic-Eocene sediments of the ITSZ and ZTZ show marked differences in their lithologies and biotas due to distinct palaeogeographic set ups, though both were laid down during the progress of the India-Asia convergence (Fig. 4). This paper attempts to decipher the apparent changes in composition, diversity and frequency of biotas that thrived in the region between the Early Cretaceous, when India commenced its northward journey, and the early Eocene, when it collided with the Asian Plate, and to relate those changes to major tectonic events that led to the India – Asia collision and the closing of the Neo-Tethys Sea.

Before dwelling on the Cretaceous-Eocene events, it will be fitting to give here a brief account of post-rift and pre-drift tectonic events and biotas. The rift that developed between the Gondwanaland and the Karakoram (Sinha *et al.*, 1999) and Lhasa blocks during the Late Permian-Triassic times progressively widened due to the sea floor spreading during the Late Callovian-Valanginian interval. In the ITSZ, it resulted in a basic magmatism represented by the Dras (Volcanic) Formation comprising basalt, andesite, agglomerate, limestone and cherty beds with radiolarians of Late Callovian-Valanginian age (Honegger *et al.*,1982; Robertson, 2000). In the ZTZ, it created fault block basins in which the Ferruginous Oolite Formation with diverse molluscan fauna including some index ammonites was deposited over Triassic-Lower Jurassic carbonates during the Callovian global sea level rise (Haq *et al.*, 1987). This was followed by the deposition of the deep marine Spiti Formation during the Late Callovian-Valanginian interval. The Spiti Formation, in part a time equivalent of the Dras Formation of the ITSZ, is generally poorly fossiliferous in the Zanskar

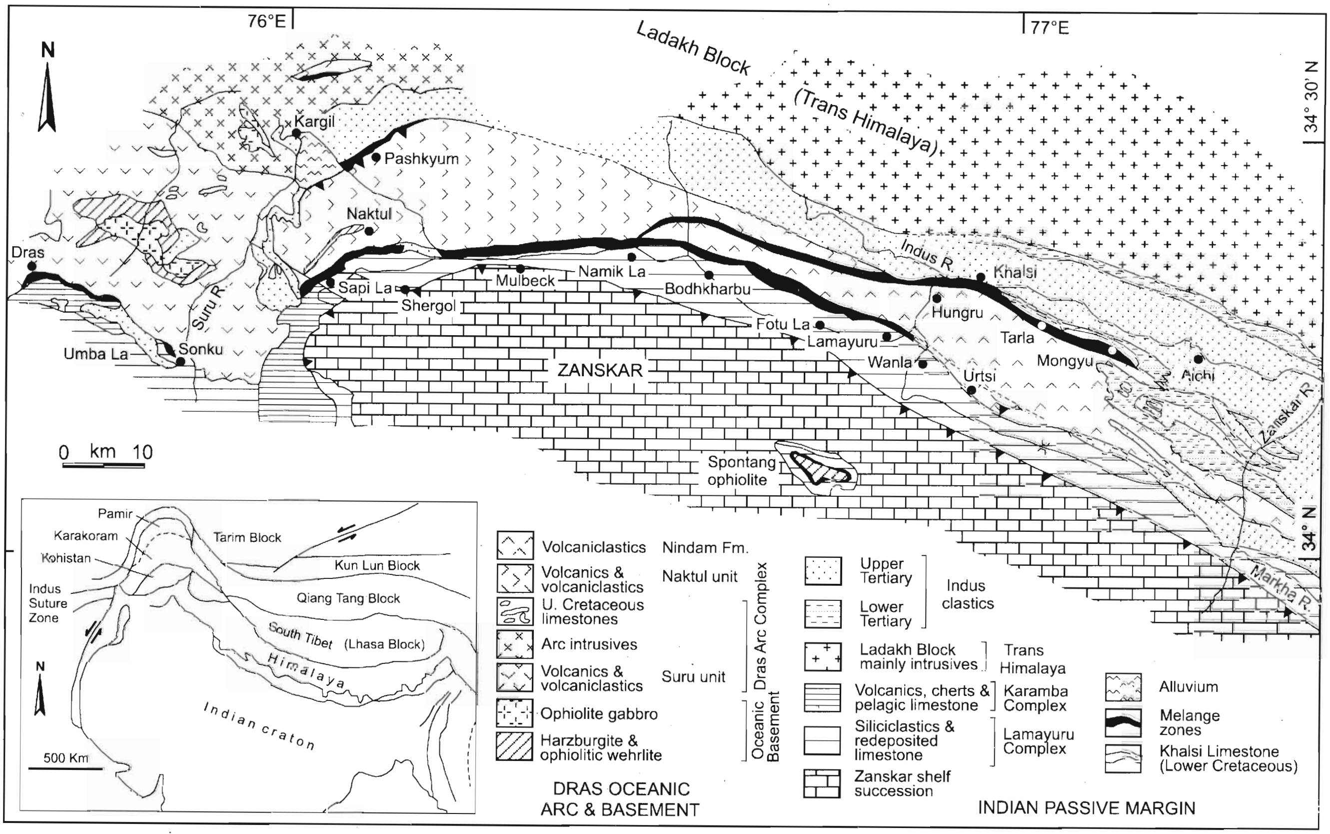


Fig. 1. Outline geological map of the Indus Suture Zone and adjacent units of Ladakh. Inset shows the general setting of the Indus Suture Zone and other tectonic blocks (after Robertson, 2000).

region, but in easterly Spiti it has yielded several index ammonites (Krishna, 1981; Krishna *et al.*, 1997). The deposition of the Spiti Formation in the ZTZ and the Dras Formation in the ITSZ was followed by the commencement of northward drift of the Indian Plate during the Hauterivian time. The subsequent events imprinted in the Cretaceous-Eocene successions of the ITSZ and the ZTZ up to the closing of the Neo-Tethys and onset of continental conditions are described below, as zones in chronological order, along with the corresponding changes observed in the biotas.

CRETACEOUS-EOCENE TECTONIC EVENTS AND BIOTAS

A. INDUS-TSANGPO SUTURE ZONE (ITSZ)

1. Deposition of platformal limestone with orbitolinids and rudists (Aptian-Early Albian)

The initiation of the northward drift of India in the Hauterivian (Early Cretaceous) time was accompanied by thickening and rising of the oceanic crust over which was deposited the platformal Khalsi Limestone containing rudist bivalves and orbitolinid foraminifers. The rudists and orbitolinids, markers for the Cretaceous Tethyan realm, indicate a shallow marine tropical to subtropical setting and show marked provincialism, though the latter were restricted to north of the Indian Plate (Desio, 1979; Baud *et al.*, 1982). Fossils of both are abundant in the Khalsi Limestone; the rudists exhibit low diversity and comprise among others *Eoradiolites gilgitensis*, *Polyconites* sp., *Toucasia* sp., *Sphaerulites* sp. cf. *S. cantabricus* and ?*Horiopleura* sp., whereas the orbitolinids show a high diversity and include *Orbitolina conoidea*, *O. discoidea*, *Mesorbitolina* sp. ex gr. *M. parva-texana*, *M. parva*, ?*M. drasensis*, *Praeorbitolina cormyi*, *Palorbitolina lenticularis* and *P. hedini*. Together they indicate an Aptian-Early Albian age (Tewari *et al.*, 1970; Shah and Gergan, 1981; Mathur, 1990a,b; Van Haver *et al.*, 1984; Mathur and Vogel, 1988). A few taxa from the Khalsi Limestone are illustrated in Plate I.

2. Commencement of subduction (Late Albian), formation of magmatic arc and volcano-sedimentary domains with deep and shallow marine biotas (Late Cretaceous)

Further drift of the Indian Plate led to subduction of its oceanic crust under the Asian Plate and disintegration of a major part of the Khalsi Limestone platform. The subduction also resulted in the formation of the Ladakh magmatic arc and other volcanic and volcano-sedimentary domains including the Nindam forearc basin in which was deposited the Late Cretaceous-early Eocene Nindam Formation. The lower part (Cenomanian-Maastrichtian) of the Nindam Formation has yielded rare radiolarians and planktic foraminifers of a low diversity (Shah and Sharma, 1987). Its poorly fossiliferous nature is attributed to climatic changes possibly due to the migration of cooler climatic zones following the drift of the Indian Plate.

3. Indian oceanic crust-Asia contact, creation of Indus Basin, deposition of Indus formation with shallow marine biotas (Late Maastrichtian-early Cuisian)

In the latest Cretaceous time, the oceanic crust of the

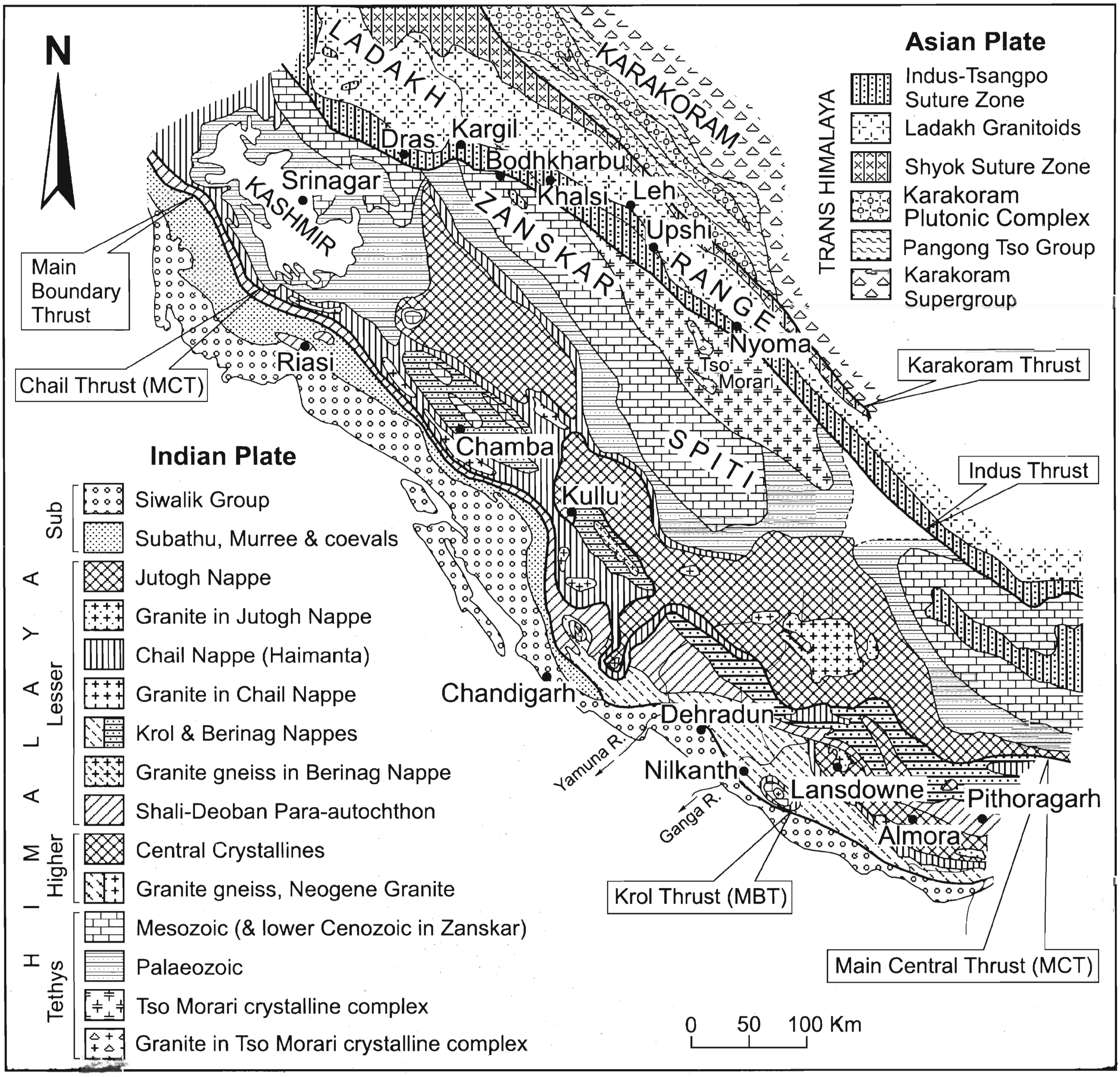


Fig. 2. Geological map of the western Himalaya showing major tectonic units (based on Thakur, 1987).

Indian Plate came in contact with the continental Asian Plate and resulted in (i) a shallowing of the Nindam Basin during the deposition of middle and upper parts of the volcano-sedimentary Nindam Formation as evidenced by the occurrence of Palaeocene palynomorphs near Dras (Mathur and Jain, 1980; Upadhyay *et al.*, 2004) and early Cuisian larger foraminifers near Hankar (Plate II), (ii) the formation of a shallow linear basin, namely the Indus Basin, to the south of the Ladakh magmatic arc. In the Indus Basin, the Palaeocene-early Eocene flyschoid Indus Formation comprising, in ascending order, the Sumdha Gompa, Nummulitic, Jurutze and Gongmaru La members, and the overlying Middle-Late Eocene molassic Hemis Conglomerate Formation were deposited. During the deposition of this succession, partly favourable environmental conditions existed for growth and diversity of biota. Although no fossils have been found in the lower part (Danian-early Thanetian) of the Sumdha Gompa Member, they are common in its younger part: frequent but less diverse larger foraminifers such as *Actinosiphon* and *Orbitolites*, frequent and moderately diverse shallow marine to fresh water molluscan and plant fossils, and frequent and moderately diverse corals occur in the successively younger Upper Thanetian beds. The overlying Nummulitic Member deposited during a transgressive phase contains highly diverse larger foraminifers (Pl. II) including some index taxa such as *Nummulites minervensis* (early Ilerdian), *Alveolina ilerdensis* (middle Ilerdian), *Assilina pomeroli* (late Ilerdian), *Nummulites burdigalensis burdigalensis* (early Cuisian), but their frequency decreases gradually from abundant in the early-middle Ilerdian to frequent in the late Ilerdian and rare

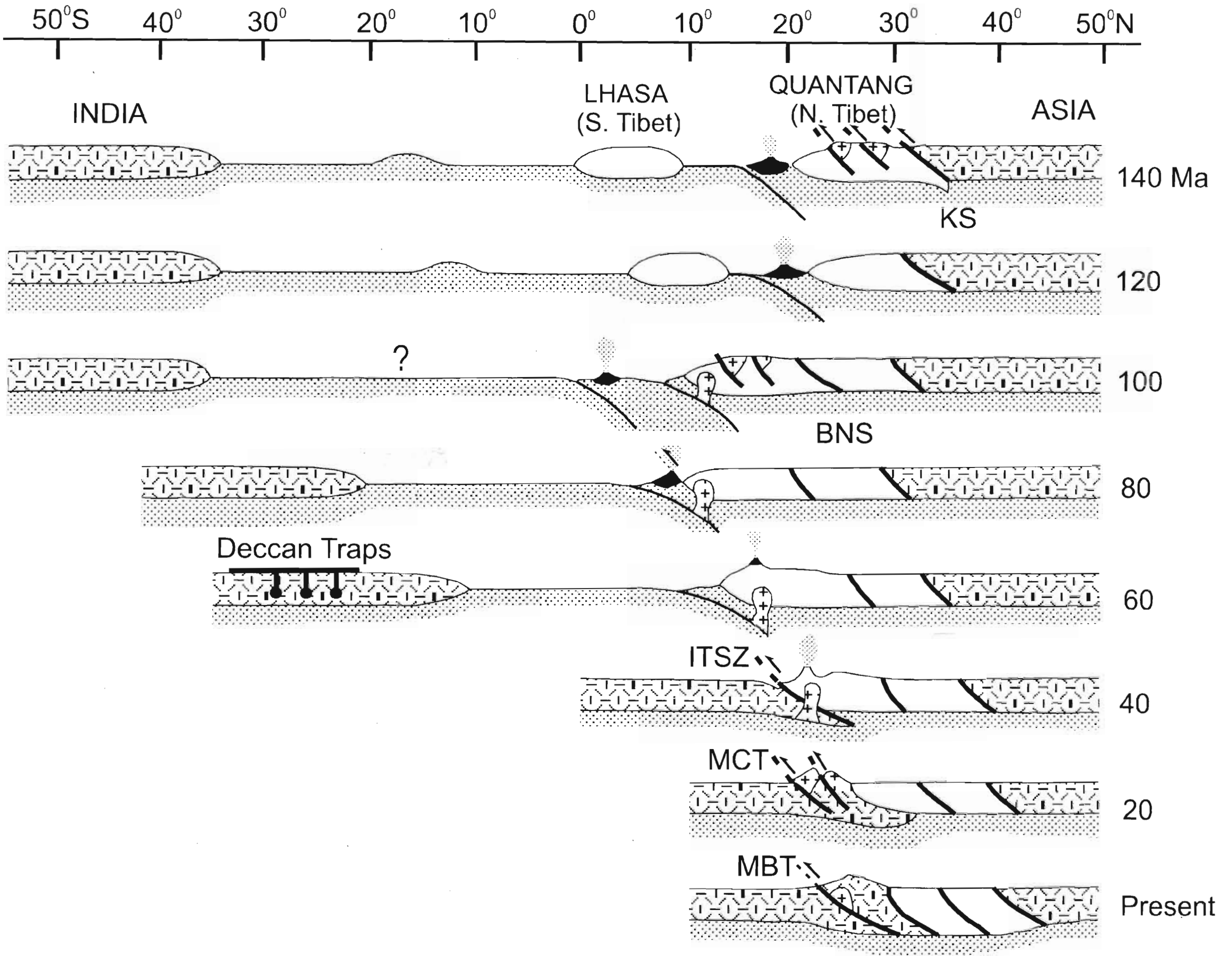


Fig. 3. Possible sequence of events beginning break up of India from the Gondwanaland through its northward drift, to India-Asia collision and closure of Neo-Tethys. BNS, Bangong Nujiang Suture; ITSZ, Indus-Tsangpo Suture Zone ; KS, Kokoxili Suture; MBT, Main Boundary Thrust; MCT, Main Central Thrust (based on Allègre *et al.*, 1984, Kearey and Vine, 1990 and Sinha and Mishra, 1997).

in the early Cuisian (Mathur and Juyal, 1996, 2000; Mathur, 1997).

4. India-Asia continental collision; emplacement of ophiolites and Ladakh granitoids; closing of Neo-Tethys; progressive continentality and appearance of brackish- fresh water biotas (middle Cuisian-Bartonian)

The India-Asia continental collision towards the end of early Cuisian led to the upheaval of the region and the progressive shallowing of the Indus Basin bringing in a continental influence. The middle Cuisian Jurutze Member of the Indus Formation, which has yielded frequent but less diverse shallow marine to brackish water molluscs in its lower part, and rare, badly preserved and less diverse plant fossils in the upper part, is considered to be a deltaic deposit. Two assemblage zones, namely the *Turritella subathooensis* Zone and the Upper Plant Fossils Zone of middle Cuisian age have been recognised in this member (Mathur, 1997; Mathur and Juyal, 2000). The succeeding Gongmaru La Member (late Cuisian), which has so far yielded only rare, badly preserved and less diverse trace fossils and worm burrows, is considered to be a fluvio-deltaic deposit. The overlying Hemis Conglomerate Formation (middle-late Eocene) with well preserved but rare and less diverse plant fossils was deposited under fluviatile conditions (Lakhanpal *et al.*, 1983; Ram- Awatar *et al.*, 2007).

The India-Asia collision also led to the emplacement of

EXPLANATION OF PLATE I

(Scale bars equal 500 μm)

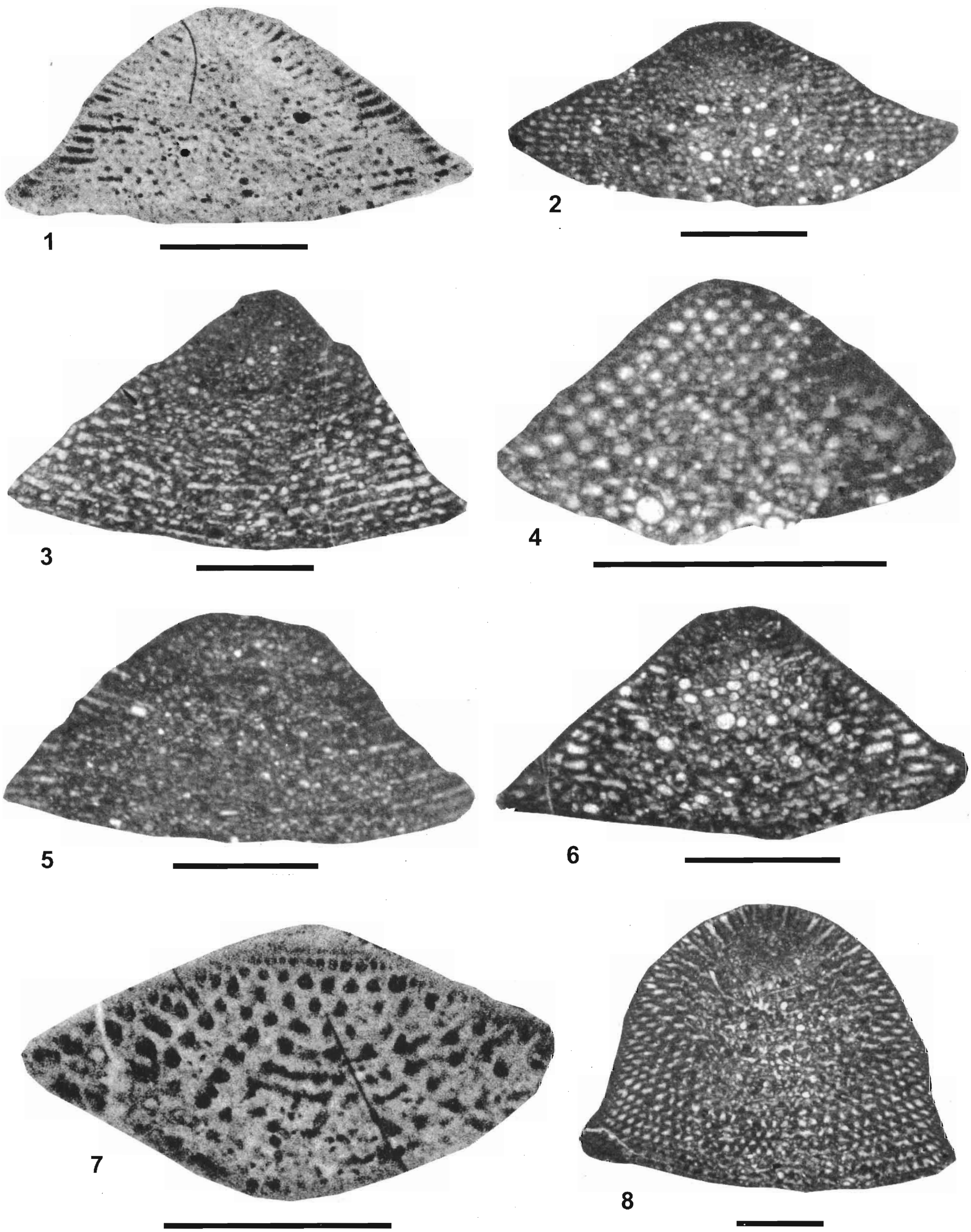
Orbitolinids in thin sections from the Khalsi Limestone, Khalsi Section.

1. ***Mesorbitolina parva-texana,*** WIMF/A 3177 (5),
2. ***M. ?drasensis,***WIMF/A 3179 (3),
3. ***M. ?drasensis,***WIMF/A 3183 (1),
4. ***Praeorbitolina cormyi,***WIMF/A 3181 (2),
5. ***Praeorbitolina cormyi,***WIMF/A 3180 (2),
6. ***Palorbitolina*** sp. (oblique sections), WIMF/A 3179 (1),
7. ***Palorbitolina*** sp. (oblique sections), WIMF/A 3177 (6),
8. ***Neorbitolinopsis*** sp. (tangential section),WIMF/A 3182 (1),

Background masked to enhance clarity.

All specimens illustrated in this Plate and in Plate II are catalogued (WIMF/A) and housed in the repository of Wadia Institute of Himalayan Geology, Dehradun (India).

Plate I



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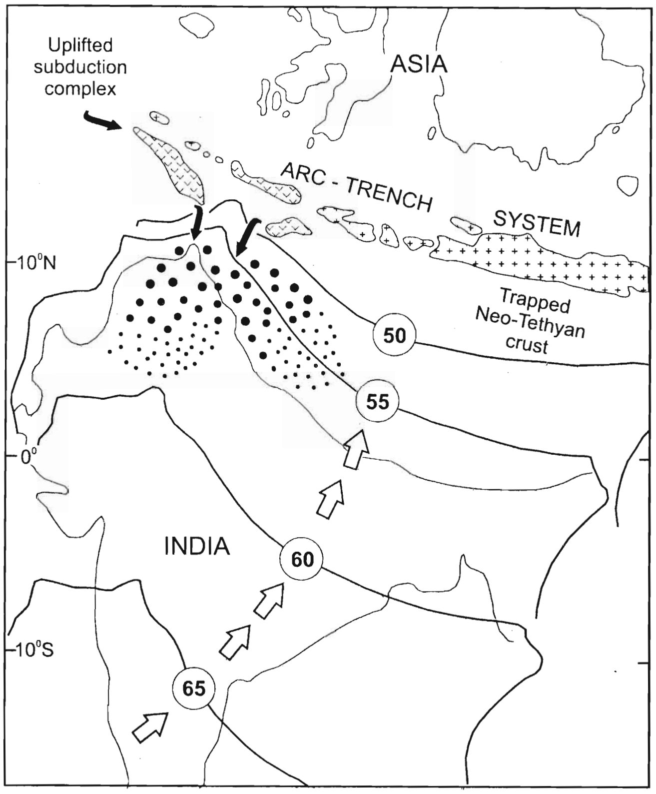


Fig. 4. Map showing progressive convergence between the Indian and Asian plates during the early Tertiary (based on Gaetani and Garzanti, 1991).

ophiolites along the suture zone in middle Cuisian, i.e. prior to the deposition of the Gongmaru La Member that contains ophiolitic matrix derived from the volcano-sedimentary Dras Volcanic and Nindam formations. Due to the continued convergence, the emplacement of the Ladakh Granitoids (Late Albian-Early Eocene) took place towards the end of Cuisian. This is indicated by the presence of pebbles of the Ladakh Granitoids and other older litho-units of the ITSZ in the Hemis Conglomerate Formation.

B. ZANSKAR TETHYAN ZONE (ZTZ)

1. Deposition of arenaceous Giumal Formation with shallow marine biotas (Hauterivian-Cenomanian)

In the ZTZ, the commencement of northward drift of India in the Hauterivian time led to the uplift of the Indian Craton causing a gradual change in facies from argillaceous (Spiti Formation) to arenaceous (Giumal Formation), the supply of terrigenous detritus being from the craton. This event marked the beginning of the Himalayan Orogeny. The Giumal Formation was deposited under shallow marine to deltaic conditions. It consists of dark grey shale and sandstone in the lower part, well developed sandstone beds with interbedded black shales containing planktic foraminifers in the middle part, a thick succession of quartzarenite followed by dark grey shale with intercalated volcanic arenite and marl containing belemnitids, ammonites and other molluscs in the upper part, and an alternating succession of quartz- and calcareous arenites containing phosphatic nodules with specimens of a diminutive ammonite *Protachantoceras* of Late Cenomanian age in the uppermost part (Gaetani *et al.*, 1986). The sudden influx of volcanic rock fragments in the upper part of the Giumal Formation suggests intraplate alkaline volcanism probably related to the commencement of subduction in the Late Albian time (Gaetani and Garzanti, 1991). No fossils are known from the lower part (Hauterivian-Barremian) of the Giumal Formation. Its middle part (Aptian-Albian) contains rare and less diverse planktic foraminifers including age diagnostic *Hedbergella delrioensis* (Aptian-?Albian); the upper part (Cenomanian) has yielded abundant moderately diverse belemnitids and some gastropods and bivalves; and the uppermost part contains rare and less diverse ammonites. This succession passes imperceptibly into the grey limestone of the overlying Chikkim Formation (Turonian-Campanian) deposited during the subduction stage. The Giumal Formation of Malla Johar area contains cherty horizons with rich radiolarian fossils (Sinha, 1989).

2. Steepening of Zanskar Shelf, deposition of limestone and marl with deep marine biotas (Turonian- Campanian)

The continued subduction of the Indian oceanic crust under the Asian Plate steepened the Zanskar shelf and the supply of terrigenous material ceased from the Indian Craton. Due to steepening of the shelf its northern part became deeper than the southern part resulting in facies variations, which have been recognized as the South Zanskar Belt (SZB) and the North Zanskar Belt (NZB). These two belts have stratigraphically similar, but lithologically noticeably different, successions. During the Turonian-Campanian, the Chikkim Limestone Formation was deposited in the SZB and the marly Shillakong Formation in the NZB. Both these lithounits have yielded index planktic foraminifers including *Whiteinella archaeocretacea* (Earliest Turonian), *Praeglobotruncana helvetica* (Early Turonian), *Marginotruncana sigali* (Middle Turonian), *Dicarinella concavata* (Late Turonian - Coniacian), *Globotruncanita elevata* (Early Campanian), *G. calcarata* (Late Campanian) and *Globotruncana ventricosa* (Middle

EXPLANATION OF PLATE II

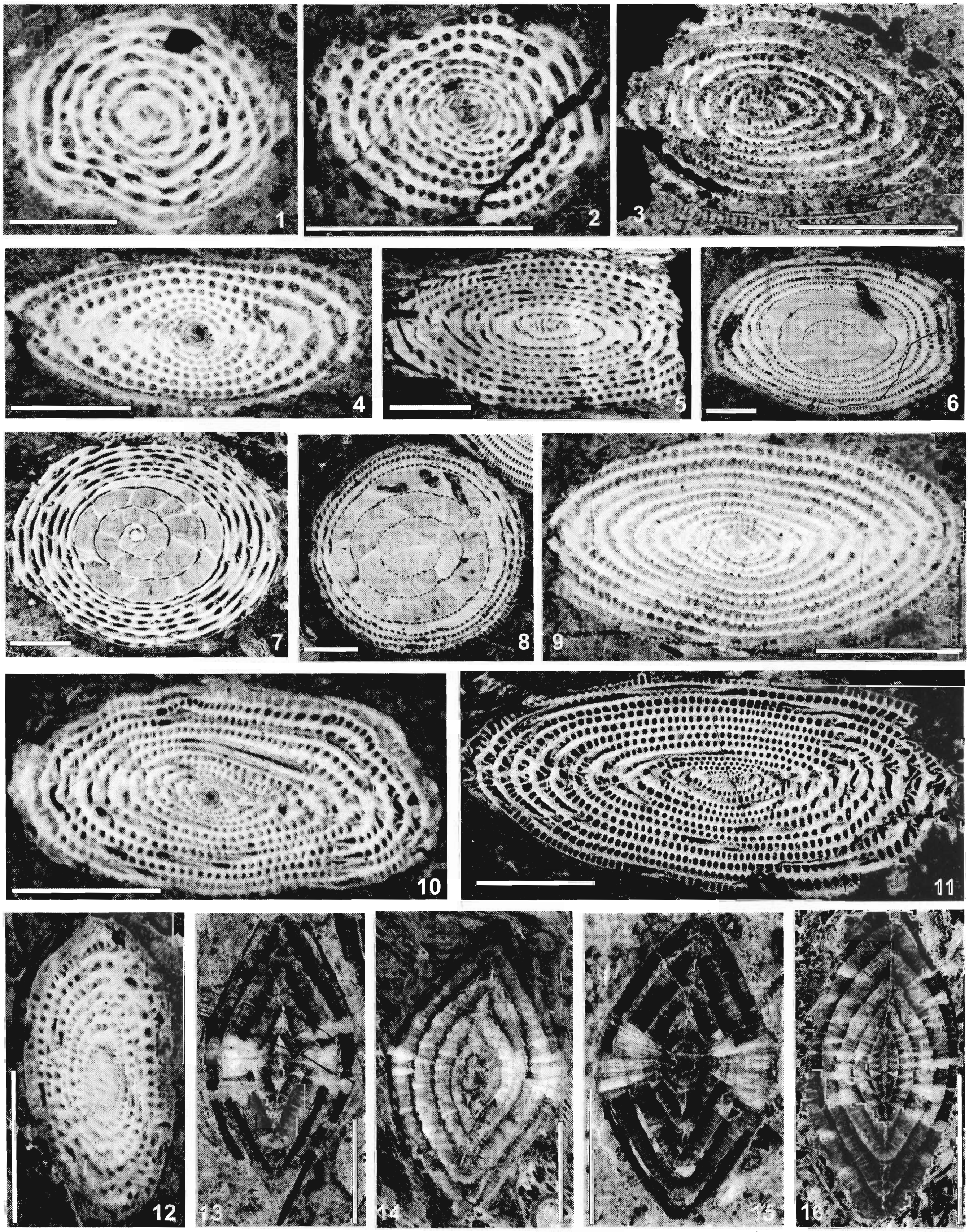
(Scale bars equal 500 μm)

Foraminifera (in thin sections) from upper part of the Nindam Formation, Hankar Section, Markha Valley (1-2, 4, 6-11, 13, 15), from the Nummulitic Member of the Indus Formation, Sumdha Gompa Section, Zanskar Valley (3, 5, 12, 14) and from the Nummulitic Member of the Indus Formation, Nidar Section, Indus Valley (16).

1. ***Glomalveolina minutula,*** WIMF/A 3148 (4),
2. ***Glomalveolina minutula,*** WIMF/A 3151 (1),
3. ***Alveolina ilerdensis,*** WIMF/A 3156 (1),
4. ***A ilerdensis-pasticillata,*** WIMF/A 3149 (1),
5. ***Alveolina ilerdensis,*** WIMF/A 3156 (2),
6. ***A. parva***, WIMF/A 3249 (3),
7. ***A. parva***, WIMF/A 3151 (2),
8. ***A. parva***, WIMF/A 3249 (1),
9. ***A. schwageri***, WIMF/A 3149 (2),
10. ***A. oblonga***, WIMF/A 3148 (2),
11. ***A. oblonga***, WIMF/A 3148 (5),
12. ***Alveolina ilerdensis,*** WIMF/A 3154 (1),
13. ***Nummulites increscens***, WIMF/A 3249 (2),
14. ***Nummulites increscens***, WIMF/A 3153 (1),
15. ***N. burdigalensis burdigalensis***, WIMF/A 3149 (3),
16. ***N. burdigalensis kuepperi***. WIMF/A 3125 (3),

Journal of the Palaeontological Society of India
Volume, 53(1), June 2008

Plate II



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Campanian) (Fuchs, 1982; Gaetani *et al.*, 1986; Premoli Silva *et al.*, 1992). In the Chikkim Limestone Formation, the diversity of planktic foraminifers is high throughout but their frequency decreases gradually from Turonian to Campanian, whereas in the Shillakong Formation both diversity and frequency remain low.

3. Uplift of Indian craton, deposition of shale-marl with deep and shallow marine biotas (Latest Campanian-Early Maastrichtian)

The Indian Craton was uplifted again in the latest Campanian probably due to epirogenic movements resuming the supply of terrigenous detritus. During the Latest Campanian-Early Maastrichtian time, the marly, argillaceous to arenaceous Kangi La Formation with rare and less diverse planktic foraminifers, frequent but less diverse corals, and rare and less diverse *Omphalocyclus* specimens was deposited in the SZB, whereas euxinic shales of the lower part of the Goma Formation with rare and less diverse planktic foraminifers were deposited in the NZB. Both these litho-units contain rich planktic foraminifers of Early Maastrichtian *Globotruncanella havanensis* Zone (Fuchs, 1982; Fuchs and Willems, 1990; Mathur and Juyal, 1994).

4. Indian oceanic crust-Asia contact; commencement of shallowing of sea, deposition of calcareous sediments with deep and shallow marine biotas (Late Maastrichtian - early Ilerdian)

The contact between the Indian oceanic crust and Asia took place in the late Maastrichtian time and the supply of terrigenous detritus from the Indian Craton ceased once again. Though southern part of the Zanskar basin became shallower, deeper conditions persisted in the northern part. In the NZB, younger part of the Goma Formation comprising euxinic argillaceous to marly sediments with index planktic foraminifers of medium diversity and frequency in its upper Maastrichtian (Fuchs and Willems, 1990; Mathur and Juyal, 1994) beds and of low diversity and frequency in the lower Palaeocene beds (Baud *et al.*, 1985) and the succeeding calcareous Lingshet Formation with several index late Thanetian-early Ilerdian larger foraminifers of medium to low diversity and frequency were deposited. In the Lingshet Formation, several assemblage zones such as a zone containing rotaliids, the *Daviesina garumnensis* Zone (late Thanetian) and *Nummulites minervensis* Zone (early Ilerdian) have been recognised (Mathur, 1997; Mathur and Juyal, 2000). In the SZB, the progressive shallowing of basin is reflected by facies as well as biotas (planktic foraminifers, larger foraminifers and oysters occurring in that order in successively younger formations) of the Kangi La-Marpo-Stumpata succession. After the deposition of the deep marine Kangi La marl, the calcareous facies prevailed during Late Maastrichtian-early Ilerdian interval when shallow marine Marpo (late Maastrichtian- earliest Thanetian) and Dibling (late Thanetian-early Ilerdian) formations with intervening deltaic Stumpata Formation (early Thanetian) were deposited. The Stumpata Formation, consisting of quartzarenite deposited during a short term global sea level fall has so far yielded only rare and less diverse crabs and oysters, whereas the Marpo and Dibling formations contain age-diagnostic larger foraminifers (Gaetani *et al.*, 1986; Mathur, 1997; Mathur and Juyal, 2000). In the Marpo Formation, four medium to less diverse and frequent assemblage zones, namely the trace fossils and *Omphalocyclus macroporus-Siderolites calcitrapoides* zones (Late Maastrichtian), rotaliid Zone (Danian-Selandian) and the *Daviesina danieli-D. garumnensis* Zone (earliest Thanetian) have been recognised, whereas in the Dibling Formation only two assemblage zones, namely the *D. langhami- Rotalia trochidiformis* Zone (late Thanetian) and the *Alveolina* sp. ex gr. *A. ilerdensis* Zone (early Ilerdian) with low diversity and medium to low frequency foraminifers have been recognised. The rotaliid Zone of the Marpo Formation may be correlated with the calcarenite occurring in the middle part (early Palaeocene) of the Jidula Formation of South Tibet from which *Rotalia*, *Lockhartia* and ostracodes have been reported (*fide* Xiaoying *et al.*, 1996).

5. Progressive shallowing of sea, deposition of shale-marl with shallow marine biotas (middle Ilerdian-early Cuisian)

The Dibling and Lingshet formations of the SZB and NZB, respectively, are overlain by the argillaceous to marly Kong Formation in both belts. The lower part (middle Ilerdian-early Cuisian) of the Kong Formation of the SZB has yielded medium to highly diverse and frequent larger foraminifers including the index taxa *Alveolina ilerdensis, Nummulites burdigalensis kuepperii* (middle Ilerdian-basal Cuisian), and *N. burdigalensis burdigalensis* (early Cuisian) (Mathur, 1997; Mathur and Juyal, 2000).

6. India-Asia collision, upheaval of Zanskar region; withdrawal of sea, deposition of brackish water oyster marl (middle Cuisian-?Lutetian)

The India-Asia collision towards the end of early Cuisian led to further shallowing of the basin particularly in the SZB. In the post-collision phase, middle-late Cuisian *Assilina placentula grande* Zone of the Kong Formation with larger foraminifers of medium to high diversity and frequency was deposited in the SZB. In the NZB this lithounit was likely deposited in slightly deeper conditions (due to northward slope of basin) than in the SZB, as it has so far yielded only larger foram-bearing limestone lenses derived from the Dibling Formation of the SZB. The top part (late Cuisian) of the Kong Formation of the SZB represented by a marl bed with rare and low diversity oysters was deposited under brackish water conditions. In the NZB, the marine conditions probably stayed longer than in the SZB because of its northward slope. Here, the Kong Formation is yet to yield any biota. The continuing convergence resulted in the upheaval of the region and the development of fluvio-deltaic conditions, which prevailed during the deposition of the succeeding molassic Chulung La Formation in the SZB. It is likely that the top beds of the Kong Formation of the SZB and NZB are diachronous and those of the latter are possibly partly homotaxial with the Chulung La Formation of the SZB. It is inferred that the Indian Craton was uplifted again towards the end of Cuisian due to orogenic movements forming a major provenance for the Chulung La Formation. The middle Kong-Chulung La succession also contains detritus derived from the obducted ophiolites and other older rocks of the ITSZ (Nicora *et al.*, 1987). The Chulung La Formation has so far yielded only rare and low diversity trace fossils, and its reference to Lutetian is tentative.

DISCUSSION AND CONCLUSIONS

The northward drift of the Indian Plate and the resultant changes in latitude, basin configuration, bathymetry, salinity,

Table 1: Middle Jurassic-Eocene stratigraphic succession of the Indus-Tsangpo Suture Zone (ITSZ), Ladakh Himalaya. Additional data compiled from Desio (1979), Srikantia and Razdan (1985), and Valdiya (1998). R (Rare), F (Frequent) and A (Abundant) denote frequency of occurrence of fossils, and L (Low/ less), M (Medium/ moderate) and H (High) denote biotic diversity.

TIME				AGE MY	VOLCANO-SEDIMENTARY BELT		SEDIMENTARY BELT			TECTONIC EVENTS
EOCENE	LATE	Priabonian		33.9			Hemis Conglomerate Formation 200-600 m Fluviatile, clastic		Plant fossils R, L	
		Bartonian		37.2						
	MID	Lutetian		40.4						
	EARLY	Ypresian	Cuisian	48.6			Indus Formation >1500 m	Gongmaru La Mb. Fluviodeltaic, shale-sandstone	Trace fossils R, L	? Emplacement of Ladakh Granitoids
								Jurutze Member Deltaic, marl	Molluscs and plant fossils R-F, L	? India-Asia continental collision; closing of sea; upheaval; progressive continentality; ophiolite emplacement
			Ilerdian	50.5	Nindam Fm. >1000 m Mudstone, volcaniclastics, chert & limestone	Sh. marine larger forams A, H		Nummulitic Mb. Shallow marine, shale-limestone	Larger forams A-R, H	
PALAEOCENE		Thanetian		55.8		Shallow marine Palynomorphs A, H		Sumdha Gompa Member Shallow marine, shale-sandstone	Corals, molluscs, plant fossils and larger forams F, L-M	
		Selandian		58.7						
		Danian		61.7						? Commencement of deposition in the Indus Basin
CRETACEOUS	LATE	Maastrichtian		65.5		Deep marine Planktic forams and radiolarians R, L				? Indian oceanic crust-Asia contact; creation of Indus Basin south of Ladakh magmatic arc
		Campanian		70.6						
		Santonian		83.5						
		Coniacian		85.8						
		Turonian		89.3						
		Cenomanian		93.5						
	EARLY	Albian		99.6	Khalsi Limestone >800 m Marine platform				Rudists A, L Orbitolinids A, H	? Start of subduction; drowning of Khalsi Limestone platform; basic volcanism; igneous activity; creation of Ladakh magmatic arc and of forearc basin for deposition of Nindam Fm.
		Aptian		112						
		Barremian		125						? Onset of deposition of orbitolinid and rudist platformal limestone (Khalsi Lst.) over rising oceanic crust/ islands
		Hauterivian		130						
		Valanginian		136	Dras Volcanic Formation >1500 m Basalt, tuff, volcaniclastics, cherty rocks				Radiolarians R, L	? Start of northward journey of India and of closing of Neo-Tethys; rising of oceanic crust and formation of islands
		Berriasian		140						
JURASSIC	LATE	Tithonian		146						
		Kimmeridgian		151						
		Oxfordian		156						
	MIDDLE	Callovian		161						? Break up of Gondwanaland; dispersion of continents; igneous activity
		Bathonian		165	Oceanic crust					
				168						

and climatic conditions also affected the biotas thriving in the region. A comprehensive picture of the Cretaceous-Eocene facies and biotas corresponding with major tectonic events witnessed by the sediments of the Indus-Tsangpo Suture Zone and the Zanskar Tethyan Zone during the course of the northward drift of India are depicted in tables 1 and 2, respectively, and are discussed below.

The beginning of northward drift of the Indian Plate in the Early Cretaceous initiated closing of the Neo-Tethys Sea along the ITSZ and rising of the oceanic crust over which the Khalsi Limestone was deposited in the Aptian-Early Albian time. Further drift of the plate led to subduction of its oceanic crust under the Asian Plate in the post-Early Albian time as evidenced by the palaeo-subduction complex, the magmatic arc, and the Nindam forearc basin deposits (Thakur, 1987; Garzanti and Van Haver, 1988; Upadhyay *et al.*, 2004). The oceanic crust came in contact with the Asian Plate towards the end of Cretaceous creating the Indus Basin south of the Ladakh magmatic arc. The Danian-lower Cuisian part of the Indus Formation was deposited in this basin in pre-collision phase, whereas its middle and upper Cuisian parts were laid down under deltaic and fluvio-deltaic set up in the post-collision phase. It is inferred that the India-Asia continental collision towards the end of early Cuisian led to the closing of Neo-Tethys along the ITSZ and onset of continental conditions.

In the ZTZ, the shallow marine to deltaic arenaceous Giumal Formation (Hauterivian-Cenomanian) succeeded the deep marine Spiti Formation after the drift commenced. The subduction of oceanic crust of the Indian Plate steepened the Zanskar shelf during Cenomanian-Turonian times making its southern part shallower than the northern and causing facies variations in the post-Cenomanian beds of the SZB and NZB (Mathur, 1990a). The supply of terrigenous material ceased from the Indian Craton during the deposition of the Turonian-Campanian Chikkim Limestone and resumed during the deposition of the Latest Campanian-Early Maastrichtian Kangi La marl in the SZB. The overlying Upper Maastrichtian-Lower Ilerdian Marpo-Dibling succession of the SZB is dominantly calcareous, but for the intervening early Thanetian arenaceous Stumpata Formation. In the NZB, the argillaceous to calcareous Goma Formation (latest Campanian-early Thanetian) is equivalent to the Kangi La-Marpo-Stumpata succession of the SZB, whereas the overlying calcareous Lingshet Formation (late Thanetian-early Ilerdian) is coeval of the Dibling Formation of the SZB. The succeeding argillaceous to marly Kong Formation (middle Ilerdian-Cuisian) was deposited in the NZB as well as in the SZB. Due to continued convergence, the Zanskar region was uplifted towards the end of the Cuisian bringing about continental conditions during which the fluvio-deltaic Chulung La Formation was deposited in the SZB. In the NZB, shallow marine conditions persisted apparently longer than in the SZB. Therefore in the NZB, it is likely that the upper part of the Kong Formation may be homotaxial with the Chulung La Formation.

The northward drift of the Indian Plate brought about marked changes in the Cretaceous-Eocene biotas inhabiting the Tethyan realm between the Indian and Asian plates. The biotas that thrived in the ITSZ, when India started drifting, were highly diverse and abundant orbitolinids and less diverse but abundant rudist bivalves occurring in the Aptian-Albian Khalsi Limestone. Their diversity and frequency diminished during the Cenomanian-Maastrichtian time (lower Nindam Formation) but increased again in the Danian-early Cuisian time (upper Nindam Formation) due to return of warmer conditions. In the Indus Basin, the Danian-lower Thanetian beds are apparently unfossiliferous as the oldest recorded fossils comprising frequent but low diversity larger foraminifers are from the upper Thanetian beds. The late Thanetian-early Cuisian interval witnessed highest biotic diversity though frequency decreased from Ilerdian to early Cuisian, when India collided with Asia. The biotic diversity seemed to drop again as the overlying Hemis Conglomerate Formation has so far yielded only a few plant fossils.

In the ZTZ, the biotic diversity observed in the Giumal Formation that was deposited as India began its northward journey, is fairly high as there are planktic foraminifers, belemnitids, ammonites and other molluscs but the frequency is generally low except of belemnitids, which were quite abundant in the Cenomanian time. From the Turonian to Early Campanian interval, mainly planktic foraminifers have been recorded. In the SZB, their diversity is high, though frequency decreases from base to the top; in the NZB they are not only rare but also much less diverse possibly due to unfavourable climate including euxinic conditions. During the Late Campanian-early Thanetian interval, the biota of the SZB was of medium to low diversity and frequency and included foraminifers, crabs and oysters; in the NZB, only the planktic foraminifers of medium to low diversity and frequency have been found in this interval. In both belts, the upper Thanetian-lower Ilerdian beds have yielded only rare to frequent larger foraminifers of low diversity. The middle Ilerdian-Cuisian interval in the SZB is marked by the presence of frequent larger foraminifers of medium to high diversity as by this time the Zanskar region had reached the northern tropics.

Summing up, the deep marine biotas (radiolarians and planktic foraminifers) thriving in lower part of the Nindam Formation were replaced by shallow marine types (larger foraminifers) in its upper part. Further, the shallow marine biota (molluscs and larger foraminifers) of lower part of the Indus Formation were replaced by fluvio-deltaic types (molluscan, plant and trace fossils) in the upper part of the formation and finally by the fluvial biota (plant fossils) in the succeeding Hemis Conglomerate Formation depicting uninterrupted progressive continentality in the ITSZ (Mathur and Juyal, 2000; Ram-Awatar et al., 2007). Similarly in the ZTZ, the deep marine biotas represented by ammonites in the Spiti Formation, planktic foraminifers and ammonites in the Giumal Formation, and planktic foraminifers in the Chikkim-Kangi La and Goma successions were replaced by the shallow marine biota, e. g. larger foraminifers, in the succeeding Marpo-Dibling-Kong and Lingshet successions and then by the fluvio-deltaic types (trace fossils) in the Chulung La Formation. In this zone, however, the trend of progressive continentality was not so smooth. The deep marine conditions depicted by the Spiti and Chikkim formations were interrupted, when the intervening Giumal Formation (Hauterivian-Cenomanian) was laid down under shallower conditions. This is attributed to uplift of the Indian Craton following the initiation of northward drift of the Indian Plate. From the Chikkim (i.e. Turonian) onwards, the trend of progressive continentality continued until the deposition of the Chulung La Formation.

ACKNOWLEDGMENTS

The authors are thankful to Prof. Anshu K. Sinha for reviewing the manuscript and suggesting several improvements. We are grateful to the Director, Wadia Institute

Table 2: Middle Jurassic-Middle Eocene stratigraphic succession of the South Zanskar (SZB) and North Zanskar (NZB) belts of the Zanskar Tethyan Zone, Ladakh Himalaya. Additional data compiled from Ganesan *et al.* (1981), Fuchs (1982), and Gaetani *et al.* (1986). R (Rare), F (Frequent) and A (Abundant) denote frequency of occurrence of fossils, and L (Low/ less), M (Medium/ moderate) and H (High) denote biotic diversity.

TIME				AGE MY	SHELF SZB →	SLOPE NZB	BIOTA	TECTONIC EVENTS
EOCENE	MID.	Lutetian		40.4	Chulung La Fm. 300 m, Fluvio-deltaic, shale-sst.	?	Trace fossils R, L	
	EARLY	Ypresian	Cuisian	48.6	Kong Fm. 170 m Shallow marine, shale-marl	Kong Fm. 170 m ?Shallow marine, shale-marl	SZB: Larger forams F, M-H NZB: Derived larger forams	◀ Upheaval of region; withdrawal of sea India-Asia collision; influx of ophiolitic matrix in younger beds
			Ilerdian	50.5	Dibling Fm. 80-120 m Shallow marine limestone	Lingshet Fm. 40-70 m Shallow marine limestone	Larger forams R-F, L	▲ Progressive shallowing of sea
PALAEOCENE		Thanetian		55.8	Stumpata Fm. 8-20 m, Deltaic, quartzarenite	Goma Fm. >80 m Deep marine, euxinic shale-marl,	SZB: crabs & oysters NZB: planktic forams R, L	◀ Short term global sea level fall
		Danian-Selandian		58.7	Marpo Fm. 100 m Shallow marine, limestone		SZB: larger forams R-F, L-M NZB: planktic forams F, M	
CRETACEOUS	LATE	Maastrichtian		65.5	Kangi La Fm. 200-400 m Deep marine, marl		SZB: forams & corals R-F, L NZB: planktic forams F, M	◀ Indian oceanic crust-Asia contact; shallowing of basin
		Campanian		70.6	Chikkim Limestone Fm. 50-120 m Deep marine, limestone	Shillakong Fm. ~100 m Deep marine, marl	SZB: planktic forams A-R, H NZB: planktic forams R, L	◀ Uplift of Indian Craton
		Santonian		83.5				
		Coniacian		85.8				
		Turonian		89.3				
		Cenomanian		93.5	Giumal Fm. 100-200 m Shallow marine and deltaic, sandstone-marl-shale	Giumal Fm. 0-8 m Shallow marine and deltaic, sandstone-marl-shale	Ammonites (late Cenomanian) R, L Belemnitids (Cenomanian) A, M Planktic forams (Aptian-?Albian) R, L Other molluscs R-F, L-M	◀ Steepening of Zanskar shelf due to subduction of Indian Plate
	EARLY	Albian		99.6				◀ Commencement of subduction; intraplate volcanism
		Aptian		112				
		Barremian		125				
		Hauterivian		130				
		Valanginian		136	Spiti Fm. 50-100 m Deep marine, euxinic shale	Spiti Fm. 0-5 m Deep marine, euxinic shale	Ammonites and other molluscs F, M	◀ Start of northward journey of India after its split from Gondwanaland; uplift of Indian Craton
		Berriasian		140				
JURASSIC	LATE	Tithonian		146				
		Kimmeridgian		151				
		Oxfordian		156				
	MIDDLE	Callovian		161	Ferrigenous Oolite Fm. 0-20 m	Ferrigenous Oolite Fm. 0-8 m	Inner shelf, shale sandstone-iron-stone, ammonites	
		Bathonian		165 168	Carbonates	Carbonates		◀ Creation of fault block basins along Late Permian-Triassic rift zones; subsidence; global sea rise

of Himalayan Geology, Dehradun for providing various facilities. The financial support from the Department of Science and Technology (Government of India) vide Grant no ESS/23/VES/154/2001 is thankfully acknowledged.

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Manuscript Accepted January 2008