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Revised stratigraphy of the lower Cenozoic succession of the Greater Indus Basin in Pakistan

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ABSTRACT – A refined stratigraphy for the lower Cenozoic succession of the Greater Indus Basin in Pakistan is presented. This region preserves an important East Tethyan marine succession through the Paleocene–Eocene, but its interpretation in terms of regional (tectonic) and global (climatic) effects has been inhibited by poor stratigraphy. Established dinoflagellate, nannofossil, planktonic foraminiferal and shallow benthonic foraminiferal biostratigraphical data for the Greater Indus Basin in Pakistan are collated, reinterpreted (where necessary) and correlated with the global standard chronostratigraphy and biostratigraphy of the early Palaeogene. Inter-regional stratigraphical correlations for the Upper Indus Basin and Lower Indus Basin are resolved. Age-diagnostic larger benthonic foraminifera from the Late Paleocene Lockhart Formation are illustrated. These collective biostratigraphical data provide a means of interpreting the lithostratigraphy and physical stratigraphical relationships of the Palaeogene succession in terms of the interplay between local tectonics (India–Asia collision) and global sea-level change. The timing of the Tethys closure, initial and final contact of the Indian–Asian plates, and dispersal of land mammals on the Indian Plate are discussed and correlated in the stratigraphical record of the basin. *J. Micropalaeontol.* **28**(1): 7–23, May 2009.

KEYWORDS: *Palaeogene, lithostratigraphy, biostratigraphy, Greater Indus Basin, Pakistan*

INTRODUCTION

The stratigraphy of the fossiliferous lower Cenozoic sediments of the Greater Indus Basin as it is represented in Pakistan has been a subject of research since the late nineteenth century. The early studies, summarized in Table 1, led to a detailed record of the lithology, biostratigraphy and palaeoenvironments, which was compiled and published by the Geological Survey of Pakistan (GSP) (Shah, 1977). This publication incorporated well-illustrated reference sections from parts of the Greater Indus Basin in Pakistan. Recent discoveries of new stratigraphical sections, combined with new published data and information from extensive petroleum exploration in the region, have provided new insights into the lithostratigraphical and biostratigraphical framework. This wealth of data has, however, led to highly variable application of stratigraphical names and a variety of conflicting stratigraphical interpretations.

The aims of this paper are to: (a) review published and unpublished lithostratigraphical and biostratigraphical information throughout the Greater Indus Basin in Pakistan; (b) provide a modern stratigraphical nomenclature for the rock units published by the Geological Survey of Pakistan (Shah, 1977) in the light of newly available evidence; and (c) discuss the palaeogeography and depositional systems of these stratigraphical units in the light of this refined stratigraphical nomenclature.

GEOLOGICAL SETTING

The lower Cenozoic succession of the Greater Indus Basin represents the northwestern continental shelf margin setting of the Indian Plate (Figs 1, 2). The basin extends over most of eastern Pakistan and the westernmost parts of India, covering an area of about 873 000 km^2 (Wandrey *et al.*, 2004) and comprises several sub-basins, plateaux and ranges (e.g. Shah, 1977). The sedimentary rock succession was deposited in the eastern part of the Tethyan Ocean. In this paper, we deal with the stratigraphy of the basin as it is represented in Pakistan. The Greater Indus Basin in Pakistan is traditionally divided into two sub-basins referred to as the Upper Indus Basin and the Lower Indus Basin (Figs 1, 2). The Upper Indus Basin, also known as the Kohat–Potwar Range, forms the northernmost element of the Greater Indus Basin in Pakistan and is bounded to the north by the Kala Chitta Range. The Salt Range composite orocline forms the southern limit (Figs 1, 2A), while the Kurram thrust fault marks its western limit. The Pezu wrench fault separates the Upper Indus Basin from the Lower Indus Basin. Lower Cenozoic sediments of the Upper Indus Basin are exposed at surface along east–west-trending fold-and-thrust belts of the Kohat, Hazara, Banu and Waziristan areas and the Kala Chitta, Surghar and Salt ranges (Fig. 2A). The Lower Indus Basin is constrained by the Mari–Khandkot–Jaisalmer High to the east, and the Kirthar Fold Belt and Foredeep to the west (Figs 1, 2B), while the Jacobabad High is sometimes used to separate the Lower and Upper basins (e.g. Kemal *et al.*, 1992), with the Upper Basin north of the Sargodha High. The tectonic history and stratigraphical framework of the region are influenced strongly by collision of the Indo-Pakistan and Asian plates (Beck *et al.*, 1995; Butler, 1995; Hodges, 2000). Indeed, the lower Cenozoic stratigraphy of the Greater Indus Basin in Pakistan is critical in terms of assessing India–Asia collision, as estimates of the timing of the initial collision vary from 65 Ma to 45 Ma (Searle *et al.*, 1987; Dewey *et al.*, 1989; Le Pichon *et al.*, 1992; Beck *et al.*, 1995; Rowley, 1996).

The Indo-Pakistan plate in the north and northwestern part of Pakistan was subject to subduction and orogenic processes at about 55 Ma at the Paleocene–Eocene boundary (de Sigoyer *et al.*, 2000; Qayyum *et al.*, 2001; Khan & Srivastava, 2006). A combination of detailed age dating and palaeobathymetric determinations indicates significant basin uplift and erosion at end Cretaceous and end Eocene times, the latter coinciding with the closure of Neo-Tethys (Wakefield & Monteil, 2002). During the collision, the existing Late Cretaceous Tethyan sediments

Author	Research undertaken
Blanford (1879)	Geology of western Sind
Davies & Pinfold (1937)	The Eocene beds of the Salt Range
Davies (1927)	The Ranikot beds at Thal
Eames (1952)	The geology of standard sections in the western Punjab and in the Kohat District, Pakistan
Fatmi (1974)	Lithostratigraphy of the Kohat-Potwar Province, Indus Basin
Haque (1956)	Foraminifera of the Ranikot and the Laki of the Salt Range, Pakistan
Hemphill & Kidwai (1973)	Stratigraphy of the Bannu and Dera Ismail Khan areas, Pakistan
Hunting Survey Corporation (1960)	Geology of part of West Pakistan
Latif (1964)	Pelagic foraminifera of the Paleocene–Eocene of Rakhi Nala, Pakistan
Latif (1970)	Geology of Southeast Hazara, Pakistan
Latif (1976)	Micropalaeontology of the Galis group of Hazara, Pakistan
Middlemiss (1896)	Geology of the Hazara and the Black Mountain
Nagappa (1959)	Foraminiferal biostratigraphy of the Cretaceous–Eocene succession in India–Pakistan
Waagen & Wynne (1872)	Geology of the upper Punjab
Williams (1959)	Stratigraphy of the Lower Indus Basin
Wynne (1874)	Geology of Mari Hill Station, Punjab

Table 1. List of key authors who have presented stratigraphical information for the Greater Indus Basin, Pakistan

accreted onto the eastern margin of the Indo-Pakistan plate and probably spilled over and spread across most of the Indo-Pakistan plate (Khan & Srivastava, 2006). The Himalaya mountain chain is a direct result of this continental collision, during which the fold-and-thrust belts of western and north-western Pakistan were initiated (Le Fort, 1996).

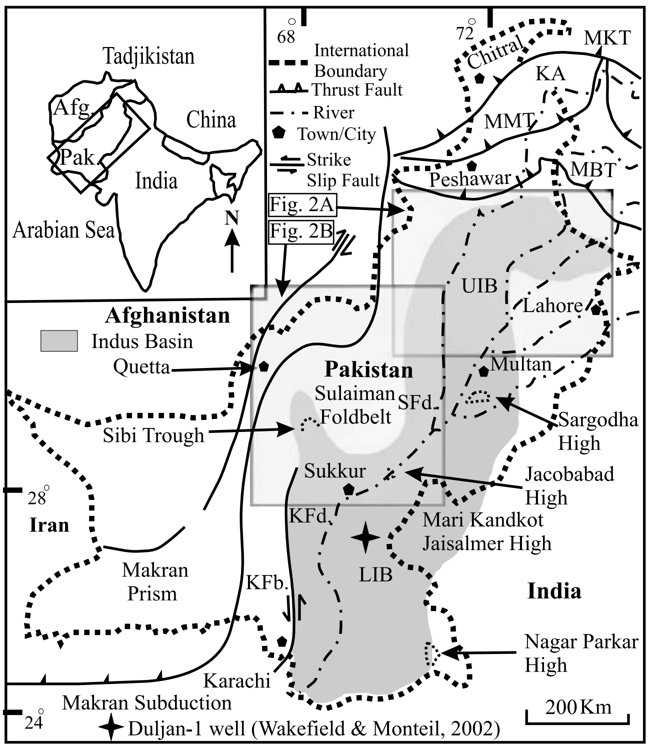


Fig. 1. Map of Pakistan, showing position of the Greater Indus Basin and major tectonic units (modified after Wakefield & Monteil, 2002). MKT, Main Kohistan Thrust; MMT, Main Mantle Thrust; MBT, Main Boundary Thrust; KFb., Kirthar Foldbelt; KFd., Kirthar Foredeep; SFd., Sulaiman Foredeep; KA, Kohistan Arc; UIB, Upper Indus Basin; LIB, Lower Indus Basin.

STRATIGRAPHY OF THE GREATER INDUS BASIN IN PAKISTAN

The rocks of lower Cenozoic age in the Greater Indus Basin in Pakistan are remarkably varied in lithology and thickness, but mainly consist of marine limestone and shale with subordinate sandstone and non-marine red beds, gypsum, anhydrite, salt and coal (Shah, 1977). Terrestrial emergence at the end of the Paleocene, followed by marine submergence in the Early Eocene (Shah, 1977), was succeeded by a short-lived regression at the close of late Early Eocene times, resulting in evaporites being deposited in the Kohat area (Nagappa, 1959). Following evaporite formation, a marine transgression at the start of the Middle Eocene affected a large area, including the western Kohat, the Lower Indus Basin, the Axial Belt and the Baluchistan Basin (Shah, 1977). During Middle and Late Eocene times different parts of Pakistan became emergent and this resulted in unconformities of varying magnitude (Shah, 1977).

A revised nomenclature for the stratigraphical units of the Greater Indus Basin in Pakistan was defined by the GSP, who compiled work from a number of authors (Shah, 1977). Subsequently published biostratigraphical work on calcareous nannofossils, dinoflagellates, planktonic and benthonic foraminifera (e.g. Köthe *et al.*, 1988; Afzal & Daniels, 1991; Butt, 1991; Weiss, 1993; Afzal, 1996; Jones, 1997; Akhtar & Butt, 1999; Warraich *et al.*, 2000; Afzal & Butt, 2000; Raza, 2001a, b; Ferrandez-Canadell, 2002; Wakefield & Monteil, 2002; Warraich & Nishi, 2003; Sameeni & Butt, 2004; Afzal *et al.*, 2005; Siddiqui, 2006) is summarized here in order to update and, where necessary, modify lithostratigraphical and biostratigraphical designations for various stratigraphical units published by the GSP (Shah, 1977): see Figures 3 to 7.

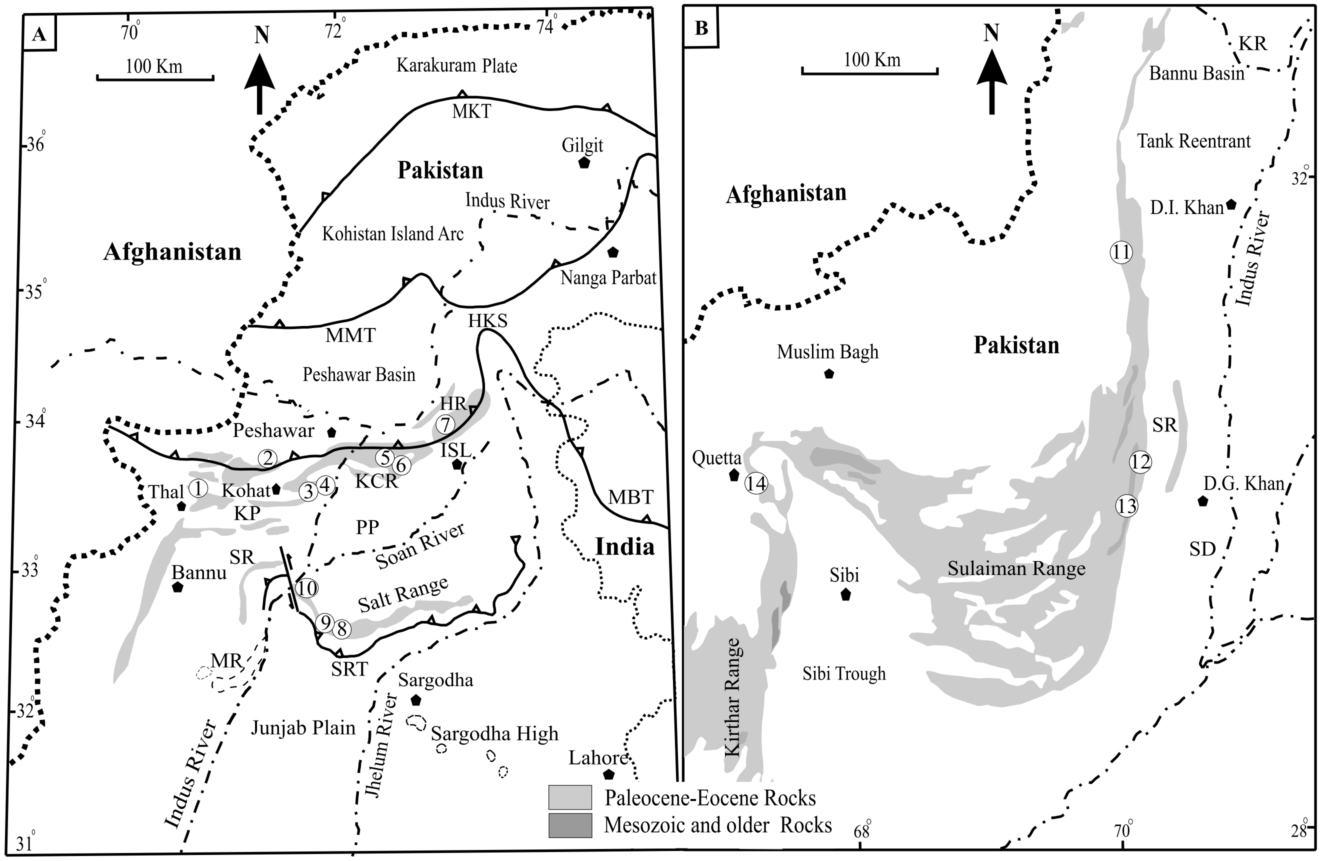


Fig. 2. (**A**) Map of the Upper Indus Basin showing distribution of Paleocene–Eocene sedimentary rocks and key stratigraphical sections (modified after Köthe *et al*., 1988). KP, Kohat Plateau; PP, Potwar Plateau; KCR, Kala Chitta Range; HR, Hazara Range; SR, Surghar Range; SRT, Salt Range Thrust; MR, Marwat Range; HKS, Hazara-Kashmir Syntaxis; ISL, Islamabad; 1, North of Hangu section; 2, Kotal Pass section; 3, Tarkhobi section; 4, Panoba section; 5, Burjianwala Laman; 6, Chak Dalla; 7, Bagnotar-Kuldana; 8, Patala Nala section; 9, Nammal Gorge section; 10, Khairabad section. (**B**) Map of part of the Lower Indus Basin showing distribution of Paleocene–Eocene sedimentary rocks and key stratigraphical sections (modified after Köthe *et al*., 1988). KR, Kurram River; SD, Sulaiman Depression; SR, Sulaiman Range; 11, Mughal Kot-Toi section; 12, Zinda Pir section; 13, Rakhi Nala section; 14, Muree Brewery section.

THE UPPER INDUS BASIN

The evolution of the lower Cenozoic stratigraphical nomenclature for the Upper Indus Basin is given in Table 2. An integrated dinoflagellate, nannofossil, shallow benthonic and planktonic foraminiferal biostratigraphy for the Upper Indus Basin, related to standard chronostratigraphy and biostratigraphy, is presented for the first time (Fig. 3). Biostratigraphical and lithostratigraphical evidence for the age of Paleocene–Eocene stratigraphical units from various parts of the Upper Indus Basin is shown in Figure 4 against global chronostratigraphy and biostratigraphy. The stratigraphical context for these units is discussed below.

Sub-basins: Kohat area, Kala Chitta Range, Hazara Range, Salt Range, Surghar Range

The Kohat area represents the northwestern part of the Upper Indus Basin and exposes a succession of Cenozoic rocks (Fig. 2A). The Kala Chitta Range marks the northern edge of the Potwar Plateau and merges northeasterly into the Hazara Range, representing the northeastern portion of the Upper Indus Basin (Fig. 2A). The Salt and Surghar ranges form the southern portion of the Upper Indus Basin. The Salt Range is an east–west-trending narrow mountain belt bounded by the Jhelum River to the east and the Indus River to the west (Fig. 2A). The Surghar Range is a north–south-trending mountain range separated from the Salt Range to the west by the Indus River and the strike-slip Kala Bagh Fault (Fig. 2A). Mesozoic and Cenozoic marine sediments of the Salt Range extend into the Surghar Range (Fig. 2A).

The Hangu Formation of Shah (1977) is the basal Cenozoic sedimentary unit in this region (Fig. 4). It comprises sandstone, siltstone and clays in the Kohat area, Kala Chitta and Hazara ranges (Shah, 1977), with argillaceous limestone beds in the Salt Range and also a coal-bearing horizon in the Surghar Range (Shah, 1977; Warwick *et al*., 1993). The formation unconformably overlies the Late Cretaceous Kawagarh Formation in most of the basin (Latif, 1976; Shah, 1977), but occasionally overlies Palaeozoic units in the Salt Range and Surghar Range (Shah, 1977). The Hangu Formation is unfossiliferous in the Kohat area, Kala Chitta and Hazara ranges (Latif, 1976; Shah, 1977; Weiss, 1993) and its chronostratigraphical position is based on regional geological context (Fig. 4). In the Salt Range, upper parts of the formation yield age-diagnostic foraminifera (Davies & Pinfold, 1937; Haque, 1956; Weiss, 1993; Ferrandez-Canadell,

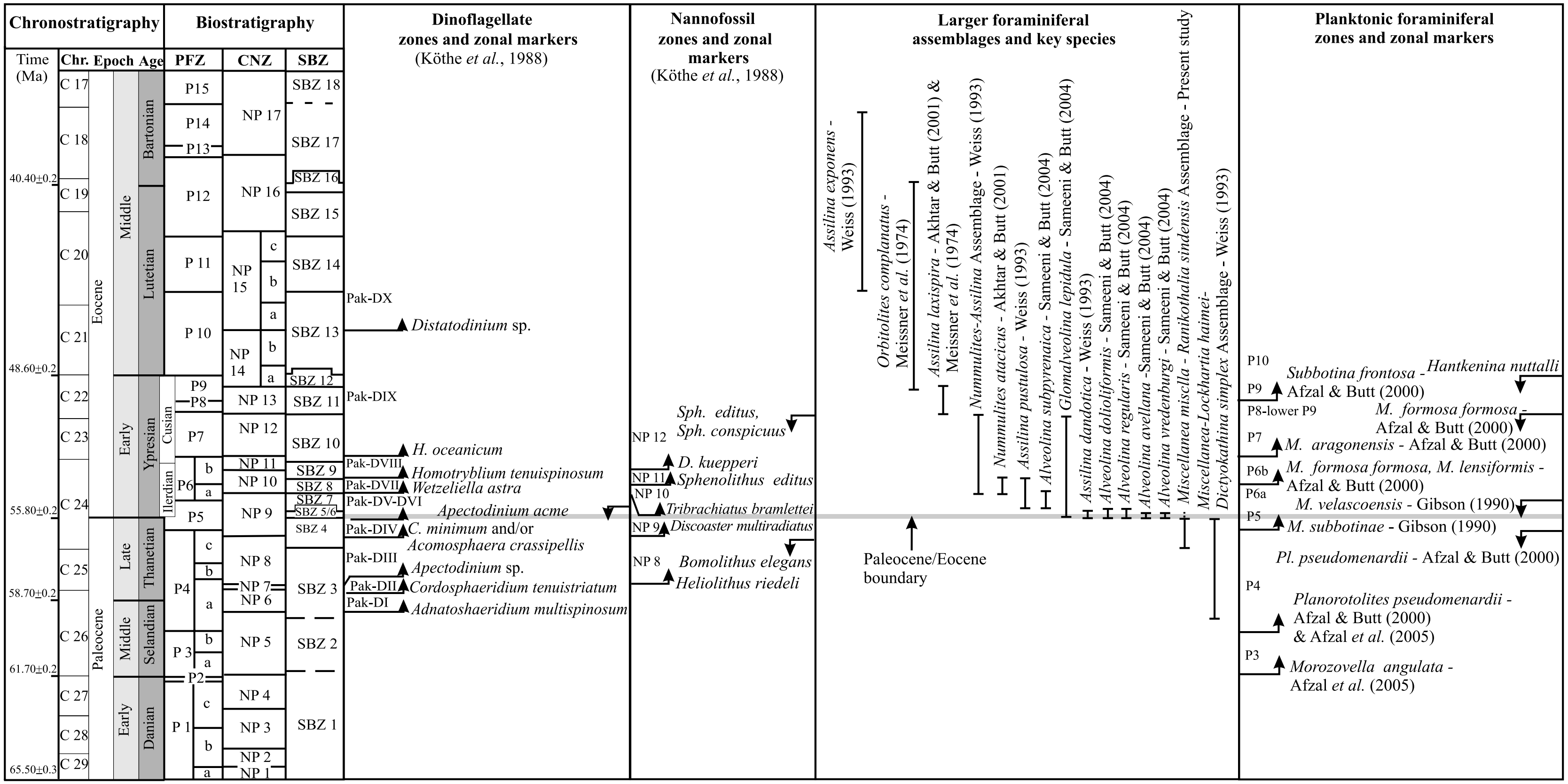


Fig. 3. Dinoflagellate, nannofossil, shallow benthonic foraminiferal and planktonic foraminiferal zones for the Paleocene–Eocene of the Upper Indus Basin. Biostratigraphical data are compiled from various sections of the Kohat Basin (Shah, 1977; Köthe *et al*., 1988; Weiss, 1993; Afzal *et al*., 2005; present study), the Salt Range (Shah, 1977; Köthe *et al*., 1988; Gibson, 1990; Weiss 1993; Afzal & Butt, 2000; Sameeni & Butt, 2004) and the Kala Chitta Range (Akhtar & Butt, 1999, 2001). The Upper Indus Basin biostratigraphy corresponds to the shallow benthonic Zones (SBZ) of Serra-Kiel *et al*. (1998) and Scheibner *et al*. (2005), calcareous nannofossil Zones (CNZ) of Martini (1971), planktonic foraminiferal Zones (PFZ) of Berggren *et al*. (1995) and chronostratigraphy of Luterbacher *et al*. (2004). The Danian/Selandian boundary is after Arenillas *et al*. (2008). The dinoflagellate Zones and datum markers, which could not be correlated with the European zonal schemes, are those established for the Greater Indus Basin in Pakistan and correlated with the nannofossil Zones of Martini (1971) by Köthe *et al*. (1988). There are additional datum markers for nannofossil Zones by Köthe *et al*. (1988).

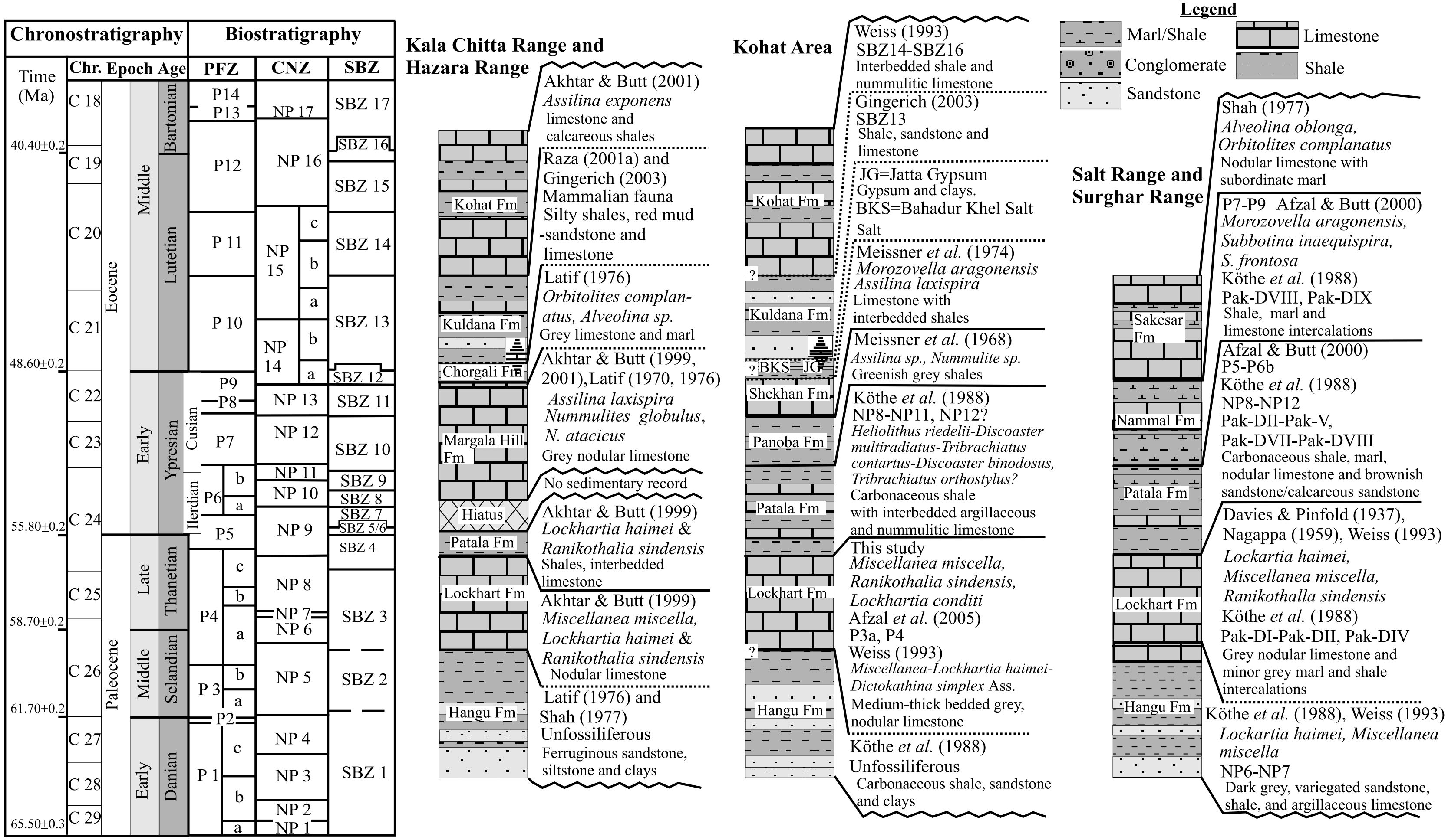


Fig. 4. Summary of biostratigraphical and lithostratigraphical evidence for Paleocene–Eocene stratigraphical units from various parts of the Upper Indus Basin. Data for the Kohat area are from various sections, including Panoba (e.g. Meissner *et al.*, 1968, 1974; Shah, 1977; Köthe *et al.*, 1988; Weiss, 1993; Gingerich, 2003), Tarkhobi (Shah, 1977; Köthe *et al.*, 1988), Kotal Pass (Afzal *et al.*, 2005; present study) and North of Hangu (Weiss, 1993). Sources for the Kala Chitta Range–Hazara Range are Latif (1970, 1976), Shah (1977), and Akhtar & Butt (1999, 2001). Sources for the Salt Range–Surghar Range and adjoining areas are Davies & Pinfold (1937), Haque (1956), Shah (1977), Köthe *et al*. (1988), Gibson (1990), Weiss (1993), Afzal & Daniels (1991), Afzal & Butt (2000), Ferrandez-Canadell (2002) and Sameeni & Butt (2004).

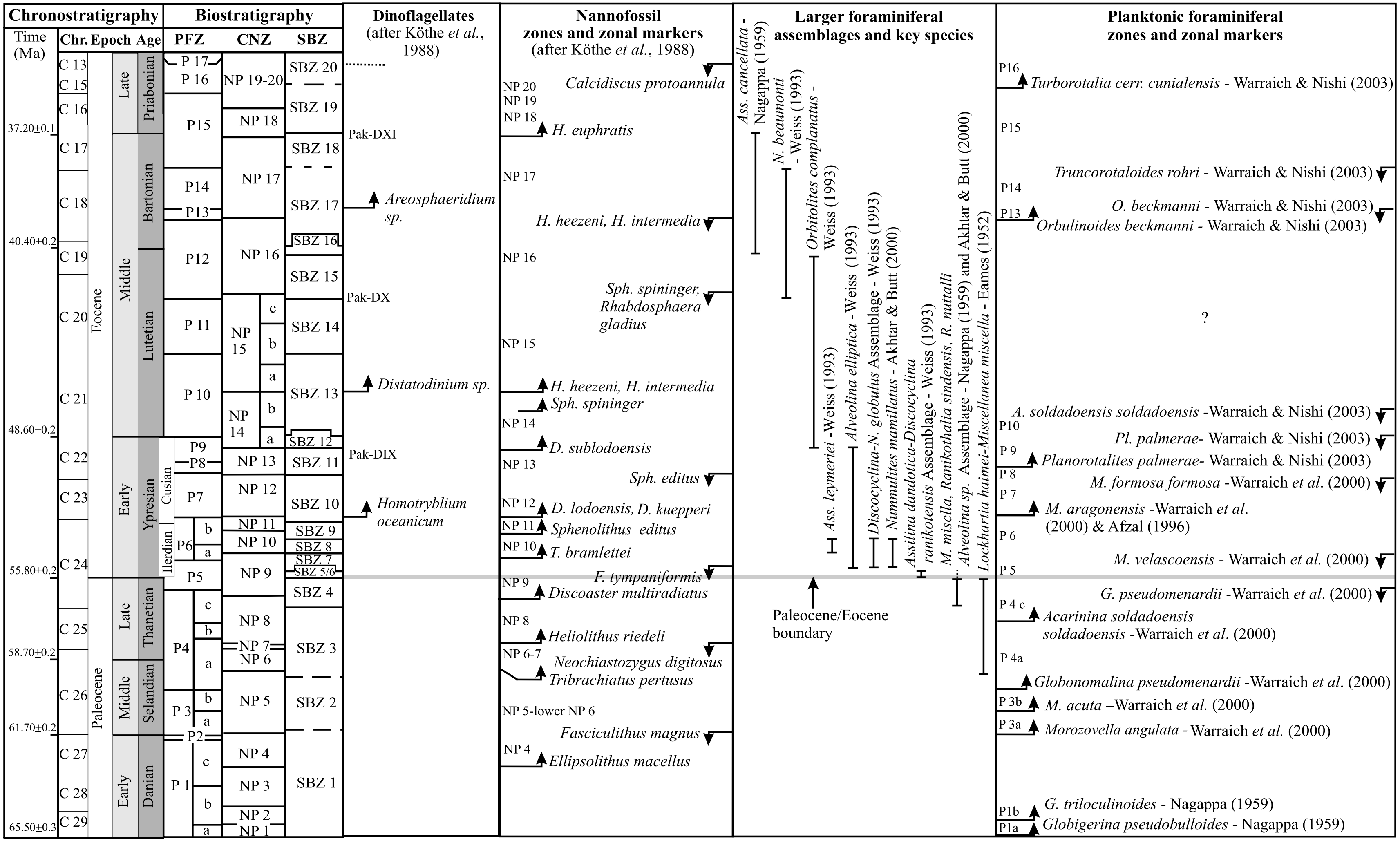


Fig. 5. Dinoflagellate, nannofossil, shallow benthonic foraminiferal and planktonic foraminiferal zones for Paleocene–Eocene stratigraphical units of the Lower Indus Basin. Biostratigraphical data are compiled from various sections of the Sulaiman and Kirthar ranges (Eames, 1952; Nagappa, 1959; Shah, 1977; Köthe *et al.*, 1988; Weiss, 1993; Afzal, 1996; Akhtar & Butt, 2000; Warraich *et al.*, 2000; Wakefield & Monteil, 2002; Warraich & Nishi, 2003). The Lower Indus Basin biostratigraphy corresponds to the standard shallow benthonic Zones (SBZ) of Serra-Kiel *et al.* (1998) and Scheibner *et al.* (2005), calcareous nannofossil Zones (CNZ) of Martini (1971), planktonic foraminiferal Zones (PFZ) of Berggren *et al.* (1995) and chronostratigraphy of Luterbacher *et al.* (2004). The dinoflagellate Zones and datum markers are established for the Greater Indus Basin in Pakistan and correlated with the nannofossil Zones of Martini (1971) by Köthe *et al.* (1988). There are additional datum markers recognized for nannofossil Zones by Köthe *et al.* (1988). Planktonic foraminiferal zones P11 and P12 cannot be recognized, hence our use of a "?" in the right-hand column for this interval.

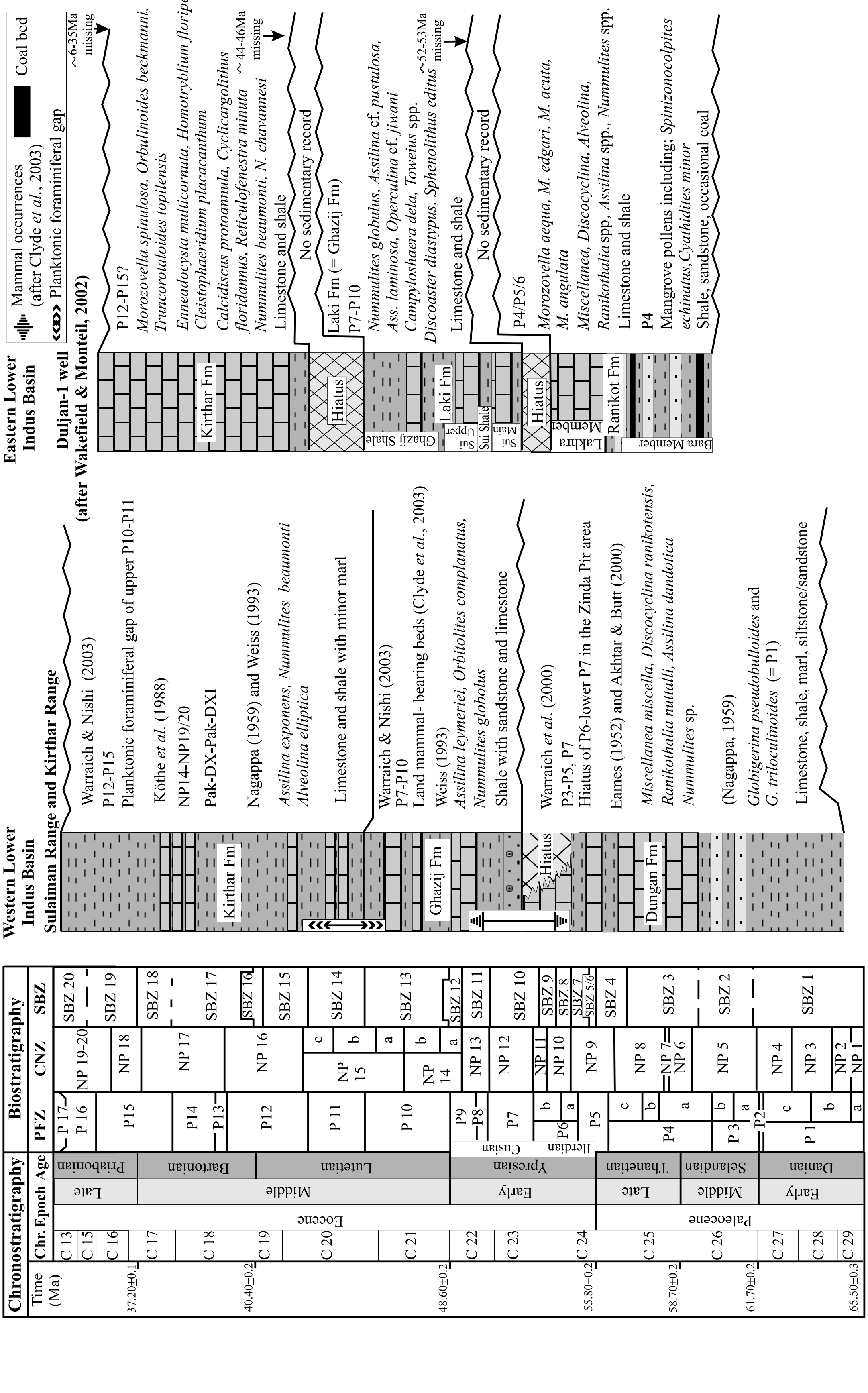


Fig. 6. Summary of biostratigraphic and lithostratigraphical evidence for Paleocene–Eocene stratigraphical units from various parts of the western Lower Indus Basin and Duljan-1 well of the eastern Lower Indus Basin (after Wakefield & Monteil, 2002). Legend as for Figure 4.

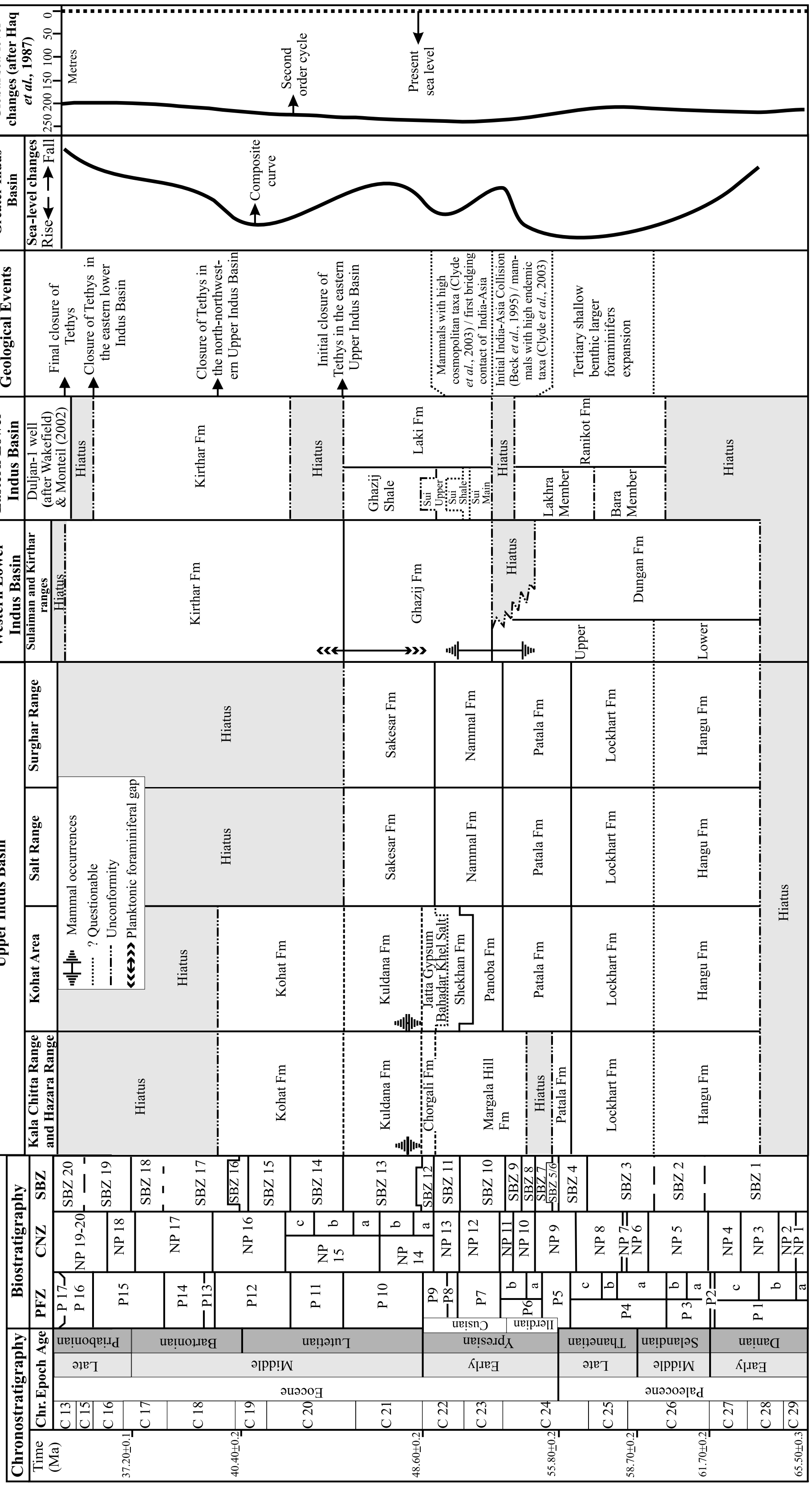


Fig. 7. Regional stratigraphical correlation of the lower Cenozoic successions of the Greater Indus Basin, Pakistan, showing significant geological events and their correlation with basin stratigraphy and global sea-level changes (second-order cycle) of Haq *et al.* (1987).

Lithostratigraphical unit	Primary reference	GSP (Shah, 1977)	Geographical distribution
Sakesar Limestone	Fermor (1935)	Sakesar Formation	Salt Range and Surghar Range
Nammal Limestone and Shale	Fermor (1935)	Nammal Formation	
Nammal Marl	Danilchik & Shah (1987)		
Habib Rahi Member	Shah (1977)	Kohat Formation	Kohat area, northern Salt Range and Kala Chitta Range
Sadkal Member			
Kaladhand Member			
Kohat Formation	Meissner *et al.* (1968)		
Kohat Shales	Eames (1952)		
Sirki Shale			
Upper Chharat			
Nummulitic Shales			
Kohat Limestone	Davies (1927)		
Kohat Shales			
Nummulitic Shales	Pinfold (1918)		
Alveolina Beds	Wynne (1874)		
Kuldana Formation	Latif (1970)	Kuldana Formation	Southern Hazara Range, Kala Chitta Range, northern Salt Range and Kohat area
Mami Khel Clay	Meissner *et al.* (1968)		
Lower Chharat Series	Eames (1952)		
Variegated Shales	Pinfold (1918)		
Kuldana Series	Middlemiss (1896)		
Kuldana Beds	Wynne (1874)		
Lora Formation	Latif (1970)	Chorgali Formation	Eastern Salt Range, Kala Chitta Range and Hazara Range
Badhrar Beds	Davies & Pinfold (1937)		
Chorgali Beds	Pascoe (1920)		
Passage Beds	Pinfold (1918)		
Jatta Gypsum	Meissner *et al.* (1968)	Jatta Gypsum	Kohat area
Kohat Series	Gee (1945)		
Margala Hill Limestone	Latif (1970)	Margala Hill Formation	Kala Chitta Range, northern Salt Range, Hazara Range and eastern Kohat area
Nummulitic Series	Middlemiss (1896)		
Hill Limestone	Wynne (1873)		
Nummulitic Formation	Waagen & Wynne (1872)		
Bahadur Salt	Meissner *et al.* (1968)	Bahadur Salt	Kohat area
Kohat Saline Series	Gee (1945)		
Gypsiferous beds	Eames (1952)	Shekhan Formation	
Upper Shekhan Limestone			
Middle Shekhan Limestone			
Lower Shekhan Limestone			
Shekhan Limestone	Davies (1927)		
Panoba Shale	Eames (1952)	Panoba Formation	
Green Clay and Sandstone	Gee (1934)		
Part of Group z (e2 b)	Pascoe (1920)		
Part of Group (3) ezc			
Green Clay	Wynne (1874)		
Kuzagali Shale	Latif (1970)	Patala Formation	Salt Range, Surghar Range, Kohat area, Kala Chitta Range and Hazara Range
Tarkhobi Shales	Eames (1952)		
Patala Shale	Davies & Pinfold (1937)		
Nummulitic Series	Middlemiss (1896)		
Hill Limestone	Wynne (1873)		
Nummulitic Formation	Waagen & Wynne (1872)		
Mari Limestone	Latif (1970)	Lockhart Formation	
Tarkhobi Limestone	Eames (1952)		
Khairabad Limestone	Gee (1934)		
Hill Limestone	Cotter (1933)		
Lockhart Limestone	Davies (1930)		
Nummulitic Series	Middlemiss (1896)		
Hill Limestone	Wynne (1873)		
Nummulitic Formation	Waagen and Wynne (1872)		
Mari Limestone	Latif (1970)	Hangu Formation	
Dhak Pass Formation	Danilchik & Shah (1987)		
Langrial Iron Ore Horizon	Khan & Ahmad (1966)		
Dhak Pass Beds	Davies & Pinfold (1937)		
Hangu Sandstone	Davies (1930)		
Hangu Shale			
Nummulitic Series	Middlemiss (1896)		
Nummulitic Formation	Waagen & Wynnee (1872)		

Table 2. Lithostratigraphical nomenclature for the Upper Indus Basin, Pakistan.

2002), nannofossils (Köthe *et al*., 1988; Warwick *et al*., 1993) and dinoflagellates (Köthe *et al*., 1988), which are identical to biota reported from the overlying basal Lockhart Formation elsewhere in the basin (Fig. 4).

The Lockhart Formation consists of nodular limestone in the Kohat area, Kala Chitta and Hazara ranges (Latif, 1970, 1976; Fatmi, 1974; Shah, 1977; Akhtar & Butt, 1999) and limestone and marl in the Salt and Surghar ranges (Shah, 1977). The Lockhart Formation yields abundant age-diagnostic larger benthonic foraminifera in the Kohat area (Weiss, 1993; present study), the Kala Chitta and Hazara ranges (Latif, 1970, 1976; Akhtar & Butt, 1999) and the Salt Range (Davies & Pinfold, 1937; Haque, 1956; Weiss, 1993). These occurrences and newly reported *Miscellanea miscella*, *Ranikothalia sindensis*, *Lockhartia conditi*, *Lockhartia haimei* and *Operculina jiwani* from the Kotal Pass, Kohat area, support maximum stratigraphical ranges through foraminiferal shallow benthonic Zones SBZ3–SBZ4 (Serra-Kiel *et al*., 1998) (Pl. 1, figs 1–12). Planktonic foraminifera from the Kohat area (Afzal *et al*., 2005), dinoflagellates (= nannofossil Zones NP6–NP8 of Martini, 1971) from the Salt Range (Köthe *et al*., 1988) and nannofossils from the Surghar Range (Warwick *et al*., 1993) also support this biostratigraphical range (Figs 3, 4).

The Lockhart Formation is succeeded by shale, sandstone and marly limestone of the Patala Formation (Shah, 1977; Akhtar & Butt, 1999). The occurrence of sandstone within the formation is restricted to the Salt and Surghar ranges (Shah, 1977; Gibson, 1990; Warwick *et al*., 1993) (Fig. 4). The Patala Formation in the Kala Chitta and Hazara ranges (Latif, 1970, 1976; Akhtar & Butt, 1999) and the Salt Range (Haque, 1956; Weiss, 1993; Sameeni & Butt, 2004) contains late Thanetian to early Ilerdian larger benthonic foraminiferal species, suggesting Zones SBZ4 to SBZ6 (Fig. 4). Age-diagnostic planktonic foraminiferal species from the Hazara Range, e.g. *Globorotalia elongata* [= *Morozovella elongata*] and *Globigerina soldadoensis* [= *Muricoglobigerina soldadoensis*] (Latif, 1976), and from the Salt Range (Weiss, 1993), indicate the *Morozovella velascoensis*–*Acarinina soldadoensis* Zone (= P4c–P5 Zones of Berggren *et al*., 1995). Planktonic foraminiferal Zones P5–P6b from the Salt Range (Afzal & Butt, 2000) and Kohat area (Weiss, 1993) provide a stratigraphical range that extends across the Paleocene–Eocene boundary (Fig. 4). Identification of dinoflagellate Zones equivalent to NP8–NP11 from the Salt Range and nannofossil Zones NP8–NP12 from the Kohat area and the Salt Range (Köthe *et al*., 1988) support a late Thanetian–early Ypresian biostratigraphical age (Figs 3, 4). There have been inconsistencies in the logging and mapping of the Patala Formation and its boundaries have been placed differently by various workers (Gibson, 1990), which has led to varying stratigraphical interpretations. However, the regional stratigraphical framework suggests a maximum age of late Thanetian–early Ypresian (Figs 4, 7).

The Patala Formation is separated by an unconformity (upper P5–P6a) from the overlying nodular limestone and marl/shale of the Margala Hill Formation in the Kala Chitta and Hazara ranges (Latif, 1970, 1976; Shah, 1977; Akhtar & Butt, 1999, 2001) (Fig. 4). In most of the Kohat area the Patala Formation is conformably overlain by greenish shales of the Panoba Formation, but in the Salt and Surghar ranges it is followed conformably by the marl/shale and limestone of the Nammal Formation (Shah, 1977) (Fig. 4).

The larger benthonic foraminifera from the Panoba Formation (Meissner *et al*., 1968, in Shah, 1977) indicate an age of SBZ10 (Fig. 4). The Margala Hill Formation yields larger benthonic foraminifera (Latif, 1970, 1976; Akhtar & Butt, 1999, 2001), which support a biostratigraphical age through Zones SBZ8–SBZ11 (Fig. 4). The larger benthonic foraminifera and zonally important planktonic foraminiferal species from the Nammal Formation (Weiss, 1993; Afzal & Butt, 2000; Sameeni & Butt, 2004) suggest a P7–P9 age (Figs 3, 4). Köthe *et al*. (1988) also recorded the same biostratigraphical age based on the recognition of nannofossil Zones NP11–NP12 and of dinoflagellates equivalent to NP11–NP14.

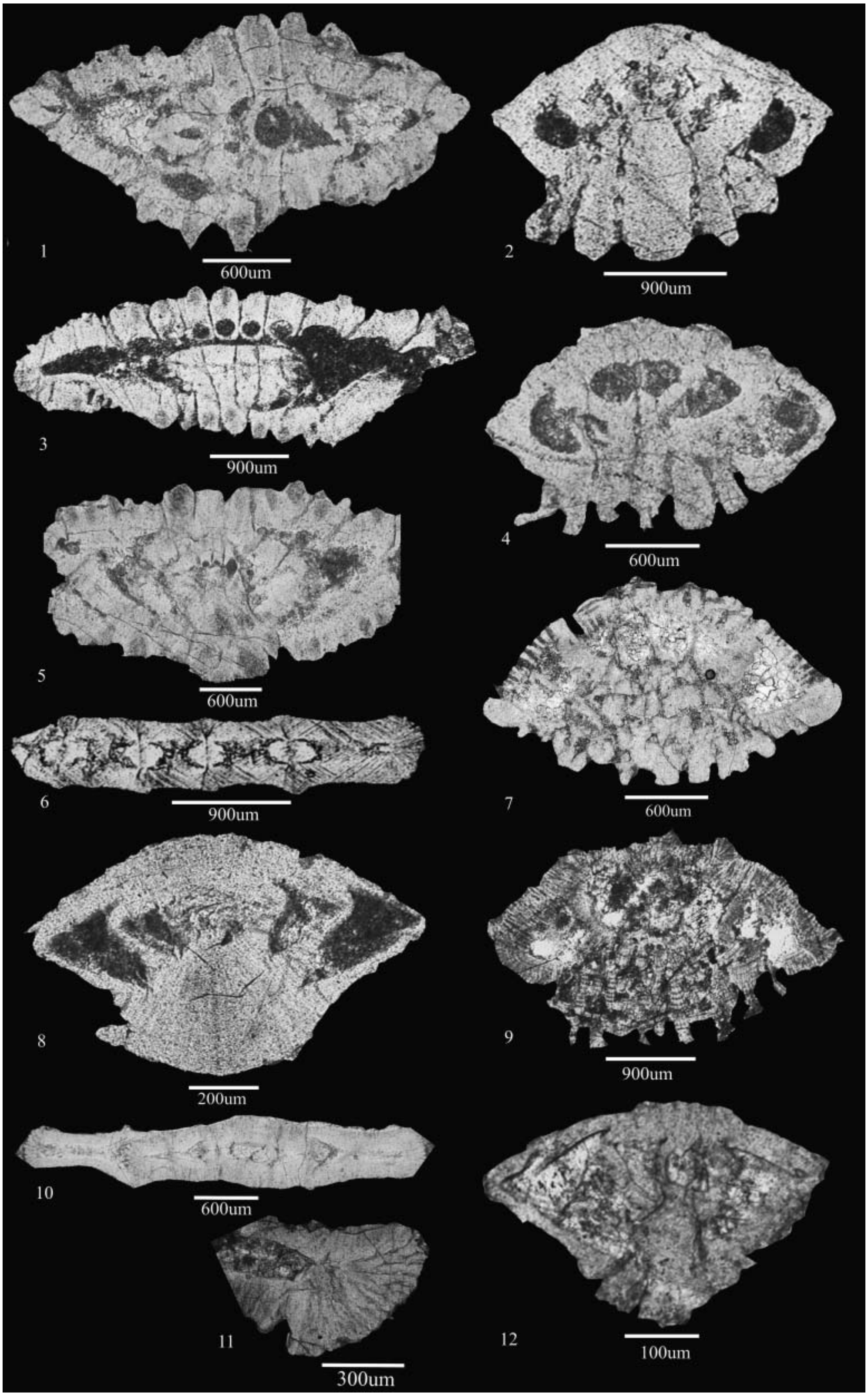
The Panoba Formation is overlain by limestone and shale of the Shekhan Formation in the northern Kohat area, and by the Jatta Gypsum or Bahadur Khel Salt in the southwest Kohat area (Shah, 1977) (Fig. 4). Limestone and marl of the Chorgali Formation overlie the Margala Hill Formation in the Kala Chitta and Hazara ranges and Sakesar Formation in the eastern Salt Range (Shah, 1977). In the Surghar Range, limestone and marl of the Sakesar Formation conformably overlie the Nammal Formation and mark the end of marine deposition in this part of the basin, being overlain unconformably by non-marine molasse sediments of Miocene age (Shah, 1977).

The Shekhan Formation is barren of nannofossils and dinoflagellates (Köthe *et al*., 1988). The larger benthonic foraminifera indicate a late Ypresian age (= SBZ11) (Nagappa, 1959; Pascoe, 1963; Shah, 1977; Weiss, 1993). The occurrence of *Assilina laxispira* and the planktonic foraminifera *Morozovella aragonensis* and others is indicative of Zones P8–P9 (Meissner *et al*., 1974) (Figs 3, 4). The Shekhan Formation is overlain by unfossiliferous evaporitic deposits of the Bahadur Khel Salt and Jatta Gypsum (Meissner *et al*., 1974; Shah, 1977) (Fig. 4).

The Chorgali Formation in the Kala Chitta, Hazara and eastern Salt ranges yields age-diagnostic larger benthonic foraminifera from Zones SBZ11–SBZ12 (Latif, 1970, 1976; Shah, 1977; Sameeni & Butt, 2004) (Fig. 4).

The shale and marl succession of the Kuldana Formation, which yields fossil mammals (Raza, 2001a), succeeds the Chorgali Formation in the Kala Chitta and Hazara ranges and the Bahadur Khel Salt and Jatta Gypsum in the Kohat area (Shah, 1977). On the basis of larger benthonic foraminifera from the Kala Chitta and Hazara ranges (Latif, 1970, 1976) and mammal faunas from different parts of the Kohat area and Kala Chitta Range (Raza, 2001a; Gingerich, 2003), the Kuldana Formation is assigned to Zone SBZ13 or older (Fig. 4). The shale and nummulitic limestone succession of the Kohat Formation overlies the Kuldana Formation in most of the Kohat area, Kala Chitta and Hazara ranges (Shah, 1977; Akhtar & Butt, 1999, 2001).

The Kohat Formation marks the last episode of marine sedimentation in the Kohat area, Kala Chitta and Hazara ranges and is overlain by non-marine molasse sediments of the Miocene Murree Formation. The late Ypresian–Lutetian age assignment for the Kohat Formation given by Shah (1977) is based on molluscs (Eames, 1952) and larger benthonic foraminifera (see Meissner *et al*., 1968). The same biostratigraphical ages can be extracted from the foraminifera record of



Explanation of Plate 1.

Biostratigraphically significant Thanetian shallow benthonic foraminifera of the Lockhart Formation from the Kotal Pass section of the Kohat area (Upper Indus Basin). **figs 1, 3, 5.** *Miscellanea miscella* D'Archiac & Haime, 1853: **1, 5,** megalospheric form, axial section; **3,** microspheric form, off-centre axial section. **figs 2, 4.** *Lockhartia conditi* Nuttall, 1926, axial section. **fig. 6.** *Operculina jiwani* Davies & Pinfold, 1937, off-centre axial section. **figs 7, 9.** *Lockhartia haimei* Davies, 1927, axial section. **fig. 8.** *Kathina selveri* Smout, 1954, axial section. **figs 10, 11.** *Ranikothalia sindensis* Davies, 1927: **10,** microspheric form, axial section; **11,** marginal cord, axial section. **fig. 12.** *Rotalia trochidiformis* Lamarck, 1804, axial section.

Meissner *et al*. (1974). Weiss (1993) reported larger benthonic foraminifera from the Kohat area of intermediate biostratigraphical age between Zones SBZ10 and SBZ17. Similarly, *Assilina exponens*, reported by Akhtar & Butt (2001), also ranges in age from Zones SBZ13 to SBZ17. These foraminiferal occurrences and the regional stratigraphical position imply a biostratigraphical range of SBZ14 to SBZ16 for the Kohat Formation (Fig. 4).

THE LOWER INDUS BASIN

The early Palaeogene sediments of the Lower Indus Basin were deposited on a broad shelf area of the passive continental margin of the Indo-Pakistan Plate (Bannert, 1992). The history of stratigraphical nomenclature for the Lower Indus Basin is given in Table 3 and the biostratigraphical framework in Figures 5 and 6. A regional stratigraphical correlation with the Upper Indus Basin is given in Figure 7. Early Palaeogene marine sediments are well exposed across the basin (Fig. 2B). The context for the different stratigraphical units from key sections is discussed below.

The Sulaiman Range and Kirthar Range

The Sulaiman Range forms a lobate structure in the northern part of the Lower Indus Basin, while the Kirthar Range forms a north–south linear feature in the southern region (Figs 1, 2B). The succession in the Sulaiman and Kirthar ranges has been studied since the nineteenth century.

The Dungan Formation of Kazmi (1995) marks the basal lithological unit of the lower Tertiary and unconformably overlies Late Cretaceous units in most of the Lower Indus Basin. It equates to the Khadro, Bara, Lakhra and Dungan formations of Shah (1977). The lowermost sandstone, siltstone and shale portion (Khadro Formation of Shah, 1977) of the formation is widely developed in the Kirthar Range, but rare or absent in the Sulaiman Range (e.g. Rakhi Nala). It has yielded planktonic foraminifera of Zone P1 (Nagappa, 1959) (Figs 5, 6). The overlying sandstone/siltstone unit (Bara Formation of Shah, 1977) of the lower Dungan Formation is widely distributed in the Kirthar Range, but rare in the Sulaiman Range. It lacks age-diagnostic fossils (Shah, 1977; Afzal, 1996; Wakefield & Monteil, 2002). The upper Dungan Formation (the Lakhra and Dungan formations of Shah (1977) and Bara and Lakhra members of Wakefield & Monteil (2002)) is dominantly limestone and shale, and is well developed in the Sulaiman and Kirthar ranges. Many biostratigraphically important larger benthonic foraminifera from the formation include *Miscellanea miscella*, *Discocyclina ranikotensis*, *D. dispansa*, *Lockhartia haimei*, *Alveolina* sp., *Ranikothalia nuttalli* and *Assilina dandotica* (in Shah, 1977; Weiss, 1993; Akhtar & Butt, 2000; Wakefield & Monteil, 2002), which suggest an age of late Thanetian to early Ilerdian. The nannofossil Zones NP4, NP7 and NP9 (Köthe *et al*., 1988) and planktonic foraminiferal Zones P7 (Afzal, 1996) and P3–P7 (Jones, 1997; Warraich *et al*., 2000) further support a Middle Paleocene–Early Eocene age. The upper contact of the formation with the overlying Ghazij Formation has been interpreted as conformable in most of the basin (Shah, 1977, 1990; Kazmi, 1995); however, Warraich *et al*. (2000) reported Zone P6–lower P7? to be missing, with a conglomeratic bed between these formations in the northwestern Sulaiman Range (Rakhi Nala and Zinda Pir areas), suggesting this relationship to be unconformable (Figs 6, 7).

The Ghazij Formation, as recognized here, corresponds to the Ghazij and Laki formations of Shah (1977), the Laki Formation of Wakefield & Monteil (2002) and the Ghazij Group of Shah (1990) and Kazmi (1995). It is dominantly shale with subordinate claystone, sandstone, limestone, coal and conglomerate. The formation is well developed in the Sulaiman Range and parts of the Kirthar Range (Shah, 1977). Early biostratigraphical ages determined from rich occurrences of larger benthonic foraminifera, e.g. *Assilina leymeriei*, *A. pustulosa*, *Orbitolites complanatus*, *Nummulites globulus*, etc. (equivalent to Zones SBZ8–SBZ13) (Eames, 1952; Nagappa, 1959) were later confirmed by Weiss (1993) and Wakefield & Monteil (2002). Planktonic foraminiferal biostratigraphical ages were first investigated by Latif (1964) and Samantha (1973) and later by Afzal (1996), who supported an age range of Zones P7–P9. This assignment has recently been confirmed by the detailed work of Wakefield & Monteil (2002) and Warraich & Nishi (2003), who reported a continuous record of planktonic Zones P7 to P10? (Figs 5, 6). Planktonic foraminiferal studies also show a gap spanning upper P10? to P11 in the upper part of the Ghazij Formation to the lower part of the Kirthar Formation in the western Sulaiman Range (Warraich & Nishi, 2003) (Figs 5, 6). However, Köthe *et al*. (1988) reported dinoflagellate Zone Pak-DIX (equivalent to nannofossil Zones NP12–lower NP14) from the upper part of the formation and Pak-DX to Pak-DXI (equivalent to upper NP14–NP19/20) from the overlying Kirthar Formation of Shah (1977) (Figs 5, 6). These results suggest a conformable relationship between the Ghazij and Kirthar formations in the western Lower Indus Basin; however, this relationship is unconformable in the eastern Lower Indus Basin with a *c*. 2 million-year hiatus, with Zone P11 absent (Wakefield & Monteil, 2002) (Figs 6, 7).

The Kirthar Formation consists of limestone and shale with minor marl (Shah, 1977). The formation is widely distributed in the Sulaiman–Kirthar ranges and is richly fossiliferous with many age-diagnostic fossils (Shah, 1977). Based on the foraminiferal records of the Hunting Survey Corporation (1960), Shah (1977) assigned a broad stratigraphical range of Ypresian–Priabonian. However, other foraminiferal studies have given an age of late Lutetian–early Priabonian based on occurrences of planktonic foraminiferal species indicative of Zone P14 (Latif, 1964) and of Zones P12–P13 and P15–P17 (Samantha, 1973). Warraich & Nishi (2003) and Wakefield & Monteil (2002) recently established the presence of a continuous record of Zones P12 to P15? (Figs 6, 7). The lower part of the Kirthar Formation is rich in larger benthonic foraminifera, including *Assilina spinosa*, *A. exponens*, *A. cancellata*, *Nummulites beaumonti* and *Discocyclina sowerbyi*, equivalent to Zones SBZ13–SBZ18 (Eames, 1952; Nagappa, 1959; Weiss, 1993), suggesting a shallow-marine environment, which may account for the gap in the planktonic foraminiferal records. The Kirthar Formation is mostly overlain by Miocene–Pliocene age molasse sediments of the Siwalik Group (Shah, 1977).

Lithostratigraphical unit	Primary reference	GSP (Shah, 1977)	Present terminology		Geographical distribution
Drazinda Member	Shah (1977)	Kirthar Formation	Kirthar Formation		Kirthar Range, Sulaiman Range and parts of Kohat area
Pir Koh Limestone and Marl Member					
Sirki member					
Habib Rahi Limestone Member					
Drazinda Shale	Hemphill & Kidwai (1973)				
Upper Gorag Member	Hunting Survey Corporation (1960)				
Lower Kirthar Member					
Spintangi Limestone					
Brahui Limestone					
Pellatispira Beds	Eames (1952)				
Upper Chocolate Clays					
Lower Chocolate Clays					
White Marl Band					
Sirki Shale					
Spintangi Limestone	Oldham (1890)				
Sohnari Member	Shah (1977)	Laki Formation	Ghazij Formation		Southern Kirthar Range and Sulaiman Range
Meting Shales and Limestone Member					
Laki Group	Hunting Survey Corporation (1961)				
Sohnari Member					
Tiyon Formation					
Basal Laki Laterite	Nuttall (1925)				
Meting Shales and Limestone	Vredenburg (1906)				
Shaheed Garh Formation	Kazmi (1995)	Ghazij Formation			Sulaiman Range and Kirthar Range
Ghazij Formation	Cheema *et al.* (1977)				
Marap Conglomerate Member	Shah (1977)				
Baska Shale and Alabaster Member					
Baska Shales	Hemphill & Kidwai (1973)				
Upper part of Gidar Dhor Group	Hunting Survey Corporation (1960)				
Tiyon Formation					
Ghazij Shales					
Marap Conglomerate					
Chat beds	Nagappa (1959)				
Ghazij Formation	Williams (1959)				
Zinda Pir Limestone (upper part)	Eames (1952)				
Upper Rakhi Gaj Shales					
Ghazij Shales					
Green and Nodular Shales					
Rubbly Limestone					
Shales with Alabaster					
Ghazij Group	Oldham (1890)				
Dungan Formation	Kazmi (1995)	Dungan Formation	Upper	Dungan Formation	Sulaiman Range and northern Kirthar Range
Karkh Group	Hunting Survey Corporation (1960)				
Dab Formation					
Dungan Group (excluding Moro Formation)					
Zinda Pir Limestone (lower part)	Eames (1952)				
Zinda Pir Shales					
Lower Rakhi Gaj Shales					
Dungan Formation	Williams (1959)				
Dungan Limestone	Oldham (1890)				
Ranikot Group	Blanford (1879)				
Dungan Formation	Kazmi (1995)	Lakhra Formation			Kirthar Range
Upper Ranikot Formation and upper parts of the Bad Kachu, Rattaro and Thar formations and lower part of the Jakker Group (Limestone)	Hunting Survey Corporation (1960)				
Upper Ranikot (Limestone)	Vredenburg (1906)				
Ranikot Group	Blanford (1879)				
Dungan Formation	Kazmi (1995)	Bara Formation	Lower		Kirthar Range and northern Sulaiman
Lower parts of the Jakker Group, Thar, Rattaro and Bad Kachu	Hunting Survey Corporation (1960)				
Ranikot Formation	Williams (1959)				
Gorge Beds	Eames (1952)				
Lower Ranikot (sandstone)	Vredenburg (1906)				
Ranikot Group	Blanford (1879)				
Dungan Formation	Kazmi (1995)	Khadro Formation			Kirthar Range and parts of the Sulaiman Range
Khadro Formation	Williams (1959)				
Thar Formation	Hunting Survey Corporation (1960)				
Bad Kachu					
The basal parts of Karkh, Gidar Dhor and Jakker groups					
Venericardita Shales	Eames (1952)				
Ranikot Group	Blanford (1879)				
Cardita Beaumonti Beds					

Table 3. Lithostratigraphical nomenclature of the Lower Indus Basin, Pakistan.

REGIONAL STRATIGRAPHICAL CONTEXT

The lower Cenozoic succession of the Greater Indus Basin in Pakistan is characterized by considerable changes in lithologies and fauna. Inter-regional stratigraphical correlations for the Greater Indus Basin in Pakistan are given in Figure 7 and are related to global sea-level variations and biochronostratigraphy.

The earliest marine Cenozoic sedimentation in the basin seems to have commenced with the Paleocene transgression (Haq *et al*., 1987). The continental near-shore facies of the Hangu Formation initially dominated in the north-northwestern parts of the basin (Hazara Range, Kala Chitta Range and Kohat area) (Latif, 1976; Köthe *et al*., 1988; Weiss, 1993; Akhtar & Butt, 1999). Southwestwards, into the Surghar and Salt ranges, it extended into shallow-marine deltaic facies, with coal and marine fossils (Shah, 1977; Warwick *et al*., 1993), and further south into the correlative planktonic and smaller benthonic foraminifera-bearing lower Dungan Formation (= Cardita Beaumonti Beds in Nagappa, 1959) (Figs 6, 7). This marine flooding was succeeded by widespread carbonate platform deposition of the Lockhart Formation in the Upper Indus Basin and upper Dungan Formation (= Bara and Lakhra members of Wakefield & Monteil, 2002) in the Lower Indus Basin. The correlative planktonic foraminifera-bearing shales of the Dungan Formation in the northwestern Sulaiman Range (e.g. Rakhi Nala and Zinda Pir areas) were deposited in an open-marine environment (Warraich *et al*., 2000). These carbonates recorded the first expansion of lower Cenozoic shallow benthonic larger foraminifera in the basin (Weiss, 1993; Akhtar & Butt, 1999; Warraich *et al*., 2000; Wakefield & Monteil, 2002; Afzal *et al*., 2005); these preferentially flourished in oligotrophic conditions (Hottinger, 1997) (Figs 4, 6). The carbonate platform was buried by deep-marine clastics of the Patala Formation (= P4c–P6) in most of the Upper Indus Basin and by the shales of the Ghazij Formation (= P7–P10) in parts of the Lower Indus Basin. The hiatus equivalent to Zones upper P5–P6a in the northern Upper Indus Basin (Kala Chitta and Hazara ranges; Akhtar & Butt, 1999, 2001) and P6–lower P7? in the western (Zinda Pir area; Warraich *et al*., 2000) and P6b–lower P7 in the eastern (Duljan-1 Well; Wakefield & Monteil, 2002) parts of the Lower Indus Basin may have been caused by compression, uplift and erosion associated with India–Asia collision (around 55 Ma; Klootwijk *et al*., 1991; Beck *et al*., 1995; Warraich & Nishi, 2003) (Fig. 7). These events were accompanied by highly significant stratigraphical changes in parts of the basin, for example, producing intermittent shallow- and deep-marine sediments (Weiss, 1993; Afzal & Butt, 1999; Warraich *et al*., 2000) and dramatic shifts from marine to continental deposits, the latter containing endemic mammal occurrences (Clyde *et al*., 2003). The Paleocene/Eocene boundary has been established in the basin through the identification of planktonic foraminiferal Zones P5/P6 (Afzal & Butt, 2000; Warraich *et al*., 2000), larger benthonic foraminiferal assemblages (Weiss, 1993; Akhtar & Butt, 1999), and nannofossil Zones NP9/NP10 (Köthe *et al*., 1988) (Figs 3–6).

The open-marine planktonic foraminifera of the lower Cenozoic successions of the Greater Indus Basin in Pakistan show abrupt changes in composition, for example there was an increase in tropical–subtropical species of the morozovellid group during P4–P5 zones followed by a decrease in morozovellids and an increase in cooler-water species of subbotinid group foraminifera during Zones P6–P7 (Afzal & Butt, 2000; Warraich *et al*., 2000; Warraich & Nishi, 2003). The shallow-marine benthonic foraminiferal communities of the Greater Indus Basin in Pakistan experienced a significant diversification of species near the Paleocene–Eocene boundary; Thanetian–earliest Ilerdian (= SBZ4–SBZ6?) small species, including *Miscellanea*, *Ranikothalia* and *Lockhartia*, were succeeded by early Ilerdian (= SBZ6–SBZ8) large species of *Nummulites*, *Discocyclina*, *Alveolina* and *Assilina* (Weiss, 1993; Akhtar & Butt, 1999, 2000; Sameeni & Butt, 2004). These marine faunal changes in the region during the late Thanetian–early Ypresian may have been associated with long-term global warming events of the lower Cenozoic (Kelly *et al*., 1996; Zachos *et al*., 2001; Scheibner *et al*., 2005).

The Ypresian–early Lutetian (P7–P10) sediments show a shallowing-upward sequence, associated with the Ypresian–Lutetian marine transgression–regression (Haq *et al*., 1987) (Figs 4, 6, 7). In the northeast (Kala Chitta, Hazara, Salt and Surghar ranges), these sediments comprise carbonate-rich units (Margala Hill Formation/Nammal Formation; Shah, 1977; Akhtar & Butt, 1999; Afzal & Butt, 2000) and in the northwest (Kohat area) a mudstone/shale-rich unit (Panoba Formation; Köthe *et al*., 1988; Weiss, 1993) and a carbonate-rich unit (Shekhan Formation; Köthe *et al*., 1988; Weiss, 1993). The higher parts of the succession include evaporites (= the Bahadar Khel Salt-Jatta Gypsum; Shah, 1977) and finally the continental red bed/sandstone mammal-bearing Kuldana Formation (Gingerich, 2003) (Figs 4, 7). The mammals of the upper Subathu Formation or Kalakot Zone of India (stratigraphically coeval to the Kuldana Formation; Sahni & Jolly, 1993) are comparable with the mammals of the Kuldana Formation (Sahni & Jolly, 1993; Gingerich, 2003). The marine regression is also recognizable in the south-southwestern parts of the basin (Lower Indus Basin), where the Ghazij Formation developed gypsum-rich, coal- and mammal-bearing beds (Clyde *et al*., 2003) (Figs 6, 7). The mammal taxa from the Ghazij Formation indicate a pattern of decreasing endemism, increasing cosmopolitanism and increasing modernity through time (= P7–lower P9; Clyde *et al*., 2003). This suggests a bridging contact of the Indian plate with the Asian plate in parts of the northwestern Lower Indus Basin, which was broken up by marine deposition of limestone and shale of the upper Ghazij and lower Kirthar formations during early Lutetian time (Johnson *et al*., 1999). The shale and carbonates of the Sakesar Formation, a marine correlative of the Kuldana Formation in the western Salt Range and Surghar Range, is overlain by Miocene–Recent terrestrial sediments derived from the Himalaya (Shah, 1977), marking the closure of Tethys in the southeastern Upper Indus Basin (Figs 4, 7).

The late Lutetian–Priabonian regression (Haq *et al*., 1987) is represented by the upper Kirthar Formation in the south-southwest and the correlative uppermost Kohat Formation in the north-northwest. This followed closure of the Tethys in the north-northwestern parts of the basin (e.g. Kohat area, Kala Chitta and Hazara ranges) (Figs 4, 6, 7). The gradual retreat of the Tethys Sea continued south-southwest through late Lutetian to Bartonian time and it finally closed in the Priabonian (P15; Warraich *et al*., 2000; Wakefield & Monteil, 2002). Oligocene marine sedimentation was restricted to the south of the Lower Indus Basin (Raza, 2001a), while the rest of the Greater Indus Basin in Pakistan remained a non-depositional lowland until the formation of Neogene molasse (Shah, 1977; Raza, 2001a).

CONCLUSIONS

The lower Cenozoic succession of the Greater Indus Basin in Pakistan preserves an excellent sedimentary and biotal record of the east Tethyan Sea. These provide significant stratigraphical evidence of locally and globally significant geologically important events.

The succession is dominated by shallow-marine shelf sediments intermixed with deep-marine sediments rich in stratigraphically important microbiota. Previously published stratigraphical data have been reinterpreted and many stratigraphical levels have been revised. In addition, biostratigraphically significant shallow benthonic foraminifera from the Lockhart Formation are illustrated. Inter-basinal correlations between various units and with the global standard biostratigraphy and chronostratigraphy are presented. These have enabled recognition of unconformities associated with ongoing India–Asia tectonics and global sea-level change about 55 Ma ago. The closure of Tethys was initiated from the north and northwest during early Lutetian time and was completed by the Priabonian in the south and southwest. This also implies that the Indian Plate came in contact with the Asian Plate in the north first, and later in the southwest, which resulted in the closure of the Tethys Sea and cessation of sedimentation in the basin.

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