Calcareous Nannofossils from Paleogene Deposits in the Salt Range, Punjab, Northern Pakistan

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Chapter B of

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Abstract

As part of a joint study between the U.S. Geological Survey and the Geological Survey of Pakistan, calcareous nannofossils were examined from one outcrop locality and one corehole in the Salt Range of northern Pakistan. Calcareous nannofossils were sparse or absent in many of the samples that were examined; however, it was possible to date several of the formations in this region. The Lockhart Limestone is early late Paleocene in age, and the overlying Patala Formation is very late Paleocene in age. The Nammal Formation, which overlies the Patala, is early Eocene in age. The Sakesar Limestone, which overlies the Nammal Formation, is early to early middle Eocene in age. In the material studied, there is a disconformity between the Patala and Nammal Formations, which corresponds to the Paleocene-Eocene boundary, and earliest Eocene strata are missing in this region.

Introduction

Purpose and Scope

The Coal Resources Exploration and Assessment Program (COALREAP), a joint study between the U.S. Geological Survey (USGS) and the Geological Survey of Pakistan (GSP), was designed to investigate, assess, and report on coal resources for Pakistan (fig. B1). This multiyear program, funded jointly by the Government of Pakistan and the U.S. Agency for International Development (USAID), targeted the major coal-bearing localities in Sindh, Punjab, and Baluchistan for investigation.

Included within COALREAP is the Potwar Regional Framework Assessment Project, which, upon completion, should provide a valuable data base for further exploration and development. The result will be a series of maps and texts that address, among other things, depositional environments of sedimentary rocks and tectonics. A team of biostratigraphers from the USGS, in cooperation with a team from the GSP, was assembled to work on the regional framework project, and this team is providing paleontological control on the timing and placement of coal deposits, as well as information about their sedimentary environments.

From 1989 to 1991, as part of the Potwar Regional Framework Assessment Project, samples were collected from the Salt Range in the coal field area of the Punjab (fig. B2). An extensive study of samples from Nammal Dam in the Salt Range was undertaken by several paleontologists who specialize in various microfossil groups. Their goal was to determine the age and paleoenvironments of the Patala Formation, which is exposed in the gorge at Nammal Dam. Formations examined in this study are, from oldest to youngest, (1) the Lockhart Limestone, a nodular limestone; (2) the Patala Formation, shaly strata interspersed with thin, coal-bearing beds that alternate with nodular limestone beds and some sandstone beds; (3) the Nammal Formation, calcareous shaly strata interbedded with massive limestone beds, the shale decreasing in proportion to the limestone as you go upsection; and (4) the Sakesar Limestone, a thick massive limestone that is very resistant to weathering. This chapter reports on calcareous nannofossils from these formations at Nammal Dam and from a corehole in the Salt Range.

Acknowledgments

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Materials and Methods

Sample Collection

In October and November 1989, N.O. Frederiksen and J.M. Self-Trail (USGS) sampled cores from seven holes that

Figure B1. Location map showing the Salt Range study area (box) and selected regional features.

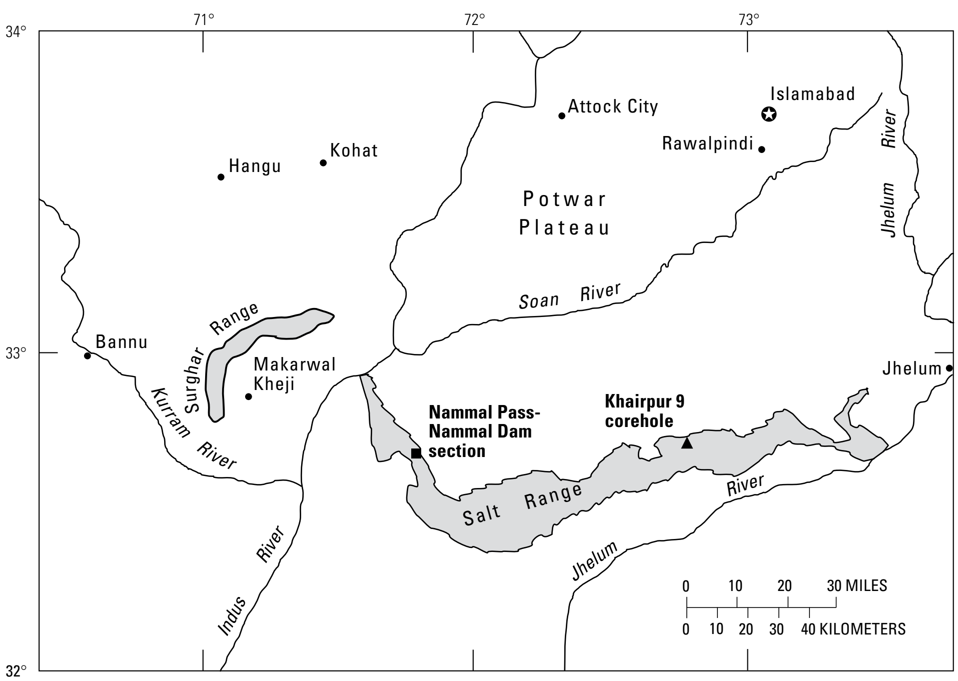


Figure B2. Sample localities in the Salt Range study area in northern Pakistan.

were drilled by the GSP from 1987 to 1989. The cores were stored at the GSP offices in the city of Lahore, Pakistan. Samples were taken for both pollen and calcareous microfossil determinations. In the current study, only samples from the Khairpur 9 corehole were examined for calcareous nannofossils. The Khairpur 9 corehole was drilled at lat 32°44′ N., long 72°47′ E. in the east-central part of the Salt Range. Twelve samples were collected from the Khairpur 9 corehole (fig. B3). Four samples were taken from the Lockhart Limestone, which has a thickness of 36 feet (ft) in the corehole, three samples from the Patala Formation (61 ft thick), and five samples from the Nammal Formation (210 ft thick). In order to facilitate comparison among the various fossil groups, portions of individual samples were processed for calcareous nannofossils, foraminifers, and ostracodes.

In addition to the 12 corehole samples, 19 outcrop samples were collected from the Nammal Dam section near the road through Nammal Pass in the western part of the Salt Range (fig. B2). In November 1989, B.R. Wardlaw and W.E. Martin (USGS) and I.H. Haydri (GSP) measured the Nammal Dam section (fig. B4), which is located at lat 32°41′ N., long 71°48′ E. (see this volume, chap. F). The type section for the Nammal Formation is in the vicinity of Nammal Dam. Much of the Patala Formation is covered with talus at this locality, and there is some disagreement concerning the actual thickness of this unit and the position of the contact between the Patala and the overlying Nammal Formation (this volume, chap. E). For the purposes of this paper, we will use the section of Wardlaw and others (this volume, chap. F).

Two samples from Nammal Dam, NP 3–1 and NP 3–3, were collected by B.R. Wardlaw in November 1989. Samples NP 2–1 through NP 2–6 and NP 2–8 through NP 2–12 were collected for calcareous microfossils by J.M. Self-Trail (USGS) and Tariq Masood (GSP) in November 1989. Further samples, G–1 through G–3, were collected by T.G. Gibson (USGS) and Masood in February 1990, and samples NP 4–1 through NP 4–3 were collected by B.R. Wardlaw and W.E. Martin in June 1991. All together, 8 samples were taken from the Patala Formation (138 ft thick), 10 samples from the Nammal Formation (295 ft thick), and 1 sample from near the bottom of the Sakesar Limestone. See figure B4 for sample positions in the outcrop section. All 19 samples were prepared and examined for calcareous nannofossils.

Sample Preparation

Calcareous nannofossil samples were heated in a convection oven overnight at a temperature of 50 degrees Celsius (°C) in order to remove all residual water. This drying process reduces the chance of calcareous nannofossil dissolution when the unprocessed portion of the sample is placed in long-term storage. A small portion of each sample was then processed, using a timed settling procedure in a column of buffered distilled water. This settling process concentrates the calcareous nannofossils by separating the size fraction containing calcareous nannofossils from other sizes of material in the sediment. Smear slides were then prepared from the concentrated sediments. Cover slips were mounted on the glass slides with Norland Optical Adhesive, an organic adhesive that contains no solvents. The slides then were cured with a 20-minute (min) exposure to ultraviolet light.

Calcareous Nannofossil Zonations and Datums

Two calcareous nannofossil zonations exist for Paleogene deposits. Martini (1971) established a zonation based mainly upon coastal plain sediments, and Bukry (1973, 1978; Okada and Bukry, 1980) based his zonation entirely on deep-sea samples that were collected as part of the Deep Sea Drilling Project. Figure B5 shows the correlation between the two calcareous nannofossil zonations and the time scale of Berggren and others (1985). (This chapter was written before Berggren and others (1995) published a revised time scale.) The two zonations have several calcareous nannofossil events in common, but they also have many differences. Because the two zonations have been correlated fairly accurately with each other, most calcareous nannofossil specialists use horizons from both zonations. This approach increases the chances for being able to place an individual calcareous nannofossil sample within a specific biostratigraphic horizon. Because of the paucity of calcareous nannofossils in many of the Pakistan samples, this broader approach, using data from the zonations of both Martini and Bukry, was used for this study. In addition, valuable biostratigraphic data are present in the calcareous nannofossil range charts of Perch-Nielsen (1985).

The data from Martini (1971), Bukry (1973, 1978), and Perch-Nielsen (1985), as well as from Bybell's calcareous nannofossil studies, were used to construct the following list of reliable calcareous nannofossil datums that are present in many marine sediments from the Paleocene through middle Eocene. An asterisk indicates a species that is used to define a horizon in the zonation of Martini (1971), and a pound sign indicates a species used to define a horizon in the zonation of Bukry (1973, 1978; Okada and Bukry, 1980). FAD is a first appearance datum, and LAD is a last appearance datum. The "List of Species" section contains the complete scientific name for each calcareous nannofossil species.

Reliable Calcareous Nannofossil Datums in Marine Sediments

LAD **Rhabdosphaera gladius*—top of Zone NP 15, middle Eocene

FAD **#Nannotetrina fulgens*—base of Zone NP 15, base CP 13a, middle Eocene

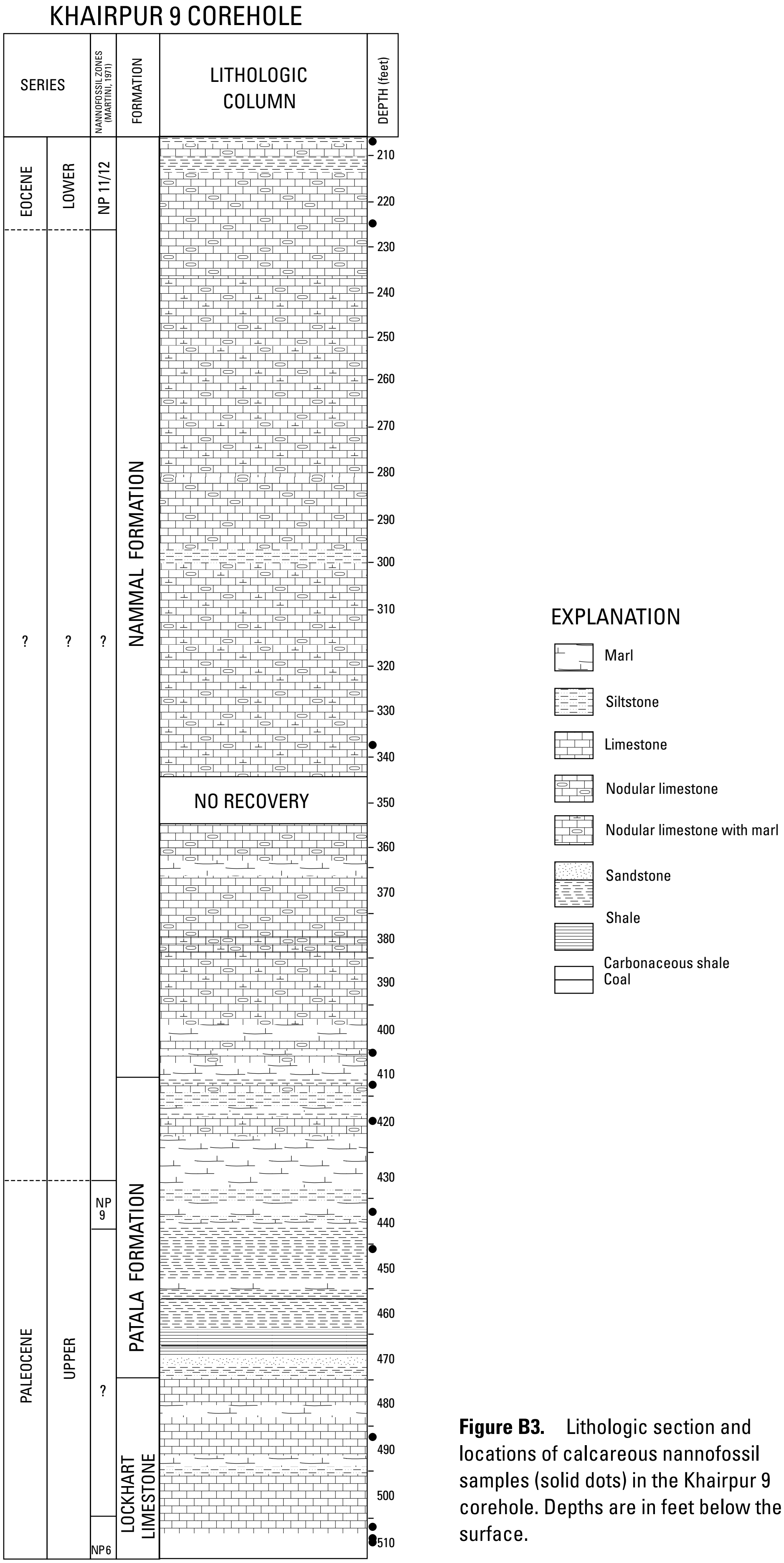
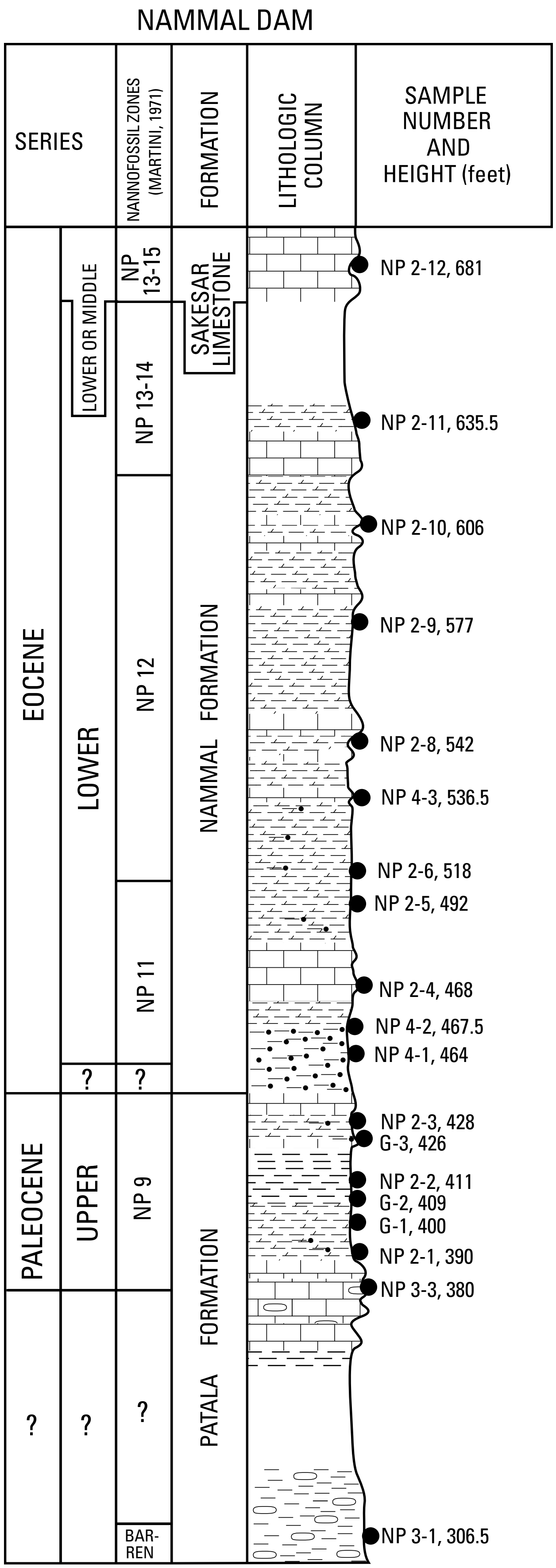


Figure B3. Lithologic section and locations of calcareous nannofossil samples (solid dots) in the Khairpur 9 corehole. Depths are in feet below the surface.



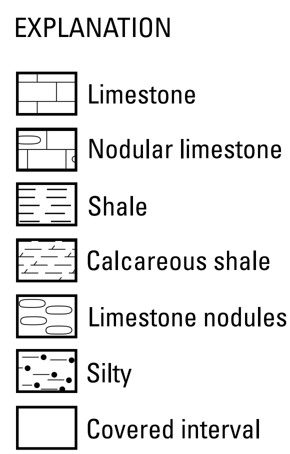
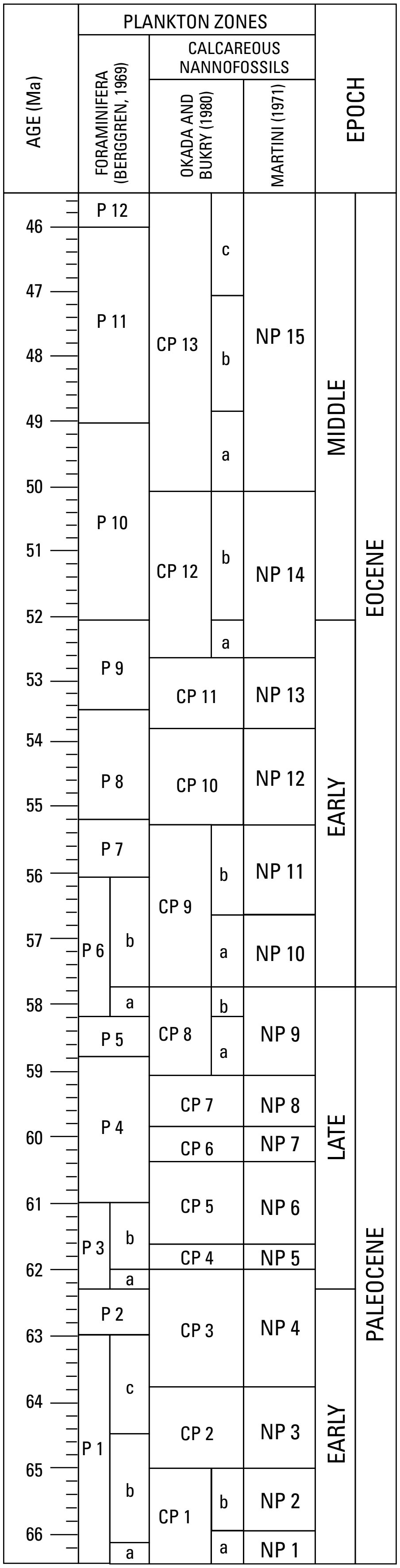


Figure B4. Lithologic section and locations of calcareous nannofossil samples (solid dots) at Nammal Dam. Sample heights are in feet above the base of the Tertiary section.



← **Figure B5.** Correlation of calcareous nannofossil and planktonic foraminiferal zones with epochs, modified from Berggren and others (1985).

FAD *Nannotetrina cristata*—near top of Zone NP 14, middle Eocene

FAD *#Rhabdosphaera inflata*—within Zone NP 14, base CP 12b

FAD **#Discoaster sublodoensis*—base of Zone NP 14, base CP 12a, early Eocene

LAD **Rhomboaster orthostylus*—top of Zone NP 12, early Eocene

FAD *Helicosphaera lophota*—near top of Zone NP 12; has been used to approximate the NP 12/NP 13 boundary, early Eocene

FAD *Helicosphaera seminulum*—mid-Zone NP 12, early Eocene

FAD **#Discoaster lodoensis*—base of Zone NP 12, base CP 10, early Eocene

FAD *Discoaster binodosus*—within Zone NP 11, early Eocene

FAD *Chiphragmalithus calathus*—within Zone NP 11, early Eocene

LAD **#Rhomboaster contortus*—top of Zone NP 10, top CP 9a, early Eocene

FAD *Rhomboaster orthostylus*—upper Zone NP 10, early Eocene

FAD *#Rhomboaster contortus*—mid-Zone NP 10, base CP 9a, early Eocene; Bukry places the base of the CP 9a Zone at the base of Martini's Zone NP 10, but this is much too low according to Bybell's studies and Perch-Nielsen (1985)

FAD *#Discoaster diastypus*—mid-Zone NP 10, base CP 9a, early Eocene

LAD *Placozygus sigmoides*—Zone NP 10, early Eocene

LAD *Fasciculithus tympaniformis*—lower Zone NP 10, early Eocene

LAD *Hornibrookina* spp.—lower Zone NP 10, early Eocene

FAD **Rhomboaster bramlettei*—base of Zone NP 10, early Eocene

LAD *Scapholithus apertus* (consistent occurrence)—upper Zone NP 9, late Paleocene

FAD *Toweius occultatus*—within Zone NP 9, late Paleocene

LAD *Biantholithus astralis*—within Zone NP 9, late Paleocene

FAD *Transversopontis pulcher*—upper Zone NP 9, late Paleocene

FAD *Discoaster mediosus*—within Zone NP 9, late Paleocene

FAD *Toweius callosus*—within Zone NP 9, late Paleocene

FAD *#Campylosphaera dela*—within Zone NP 9, base CP 8b, late Paleocene (includes *C. eodela*)

FAD *Lophodolithus nascens*—within Zone NP 9, late Paleocene

FAD **#Discoaster multiradiatus*—base of Zone NP 9, base CP 8a, late Paleocene

FAD **Heliolithus riedelii*—base of Zone NP 8, late Paleocene

FAD *#Discoaster mohleri*—base CP 6, approximately equivalent to base of Martini's Zone NP 7, late Paleocene
FAD *#Heliolithus kleinpellii*—base of Zone NP 6, base CP 5, late Paleocene
FAD *Heliolithus cantabriae*—mid-Zone NP 5, late Paleocene
FAD *Scapholithus apertus*—within Zone NP 5, late Paleocene
FAD *Toweius eminens* var. *tovae*—within Zone NP 5, late Paleocene
FAD *#Fasciculithus tympaniformis*—base of Zone NP 5, base CP 4, late Paleocene
FAD *Toweius pertusus*—within Zone NP 4
FAD *Ellipsolithus distichus*—near base of Zone NP 4, early Paleocene
FAD **Ellipsolithus macellus*—base of Zone NP 4, early Paleocene
FAD **Chiasmolithus danicus*—base of Zone NP 3, early Paleocene
FAD *#Cruciplacolithus tenuis*—base of Zone NP 2, base CP 1b, early Paleocene

Previous Studies

Haq (1971) examined Paleogene calcareous nannofossils from the Salt Range and the Sulaiman Range in Pakistan. Cheema and others (1977) studied foraminifers, mollusks, and echinoids from various Cenozoic localities in Pakistan. Köthe (1988) examined calcareous nannofossils and dinoflagellates from the Salt Range, the Surghar Range, and the Sulaiman Range.

Köthe (1988) established 11 local dinoflagellate zones, which she correlated with Martini's (1971) calcareous nannofossil zones. Although her Pak-D I and Pak-D II Zones contained no calcareous nannofossils, she indirectly correlated them with Zones NP 6 and NP 7 (late Paleocene). Köthe considered her Pak-D III Zone to be approximately equivalent to Zone NP 8 (late Paleocene). She indicated that dinoflagellate Zones Pak-D IV, V, and VI fall within calcareous nannofossil Zone NP 9 (late Paleocene). Dinoflagellate Zone Pak-D VII was considered to be equivalent to much of calcareous nannofossil Zone NP 10 (early Eocene). Dinoflagellate Zone Pak-D VIII consists of the uppermost part of Zone NP 10 and all of calcareous nannofossil Zone NP 11 (early Eocene). Calcareous nannofossil Zones NP 12, NP 13, and NP 14 (early and middle Eocene) are equivalent to dinoflagellate Zone Pak-D IX. Pak-D X and XI are middle to late Eocene in age (Zones NP 15 to NP 20).

Lockhart Limestone

The Lockhart Limestone samples that Köthe (1988) examined were barren of calcareous nannofossils. However, her samples from the underlying Dhak Pass beds of the Hangu Formation contained questionably late Paleocene, calcareous nannofossil assemblages. Köthe placed dinoflagellates from a sample that is questionably Lockhart Limestone at Nammal Gorge within Pak-D I Zone (Zone NP 6 or NP 7, late Paleocene in age). On the basis of foraminiferal data, Cheema and others (1977) also indicated a Paleocene age for the Lockhart Limestone.

Patala Formation

Köthe (1988) considered the age of the Patala Formation to range from calcareous nannofossil Zones NP 8 to NP 12 (late Paleocene and early Eocene), based on the presence of calcareous nannofossils as well as on the presence of dinoflagellate assemblages. She believed that the contact between the Patala Formation and the overlying Nammal Formation was diachronous. Köthe listed several calcareous nannofossil and dinoflagellate species from the Patala Formation at Nammal Gorge; she placed these strata within dinoflagellate Zones Pak-D II, III, and IV or in calcareous nannofossil Zones NP 8 and NP 9 (late Paleocene). She was unsure of the exact placement within a calcareous nannofossil zone for the lowest part of the Patala Formation at Nammal Gorge (in dinoflagellate Zone Pak-D II). Calcareous nannofossil zonal markers were rarely present in Köthe's Patala samples, particularly in samples she identified as Eocene, and in many instances she was forced to rely upon species with poorly documented biostratigraphic ranges. In addition, the contact between the Patala Formation and the overlying Nammal Formation is not clearly defined, which is evidenced by the fact that this contact at Nammal Gorge has been placed at different stratigraphic positions in various geological studies (see this volume, chap. E). It is the current authors' opinion that Köthe did not prove the diachronism of the boundary between the Patala and Nammal and that additional, more extensive investigations of the lithologic units and their contained fossils will reveal that this boundary is indeed more nearly isochronous and probably represents the Paleocene-Eocene boundary.

Haq (1971) examined calcareous nannofossils in samples from the Salt Range (Nammal Gorge) and placed his two samples from the Patala Formation in the *Discoaster multiradiatus* Zone of Hay and others (1967), which is equivalent to Zone NP 9.

Nammal Formation

Köthe (1988) considered the Nammal Formation to be early Eocene in age (Zones NP 11 and NP 12) on the basis of calcareous nannofossil and dinoflagellate data. Köthe examined 11 samples from the Nammal Formation in the Salt Range. She placed the seven Nammal Formation samples at Nammal Gorge in dinoflagellate Zone Pak-D VIII (equivalent to Zone NP 11) based on the presence of *Homotryblium tenuispinosum* in the bottom sample. However, as is discussed by Edwards (this volume, chap. C), the first appearance datum of this species is somewhat uncertain and has been reported, but not documented, in material as old as the late Paleocene.

Using calcareous nannofossils, Köthe placed the seven Nammal samples into Zone NP 11. Zone NP 11 often is difficult to identify with certainty by using calcareous nannofossils because this zone is based upon the absence of marker species from both Zone NP 10 and Zone NP 12. *Chiphragmalithus calathus*, one species that is restricted to Zone NP 11, is not on any of Köthe's occurrence charts.

Köthe (1988, fig. 5) considered the first occurrence of *Sphenolithus editus* to be at the base of Zone NP 11 and used the presence of this species in the Nammal Formation at Nammal Gorge to place these strata within Zone NP 11. Perch-Nielsen (1985, fig. 69) plotted the range of *S. editus* in Zones NP 11 and NP 12. However, *S. editus* originally was described from Egypt by Perch-Nielsen and others (1978), where this species first occurred 5 meters (m) below a sample that still is in Zone NP 10, on the basis of the presence of *Rhomboaster contortus* (occurs only within NP 10). If these data are accurate, *S. editus* first appears in the upper part of Zone NP 10, and this species alone cannot be used to define a Zone NP 11 date for the Nammal. *Sphenolithus conspicuus*, which Perch-Nielsen (1985, fig. 69) figured as occurring in Zones NP 11 and NP 12, also was reported by Köthe to occur in the Nammal Formation at Nammal Gorge. These two sphenoliths have been documented and illustrated in very few publications to date, and while they may indeed first occur in or very near Zone NP 11, it would seem that it is also possible for them to have a longer range. Although it is difficult to use Köthe's data for precise placement of Nammal Formation strata within a specific calcareous nannofossil zone, these data clearly do indicate that the Nammal Formation is early Eocene (not Paleocene) in age.

Haq (1971) was unable to obtain any accurate dates for the Nammal Formation due to poor preservation of the calcareous nannofossils.

Sakesar Limestone

On the basis of foraminifers, Cheema and others (1977) assigned an early Eocene age to the Sakesar Limestone. Köthe (1988) examined one Sakesar Limestone sample, which was barren.

Results of this Study

Khairpur 9 Corehole

Calcareous nannofossil occurrences for the 12 Khairpur 9 samples are listed in figure B6. Of the four Lockhart Limestone samples examined, only the deepest sample at 509.9 ft contained a sufficiently diverse, calcareous nannofossil assemblage for an age determination. *Heliolithus cantabriae*, a species that has its FAD in the upper half of Zone NP 5, is present in this sample, as is *H. kleinpellii*, a species that first occurs at the base of Zone NP 6. No calcareous nannofossil species with a FAD in Zone NP 7 are present in this sample, which indicates that the sample at 509.9 ft most probably represents Zone NP 6 (early late Paleocene). Therefore, at least part of the Lockhart Limestone in the Khairpur 9 corehole appears to be early late Paleocene in age.

Of the three Patala Formation samples examined, only the two samples from the middle portion of the formation contained calcareous nannofossils. The sample from the upper portion of the formation at 420.4 ft is barren of these fossils. The samples at 446.9 and 438.6 ft both contain the species *Discoaster multiradiatus*, which has its FAD at the base of Zone NP 9 (the youngest Paleocene zone; see fig. B5). The absence of members of the genus *Rhomboaster* (first appears at the base of Zone NP 10) normally would be used to restrict this material to Zone NP 9. However, this genus is rare in Pakistan. Köthe (1988) listed *R. bramlettei* from one Patala sample from the Kohat area at Tarkhobi, and both Köthe (1988) and Haq (1971) reported the presence of *R. orthostylus* in several samples. The presence of *R. orthostylus* can be confirmed with illustrations in Haq (1971) and Köthe (1988), but *R. bramlettei* was not illustrated. Either Köthe's identification of *R. bramlettei*, a species that occurs only in the Eocene, in what she considers to be the Patala Formation (found to be only Paleocene in age in this study) or placement of these strata within the Patala Formation is suspect (see "Biostratigraphic Syntheses" section). Bybell did find *R. bramlettei* at Choppar Rift in Baluchistan in the basal Ghazig Formation. Therefore, while the presence or absence in the Patala Formation of the species *R. bramlettei* continues to be uncertain, the species definitely does occur in Pakistan. The absence of any members of the genus *Rhomboaster* indicates that the Patala Formation in the Khairpur 9 corehole most likely is Paleocene in age.

The sample from 338.4 ft in the Nammal Formation is barren of calcareous nannofossils, and the samples from 206.0, 405.2, and 412.9 ft contain no identifiable specimens. Only the sample from the upper part of the Nammal Formation at 225.5 ft in the Khairpur 9 corehole can be dated with calcareous nannofossils. *Discoaster barbadiensis*, which first occurs sporadically within upper Zone NP 10 and consistently within Zone NP 11 (Bybell and Self-Trail, 1997), is present in the sample from 225.5 ft. *Discoaster barbadiensis* ranges well up into the Eocene. However, *Toweius callosus* and *T. pertusus*, which are present in this sample, occur no higher than Zone NP 12, and *Zygodiscus herlyni* has its LAD in Zone NP 11 (Bybell and Self-Trail, 1997). Therefore, the upper part of the Nammal Formation in the Khairpur 9 corehole is most probably in Zone NP 11 (early Eocene).

On the basis of planktonic and benthic foraminifers, Gibson (this volume, chap. E) determined that in the Khairpur 9 corehole, the Lockhart Limestone, the Patala Formation, and the lower part of the Nammal Formation were all deposited in shallow, inner neritic, open-marine environments at water depths of less than 100 ft. Calcareous nannofossils never are abundant in shallow-water deposits, and this shallow depositional environment explains the relative paucity of calcareous

KHAIRPUR 9 COREHOLE

EPOCH		CALCAREOUS NANNOFOSSIL ZONES (MARTINI, 1971)	FORMATION	*Coccolithus pelagicus*	*Discoaster barbadiensis*	*Discoaster multiradiatus*	*Discoaster salisburgensis*	*Fasciculithus aubertae*	*Fasciculithus thomasii*	*Heliolithus cantabriae*	*Heliolithus kleinpellii*	*Placozygus sigmoides*	*Sphenolithus* sp.	*Thoracosphaera* sp.	*Toweius callosus*	*Toweius pertusus*	*Zygodiscus herlyni*	Placoliths	Abundance	Preservation	DEPTH (feet)
EOCENE	EARLY	?	NAMMAL FORMATION															●	R	P	206.0
EOCENE	EARLY	NP 11	NAMMAL FORMATION	●	●								●		●	●		●	F	P	225.5
?	?	?	NAMMAL FORMATION																Barren		338.4
?	?	?	NAMMAL FORMATION															●	R	P	405.2
?	?	?	NAMMAL FORMATION															●	R	P	412.9
?	?	?	PATALA FORMATION																Barren		420.4
PALEOCENE	LATE	NP 9	PATALA FORMATION			●									●				R	P	438.6
PALEOCENE	LATE	NP 9	PATALA FORMATION	●		●	●	●	●					●		●	●		F	P	446.9
PALEOCENE	LATE	?	LOCKHART LIMESTONE															●	R	P	487.8
PALEOCENE	LATE	?	LOCKHART LIMESTONE													●			R	F	507.9
PALEOCENE	LATE	?	LOCKHART LIMESTONE															●	R	P	509.0
PALEOCENE	LATE	NP 6	LOCKHART LIMESTONE	●						●	●	●				●			R	F	509.9

Figure B6. Calcareous nannofossil occurrences in the Khairpur 9 corehole. Abundance: F, frequent or one specimen per 1–10 fields of view at × 500 magnification; R, rare or one specimen per 10–100 fields of view at × 500 magnification. Preservation: F, fair preservation; P, poor preservation.

nannofossils in these formations in the Khairpur 9 corehole (table B1).

Nammal Dam Section

Nineteen samples were examined for calcareous nannofossils at Nammal Dam: eight from the Patala Formation, ten from the Nammal Formation, and one from the Sakesar Limestone (fig. B4). Calcareous nannofossil occurrences for these samples are listed in figure B7. The abundance of calcareous nannofossils increases upward through the Patala. The lowest Patala sample at 306.5 ft is barren of calcareous nannofossils; the next sample at 380 ft has frequent nannofossils; samples at 390, 400, and 409 ft have common calcareous nannofossils; and the upper three Patala samples at 411, 426, and 428 ft have abundant calcareous nannofossils. Some nannofossils from the sample at 428 ft are shown in plate B1.

Discoaster multiradiatus, which occurs commonly throughout Zones NP 9 and NP 10 and less commonly in NP 11 (Bybell and Self-Trail, 1997), is present in all seven of the fossiliferous Patala samples. *Scapholithus apertus*, which has its last consistent occurrence very near the top of Zone NP 9 (Bybell and Self-Trail, 1997) (the highest Paleocene zone), is also present in all of the Patala samples, except at 409 ft. The occurrence of these two species confines the Patala to Zone NP 9. In addition, *Campylosphaera dela* and *Lophodolithus nascens* are present at 390 ft and (or) 400 ft. As can be seen from the calcareous nannofossil species list in the “Calcareous Nannofossil Zonations and Datums” section and as recorded by Bybell and Self-Trail (1995), *C. dela* and *L. nascens* have their FAD’s within Zone NP 9. According to Perch-Nielsen (1985, figs. 19,

Table B1. Calcareous nannofossil diversity in the Khairpur 9 corehole compared with water-depth information as determined from planktonic and benthic foraminifers.

[Water depth and depositional environment data from T.G. Gibson (this volume, chap. E). <, less than]

Depth in core (feet)	Water depth (feet)	Formation	Depositional environment	Zone	Calcareous nannofossils
405.2	<100	Nammal	Shallow, inner neritic, open marine	?	Placoliths
420.4	<100	Patala	Shallow, inner neritic, open marine	?	Barren
438.6	<100	Patala	Shallow, inner neritic, open marine	NP 9/NP 10	Two species
487.8	<100	Lockhart Limestone	Shallow, inner neritic, open marine	?	Placoliths
509.9	<100	Lockhart Limestone	Very shallow, inner neritic, open marine	NP 6	Five species

80), *C. dela* has its FAD in mid-NP 9, and *L. nascens* has its FAD in the upper fourth of Zone NP 9. Bybell's unpublished data from the Gulf and Atlantic Coastal Plains of the United States support these occurrences. Samples at 390 and 400 ft, therefore, can be placed in the upper fourth of Zone NP 9 but not in the uppermost part of Zone NP 9 because they contain *S. apertus*. The samples at 411, 426, and 428 ft contain both *S. apertus* and *Transversopontis pulcher*. *Transversopontis pulcher* has its FAD very near the top of Zone NP 9, and *S. apertus* and *T. pulcher* have overlapping ranges for a very short period of time in upper Zone NP 9 (Bybell and Self-Trail, 1995). In summary, the upper part of the Patala Formation at Nammal Dam can be placed within the very upper part, but not the very uppermost part, of the Paleocene. Haq (1971) placed his Patala samples within Zone NP 9, and Köthe (1988) also placed the upper part of the Patala at Nammal Gorge within Zone NP 9.

Calcareous nannofossils are less abundant and less diverse in the Nammal Formation than they are in the Patala, and most of the species that are present are not biostratigraphically useful. For this reason, it was much more difficult to ascertain an age for the Nammal. The sample at 464 ft has abundant calcareous nannofossils, but the remaining nine Nammal samples only have common or frequent nannofossils (fig. B7).

Discoaster multiradiatus (occurs only in Zones NP 9, NP 10, and sporadically in NP 11) is present in samples at 464, 467.5, and 468 ft (lower fourth of the Nammal). A questionable occurrence of *D. multiradiatus* at 518 ft most likely is a result of reworking or contamination.

Because the underlying Patala is in upper Zone NP 9, the lower Nammal up to 468 ft is within uppermost Zone NP 9 or Zones NP 10 or NP 11. The absence of *Placozygus sigmoides, Hornibrookina* species, and *Fasciculithus* species, which all last occur in the lower part of Zone NP 10 and which all are present in the underlying Patala Formation at Nammal Dam, indicates that the Nammal Formation is younger than the lower part of Zone NP 10 (earliest Eocene). If the lower part of the Nammal were within any portion of Zone NP 10, considering the diversity of the samples (18–21 species) and the resistance of the genus *Rhomboaster* to dissolution, one could reasonably assume that at least one of the three *Rhomboaster* species should be present (FAD's of these three members of the genus *Rhomboaster* occur in Zone NP 10). The absence of these species strengthens the assumption that the lowest portion of the Nammal Formation is not in Zone NP 10, but is in Zone NP 11. In addition, the presence of *Discoaster multiradiatus*, which occurs no higher than Zone NP 11, would indicate a Zone NP 11 placement. This, in combination with lower Nammal Formation data from Köthe that she interpreted to indicate a Zone NP 11 date, strengthens the placement of the lower part of the Nammal Formation at Nammal Dam within the early Eocene Zone NP 11. Therefore, Zone NP 10 appears to be missing at Nammal Dam, and the Paleocene-Eocene boundary occurs at the Patala-Nammal contact (Zones NP 9 to NP 11) or between samples at 428 and 464 ft.

The Nammal Formation samples at 518, 536.5, 542, 577, and 606 ft tentatively are placed within the early Eocene Zone NP 12, on the basis of the presence of *Blackites creber* and *Transversopontis pulcheroides* (FAD's probably in Zone NP 12) and *Ellipsolithus macellus* and *Toweius pertusus* (LAD's near the top of Zone NP 12). A questionable occurrence at 518 ft of a poorly preserved specimen, which tentatively is identified as *Zygodiscus herlyni* (LAD in Zone NP 11) and which may be due to reworking or may be a different *Zygodiscus* species, is not considered to be biostratigraphically significant.

The highest Nammal Formation sample at 635.5 ft contains *Discoaster kuepperi* (LAD in the upper part of Zone NP 14) and does not contain *E. macellus* (LAD near top of Zone NP 12), which probably confines this sample to Zone NP 13 or lower Zone NP 14 (early Eocene). Köthe (1988) did not distinguish any age differences in her Nammal Formation samples at Nammal Gorge and placed them all within Zone NP 11.

One sample from the Sakesar Limestone was examined at Nammal Dam (681 ft), and this sample contains *Lophodolithus nascens* (LAD in the lower part of Zone NP 15, according to Perch-Nielsen (1985)). The presence of this species and the fact that it overlies probable Zone NP 13/14 strata indicate that the Sakesar most likely is in Zones NP 13, NP 14, or NP 15 (early to early middle Eocene). Cheema and others (1977) placed the Sakesar Limestone at Nammal Gorge in the early Eocene.

NAMMAL DAM

HEIGHT (feet)	681	635.5	606	577	542	536.5	518	492	468	467.5	464	428	426	411	409	400	390	380	306.5
FORMATION	SAKESAR LIMESTONE	NAMMAL FORMATION										PATALA FORMATION							
EPOCH	EOCENE											PALEOCENE							?
	EARLY OR MIDDLE		EARLY									LATE							?
CALCAREOUS NANNOFOSSIL ZONES (MARTINI, 1971)	NP 13-15	NP 13/14	NP 12					NP 11				NP 9							BARREN
Abundance	F	F	F	F	F	C	C	F	F	C	A	A	A	A	C	C	C	F	
Preservation	P	P	P	P	P	P	P	F	P	P	P	P	G	F	F	G	P	F	
Biantholithus sparsus												•							
Blackites creber				•		•													
Blackites herculesii						•	•												
Blackites spinosus					•														
Braarudosphaera bigelowii					•	•								•		•	•		
Campylosphaera dela	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•		
Chiasmolithus bidens							•				•		•		•	•	•		
Chiasmolithus consuetus s. ampl.		•	•		•	•	•		•	•	•	•	•	•	•	•	•		
Coccolithus eopelagicus												•		•			•		
Coccolithus pelagicus	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	
Cruciplacolithus sp.							•		•		•		•			•	•		
Cyclagelosphaera prima												•							
Cyclococcolithus sp.		•		•	•		•					•	•		•				
Discoaster barbadiensis					•	•													
Discoaster falcatus													•						
Discoaster kuepperi		•			•	•													
Discoaster limbatus													•		•				
Discoaster mediosus														•					
Discoaster multiradiatus							?		•	•	•	•	•	•	•	•	•	•	
Discoaster salisburgensis											•	•		•	•	•			
Ellipsolithus distichus													•	•		•			
Ellipsolithus macellus			•	•	•	•	•				•	•							
Ericsonia subpertusa	•	?					?		?	?		•		•			•		
Fasciculithus alanii													•	•	•	•	•		
Fasciculithus aubertae													•		•	•			
Fasciculithus involutus													•	•	•	•			
Fasciculithus schaubii														•					
Fasciculithus thomasii														•	•	•			
Fasciculithus tympaniformis													•	•		•	•		
Hornibrookina sp.												•							
Lophodolithus nascens	•				•		•					•	•				•		
Markalius apertus											?	•	•	•	•				
Markalius inversus						•			•		•	•	•	•			•		
Micrantholithus sp.					•	•					•								
Neochiastozygus sp.		•			•				•			•							
Neochiastozygus concinnus						•	•		•	•	•	•	•		•	•	•		
Placozygus sigmoides											•	•	•	•		•	•		
Pontosphaera spp.		•			•	•			•	•	•			•					
Rhabdosphaera perlonga						•													
Scapholithus apertus												•	•	•		•	•	•	
Sphenolithus anarrhopus						•	•		•	•	•						•		
Sphenolithus primus/moriformis	•				•		•		•				•						
Sphenolithus radians		?			?														
Thoracosphaera sp.			•				•		•	•	•	•	•	•	•	•	•	•	
Toweius callosus			•	•	•	•	•		•		•	•	•	•	•	•	•	•	
Toweius eminens var. *eminens*													?						
Toweius eminens var. *tovae*													•						
Toweius pertusus			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
Transversopontis pulcher s.l.	•	•	•	•	•	•	•		•	•	•	•	•	•					
Transversopontis pulcheroides		•					•		1										
Zygodiscus herlyni							?				•	•	•	•	•	•	•		
Zygrhablithus bijugatus			•		•	•	•	•	•	•	•	•							

Figure B7. Calcareous nannofossil occurrences at Nammal Dam. Abundance: A, abundant or 10 or more specimens per field of view at × 500 magnification; C, common or 1–10 specimens per field of view at × 500 magnification; F, frequent or one specimen per 1–10 fields of view at × 500 magnification. Preservation: G, good preservation; F, fair preservation; P, poor preservation. A question mark (?) indicates a questionable occurrence, and "1" indicates that only one specimen was seen in the sample.

Coal beds, which are found to the east in the Khairpur 9 corehole, are missing at Nammal Dam. On the basis of planktonic and benthic foraminifers at both locations, Gibson (this volume, chap. E) concluded that deeper water deposition occurred at Nammal Dam. He ascertained that the lower Patala at 306.5 ft in the Nammal Dam section is indicative of water depths less than 100 ft (inner neritic, possibly of lowered salinity) (table B2). The water depths increase upward in the section, and at 428 ft the upper part of the Patala is postulated to have been deposited in water depths of 300–600 ft (outer neritic). This depth increase contrasts significantly with the continuously shallow water depths described for the Khairpur 9 corehole (table B1). The deeper water deposition at Nammal Dam explains the greater abundance of calcareous nannofossils at this locality, particularly within the upper part of the Patala Formation (table B2), as opposed to the lower floral abundance in the Khairpur 9 corehole.

Biostratigraphic Syntheses

Lockhart Limestone

Calcareous nannofossils from the Khairpur 9 corehole give an age for the Lockhart Limestone of probable Zone NP 6 (early late Paleocene).

Gibson (this volume, chap. E) examined the foraminifers from the Lockhart Limestone at Nammal Dam and was unable to make any age estimates for this formation. He reported the presence of *Globanomalina ovalis*, a species indicative of the late Paleocene or earliest Eocene, in the Lockhart Limestone at 487.8 ft in the Khairpur 9 corehole. This finding supports the calcareous nannofossil data.

Patala Formation

Calcareous nannofossils that were examined in this study place much of the Patala Formation within the upper part of Zone NP 9 (uppermost Paleocene). Gibson (this volume, chap. E) discussed the age of the Patala on the basis of current and previous foraminiferal studies. The presence of *Morozovella velascoensis* and *M. subbotinae* in Gibson's foraminiferal samples from 390, 411, and 428 ft at Nammal Dam placed the upper portion of the Patala within the latest Paleocene foraminiferal Zone P6a of Blow (1969) or the upper part of the *M. velascoensis* Zone of Toumarkine and Luterbacher (1985). Gibson (this volume, chap. E) obtained no foraminiferal age data from the Patala in the Khairpur 9 corehole.

Edwards (this volume, chap. C) examined the dinoflagellates from the upper part of the Patala Formation at Nammal Dam and considered these strata to be late Paleocene in age. According to Edwards, the presence of *Apectodinium homomorphum*, which occurs in the Patala at 306.5, 390, and 411 ft, indicates an age no older than calcareous nannofossil Zone NP 7 or NP 8; the presence of *A. augustum* in Edwards' Patala samples at 411 and 428 ft indicates a most likely placement within Zone NP 9. This is confirmed by the calcareous nannofossils at Nammal Dam, which indicate placement within the upper part of Zone NP 9 for the Patala. Edwards (this volume, chap. C) also reported the questionable presence of *A. homomorphum* from the middle of the Patala Formation in the Khairpur 9 corehole at 446.9 ft. The calcareous nannofossil sample from 446.9 ft, which occurs in Zone NP 9, confirms these data.

Frederiksen and others (this volume, chap. D) examined spore and pollen assemblages from three Patala samples at Nammal Dam: approximately 7 ft below sample NP 3–1 (299 ft), near sample NP 2–1 (390 ft), and approximately at the same level as sample G–1 (400 ft). Spores and pollen grains are sparse but do indicate a questionable late Paleocene age. In addition, spores and pollen were examined from seven Patala samples in the Khairpur 9 corehole (this volume, chap. D). Four of the samples were barren or could not be dated, and the samples from 421.1 and 465.3 ft are late Paleocene in age. A sample from 457.9 ft gives a probable late Paleocene age.

As mentioned above, Köthe's (1988) use of the name Patala for Eocene sediments is suspect, and the current authors believe that the entire Patala is Paleocene in age.

Table B2. Calcareous nannofossil diversity at Nammal Dam compared with water-depth information as determined from planktonic and benthic foraminifers.

[Water depth and depositional environment data from T.G. Gibson (this volume, chap. E). <, less than]

Sample	Position (feet)	Water depth (feet)	Formation	Depositional environment	Zone	Calcareous nannofossils (no. of species)
NP 2–3	428	300–600	Patala	Outer neritic	NP 9	25
NP 2–2	411	300	Patala	Middle neritic	NP 9	25
NP 2–1	390	150–300	Patala	Middle neritic	NP 9	21
NP 3–3	380	100–150	Patala	Shallow, inner neritic	NP 9	6
NP 3–1	306.5	<100	Patala	Inner neritic, possible low salinity	?	Barren

Nammal Formation

Calcareous nannofossils in this study indicate that the Nammal Formation is early Eocene in age. The lower part of this formation is placed in Zone NP 11, the middle in Zone NP 12, and the top in either Zone NP 13 or NP 14.

Gibson (this volume, chap. E) obtained no foraminiferal age data from the Nammal Formation at Nammal Dam. However, he concluded that if Haque's (1956) reported occurrence of the planktonic foraminifer *Morozovella velascoensis* in the lower part of the Nammal Formation in Nammal Gorge is accurate, this would indicate a latest Paleocene age. This occurrence would correspond to between approximately 438 and 468 ft in the section of Wardlaw and others (this volume, chap. F) or the lowest part of the Nammal. Calcareous nannofossils indicate Eocene strata as far down in the section as 464 ft. On the basis of Haque's (1956) foraminiferal data, there is a possibility that the lowest part of the Nammal below 464 ft may be Paleocene in age, although the current authors consider this to be unlikely. Gibson (this volume, chap. E) reported the presence of one specimen each of *Acarinina* sp. and *Globanomalina ovalis*, which are indicative of a late Paleocene or early Eocene age, in the Nammal Formation in the Khairpur 9 corehole, at a depth of 405.2 ft.

Edwards (this volume, chap. C) reported the presence of the dinoflagellate species *Homotryblium tenuispinosum sensu ampl.* in samples from the Nammal Formation at Nammal Dam (468, 577, 635.5, and 681 ft). There is some disagreement concerning the exact placement for the FAD of this species, but it generally is agreed that *H. tenuispinosum* first appears in the lower Eocene. Edwards (this volume, chap. C) considers that these samples "containing *H. tenuispinosum sensu ampl.* are most probably of early Eocene age," although she recognizes that the FAD is unlikely to coincide exactly with the base of the Eocene.

Sakesar Limestone

Calcareous nannofossils from one Sakesar sample at Nammal Dam (681 ft) indicate an age of Zones NP 13, NP 14, or NP 15 (early or early middle Eocene).

Conclusions

Although calcareous nannofossils are sporadic in their occurrence in Paleogene strata from the Salt Range of Pakistan, they are present in sufficient numbers to assign ages to the four units studied. The oldest unit examined, the Lockhart Limestone, was deposited in the early late Paleocene (Zone NP 6). The Lockhart is overlain by the Patala Formation, which was deposited near the end of the Paleocene (in uppermost but not very uppermost Zone NP 9). There is some controversy concerning the placement of the lithologic boundary between the Patala and the overlying Nammal Formation. However, when we use the lithologic placement for this boundary of Wardlaw and others (this volume, chap. F), there is an unconformity at the Patala-Nammal boundary, and the earliest Eocene Zone NP 10 is missing. The lowest Nammal Formation that was sampled is early Eocene in age, probably Zone NP 11. The early Eocene Zone NP 12 is also well represented in the Nammal. The upper part of the Nammal most likely is also early Eocene in age (Zone NP 13 or NP 14), and there is a presumed unconformity between the Nammal and the overlying Sakesar Limestone. The duration of this unconformity is unknown because the Sakesar can be dated no more accurately than early or early middle Eocene (Zones NP 13 to NP 15).

Calcareous nannofossil abundances support the presence of deeper water deposition in the western Salt Range at Nammal Dam (middle-to-outer neritic environments) and shallower water deposition to the east at the Khairpur 9 corehole (inner neritic environments) during the Paleocene and Eocene.

List of Species

[Plate citations refer to this chapter]

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Biantholithus sparsus Bramlette & Martini 1964
Blackites creber (Deflandre *in* Deflandre and Fert 1954) Stradner & Edwards 1968
Blackites herculesii (Stradner 1969) Bybell & Self-Trail 1997
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Braarudosphaera bigelowii (Gran & Braarud 1935) Deflandre 1947
Campylosphaera dela (Bramlette & Sullivan, 1961) Hay & Mohler 1967 (pl. B1, figs. 4, 5)
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Discoaster mohleri Bukry & Percival 1971

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Sphenolithus moriformis (Brönnimann & Stradner 1960) Bramlette & Wilcoxon 1967
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Toweius occultatus (Locker 1967) Perch-Nielsen 1971
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Plate B1

Plate B1

[Figures 1–12 are scanning electron micrographs of calcareous nannofossils from the Patala Formation (428 ft) at Nammal Dam in Zone NP 9 (late Paleocene). Scale bar equals 2 µm]

Figures 1–3. *Coccolithus pelagicus*.

1. Distal view.
2. Distal view.
3. Proximal view.

4, 5. *Campylosphaera dela*.

4. Distal view.
5. Proximal view.

6. *Discoaster* sp. Strongly curved side.

7. *Discoaster multiradiatus*.

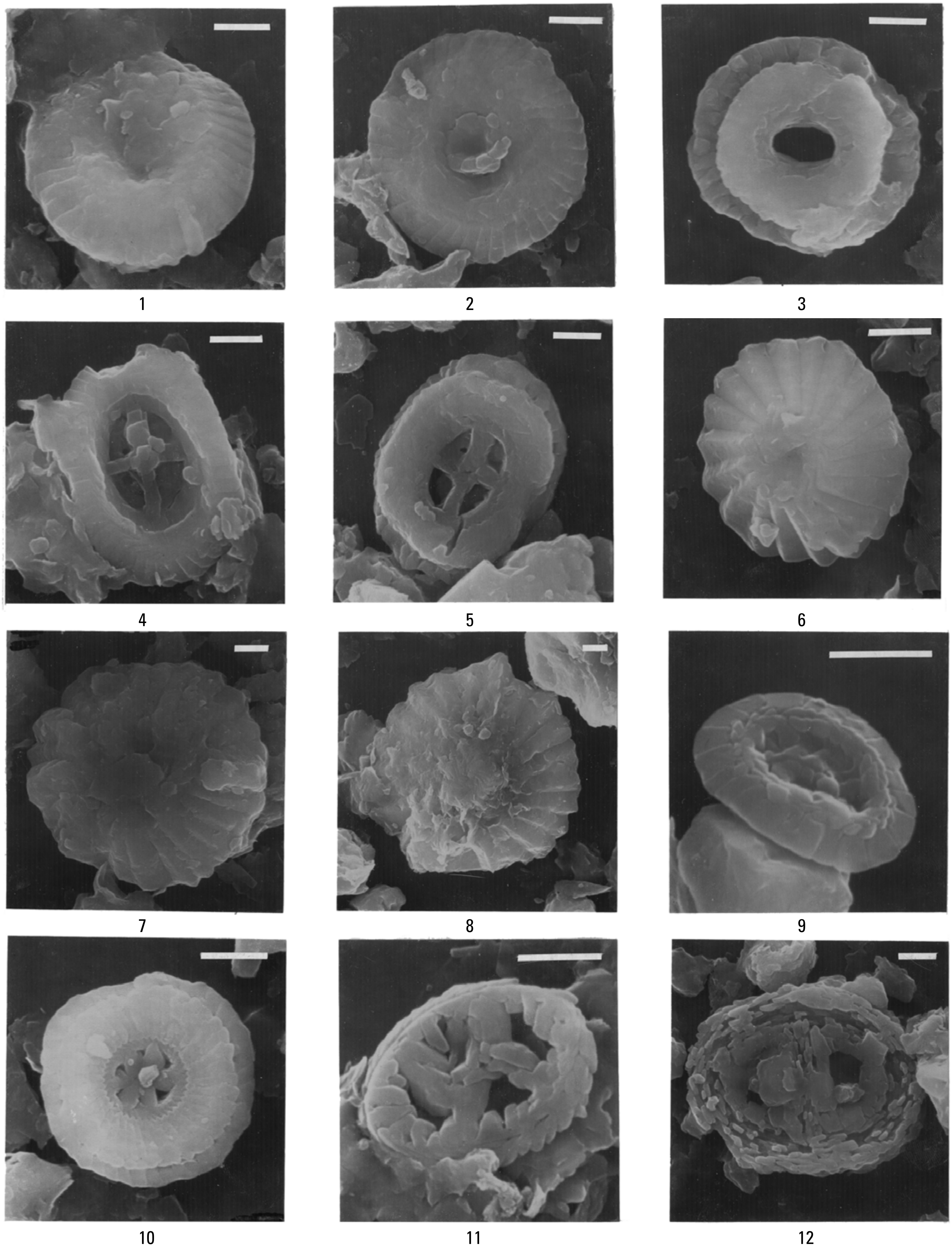
8. *Discoaster salisburgensis*.

9. *Hornibrookina* sp. Distal view.

10. *Toweius* sp. Proximal view.

11. *Neochiastozygus* sp. Proximal view.

12. *Transversopontis pulcher*. Distal view.



Coccolithus, Campylosphaera, Discoaster, Hornibrookina, Toweius, Neochiastozygus, and *Transversopontis*