Upper Paleocene Foraminiferal Biostratigraphy and Paleoenvironments of the Salt Range, Punjab, Northern Pakistan

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Chapter E of

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Abstract

Planktonic foraminiferal species, which were recovered from the uppermost part of the Patala Formation at Nammal Dam in the Salt Range, Punjab, Pakistan, indicate that these strata are in the planktonic foraminiferal *Morozovella velascoensis*/*M. subbotinae* Zone (Zone P6a) of latest Paleocene age. Diagnostic planktonic species are not present in samples from the lower and middle parts of the Patala Formation, and specimens are too poorly preserved to identify in our samples from the Nammal Formation at Nammal Dam. No age-diagnostic planktonic species are present in any samples that were examined from the Lockhart Limestone or the Patala and Nammal Formations in the Khairpur 9 corehole farther east in the Salt Range; thus, no age assignments can be made for these units in those areas on the basis of the foraminifers.

Benthonic foraminiferal assemblages that were examined from the Lockhart Limestone and the Patala and Nammal Formations in the Khairpur 9 corehole suggest deposition in shallow, open-marine, inner neritic environments in waters that are less than 100 feet deep. The lower and middle parts of the Patala Formation at Nammal Dam also were deposited in inner neritic environments in similar to slightly deeper waters; however, significant deepening to outer neritic environments (300- to 600-foot water depth) is indicated for strata in the uppermost part of the Patala Formation at Nammal Dam. Severe diagenetic alteration of smaller foraminifers in samples from the Lockhart Limestone and Nammal Formation at Nammal Dam precluded their use in this study.

Introduction

Purpose and Scope

Paleocene and Eocene strata in northern Pakistan are well exposed in the Salt Range of the Punjab (figs. E1, E2). One of the best known exposures of these strata is in Nammal Gorge in the western Salt Range (Nammal Dam section, fig. E2). Lower Paleogene units that are well exposed in Nammal Gorge are, from oldest to youngest, the Hangu Formation, Lockhart Limestone, Patala Formation, Nammal Formation, and Sakesar Limestone. Nammal Gorge is the type locality of the Nammal Formation.

The Paleocene and Eocene strata exposed in Nammal Gorge form one of the most important stratigraphic sections in Pakistan. The Nammal Gorge section is the only Paleocene and Eocene section in Pakistan in which biostratigraphic successions of both the larger and smaller foraminifers have been studied. In addition, studies have been made of the distribution of other biostratigraphically important microfossil groups—the calcareous nannofossils (Köthe, 1988; Bybell and Self-Trail, this volume, chap. B), dinoflagellates (Köthe, 1988; Edwards, this volume, chap. C), and spores and pollen (Frederiksen and others, this volume, chap. D).

Davies and Pinfold (1937) described the larger foraminifers of the Hangu Formation through the Nammal Formation in Nammal Gorge. Haque (1956) made a comprehensive study of the smaller foraminifers of the Paleocene and Eocene from Nammal Gorge. Haque described new genera and species for both benthonic and planktonic foraminifers and made a generalized biostratigraphic and paleoenvironmental analysis of the strata. Recently, Köthe (1988) studied Paleogene calcareous nannofossils and dinoflagellates from Nammal Gorge. These previous studies establish Nammal Gorge as a reference section for local and regional biostratigraphy, paleogeography, and paleoenvironmental analysis and facies patterns in the Punjab, and this section can be used for comparative studies with sections in the other provinces of Pakistan.

The Nammal Gorge Paleogene section is considered to be a critical locality both for regional stratigraphic studies (Hunting Survey Corporation, 1961) and for interregional studies (Nagappa, 1959; McGowran, 1968; Adams, 1970). Adams (1970), noting the regional importance of this locality, suggested that there should be additional investigation there.

Since 1985, the U.S. Geological Survey (USGS) and the Geological Survey of Pakistan (GSP) have been con-

Figure E1. Location map showing the Salt Range study area (box) and selected regional features.

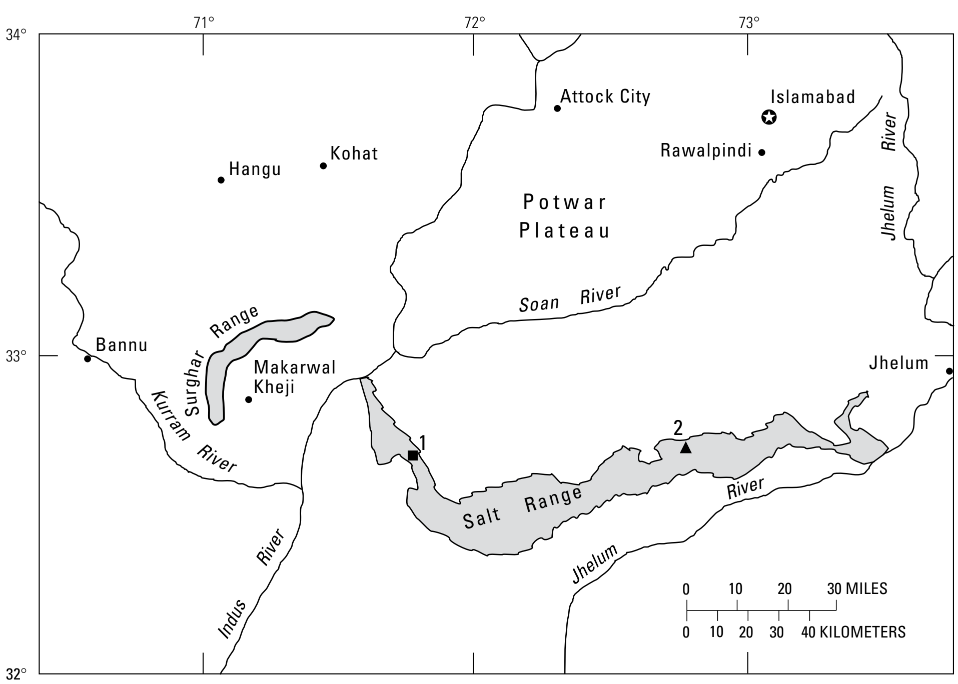

Figure E2. The Salt Range study area in northern Pakistan showing locations of the sections studied: 1, Nammal Dam section; 2, Khairpur 9 corehole.

ducting a Coal Resources Exploration and Assessment Program (COALREAP) in Pakistan, under the auspices of the U.S. Agency for International Development (USAID) and the Government of Pakistan (GOP). In November 1989, Bruce R. Wardlaw and Jean M. Self-Trail (USGS) and Tariq Masood (GSP) collected samples from the Patala and Nammal Formations at the Nammal Dam section in Nammal Gorge as part of a stratigraphic study of the Paleogene strata of the Salt Range; the purpose was to determine the age and paleoenvironments of the coal beds occurring locally in the Patala Formation in the Salt Range. I conducted additional examination and sampling of the Nammal Dam Paleogene section during February 1990.

Preliminary examination of the foraminiferal assemblages in the USGS samples from the Nammal Dam section suggested that a more detailed biostratigraphic and paleoenvironmental analysis of the Patala Formation could be made at this time because of the significant advances since Haque's (1956) study of planktonic foraminiferal biostratigraphy and of benthonic foraminiferal paleoenvironmental analysis. This new biostratigraphic information may resolve age uncertainty in Pakistan for some of Haque's genera and species that have been incorporated into regional and global interpretations (Banner, 1989).

It is difficult to obtain smaller foraminifers from outcrop samples in the central and eastern parts of the Salt Range because of intense diagenetic alteration of specimens near the surface. However, the availability of samples from the GSP Khairpur 9 corehole in the central Salt Range (fig. E2) made it possible to use smaller foraminifers to study the age and paleoenvironments of the Lockhart Limestone and the Patala and Nammal Formations. Foraminiferal assemblages in the Khairpur 9 corehole indicate that Paleocene units in this area, particularly the Patala, were deposited in shallower marine environments than the same units in the Nammal Gorge area in the western Salt Range. Warwick and Shakoor (1988) and Gee (1989) also proposed shallower water environments in the eastern Salt Range than those found in the western Salt Range. Their proposed paleobathymetric model is based upon the presence of high-sulfur coal beds in the Patala Formation in the central and eastern Salt Range. Intercalation of coal beds and terrestrial facies into the marine sediments suggests shallow-water deposition for the marine strata. The coal facies is missing in the Patala Formation in the western Salt Range, and it appears that the westerly sections were subject to more continuous marine sedimentation and, by implication, accumulated in deeper marine waters.

Acknowledgments

Elizabeth Hill (USGS) prepared the foraminiferal assemblages and illustrations. C. Wylie Poag and Richard Z. Poore (USGS) gave useful advice on the taxonomy of the foraminiferal assemblages. Laurel M. Bybell and Christopher Wnuk (USGS) made helpful suggestions on the manuscript. This work was done as part of the Coal Resources Exploration and Assessment Program in Pakistan, under the auspices of the U.S. Agency for International Development and the Government of Pakistan.

Methods and Materials

Sample Preparation

Foraminiferal samples were taken from the less indurated, more shaly horizons whenever possible. These samples were disaggregated by gently heating and shaking them in a water solution of calcium carbonate. Processing of the more shaly lithology frequently yielded large numbers of smaller foraminifers, which have fair to good preservation. The larger sized planktonic and benthonic foraminifers in these samples usually could be identified at the species level, while immature specimens and smaller sized species were more difficult to identify because they exhibit greater diagenetic alteration. Detailed biostratigraphic and paleoenvironmental interpretations can be made only on the better preserved Punjab samples.

It was necessary to disaggregate samples from moderately to strongly indurated intervals, usually represented by limestone and marl, by means of a process using repeated cycles of heating and cooling of the samples that were submerged in varsol. Samples with this degree of induration usually yielded few smaller foraminifers, and commonly these specimens are so recrystallized that they cannot be identified even at the generic level. These indurated samples could not be used in this study, and the following discussion pertains entirely to the less indurated, more shaly horizons. After disaggregation, the foraminifer-bearing samples were washed through a 63-micrometer (µm) sieve. If most of the foraminiferal specimens in a sample were preserved well enough to be identified at the species level, a microsplitter was used to divide the assemblage into a subsplit of 300–1,000 specimens. The size of the subsplit was determined by the proportion of planktonic to benthonic specimens; the objective was to obtain a sample split that contained about 300 smaller benthonic specimens. The foraminifers were then mounted on microfossil slides and sorted into recognizable species. Smaller benthonic, larger benthonic, and planktonic specimens in the subsplit were counted to determine the proportions of each group in a sample. Preservation varies among the different genera and species. A high degree of recrystallization of smaller specimens probably results in the recognition of fewer species in a sample than actually exist because the different species of the smaller genera, such as *Bolivina*, *Buliminella*, and *Cassidulina*, are not distinguishable in most samples.

Samples

Five USGS samples from the Patala Formation at the Nammal Dam section, western Salt Range, yielded usable foraminiferal assemblages: NP (for Nammal Pass) 3–1, 3–3, 2–1, 2–2, and 2–3 (fig. E3). Samples NP 3–1 and NP 3–3 were collected by B.R. Wardlaw (USGS), and the three other samples were collected by J.M. Self-Trail (USGS) and Tariq Masood (GSP). Samples from the overlying Nammal Formation were also examined, but foraminiferal specimens were so diagenetically altered that few were identifiable at the species level.

Five samples also were examined from less indurated intervals in the Lockhart Limestone, and the Patala and Nammal Formations in the GSP Khairpur 9 corehole (fig. E2), central Salt Range. The GSP geologist for this corehole was Muhammad Anwar, and sampling intervals from the corehole were selected by N.O. Frederiksen and J.M. Self-Trail (USGS). No samples from the eastern Salt Range were available for study.

The foraminiferal assemblage slides from the 10 samples studied are deposited in the Cushman foraminiferal collection at the U.S. National Museum of Natural History (USNM) in Washington, D.C.

Paleogene Stratigraphy at Nammal Dam

Paleocene and Eocene formations in the Nammal Dam section are, from oldest to youngest, the Hangu Formation (mostly sandstone and shale), the Lockhart Limestone, the Patala Formation (mostly shale with subordinate limestone and sandstone beds), the Nammal Formation (dominantly marly shale and marl interbedded with some limestone in the lower part, and mainly limestone interbedded with some shale and marl in the upper part), and the Sakesar Limestone.

Sample locations are shown (fig. E3) on the Nammal Dam stratigraphic section that was measured by Wardlaw and others (this volume, chap. F). Although the samples containing abundant foraminifers can be placed approximately within the earlier published Nammal Gorge section of Haque (1956), there are several differences in the formational thicknesses and boundaries between the section of Wardlaw and others and that of Haque.

The section of Wardlaw and others (this volume, chap. F) was measured on the south wall of an east-branching side canyon leading toward Nammal Dam. The branching is located where the lower part of the Lockhart Limestone is exposed in the floor of the gorge. In this side canyon, the middle part of the Patala Formation forms a low, fairly flat surface traversed by a small stream; this results in poor exposure of the middle beds. This part of the section is represented by the covered interval shown in figure E3.

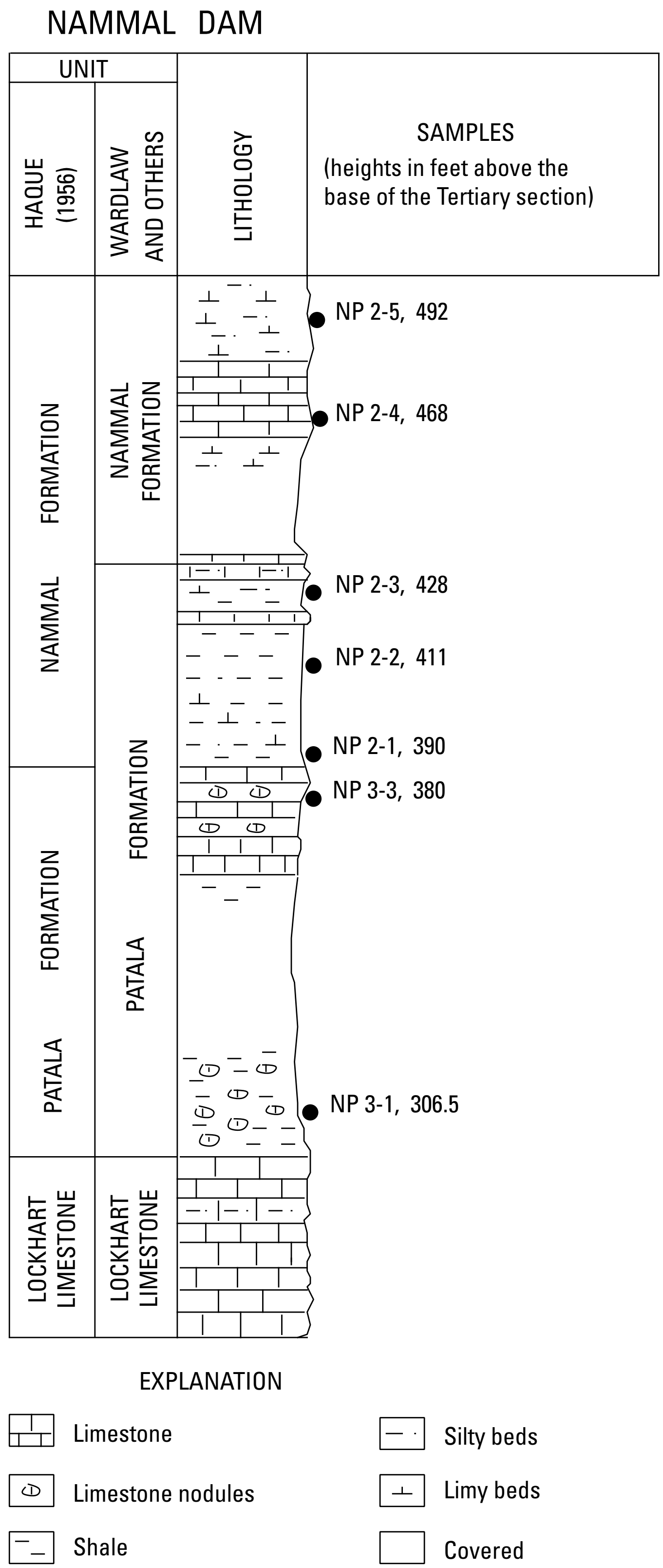

Figure E3. Lithologic section in Nammal Gorge at Nammal Dam measured by Wardlaw and others (this volume, chap. F) showing location of samples (solid circles) studied. Inferred relation of this section with section given by Haque (1956) is shown at left. See figure E2 for location.

Although Haque (1956) did not give a more precise location other than Nammal Gorge for his section, his detailed description does not show a covered interval in the middle of the Patala, suggesting that Haque's section was taken in a different location from the section of Wardlaw and others. A steeply dipping wall on the northward extension of the main gorge beyond the branching of the side canyon to Nammal Dam is the likely place for Haque's section. Examination of my photographs of this northern wall suggests that an apparently complete exposure of the Patala Formation is present there. A photograph of the place of divergence of the side canyon to Nammal Dam and also of the possible northern wall of the gorge sampled by Haque is shown in the work of Davies and Pinfold (1937, pl. 2).

The thickness of the entire Patala Formation in Haque's section is considerably greater than in the section of Wardlaw and others. Haque indicated a thickness of about 340 feet (ft) from the top of the Lockhart Limestone to the top of the dark-gray shales herein placed in the uppermost part of the Patala; this contrasts with a thickness between these same two horizons of approximately 130 ft in the section of Wardlaw and others. The two measured sections are probably from two adjacent canyons, and the reason for the thickness difference is unknown but is possibly due to removal or addition of the section by faulting or inaccurate measurement through the covered interval by Wardlaw and others.

The contact between the Lockhart Limestone and Patala Formation occurs in approximately the same stratigraphic position in both the section measured by Wardlaw and others and the section measured by Haque. However, the contact between the Patala Formation and the overlying Nammal Formation has been placed differently by various workers because of the gradual lithologic change from the shaly Patala to the shaly/limy lower part of the Nammal. Wardlaw and others (fig. E3) placed the boundary at the top of the dark-gray shale, where a significant limestone ledge-forming bed appears; above this point the shales become more calcareous or marly, they are more bluish gray, and limestone interbeds gradually become more common and thicker. Haque (1956) placed the top of his Patala Formation at the base of the dark-gray shale (fig. E3). Thus, these dark-gray shale beds, which are the main focus of the present study, are considered the uppermost part of the Patala by Wardlaw and others and the lowermost part of the Nammal by Haque. Jurgan and others (1988) considered the top of the Patala to occur where the limestone interbeds become considerably thicker and more prominent and dominate the section. This interpretation would place the contact between the Patala and Nammal Formations higher than that of either Haque or Wardlaw and others.

Several interpretations have been made about the nature of the contact between the Patala and Nammal Formations in Nammal Gorge. Davies and Pinfold (1937) proposed an unconformity between the top of the Patala Formation and the overlying Nammal Formation, but Haque (1956) showed the succession as continuous and conformable. Adams (1970) placed an unconformity between the Patala and Nammal Formations based upon his interpretation of the larger foraminiferal change reported by Davies and Pinfold (1937). Wardlaw (oral commun., 1990) proposed a disconformable contact on the basis of the lithologic change and the presence of clasts in the base of his Nammal Formation. Because of the range of formational boundaries that have been identified in this gradational section, any hypothesis about the nature of this contact must take into account that different workers are discussing different horizons.

Age and Planktonic Foraminiferal Biostratigraphy

The Patala Formation in the Salt Range was considered to be of early Eocene age in early studies (Davies and Pinfold, 1937). Smoot and Haque (1956) subsequently placed both the underlying Lockhart Limestone (equivalent to the Khairabad Limestone) and the Patala Formation in the upper Paleocene on the basis of the larger foraminiferal assemblages. Haque (1956) tentatively considered the Patala to be of late Paleocene age on the basis of the overall age relation of the few smaller benthonic foraminifers that he found in the formation. The Patala Formation was retained in the upper Paleocene by Shah (1977). Haque (1956) considered the lowermost shaly strata of the Nammal Formation to be of late Paleocene age on the basis of the smaller benthonic and planktonic foraminifers. Haque correlated the Nammal with the Midway Group of the U.S. Gulf Coast; however, this placement is too old, as indicated by data from this study. Haque considered the remainder of the Nammal to be early Eocene in age, and Shah (1977) maintained this age placement. Haque's paper was published at a time when the biostratigraphic importance of planktonic foraminiferal species was just beginning to be recognized. However, his accurate identification and illustration of several planktonic species from the Nammal Gorge section (*Morozovella acuta* and *M. velascoensis*) allowed subsequent workers to recognize these species and revise the age of the lower part of the Nammal Formation to the late Paleocene (McGowran, 1968; Banner, 1989).

A more precise age within the late Paleocene is not possible on the basis of the species that Haque recorded. There are additional biostratigraphically useful species in the current samples, however, that make possible a more refined age assignment, as discussed below. These biostratigraphically useful specimens come from what Haque (1956) considered to be the basal part of the Nammal Formation, but what Wardlaw and others (this volume, chap. F) now consider the uppermost part of the Patala Formation.

The age determination of the remainder of the lowermost part of the Nammal Formation depends upon Haque's reported upper range of *M. velascoensis*. Foraminiferal specimens from

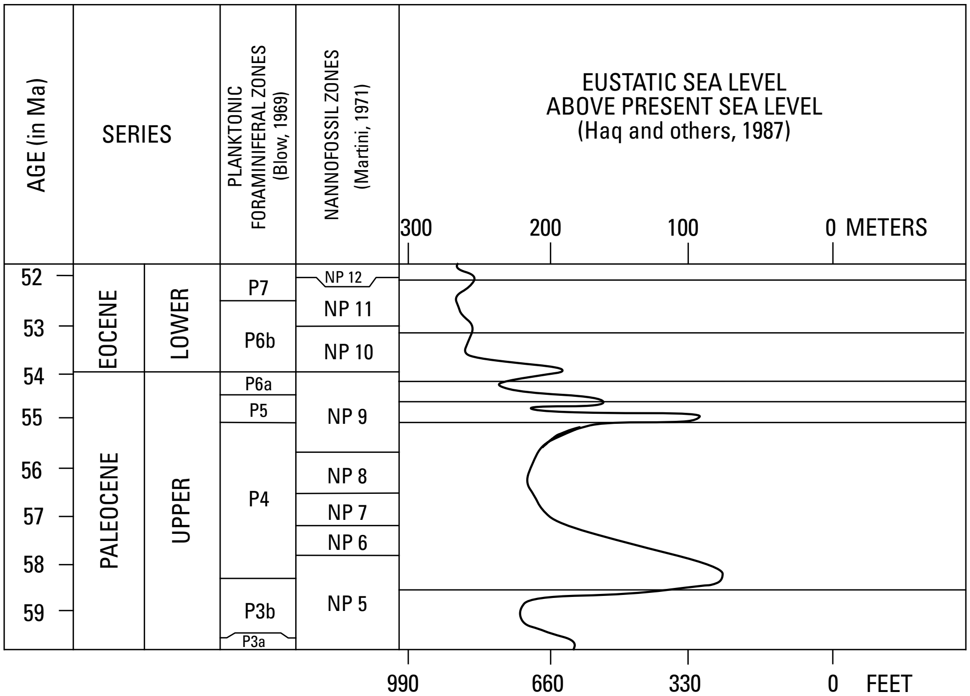

Figure E4. Age relations of planktonic foraminiferal zones, calcareous nannofossil zones, and eustatic sea-level changes.

our samples from approximately equivalent intervals are too recrystallized to use for dating.

The age ranges of the planktonic species are taken from Stainforth and others (1975), Blow (1969, 1979), and Toumarkine and Luterbacher (1985). Figure E4 shows the planktonic foraminiferal and calcareous nannofossil zonations across the Paleocene-Eocene boundary and the eustatic sea-level curves proposed for this part of the Paleogene by Haq and others (1987).

Nammal Dam Section

Lockhart Limestone

Our samples from the Lockhart Limestone in the Nammal Dam section contain only highly recrystallized foraminifers. Accurate identifications are not possible.

Patala Formation

Samples NP 3–1 of Wardlaw and others (fig. E3) from the lower part of the Patala Formation in the Nammal Dam section and NP 3–3 from the lower beds of the upper part of the Patala contain only a few immature planktonic foraminiferal specimens that compose only 0.7 percent and 2.7 percent, respectively, of the smaller foraminiferal assemblage (table E1 and fig. E5). These few specimens represent a low-diversity, non-age-diagnostic assemblage composed mainly of species of *Subbotina*. Haque (1956) reported no planktonic specimens from the lower part of the Patala and only three long-ranging planktonic species from his upper part of the Patala.

The three samples in the dark-gray shale at the top of the Patala, namely, NP 2–1, NP 2–2, and NP 2–3 (fig. E3), contain abundant planktonic specimens (table E1). The proportion of planktonic specimens relative to benthonic specimens, as well as the planktonic species diversity, increases upward from the lowest of these Patala samples to the uppermost (fig. E5 and table E1).

Sample NP 2–1, which has the lowest planktonic percentage of the upper three samples, 24.6 percent (fig. E5 and table E1), contains a moderately diverse planktonic assemblage that includes the following species: *Cheiloguembelina midwayensis nammalensis* (Haque), *Globanomalina ovalis* Haque, *Morozovella acuta* (Toulmin), *M. aequa* (Cushman & Renz), and *M. subbotinae* Morozova.

The presence of *M. subbotinae* in this sample, which is late Paleocene based on the presence of the late Paleocene marker species *M. velascoensis* in the two overlying samples, indicates placement in the latest Paleocene *M. velascoensis/M. subbotinae* Zone, or Zone P6a of Blow (1969) (fig. E4). This zone is equivalent to the upper part of the *M. velascoensis* Zone of Toumarkine and Luterbacher (1985). The calcareous nannofossil assemblage from the same sample also indicates a late late Paleocene age; this sample can be placed in the upper quarter of calcareous nannofossil Zone NP 9 of Martini (1971) (Bybell and Self-Trail, this volume, chap. B).

The overlying sample NP 2–2 contains more abundant (49.1 percent) planktonics (fig. E5 and table E1) and a more diverse planktonic foraminiferal assemblage than does sample

Table E1. Counts of the various foraminiferal components in assemblages from the Patala Formation in the Nammal Dam section.

[Smaller benthonic species are less than 250 µm in maximum dimension; larger benthonic species are more than 250 µm in maximum dimension]

Sample no.	Total foraminiferal specimens	No. of specimens: Smaller benthonics	Larger benthonics	Planktonics	Planktonic percentage*	No. of smaller benthonic species	tau values**
NP 2–3	1,238	540	0	698	56.4	31	1,748
NP 2–2	1,024	459	62	503	49.1	23	1,129
NP 2–1	1,045	732	56	257	24.6	25	615
NP 3–3	879	776	79	24	2.7	22	59
NP 3–1	595	591	0	4	.7	18	13

* Planktonic percentage is the percentage of the total number of foraminiferal specimens that is planktonic.

** The tau values are obtained by multiplying the planktonic percentages times the number of smaller benthonic species (Gibson, 1988).

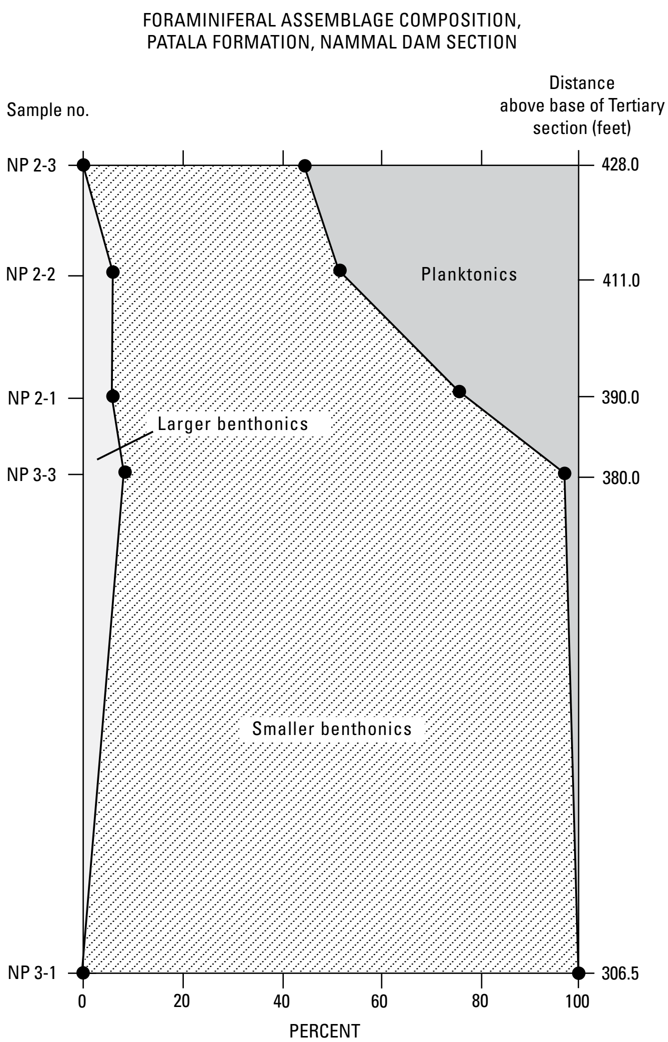

Figure E5. Upward increase in the proportion of planktonic foraminifers and the changes in abundance in the smaller and larger benthonic foraminifers in samples from the Patala Formation at the Nammal Dam section. Data plotted are in table E1.

NP 2–1. The biostratigraphically most important species from this sample are *Acarinina soldadoensis soldadoensis* (Bronnimann), *A. wilcoxensis* (Cushman & Ponton), *Cheiloguembelina midwayensis nammalensis* (Haque), *Globanomalina ovalis* Haque, *G. simplex* Haque, *Morozovella acuta* (Toulmin), *M. aequa* (Cushman & Renz), *M. occlusa* (Loeblich & Tappan), *M. quetra* (Bolli), *M. subbotinae* (Morozova), *M. velascoensis* (Cushman), and *Subbotina velascoensis* (Cushman).

The co-occurrence of *M. velascoensis*, *M. subbotinae*, and *M. quetra* also places this sample in the latest Paleocene *M. velascoensis/M. subbotinae* Zone, or Zone P6a of Blow (1969).

The uppermost Patala sample NP 2–3 contains the highest percentage of planktonic foraminiferal specimens (56.4 percent; fig. E5 and table E1) of any of the Patala samples at this locality. The planktonic assemblage in sample NP 2–3 is similar to that found in NP 2–2; however, *M. velascoensis* specimens are much more abundant in sample NP 2–3 than in NP 2–2; this abundance may reflect the deeper water depositional environment postulated for sample NP 2–3. The biostratigraphically important planktonic foraminiferal species found in sample NP 2–3 are *Acarinina soldadoensis soldadoensis* (Bronnimann), *Cheiloguembelina midwayensis nammalensis* (Haque), *Globanomalina ovalis* Haque, *G. simplex* Haque, *Morozovella acuta* (Toulmin), *M. aequa* (Cushman & Renz), *M. subbotinae* (Morozova), *M. marginodentata* (Subbotina), and *M. velascoensis* (Cushman).

The co-occurrence of *M. velascoensis*, *M. subbotinae*, and *M. marginodentata* indicates that this sample also should be placed in the *M. velascoensis/M. subbotinae* Zone, or Zone P6a of Blow (1969) (fig. E4).

Nammal Formation

Our samples from the Nammal Formation at Nammal Dam contain only highly recrystallized foraminifers. Planktonic specimens, particularly species of *Acarinina* and *Subbotina*, are common in the Nammal Formation, but accurate identification is not possible because of their poor state of preservation.

The comparable position of our sample NP 2–3 in Haque's (1956) section can be determined with certainty, as numerous foraminiferal species, such as *Marginulina glabra nammalensis* Haque, *Vaginulinopsis saundersi* (Hanna and Hanna), *Uvigerina subproboscidea* Haque, and *Coleites ornatus* Haque, which are found in NP 2–3, were reported by Haque (1956) to occur only in his sample B77 or immediately adjacent samples. Haque's sample B77 is located at the top of a relatively thick dark-gray shale and immediately below a limestone ledge. Our sample NP 2–3 also is located at the top of a dark-gray shale sequence and just below a limestone ledge.

Haque (1956) reported *M. velascoensis* in his samples B68–B83, which span the lower 85 ft of his Nammal Formation from its base to the top of the marly shale just below the limestone in which our sample NP 2–4 was taken (fig. E3); his illustrated specimen from sample B77 appears to be representative of this species. The last appearance of *M. velascoensis* marks the top of the *M. velascoensis* zone (the top of the Paleocene in most intercontinental zonations, that is, the zonations of Stainforth and others, 1975; Berggren and others, 1985; Toumarkine and Luterbacher, 1985; Haq and others, 1987), and this occurrence places the lower part of the Nammal Formation of Haque (1956), as well as that of Wardlaw and others (this volume, chap. F), into the latest Paleocene.

The placement by Wardlaw and others (this volume, chap. F) of the lowermost shale unit of Haque's (1956) Nammal Formation into the uppermost part of their Patala Formation (this includes Haque's samples B68–B77) still leaves approximately the lower 40 ft of their Nammal Formation (Haque's samples B78–B83) in the latest Paleocene by virtue of Haque's identification of *M. velascoensis* in these beds. Samples from this interval were not available for examination, and I could not confirm the identification of this species in these beds.

The preservation of foraminifers generally deteriorates upward in the Nammal Formation, and it is possible that even more of the Nammal could contain *M. velascoensis* and also be of latest Paleocene age. Foraminifers in samples NP 2–4 and NP 2–5 in the lower part of the Nammal and in the seven samples in the Nammal Formation above NP 2–5 are too highly recrystallized for accurate identification.

McGowran (1968) examined the faunal list and illustrations in Haque (1956); he considered that some of the lowest beds in the Nammal Formation, which Haque considered to be early Eocene in age, were late Paleocene in age. I concur with this later placement. McGowran's reinterpretation of Haque's figure of *M. aragonensis* (Nuttall) as being of *M. occlusa* (Loeblich and Tappan) agrees with our samples from the same interval; abundant *M. occlusa* are present, whereas *M. aragonensis* is absent.

McGowran also considered that Haque's illustrated specimen of *Pseudogloborotalia membranacea* (Haque, 1956, pl. 22, figs. 3a, b), which is from strata that all workers consider to be the Patala Formation, belonged instead to *Globorotalia* (=*Planorotalites*) *pseudomenardii* (Bolli); the latter species is characteristic of late Paleocene Zone P4 (fig. E4). Haque's illustrated specimen from the Patala is from his sample B46, which is from approximately the same stratigraphic position as our sample NP 2–1. The planktonic foraminifers and calcareous nannofossils from sample NP 2–1 indicate a younger placement in the late Paleocene, in Zone P6a, as discussed above. In my opinion, this illustration is inconclusive as to which species of the *Planorotaloides* complex this figure belongs. My examination of the planktonic assemblages from the Nammal Dam samples shows that although several species, such as *P. planoconica* Subbotina, of the *Planorotalites* complex are present, *P. pseudomenardii* is not present, and McGowran's reidentification of this figure of Haque is considered to be incorrect.

Haq (1971), in the initial study of calcareous nannofossils from the Patala Formation in Nammal Gorge, placed this formation in the *Discoaster multiradiatus* Zone (=Zone NP 9 of Martini (1971)) (fig. E4). Köthe (1988), from her study of dinoflagellates and calcareous nannofossils that she collected in the Patala Formation at Nammal Gorge, correlated this formation with calcareous nannoplankton Zones NP 8 and NP 9. However, Köthe did not give detailed stratigraphic sections and locations for her samples, and it is not possible to correlate her samples with those collected in the current study of the Nammal Dam section. The strata placed in Zone NP 8 by Köthe are presumably from the lower part of the Patala; their placement in Zone NP 8 is not based upon the calcareous nannofossils but upon an indirect correlation of the first occurrence of the dinoflagellates *Apectodinium*. Unfortunately, Köthe did not obtain both diagnostic calcareous nannofossils and dinoflagellates from the same set of samples in many of her studied sections in Pakistan; thus, the equivalence of her dinoflagellate zonation and the standard calcareous nannofossil zonation remains somewhat uncertain. Her placement of the upper beds of the Patala at Nammal Gorge into Zone NP 9 agrees with the current placement based on planktonic foraminifers. The more refined placement of the uppermost part of the Patala into planktonic foraminiferal Zone P6a or the upper part of Zone NP 9, done herein on the basis of the planktonic foraminifers, is corroborated by the most recent examination of the calcareous nannofossils from the same Nammal Dam samples.

Bybell and Self-Trail (this volume, chap. B) found calcareous nannofossils characteristic of Zone NP 9 in sample NP 3–3 and an assemblage characteristic of the upper quarter of Zone NP 9 in samples NP 2–2 and 2–3; sample NP 3–1 from the lower part of the Patala was barren of calcareous nannofossils.

Khairpur 9 Corehole

Abundant smaller benthonic foraminifers are present in the five samples prepared from the less indurated intervals in

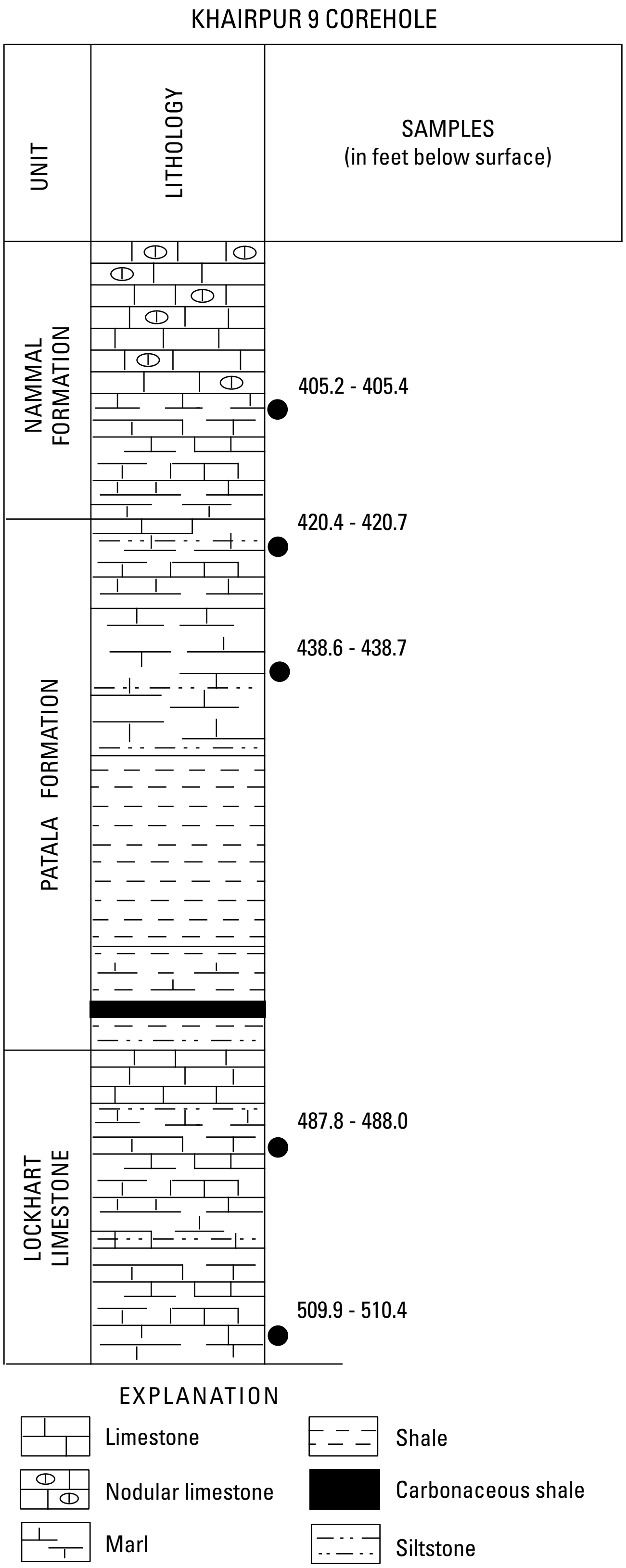

Figure E6. Lithologic section of examined part of the Khairpur 9 corehole and location of samples (solid circles). Total depth of corehole is 514 ft; samples are shown in feet below surface. See figure E2 for location.

the Khairpur 9 corehole (fig. E6). Few planktonic specimens were recovered from the five samples, and they do not yield any detailed biostratigraphic information.

Two samples were examined from the Lockhart Limestone. The sample at 487.8–488.0 ft contains only two specimens of the planktonic foraminifer *Globanomalina ovalis* Haque, which has an undetermined range in the late Paleocene and earliest Eocene. The other Lockhart sample at 509.9–510.4 ft contains no planktonic specimens. The sample from the Patala Formation at 420.4–420.7 ft does not contain any planktonic specimens, and the sample at 438.6–438.7 ft has only a single *Globanomalina ovalis*. The one sample examined from the Nammal Formation (fig. E6) contains only two planktonic specimens; one is a broken juvenile specimen of the genus *Acarinina* sp. and the other belongs in *Globanomalina ovalis*, which indicates only late Paleocene to earliest Eocene age.

Bybell and Self-Trail (this volume, chap. B, fig. B6) were able to use calcareous nannofossils to date some of the samples from the Khairpur 9 corehole. Their lowest Lockhart Limestone sample at 509.9 ft is placed in Zone NP 6 (fig. E4), of early late Paleocene age. The sample from the Patala Formation at 438.6 ft is placed in Zone NP 9, of late late Paleocene age. The upper part of the Nammal Formation, at 225.5 ft, was placed in Zone NP 11 of early Eocene age, but samples from the lower part of the Nammal were not datable.

Benthonic Foraminiferal Biostratigraphy

Not enough is presently known about the biostratigraphic distribution of smaller benthonic foraminifer species occurring in the upper Paleocene and Eocene strata of the Punjab to allow this group to be used for correlation. The only studied and published section of the biostratigraphic distribution of smaller benthonic species in the Salt Range is that of Haque (1956). Haque found that a significant number of benthonic species are restricted to only a small part of the Nammal Gorge upper Paleocene and lower Eocene section. However, the distribution of smaller benthonic species, as well as larger ones, is to a greater or lesser degree controlled by paleoenvironmental factors. Thus, the biostratigraphic applicability of the species ranges from the Nammal Gorge sections to other localities in the Punjab and other parts of Pakistan is to a large extent controlled by the similarity in paleoenvironments among the different areas.

Anomalinoides bandyi (Haque) is one example in the present study where the changes in the depositional environment through time varied at different localities and resulted in differing stratigraphic ranges for this benthonic species. Haque reported this species only from the Lockhart Limestone and Patala Formation (of Haque) in the Nammal Gorge section in the western Salt Range; these formations were considered by Haque (and also by myself) to be of shallow-marine origin in the area of the gorge. This species is absent from the shale at the base of the Nammal Formation of Haque (1956) (the uppermost bed of the Patala of Wardlaw and others, this volume, chap. F) and throughout the remainder of the Nammal. I consider these beds to have been deposited in marine environments of considerably deeper water, as discussed below. Thus *A. bandyi* appears to be found only in shallow-marine environments, as is true of many other species of this genus. In the Khairpur 9 corehole in the central Salt Range, however, where the Lockhart Limestone and the Patala and Nammal Formations were all deposited in shallow-marine environments, *A. bandyi* exhibits a considerably longer stratigraphic range by occurring in all three formations.

Other environmentally sensitive species show a similar extension of their stratigraphic range to the east in the central part of the Salt Range (in the Khairpur 9 corehole), where the paleobathymetry remained shallow throughout deposition of the Lockhart Limestone and the Patala and Nammal Formations; these species have a shorter range in the western Salt Range in the Nammal Gorge section, where only the Lockhart and lower and middle parts of the Patala were deposited in shallow neritic environments, and the paleobathymetry became considerably deeper during deposition of the upper part of the Patala and Nammal Formations. *Sakhiella nammalensis* Haque is found only in the upper middle part of the Patala at Nammal Dam but occurs in the Lockhart Limestone and the Patala and Nammal Formations in the Khairpur 9 corehole. *Woodella nammalensis* Haque, known only from the upper middle part of the Patala at Nammal Dam, is found in the Lockhart Limestone and Patala Formation in the Khairpur 9 corehole.

Geographic differences in the stratigraphic range of some benthonic species are not always easily correlatable to paleobathymetric changes. Many other specific environmental factors, some not readily correlative with water depth, may also control the distribution of a species. *Pseudowoodella mamilligera* Haque is restricted to the upper part of the Patala Formation and lower part of the Nammal Formation at Nammal Dam, occurring in an interval characterized by middle to outer neritic environments, but this species has a longer range through the Lockhart Limestone and the Patala and Nammal Formations in the Khairpur 9 corehole, where it occurs in sediments deposited in inner neritic environments.

Thus, the biostratigraphic use of smaller benthonic species will have to be examined carefully in a number of geologic sections to ascertain the true first and last occurrences of particular species. With more study, the range of these benthonic species can be correlated with the biostratigraphic ranges of planktonic foraminifers and calcareous nannofossils in order to determine the actual overall ranges of the benthonic species, not just their paleoenvironmentally controlled local ranges.

Because many of the Paleocene and Eocene exposures in the Punjab consist largely of strata deposited in shallow-water environments and thus have sparse planktonic foraminifers, it will be quite useful to develop a series of benthonic foraminiferal zones for local and possibly regional correlation. Even in the present limited study, some species appear to be restricted to a single horizon or formation both at Nammal Dam and in the Khairpur 9 corehole. For example, *Ornatanomalina geei* Haque, a robust form that seems to be moderately resistant to diagenetic effects, is found only in the Lockhart Limestone in both study areas and may prove to be biostratigraphically useful.

Bias in the quality of preservation of specimens is an additional complicating factor in determining species ranges, particularly for the smaller benthonic species ranges in Pakistan. The poor preservation found in foraminiferal assemblages in many intervals, particularly in the more highly recrystallized carbonate strata, makes it difficult to determine the true species ranges.

Paleoenvironments

The Patala Formation becomes thinner to the east of Nammal Gorge and contains thin coal beds along with elongate quartzose sand bodies in the central and eastern part of the Salt Range according to Warwick and Shakoor (1988), Gee (1989), and Warwick and Husain (1990). These authors proposed that the Patala strata in the central and eastern Salt Range were deposited in back-barrier and other freshwater to near-marine environments, as indicated by the presence of the coal beds. No Paleocene coal beds are present in the western Salt Range; thus, they considered that the Patala strata in the Nammal Gorge area were deposited in somewhat deeper water, open-marine environments.

Foraminiferal assemblages from the Patala Formation in the Nammal Dam section in the western Salt Range and from the Khairpur 9 corehole in the central Salt Range (fig. E2), where the Patala contains coal, were examined to determine the depositional setting for these units in the two areas. Foraminiferal assemblages were also examined from the overlying Nammal Formation and the underlying Lockhart Limestone in the Khairpur 9 corehole for comparison with the Patala assemblages. Fairly well preserved foraminiferal assemblages occur in a few intervals in all three formations in the Khairpur 9 corehole; however, at Nammal Dam, adequately preserved assemblages were found only in the Patala Formation.

The paleoenvironmental interpretations, mainly paleobathymetric, determined in this study are based upon both the total foraminiferal assemblage characteristics and the presence of particular foraminiferal genera and species in the samples.

The papers cited in subsequent paragraphs discuss the relation between bathymetry and the distribution of various foraminiferal assemblage characteristics. These papers also contain extensive bibliographies of earlier studies. In addition, the foraminiferal compilations of Murray (1973, 1991), Boltovskoy and Wright (1976), and Haynes (1981) also contain additional information concerning the assemblage characteristics discussed below.

The paleoenvironmental analyses presented in this study are based on the following characteristics and bathymetric patterns of assemblages:

1. Increasing benthonic species diversity with increasing water depth (Gibson and Buzas, 1973),
2. Increasing percentage of planktonic foraminiferal specimens within an assemblage with increasing water depth (Gibson, 1989),
3. Increasing tau values (defined as the mathematical product of planktonic percentage times the number of smaller benthonic species (Gibson, 1988)) with increasing water depth,
4. Restriction of certain genera and species to specific bathymetric intervals, both in the living and in earlier Cenozoic assemblages (Phleger, 1960; Murray, 1973; Berggren and Aubert, 1975; Van Morkhoven and others, 1986; Olsson and Wise, 1987),
5. Occurrence or increasing abundance of larger foraminiferal specimens interpreted to indicate shallow-marine waters (a maximum depth limit of 35 meters (115 ft) for most genera is given by Murray (1973)) in the photic zone, and
6. The presence of diverse planktonic assemblages that include species of *Morozovella* and *Acarinina*, which are interpreted to indicate accumulation in deeper waters than low-diversity assemblages mainly composed of *Subbotina* species.

The provincialism of some benthonic genera and species that are common in the Salt Range Paleogene assemblages makes paleoenvironmental determination more difficult because these taxa are absent from other areas where foraminiferal paleoenvironmental relationships have been studied. This limitation is particularly marked at the species level, but it extends also to the generic level; species belonging to the genera *Ornatanomalina*, *Sakhiella*, *Woodella*, and *Pseudowoodella* are common to abundant components of the benthonic assemblage in many samples examined in this study, but these genera presently appear to be endemic to Pakistan. It will be necessary to establish the paleoenvironmental limits for these taxa by relating their occurrences to regional lithofacies associations and to distribution with other, better understood foraminiferal paleoenvironmental indicators.

Nammal Dam Section

Detailed foraminiferal data for the five samples studied from the Patala Formation in the Nammal Dam section are given in figure E5 and table E1. The samples are discussed from oldest to youngest (fig. E3).

Sample NP 3–1.—The diversity of smaller benthonic species, 18, is the lowest in sample NP 3–1 of all the samples. The dominant benthonic species are *Asterigerina cuniformis* Haque, *Cibicides* sp., and *Nonion* sp. cf. *N. graniferum* (Terquem). The very small planktonic foraminiferal component (0.7 percent of the total smaller foraminiferal specimens) consists of immature specimens of *Subbotina*.

Sample NP 3–1 has a low tau value of 13 (table E1); its dominant benthonic species belongs to the genus *Asterigerina*, a genus considered characteristic of normal-marine, inner shelf environments (Murray, 1973; Boltovskoy and Wright, 1976; Haynes, 1981). These results suggest deposition in inner neritic water depths of less than 100 ft. The absence of larger foraminifers from this sample may indicate waters of slightly lower than normal open-ocean salinity because most living, larger foraminiferal species occur in fully marine to slightly hypersaline environments (Murray, 1973).

Sample NP 3–3.—This sample has 22 smaller benthonic species. The assemblage is dominated by both *Asterigerina texana nammalensis* Haque and larger foraminiferal specimens. Other relatively abundant or characteristic benthonic species in this sample are *Nonionella* spp. (including *N. lakiensis* Haque), a large *Neorotalia* sp., *Woodella nammalensis* Haque, *W. granosa* Haque, *Cibicides alleni* (Plummer), and *Sakhiella nammalensis* Haque. The relatively small planktonic component (2.7 percent) consists predominantly of immature planktonic specimens.

The moderately low tau value of 59, together with the dominance of the shallow-water benthonic species *A. texana nammalensis* and *C. alleni* (the latter considered characteristic of nearshore to shallow-shelf environments by Olsson and Wise (1987)), suggests deposition in shallow, inner neritic, open-marine water, no deeper than 100–150 ft. The precise depth distributions of the other characteristic benthonic species in this sample, *Woodella* spp. and *S. nammalensis*, are not known directly, but their widespread abundance in all the shallow-water facies in the Khairpur 9 corehole and absence from the deeper water facies in the Nammal Dam section suggest that they live in very shallow marine environments (Warwick and Shakoor, 1988; Gee, 1989).

Sample NP 2–1.—This sample contains 25 smaller benthonic species. The dominant foraminifers in this sample are *Cibicides alleni* (Plummer) and larger foraminiferal specimens. Other important constituents are *Nonionella* spp., *Elphidium* sp., and *Anomalinoides acutus* (Plummer). Small numbers of specimens of *Uvigerina* sp. and *Bolivina* spp. are recorded for the first time in Nammal Gorge. The considerably higher planktonic component (24.6 percent) contains some mature specimens of *Morozovella acuta*, *M. aequa*, and *M. subbotinae*.

The considerable increase in tau value to 615, along with the initial appearance of *A. acutus* (considered by Olsson and Wise (1987) to be characteristic of middle to outer shelf depths), suggests deposition in middle neritic depths of 150–300 ft.

Sample NP 2–2.—In this sample, planktonic specimens compose 49.1 percent of the assemblage. Important benthonic species are *Nonionella* sp., *Alabamina wilcoxensis* Toulmin, *C. alleni* (Plummer), *A. acutus* (Plummer), *Elphidium* sp., *Coleites ornatus* Haque, and *Quinqueloculina gapperi* Haque (the species used by Haque as the marker species for his Zone III or the upper dark-gray shale bed of the Patala). Specimens of *Bulimina*, *Bolivina*, and *Uvigerina* are more abundant in this sample than in the underlying strata.

An increase in the tau value to 1,129, the presence of *A. acutus*, and the increasing abundance of *Bulimina*, *Bolivina*, and *Uvigerina* suggest that these sediments were deposited in middle neritic depths of around 300 ft that contained lowered oxygen levels. The presence of *C. alleni*, a species considered characteristic of inner to inner middle neritic depths, as well as the presence of *Elphidium* sp., a genus mostly characteristic of inner neritic depths, would appear to limit the sample to no greater than middle neritic depths.

Sample NP 2–3.—This sample has the highest number of smaller benthonic species, 31, and the highest proportion of planktonic specimens, 56.4 percent, and thus has the highest tau value of 1,748. No single benthonic species dominates the assemblage, but species of *Bolivina*, *Bulimina*, and *Uvigerina* are the most abundant. Numerous species that appear for the first time in this sample are *Uvigerina subproboscidea* Haque, *Tappanina selmensis* (Cushman), *Cibicidoides* sp., *Tritaxia midwayensis* (Plummer), *Vaginulinopsis saundersoni* (Hanna and Hanna), *Marginulina glabra nammalensis* Haque, *Nodosaria nammalensis* Haque, and *Frondicularia* sp. cf. *F. tenuissima* Hantken.

Deposition in outer neritic water depths of approximately 300–600 ft is suggested by the following: the high tau value; the diverse planktonic assemblage, which contains abundant adult specimens of *Morozovella*, especially *M. velascoensis*; the complete absence of the larger foraminifers and the smaller foraminifers *Elphidium* sp. and *C. alleni*; the dominance of the benthonic assemblage by species of *Uvigerina*, *Bolivina*, *Bulimina*, and lagenids; and the presence of *Tappanina selmensis* (considered a predominantly outer neritic species by Van Morkhoven and others (1986)).

Khairpur 9 Corehole

The five samples examined from the Khairpur 9 corehole, located in the Salt Range to the east of the Nammal Dam section, come from three formations and are discussed from oldest to youngest (fig. E6).

Lockhart Limestone

Most of the Lockhart Limestone in the Khairpur 9 corehole is made up of limestone and indurated marl, but some softer, shaly intervals in the lower part of the formation contained the following two relatively well-preserved foraminiferal assemblages.

Sample at 509.9–510.4 ft.—The dominant benthonic species is *Anomalinoides bandyi* (Haque); other common species are *Asterigerina texana nammalensis* Haque, *Sakhiella nammalensis* Haque, *Cibicides alleni* (Plummer), *Cibicides* sp., and *Elphidium* sp. Larger foraminiferal specimens are abundant; planktonic specimens are absent.

Cibicides alleni is considered to be characteristic of nearshore and shallow-shelf environments (Olsson and Wise, 1987). *Asterigerina* is considered to be characteristic of normal-marine, inner shelf environments (Murray, 1973; Boltovskoy and Wright, 1976; Haynes, 1981). The other common benthonic species are all characteristic of the strata that were interpreted in this study on the basis of foraminiferal data from the Patala Formation in the Nammal Dam section as having been deposited in shallow, inner neritic environments. The abundance of larger foraminifers and the total absence of planktonic specimens also suggest very shallow, open-marine waters that probably were less than 100 ft deep.

Sample at 487.8–488.0 ft.—The common benthonic species are *Ornatanomalina geei* Haque, *Cibicides* sp., *Pseudowoodella mamilligera* Haque, and *Sakhiella nammalensis* Haque. Larger foraminifers are abundant; only two planktonic specimens are present.

Most of the benthonic species and genera occurring in this sample are endemic to Pakistan. These same taxa are found in Patala strata that are interpreted on other faunal evidence as having been deposited in shallow water in the Nammal Dam section. The presence of these genera and species, combined with the presence of abundant larger foraminifers and very few planktonic specimens, suggests deposition in shallow, inner neritic, open-marine environments at water depths probably less than 100 ft.

Patala Formation

The lower part of the Patala Formation in the Khairpur 9 corehole is dominated by shale, but it also contains a highly carbonaceous shale interval. Two relatively well-preserved foraminiferal assemblages occur in the marl and limestone beds that make up the upper part of the formation.

Sample at 438.6–438.7 ft.—The smaller benthonic assemblage in the sample is dominated by *Asterigerina texana nammalensis* Haque. Other important species are *Woodella nammalensis* Haque, *Sakhiella nammalensis* Haque, *Cibicides* sp., and *Pseudowoodella mamilligera* Haque. Larger foraminifers are abundant, but no planktonic specimens are present.

The benthonic assemblage is dominated by *Asterigerina* and larger foraminifers, which are both considered indicative of open-marine, inner neritic environments. This conclusion is supported by the species composition of the remaining important smaller benthonic species (for example, the endemic species that were determined to occur in shallow, inner neritic environments of the Patala at Nammal Dam as interpreted from the lithofacies patterns and other foraminiferal evidence) and by the absence of planktonic specimens. All of these characteristics suggest a shallow, inner neritic, open-marine depositional environment that was probably less than 100 ft deep.

Sample at 420.4–420.7 ft.—Asterigerina texana nammalensis Haque is the most abundant smaller benthonic species in the sample. *Sakhiella nammalensis* Haque and *Cibicides* sp. also are common. Larger foraminifers are abundant; planktonic specimens are absent.

These characteristics suggest deposition in a shallow, inner neritic, open-marine environment less than 100 ft deep.

Nammal Formation

The upper part of the Nammal Formation in the Khairpur 9 corehole is a nodular limestone; the lower part consists of interbedded limestone and marl that yielded one useful foraminiferal sample at 405.2–405.4 ft. The sample is dominated by *Cibicides* sp. and larger foraminifers. Other important benthonic species are *Pseudowoodella mamilligera* Haque, *Anomalinoides bandyi* Haque, *Sakhiella nammalensis* Haque, *Elphidium* sp., and *Asterigerina texana nammalensis* Haque. Only two planktonic specimens are present.

The benthonic species present, the abundance of larger foraminifers, and the sparsity of planktonic specimens are characteristics similar to the other samples in the Khairpur 9 corehole and suggest deposition in shallow, inner neritic paleoenvironments less than 100 ft deep.

Regional Relations

The three formations that were studied from the Khairpur 9 corehole all appear to have been deposited predominantly in very shallow marine environments less than 100 ft deep. The changes in lithology from carbonate to shale, thus, must be largely related to the supply of fine clastic material to this area rather than to water depth. The presence of back-barrier coal beds in the central and eastern Salt Range indicates periodically lowered sea levels in this area. Nevertheless, the major part of all three formations in the central Salt Range, as interpreted from the foraminiferal assemblages examined herein, was deposited in very shallow, open-marine environments rather than in restricted, brackish environments.

At Nammal Dam, the foraminiferal assemblages from the lower and middle parts of the Patala Formation also were deposited in very shallow marine, or possibly even marginal-marine environments in the case of the lowest sample. There is little difference in water depth between the two areas except for the upper dark-gray shale of the Patala Formation in the Nammal Dam section. The middle to outer neritic environments represented in this upper shale indicate deposition in much deeper water than any found to date in the central and eastern Salt Range.

The deepening paleobathymetric trend in the uppermost Paleocene in the western Salt Range may be a result of eustatic sea-level change in the latest Paleocene, localized tectonic downwarp, or a more regional downwarp. Detailed biostratigraphic and paleoenvironmental examination of sections in surrounding areas of the southern Punjab, Sindh, and Baluchistan can help determine the dominant cause of this paleobathymetric increase.

In the Nammal Dam section, the water depth increases from approximately 100–150 ft in the middle Patala to about 300–600 ft in the uppermost part of the Patala. This represents a minimum increase of about 150 ft, or a maximum increase of about 500 ft. Haq and others (1987) indicated a sea-level rise of about 150 ft within Zone P6a (the upper part of Zone NP 9) (fig. E4). Thus, the minimum water depth increase at Nammal Dam concurs with the postulated global sea-level rise. If the water depth increase at Nammal Dam is considerably greater than 150 ft, it appears that, in addition to possible global sea-level rise, other forces are involved.

The recognition, to date, of the occurrence of a latest Paleocene bathymetric deepening trend only at Nammal Dam in the western Salt Range, and not farther to the east in the Salt Range, suggests that it is controlled by local or larger scale tectonics. It is possible, however, that nonrecognition of deep-water strata in the Khairpur 9 corehole in the central Salt Range may be because (1) sampling missed deep-water parts of this interval, (2) poor preservation of the foraminiferal assemblages resulted in their not being paleobathymetrically identifiable, or (3) the deeper water strata were subsequently eroded from the section. Increased biostratigraphic and paleoenvironmental control will be needed in the central and eastern Salt Range to evaluate these possibilities.

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