Regional Studies of the Potwar Plateau Area, Northern Pakistan

Edited by Peter D. Warwick and Bruce R. Wardlaw

Prepared in cooperation with the
Geological Survey of Pakistan,
under the auspices of the
U.S. Agency for International Development,
U.S. Department of State, and the
Government of Pakistan

This volume is published as chapters A through I.
The chapters are also available separately on the World Wide Web.

Bulletin 2078

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2007

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Suggested citations:
Warwick, P.D., and Wardlaw, B.R., eds., 2007, Regional studies of the Potwar Plateau area, northern Pakistan: U.S. Geological Survey Bulletin 2078–A–I, chapters are separately paged, 5 oversize plates in pocket. (Also available online.)

Edwards, L.E., 2007, Paleocene and Eocene dinocysts from the Salt Range, Punjab, northern Pakistan, chap. C *of* Warwick, P.D., and Wardlaw, B.R., eds., Regional studies of the Potwar Plateau area, northern Pakistan: U.S. Geological Survey Bulletin 2078, p. C1–C10, fossil pls. C1, C2. (Also available online.)

Library of Congress Cataloging-in-Publication Data

Regional studies of the Potwar Plateau area, northern Pakistan / edited by Peter D. Warwick and Bruce R. Wardlaw.
p. cm. — (U.S. Geological Survey bulletin ; 2078)
"Prepared in cooperation with the Geological Survey of Pakistan, under the auspices of the U.S. Agency for International Development, U.S. Department of State, and the Government of Pakistan."
Includes bibliographical references.
1. Geology—Pakistan—Potwar Plateau Region. 2. Paleontology—Pakistan—Potwar Plateau Region. I. Warwick, Peter D. II. Wardlaw, Bruce R. III. Geological Survey of Pakistan. IV. Series.
QE75.B9 no. 2078
[QE295.4]
557.3 s—dc20
[555.491]

95–9726
CIP

ISBN 978–1–411–32093–2

Editors' Preface

By Peter D. Warwick and Bruce R. Wardlaw, U.S. Geological Survey

The papers in this volume are products of a cooperative program between the Geological Survey of Pakistan (GSP) and the U.S. Geological Survey (USGS), sponsored by the Government of Pakistan and the U.S. Agency for International Development. The focus of the program, the Coal Resources Exploration and Assessment Program (COALREAP), was to explore and assess Pakistan's indigenous coal resources. As part of COALREAP, GSP and USGS geologists conducted regional geologic studies from 1988 to 1991 of the coal-bearing areas in the Potwar region of northern Pakistan. These studies are called the Potwar Regional Framework Assessment Project. An overview of the project study area is presented in chapter A by Peter Warwick, who served as the project chief and the resident logistical support for most of the program.

The group of paleontology papers (chaps. B–E) stems from a desire to provide a stratigraphic, biostratigraphic, and paleoenvironmental framework for the coal deposits in the Potwar Plateau area in an efficient and cost-effective way. To this end, a reference section was selected from which to obtain faunal and floral analyses. The composite sections at Nammal Pass and Nammal Dam (figs. 1 and 2) served as the basis for this regional reference. Various biotic components were analyzed from samples from several other sections in the area and compared with the reference section. Spores and pollen (chap. D) from carbonaceous shales and borehole samples and ostracodes from both surface and subsurface samples appear plentiful enough to provide regional correlation with the reference section. The ostracode studies were not completed at the time this volume was assembled. Planktic foraminifers (chap. E) and nannofossils (chap. B) are sparse or badly recrystallized in most of the sections. Dinocysts (chap. C) seem to be more common than planktic foraminifers and nannofossils but are typically poorly preserved and were not investigated in every section.

The regional stratigraphic framework in which coal-bearing beds occur was investigated. The compilation of the paleontologic data and the general stratigraphic framework of the Paleocene and lower Eocene rocks in the Potwar area are presented in chapter F.

A pilot study for environmental geology in Pakistan (chap. G) was undertaken in the capital city area of Islamabad-Rawalpindi (fig. 1), which is on the northern edge of the Potwar Plateau.

Selected minerals and industrial commodities were evaluated in the Potwar Plateau area, as described in chapter H. Clay mineral resources were also evaluated, but the results are not presented in this volume. Finally, the coal-bearing Paleocene Patala Formation, which makes up the bulk of the Salt Range coal field, was carefully examined. Chapter I describes its character and distribution.

Update in 2007.—Although this Bulletin 2078 is being released in 2007, the writing and technical reviews were completed in 1993, and the chapters reflect the work done until that time. During the long production process for the Bulletin, which ultimately resulted in the oversize plates being digitized, the scientific content of the chapters was not changed, and most reports published since 1993 were not cited. A change in the age of the Patala Formation is discussed below, but the age discussions and illustrations in the chapters were not updated.

This manuscript was completed before the international agreement on the placement of the Paleocene-Eocene boundary occurred (ratified in 2003, according to Gradstein and others, 2004, p. 30). The boundary is now accepted to correlate with the base of the major negative carbon isotope excursion and is somewhat below the base of calcareous nannoplankton Zone NP 10 and thus is within the uppermost part of Zone NP 9. According to Bybell's studies in the U.S. Gulf of Mexico and Atlantic Coastal Plains, the calcareous nannofossil species *Transversopontis pulcher s.1.* first appears just below the Paleocene-Eocene boundary, and the last consistent occurrences of *Toweius eminens* var. *tovae* and *Scapholithus apertus* are very near the boundary (Laurel M. Bybell, USGS, written commun., 2006). The carbon isotope excursion correlates with the worldwide acme of the dinoflagellate genus *Apectodinium* (Crouch and others, 2001) and with the range base of the species *Apectodinium augustum* (Powell and Brinkhuis *in* Luterbacher and others, 2004, p. 396).

For the purposes of this Bulletin, the upper part of the Patala Formation must now be placed within the Eocene, rather than in the Paleocene. At the Nammal Dam location, the Patala Formation sample from 411 feet contains the lowest occurrence of the dinoflagellate *Apectodinium augustum* and the lowest occurrence of the calcareous nannofossil *Transversopontis pulcher s.1.* The sample from 409 feet does not contain these two species. Therefore, the Paleocene-Eocene boundary can be assumed to occur between 409 feet and 411 feet.

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Gradstein, F.M., Ogg, J.G., and Smith, A.G., 2004, Chronostratigraphy; Linking time and rock, *in* Gradstein, F.M., Ogg, J.G., and Smith, A.G., eds., A geologic time scale 2004: New York, Cambridge University Press, p. 20–46.

Luterbacher, H.P., Ali, J.R., Brinkhuis, Henk, Gradstein, F.M., Hooker, J.J., Monechi, Simonetta, Ogg, J.G., Powell, A.J., Röhl, U., and Sanfilippo, Annika, 2004, The Paleogene Period, *in* Gradstein, F.M., Ogg, J.G., and Smith, A.G., eds., A geologic time scale 2004: New York, Cambridge University Press, p. 384–408.

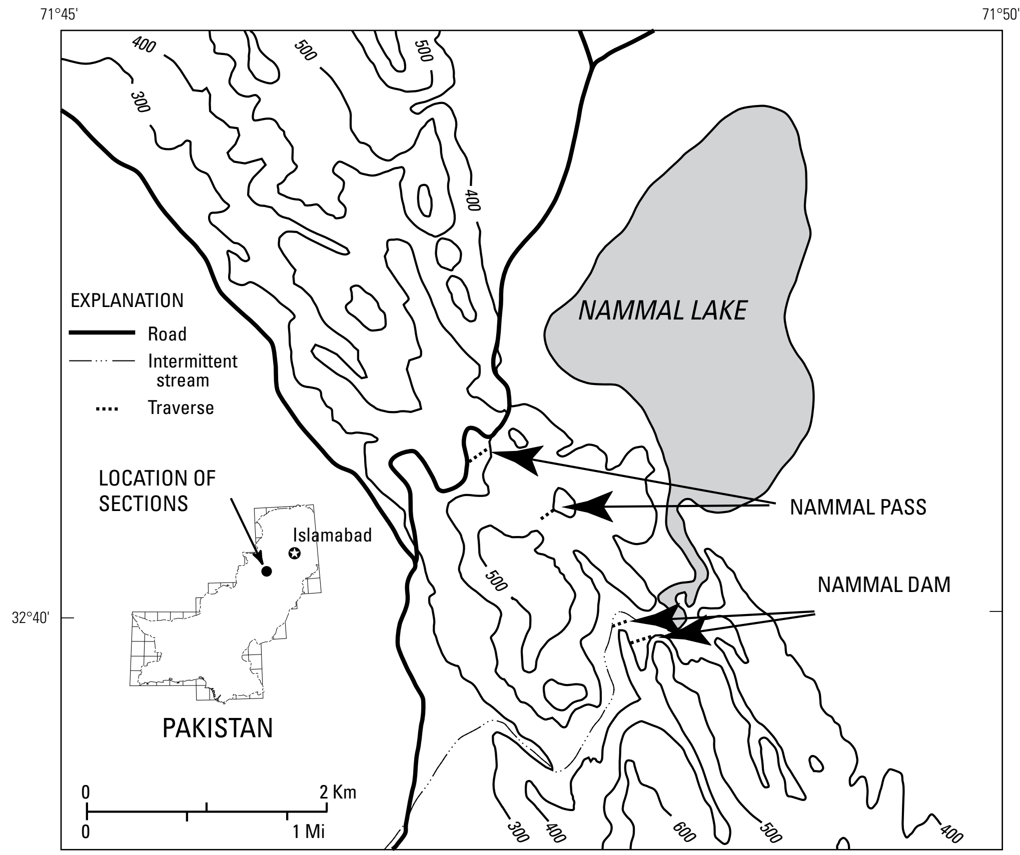

Figure 1. Location of traverses of measured section at Nammal Pass and Nammal Dam. Contour interval is 100 meters. Map portion taken from Survey of Pakistan topographic map 38 P/14 (1987, scale 1:50,000).

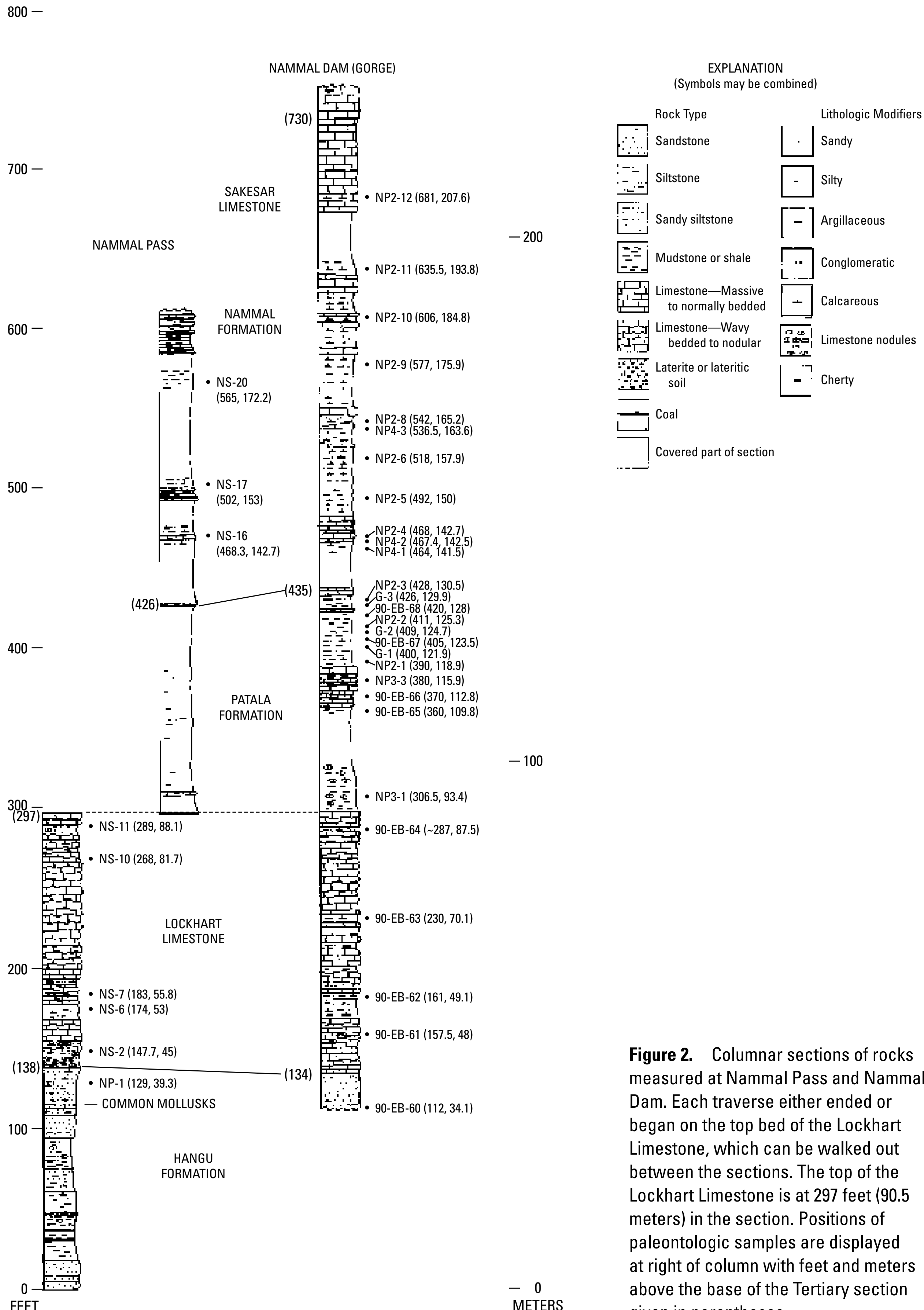

Figure 2. Columnar sections of rocks measured at Nammal Pass and Nammal Dam. Each traverse either ended or began on the top bed of the Lockhart Limestone, which can be walked out between the sections. The top of the Lockhart Limestone is at 297 feet (90.5 meters) in the section. Positions of paleontologic samples are displayed at right of column with feet and meters above the base of the Tertiary section given in parentheses.

Contents

[Letters designate the chapters]

Conversion Factors

Various units used in chapters A–I are listed in the first column below.

Multiply	By	To obtain
Length		
micrometer (µm)	0.00003937	inch
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
foot (ft)	0.3048	meter
Area		
square centimeter (cm^2)	0.1550	square inch
square meter (m^2)	10.76	square foot
hectare (ha)	2.471	acre
square kilometer (km^2)	0.3861	square mile
Mass		
kilogram (kg)	2.205	pound avoirdupois
metric ton (1,000 kg)	1.102	ton (2,000 pounds)
ton (2,000 pounds)	0.9072	metric ton (1,000 kg)
Density		
gram per cubic centimeter (g/cm^3)	0.03613	pound per cubic inch
Compressive strength		
kilogram per square centimeter (kg/cm^2)	14.22	pound-force per square inch
Heat per unit mass		
British thermal unit per pound (Btu/lb)	2.326	kilojoule per kilogram

Temperature.—To convert temperatures from degrees Celsius (°C) to degrees Fahrenheit (°F), use the following equation:

$$°F = (1.8 \times °C) + 32$$

Age designations.—The age of a geologic event or the age of an epoch boundary is expressed as ka (kilo-annum, thousands of years ago) or Ma (mega-annum, millions of years ago). Intervals of time are expressed as m.y. (million years duration). Some examples follow. The unconformity was dated at 1.9±4 Ma. During the last 1.5 m.y., erosion dominated. Thermoluminescence ages of the loess are greater than 170 ka.

Overview of the Geography, Geology, and Structure of the Potwar Regional Framework Assessment Project Study Area, Northern Pakistan

By Peter D. Warwick, U.S. Geological Survey

Chapter A of

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Bulletin 2078–A

U.S. Department of the Interior
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Plate

[Plate is in pocket]

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Overview of the Geography, Geology, and Structure of the Potwar Regional Framework Assessment Project Study Area, Northern Pakistan

By Peter D. Warwick

Abstract

A 32,000-square-kilometer area in northern Pakistan, which includes the Salt Range and the Potwar Plateau, has been the subject of a multidisciplinary Regional Framework Assessment Project by the U.S. Geological Survey and the Geological Survey of Pakistan. The framework project was designed to produce a wide-ranging geologic data base for the coal-producing areas in the Potwar area of northern Pakistan and will, the authors hope, serve as a model for other multidisciplinary geologic studies in Pakistan. The following eight chapters in this Bulletin contain a compilation of the regional geology and structure of the study area, studies of the biostratigraphy and sedimentology of coal-bearing units, review of the economic minerals, and environmental studies.

These reports focus on a semiarid area that contains diverse physiographic features ranging from river flood plains to mountain ranges. Rocks exposed in the area range in age from Precambrian to Holocene and are part of the active foreland fold-and-thrust belt of the Himalayas of northern Pakistan.

Introduction

The purpose of this paper is to provide a geographic and geologic introduction to the Potwar Regional Framework Assessment Project (PRFAP) study area. The papers in this volume are products of a cooperative program between the Geological Survey of Pakistan (GSP) and the U.S. Geological Survey (USGS), sponsored by the Government of Pakistan and the U.S. Agency for International Development (USAID). The focus of the program, the Coal Resources Exploration and Assessment Program (COALREAP), is to explore and assess Pakistan's indigenous coal resources. As part of COALREAP, GSP and USGS geologists, from 1988 to 1991, conducted regional geologic studies (PRFAP) of the coal-bearing areas in the Potwar region of northern Pakistan outlined by lats 32°22′ N. and 34° N. and longs 71°30′ E. and 73°30′ E. (figs. A1, A2).

The PRFAP was designed to provide training to GSP geologists in various aspects of geology. The results of the project, contained in chapters B through I of this volume, consist of a series of papers and maps addressing the regional geology, paleontology and carbonate geology, environments of deposition for coal-bearing rocks, and energy and mineral resources of the study area. A detailed environmental study of the capital area of Islamabad is also provided. These maps and studies will, the authors hope, provide a valuable data base for further exploration and development.

Acknowledgments

Project management of the PRFAP was provided by A.H. Kazmi and Farhat Husain of the GSP and by E.A. Noble and M.J. Terman of the USGS. J.C. Thomas (USGS) helped prepare the Landsat multispectral scanner (MSS) image base map (pl. A1). V.S. Williams (USGS) and M.K. Pasha (GSP) assisted with the map of physiographic features for the Potwar area (fig. A2). B.R. Wardlaw's (USGS) review of paleontological contributions for this volume is found in the "Overview of the Potwar Regional Framework Assessment Project Studies" section below. Funding was provided by USAID through Project 391–0478: Energy Planning and Development Project, Coal Resource Assessment Component 2a; Participating Agency Service Agreement (PASA) 1PK–0478–P–IC–5068–00.

Cultural and Physical Geography of the Potwar Regional Framework Assessment Project Study Area

The PRFAP study area covers approximately 32,000 square kilometers (km^2) (fig. A1). The image base map (pl. A1) used by the various groups in this study is a geometrically corrected mosaic of Landsat MSS scenes. Most of the area is within the Punjab; however, parts of the northwestern and northeastern study area extend into the North-West Frontier Province (NWFP). The boundary for these two provinces generally follows the Indus River. The largest cities within the study area are Rawalpindi, which is the second largest city in Pakistan; Islamabad, the capital of Pakistan; and part of Peshawar, the provincial capital of the NWFP. Other important towns in the area are Khewra and Mianwali in the southern part of the area; Kalabagh, Attock City, and Chakwal in the central part of the area; and Murree and Haripur in the northern part of the area (pl. A1).

The major cities and smaller towns are connected by a complex network of roads, most of which are paved but not always in good repair. Rail lines connect the major cities. An extensive network of irrigation canals provides water for agri-

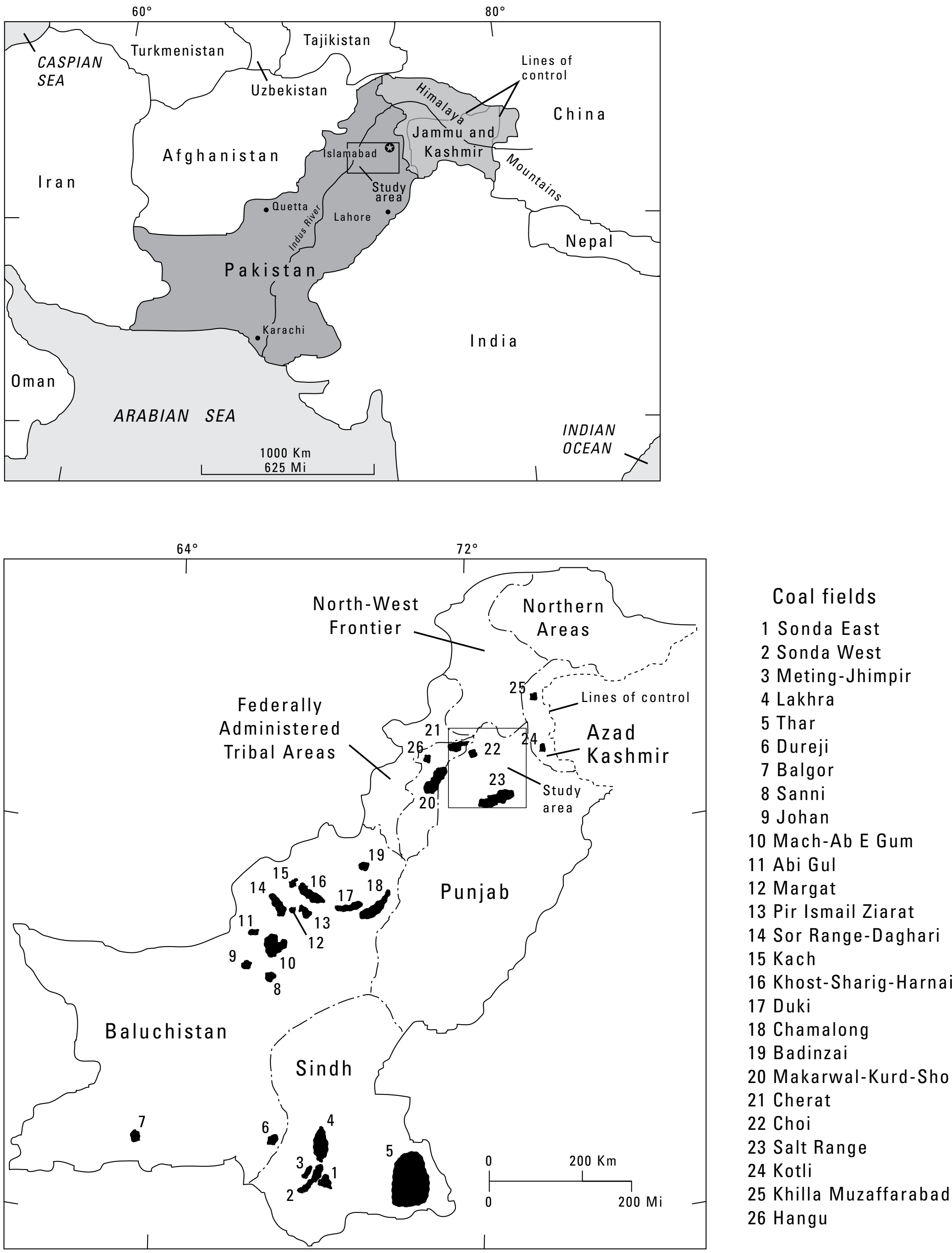

Figure A1. Location of Pakistan coal fields and occurrences. Box shows Potwar Regional Framework Assessment Project study area (after Schweinfurth and Hussain, 1988).

culture in areas near the Indus and Jhelum Rivers. The central part of the study area, which includes the Potwar Plateau, is not irrigated but is arable.

The climate of most of the area is semiarid and has less than 25 centimeters (cm) of rainfall per year. The higher elevations of the northern part of the area receive more than 100 cm of rainfall per year (Ahmad, 1969). Minimum and maximum mean temperatures in Rawalpindi (at an elevation of 510 meters (m)) are 14.8°C and 28.9°C, respectively (Nyrop and others, 1975). Temperatures vary in the study area relative to elevation.

The greatest elevation in the Potwar area is located in the Southern Hazara Range (fig. A2), where elevations commonly exceed 1,200 m above sea level. The lowest elevations in the area are associated with the Indus and Jhelum River Plains, where river levels are lower than 300 m. The elevations on the Potwar Plateau are generally between 300 and 600 m.

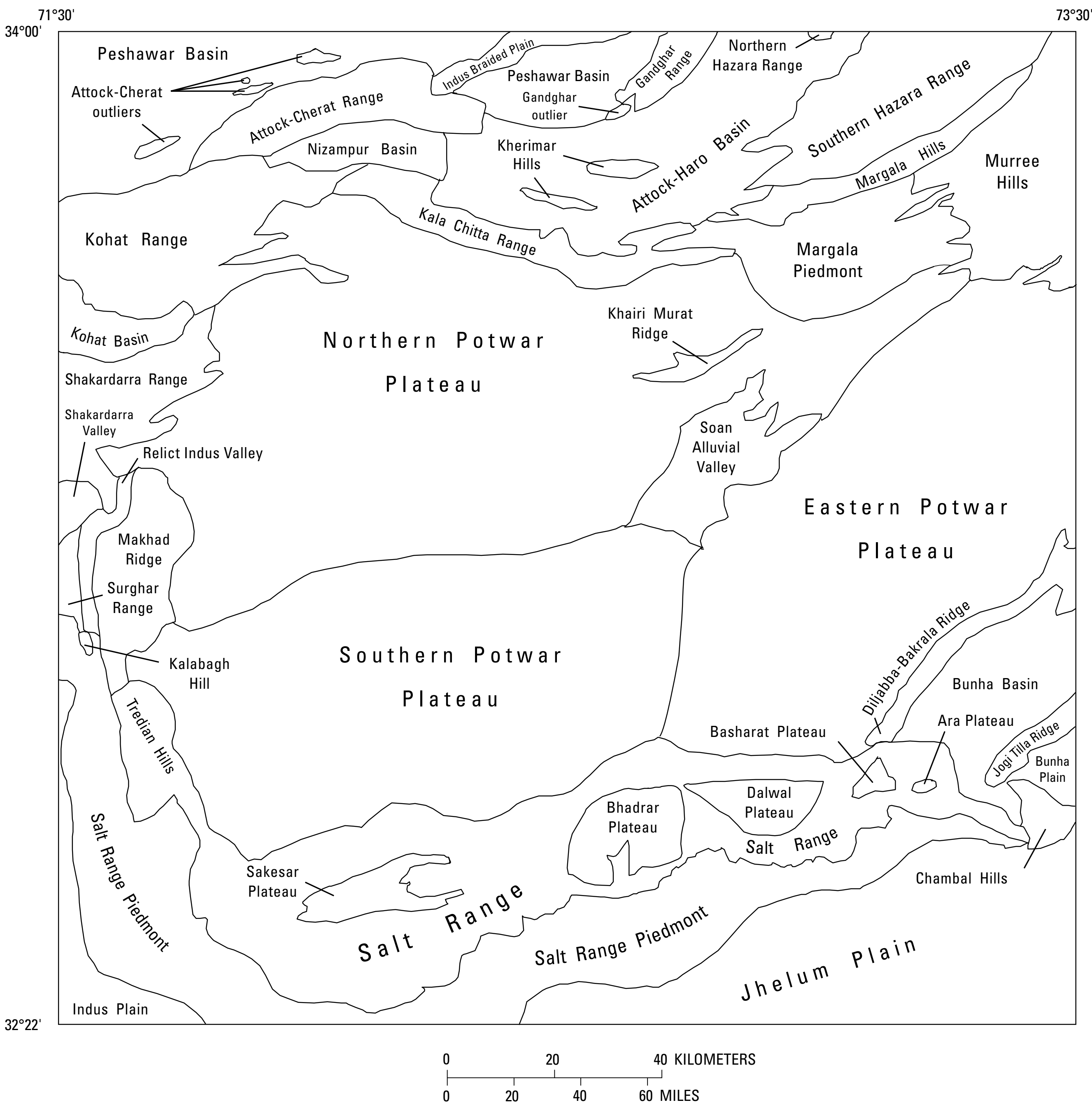

Figure A2. Generalized map showing the various physiographic features of the Potwar Regional Framework Assessment Project study area.

The principal river in the Potwar area is the Indus, which flows south through the western part of the study area (pl. A1). The Kabul River flows east out of Afghanistan and joins the Indus near Attock City in the northwestern part of the study area. The major drainage in the central part of the Potwar Plateau is toward the west via the Soan River, which joins the Indus River northeast of the town of Kalabagh. The Jhelum River joins the Indus River south of the study area.

Forty-two physiographic regions can be defined in the Potwar study area (fig. A2), including plateaus, flood plains, valleys, basins, hills, ridges, piedmonts, and ranges (table A1). The names of the physiographic features in this report were obtained from previously published names or from locality names in the area of the feature. The boundaries of the features were generally defined by the outline of the physiographic feature that can be observed on the 1:250,000-scale image base map of the Potwar region (pl. A1).

The dominant physiographic feature in the study area is the highly dissected Potwar Plateau, which covers about 18,000 km^2 in the central part of the area (Elahi and Martin, 1961). The southern part of the study area contains part of the Jhelum and Indus Plains, which extend for hundreds of kilometers south and east of the Salt Range. In the study area, these plains are covered by alluvium from the Jhelum and Indus Rivers. The Salt Range and its associated piedmont, plateaus, and hills lie north and east of these alluvial deposits. East of the Salt Range are the Bunha Basin and Plain, which drain into the Jhelum Plain a few kilometers east of the study area.

The western and northwestern parts of the study area consist of tectonically active ranges and valleys. The Relict Indus Valley (fig. A2) appears to have been the former position of the Indus River that was forced to occupy its present position due to tectonic uplifts (McDougall, 1989). The Kohat Plateau, as discussed by Fatmi (1973) and Yeats and Hussain (1987), has been divided into several regions, including the Shakardarra Valley and Range and the Kohat Basin and Range. North and east of the Kohat Range are the Attock-Cherat and Kala Chitta Ranges and the Indus Braided Plain. The Peshawar and Attock-Haro Basins extend along the northwestern and central borders of the study area. The northern and northeastern parts of the study area are characterized by several mountain and hill ranges, which include the Southern Hazara Range, the Margala and Murree Hills, and their associated piedmont aprons.

Table A1. Physiographic features and regions of the Potwar Regional Framework Assessment Project study area.

Feature	Area
Plateau	Sakesar
	Bhadrar
	Dalwal
	Basharat
	Ara
	Eastern Potwar
	Southern Potwar
	Northern Potwar
	Kohat (consists of the Shakardarra Valley and Range and the Kohat Basin and Range)
River flood plain	Indus Plain
	Jhelum Plain
	Bunha Plain
	Indus Braided Plain
Valley	Soan Alluvial
	Relict Indus
	Shakardarra
Basin	Bunha
	Kohat
	Nizampur
	Attock-Haro (Campbellpore)
	Peshawar
Hill	Tredian
	Kalabagh
	Chambal
	Kherimar
	Margala
	Murree
Ridge	Jogi Tilla
	Diljabba-Bakrala
	Makhad
	Khairi Murat
Piedmont	Salt Range
	Margala
Range	Surghar
	Salt
	Shakardarra
	Kohat
	Kala Chitta
	Attock-Cherat
	Gandghar
	Southern Hazara
	Northern Hazara

Geology of the Potwar Regional Framework Assessment Project Study Area

Stratigraphy

The stratigraphic succession exposed in the study area ranges in age from Precambrian to Quaternary. In the Attock-Cherat Range and the Hazara Ranges (fig. A2), Precambrian limestone, argillite, and quartzite form the base of the exposed stratigraphic section, which is thrust over younger strata in many places (Yeats and Lawrence, 1984; Hylland, 1990). In the Salt Range area, thrusts and associated salt diapirism bring to the surface strata containing evaporites of Precambrian age (Gee, 1980, 1989). These ductile evaporites underlie the Potwar Plateau and form a zone of décollement for regional thrusting (fig. A3; Butler and others, 1987; Jaumé and Lillie, 1988; Pennock and others, 1989). The evaporites are locally interlayered with or intruded by igneous rocks of the Khewra Trap (Martin, 1956; Faruqi, 1986; M.Q. Jan, University of Peshawar, oral commun., 1992).

Overlying the Precambrian rocks in the study area is a sedimentary sequence of Cambrian, Permian to Middle Cretaceous, Paleogene, and Neogene strata (Shah, 1977; Gee, 1980; Baker, 1988). The absence of Ordovician through Carboniferous and Upper Cretaceous rocks across much of the area marks some of the major unconformities in the stratigraphy (Shah, 1977). However, limestone, shale, and quartzite of probable Silurian and Devonian age, which are intruded locally by diabase, are exposed in the Attock-Cherat Range (Yeats and Hussain, 1987, 1989). Oligocene sedimentary rocks are generally absent from the study area because of the major unconformity between Eocene and Miocene rocks. The Miocene clastic rocks were shed from the ongoing Himalayan uplifts associated with the collision of the Indian subcontinent and Asia (Yeats and Lawrence, 1984).

The sedimentary rocks exposed on the Potwar Plateau and adjacent Kohat Plateau are Eocene limestone, evaporites, and red beds; Miocene to Pleistocene fluvial sediments and terrace gravel and loess; and Holocene alluvium (Elahi and Martin, 1961; Wells, 1983, 1984; Rendell, 1988; Warwick and Wardlaw, 1992). Much of the area is covered by terrestrial Neogene foreland-basin deposits (Burbank and Raynolds, 1988).

The Paleozoic, Mesozoic, and Cenozoic sequence exposed in the Salt Range underlies the alluvial cover of the Jhelum and Indus Plains south of the study area (Yeats and Lawrence, 1984). Exploratory drilling immediately south of the Salt Range has shown that pre-Miocene erosion has removed Cambrian to Eocene rocks in that area (Baker and others, 1988).

Structure

The Potwar Plateau region is an area of active oil and gas exploration and production. Recent studies (Butler and others, 1987; Leathers, 1987; Baker and others, 1988; Jaumé and Lillie, 1988; Pennock, 1988; Pennock and others, 1989; Raza and others, 1989; Hylland, 1990; Jaswal, 1990; McDougall and Hussain, 1991) have combined seismic-reflection profiles, petroleum exploration well logs, Bouguer gravity anomaly maps, and surface geology to construct regional structural cross sections that detail the thrust-related tectonics of the area (fig. A3).

The study area (fig. A4) is part of the active foreland fold-and-thrust belt of the Himalayas of northern Pakistan (Burbank and Raynolds, 1988; Jaumé and Lillie, 1988; Pennock and others, 1989). The area consists of several structural-tectonic subdivisions (fig. A4), such as the Salt Range along the southern part of the area, the Kohat Plateau along the western part of the area, the Potwar Plateau in the central part of the area, and the Northern Folded Zone and the Kala Chitta Fold Belt along the northern part of the area (Khan and others, 1986; Gee, 1989).

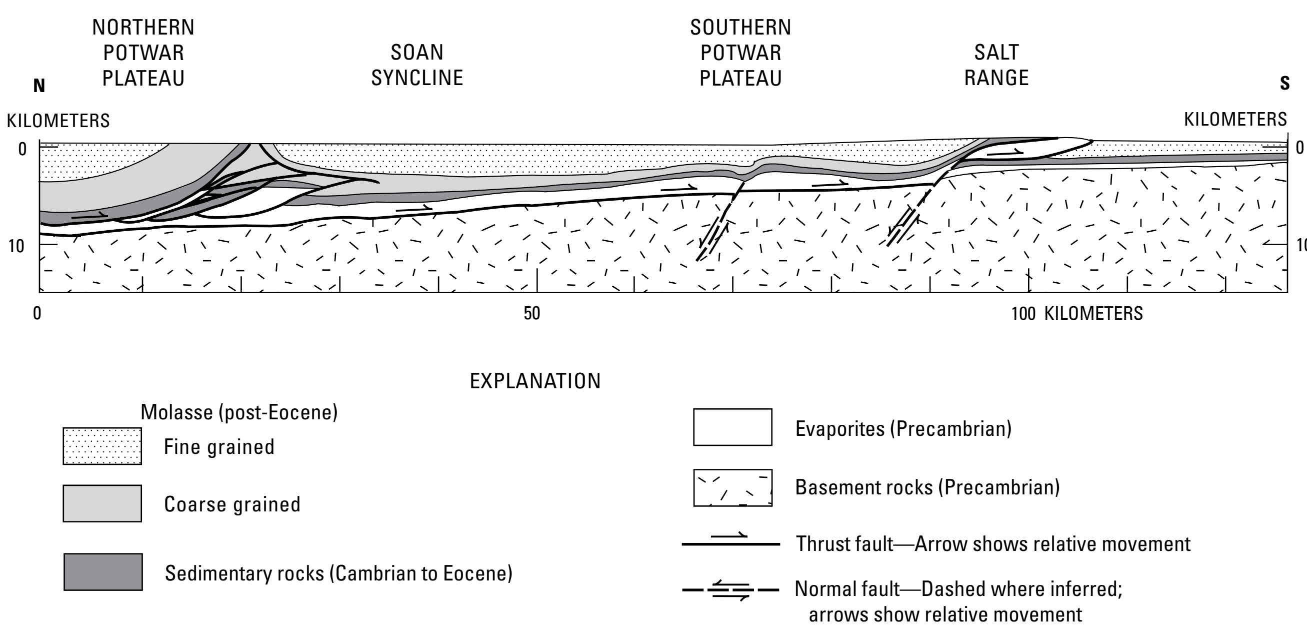

Figure A3. Generalized cross section across the western Potwar Plateau and the west-central Salt Range (after Jaumé and Lillie, 1988; Gee, 1989).

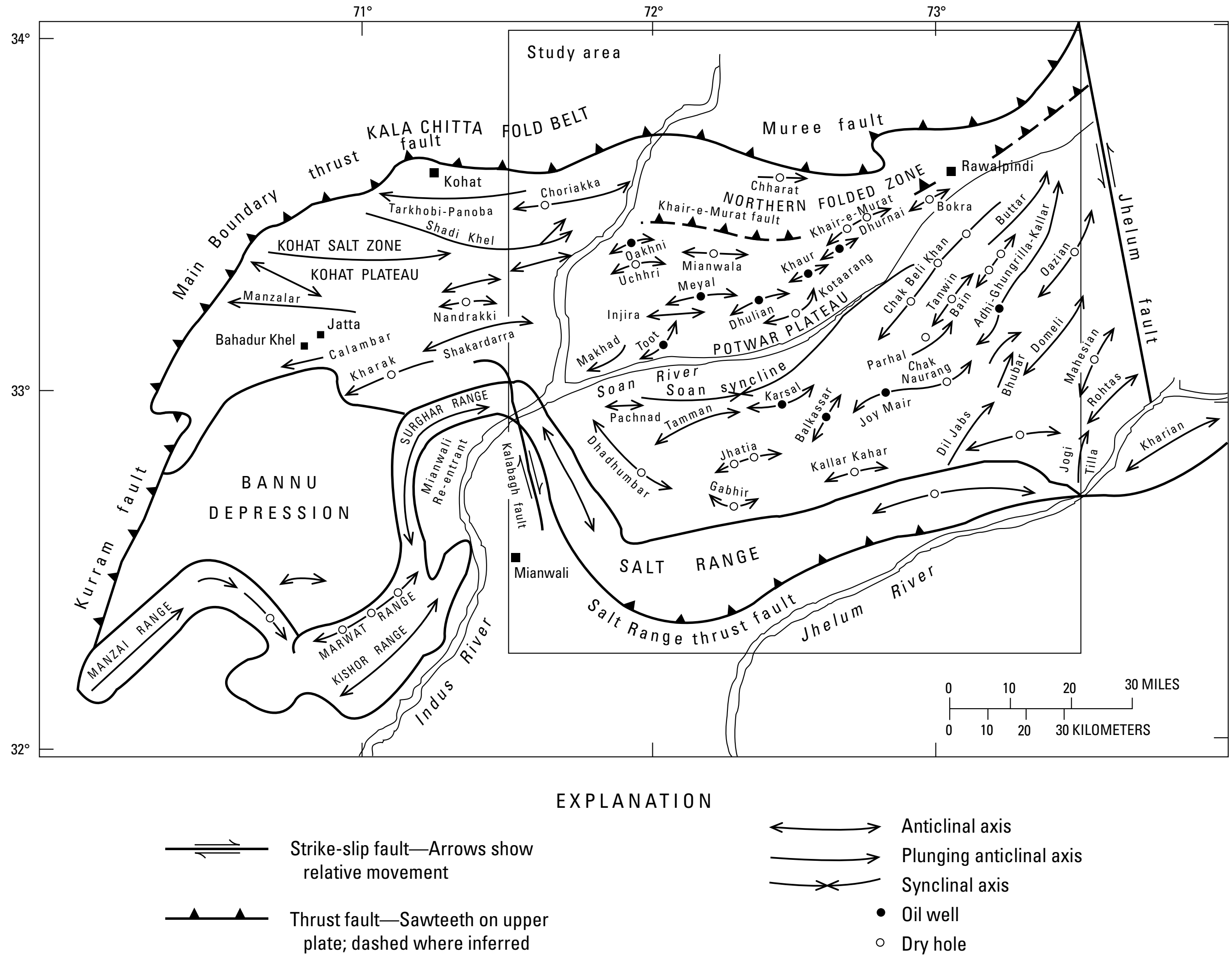

Figure A4. Structural map of the Kohat-Potwar Plateaus, northern Pakistan (after Khan and others, 1986; Gee, 1989).

The Salt Range is the surface expression of the leading edge of décollement thrusts over northward offsets of the crystalline basement (Crawford, 1974; Seeber and Armbruster, 1979; Yeats and Lawrence, 1984; Yeats and others, 1984). Seismic and drill-hole data indicate total southward displacement of the Salt Range and Potwar Plateau of at least 20 kilometers (km) (Farah and others, 1977; Johnson and others, 1986; Baker, 1988; Lillie and others, 1987; Baker and others, 1988). The western part of the Salt Range is characterized by a major strike-slip fault that extends along the western Salt Range and Indus River (Baker and others, 1988; McDougall and Khan, 1990).

In the central part of the study area, paleomagnetic data indicate that counterclockwise, thrust-related rotation of the Potwar Plateau rocks generally increases from less than 10° in the western part to more than 50° in the eastern part of the plateau (Johnson and others, 1986). The southern part of the Potwar Plateau is characterized by northward-dipping strata and local open folds of low structural relief and axes that generally parallel the trend of the Salt Range (fig. A4). The northern part of the Potwar area is characterized by strong folding and thrust faulting; the major structural trends change from east trending in the western part of the area to northeast trending in the eastern part of the area. The Soan River generally flows through the Soan syncline, which is a major structural downwarp with a sedimentary pile more than 5 km thick in the central part of the study area (Leathers, 1987; Baker, 1988).

The Northern Folded Zone is characterized by stacked imbricate thrusts within the sedimentary pile, which are separated by salt-glide zones (Jaswal, 1990). Thrust faulting in the Kala Chitta Fold Belt, which consists of the Attock-Cherat, Gandghar, and Hazara Ranges, brings Precambrian basement rocks to the surface (Yeats and Hussain, 1987, 1989; Hylland, 1990).

The Kohat region, west of the Potwar area, has not been a major target for oil and gas exploration in the past. However, preliminary results from recent seismic surveys in the area indicate that the regional thin-skinned thrusting common in the Potwar area may be replaced by transpressional structural features with significant vertical displacements (>3 km) that bring Mesozoic and Cenozoic rocks to the surface (Pivnik and Sercombe, 1992).

Overview of the Potwar Regional Framework Assessment Project Studies

The following chapters in this Bulletin cover various aspects of the geology of the PRFAP study area. These study topics are paleontology and carbonate geology, environments of deposition for coal-bearing rocks, environmental geology, and energy and mineral resources of the study area.

Chapters B–F provide a basic biostratigraphic framework for the Paleocene and lower Eocene rocks within and surrounding the PRFAP study area. These contributions are discussed in the editors' preface by P.D. Warwick and B.R. Wardlaw. L.M. Bybell and J.M. Self-Trail (chap. B) examined nannofossil floras from the Nammal Dam area, western Salt Range, and from a drill hole located on the Dalwal Plateau, eastern Salt Range (fig. A2). L.E. Edwards (chap. C) discusses dinocyst occurrences from the Nammal Dam area, the Dalwal Plateau area, and the Basharat Plateau area of the eastern Salt Range (fig. A2). N.O. Frederiksen and others (chap. D) report spore and pollen assemblages from several stratigraphic sections and drill holes in the western, central, and eastern parts of the Salt Range. T.G. Gibson (chap. E) reports on benthic and planktic foraminifers from the Nammal Dam area and the Dalwal drill hole. B.R. Wardlaw and others (chap. F) describe the sections and selected drill holes sampled for paleontological examination around the Potwar Plateau and provide a preliminary sequence-stratigraphic model for Paleocene and Eocene deposition.

Chapter G, by Iqbal Sheikh and others, reviews the environmental geology of the Islamabad area. Environmental and geologic maps of the Islamabad-Rawalpindi area are presented at scales of 1:50,000 and 1:100,000. Harald Drewes and others (chap. H) discuss the occurrence of selected minerals and industrial commodities within the PRFAP study area and present the data on a 1:250,000-scale map. P.D. Warwick and Tariq Shakoor (chap. I) analyze the depositional environments of the coal-bearing Paleocene Patala Formation in the Salt Range, which is the primary coal-producing area in the PRFAP study area.

Finally, a review of the geology and structure of the PRFAP area may be found in Drewes (1995).

Conclusions

As the demand on water, energy, mineral, and agricultural resources of northern Pakistan continues to grow, planning agencies should have available to them geologic data on which to base informed decisions. The results presented in this volume on the geology of the Potwar Regional Framework Assessment Project area should serve as a tool for continued development and growth in the Potwar region and as a guide for future multidisciplinary, geologic evaluations of other areas in Pakistan.

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

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Chapter B of

Regional Studies of the Potwar Plateau Area, Northern Pakistan

Edited by Peter D. Warwick and Bruce R. Wardlaw

Prepared in cooperation with the
Geological Survey of Pakistan,
under the auspices of the
U.S. Agency for International Development,
U.S. Department of State, and the
Government of Pakistan

Bulletin 2078–B

U.S. Department of the Interior
U.S. Geological Survey

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

By Laurel M. Bybell and Jean M. Self-Trail

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

This work was done as part of COALREAP, a collaborative program between the U.S. Geological Survey and the Geological Survey of Pakistan. This cooperative program is under the auspices of the U.S. Agency for International Development and the Government of Pakistan. We appreciate the thoughtful reviews of L.E. Edwards, N.O. Frederiksen, and T.G. Gibson of the USGS. We thank Tariq Masood and I.H. Haydri of the Geological Survey of Pakistan for their assistance in collecting some of the samples used in this study.

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.

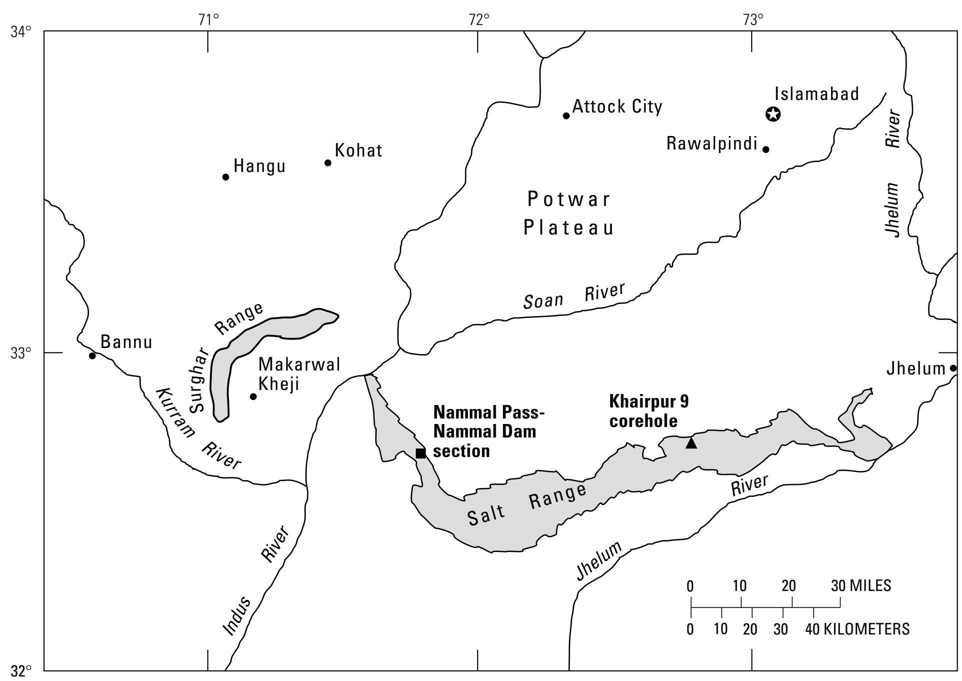


Figure B2. Sample localities in the Salt Range study area in northern Pakistan.

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

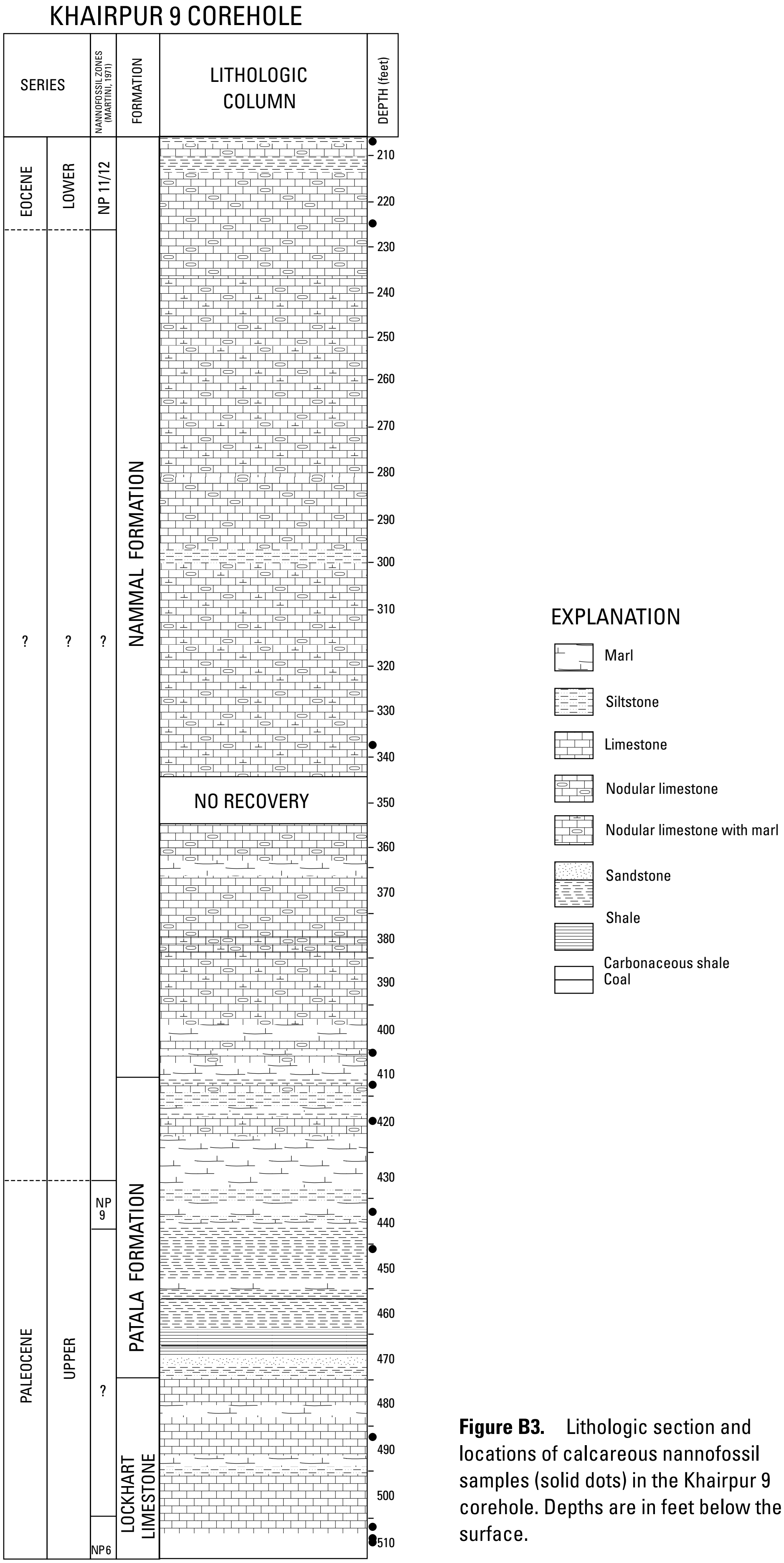


Figure B3. Lithologic section and locations of calcareous nannofossil samples (solid dots) in the Khairpur 9 corehole. Depths are in feet below the surface.

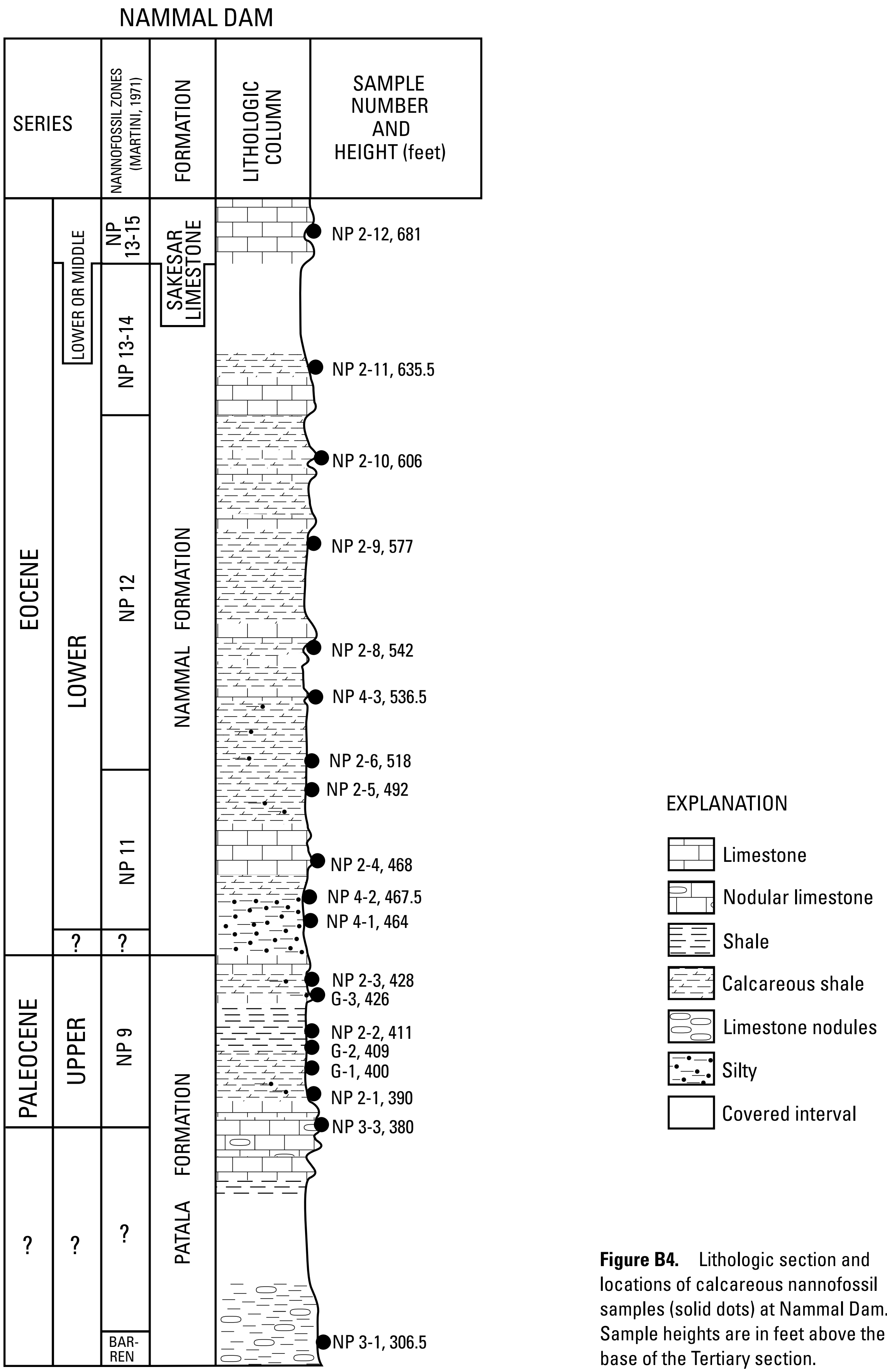
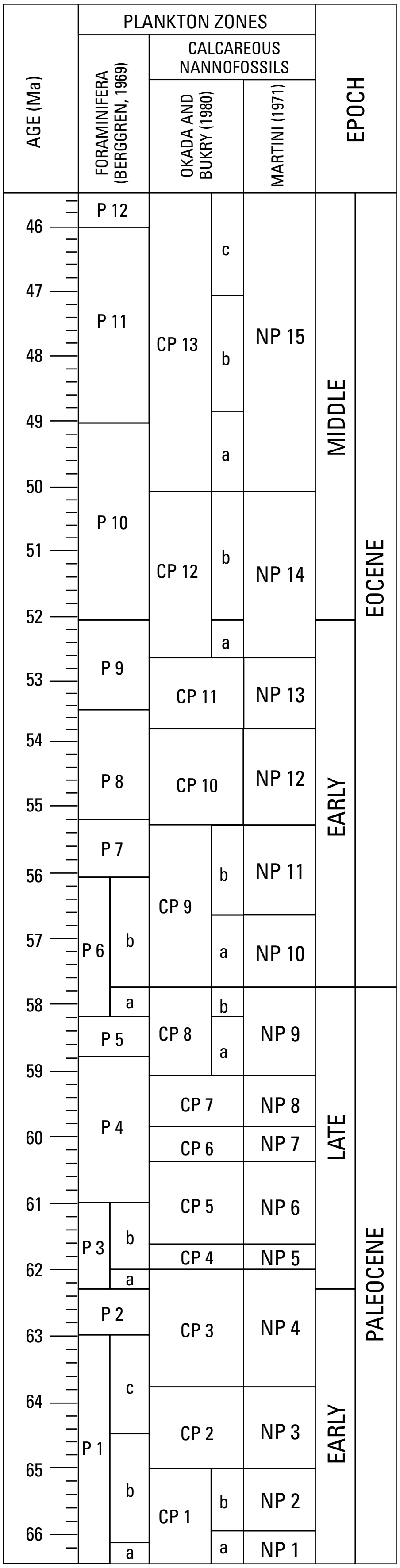


Figure B4. Lithologic section and locations of calcareous nannofossil samples (solid dots) at Nammal Dam. Sample heights are in feet above the base of the Tertiary section.



← **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	NAMMAL 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	
Bianthalithus 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]

Biantholithus astralis Steinmetz & Stradner 1984
Biantholithus sparsus Bramlette & Martini 1964
Blackites creber (Deflandre *in* Deflandre and Fert 1954) Stradner & Edwards 1968
Blackites herculesii (Stradner 1969) Bybell & Self-Trail 1997
Blackites spinosus (Deflandre & Fert 1954) Hay & Towe 1962
Braarudosphaera bigelowii (Gran & Braarud 1935) Deflandre 1947
Campylosphaera dela (Bramlette & Sullivan, 1961) Hay & Mohler 1967 (pl. B1, figs. 4, 5)
Chiasmolithus bidens (Bramlette & Sullivan 1961) Hay & Mohler 1967
Chiasmolithus consuetus (Bramlette & Sullivan 1961) Hay & Mohler 1967
Chiasmolithus danicus (Brotzen 1959) Hay & Mohler 1967
Chiphragmalithus calathus Bramlette & Sullivan 1961
Coccolithus eopelagicus (Bramlette & Riedel 1954) Bramlette & Sullivan 1961
Coccolithus pelagicus (Wallich 1877) Schiller 1930 (pl. B1, figs. 1–3)
Cruciplacolithus tenuis (Stradner 1961) Hay & Mohler *in* Hay and others, 1967
Cyclagelosphaera prima (Bukry 1969) Bybell & Self-Trail 1995
Discoaster barbadiensis Tan Sin Hok 1927
Discoaster binodosus Martini 1958
Discoaster diastypus Bramlette & Sullivan 1961
Discoaster falcatus Bramlette & Sullivan 1961
Discoaster kuepperi Stradner 1959
Discoaster limbatus Bramlette & Sullivan 1961
Discoaster lodoensis Bramlette & Riedel 1954
Discoaster mediosus Bramlette & Sullivan 1961
Discoaster mohleri Bukry & Percival 1971

Discoaster multiradiatus Bramlette & Riedel 1954 (pl. B1, fig. 7)
Discoaster salisburgensis Stradner 1961 (pl. B1, fig. 8)
Discoaster sublodoensis Bramlette & Sullivan 1961
Ellipsolithus distichus (Bramlette & Sullivan 1961) Sullivan 1964
Ellipsolithus macellus (Bramlette & Sullivan 1961) Sullivan 1964
Ericsonia subpertusa Hay & Mohler 1967
Fasciculithus alanii Perch-Nielsen 1971
Fasciculithus aubertae Haq & Aubry 1981
Fasciculithus involutus Bramlette & Sullivan 1961
Fasciculithus schaubii Hay & Mohler 1967
Fasciculithus thomasii Perch-Nielsen 1971
Fasciculithus tympaniformis Hay & Mohler *in* Hay and others, 1967
Helicosphaera lophota (Bramlette & Sullivan 1961) Locker 1972
Helicosphaera seminulum Bramlette & Sullivan 1961
Heliolithus cantabriae Perch-Nielsen 1971
Heliolithus kleinpellii Sullivan 1964
Heliolithus riedelii Bramlette & Sullivan,1961
Lophodolithus nascens Bramlette & Sullivan 1961
Markalius apertus Perch-Nielsen 1979
Markalius inversus (Deflandre *in* Deflandre and Fert, 1954) Bramlette & Martini 1964
Nannotetrina cristata (Martini 1958) Perch-Nielsen 1971
Nannotetrina fulgens (Stradner 1960) Achuthan & Stradner 1969
Neochiastozygus concinnus (Martini 1961) Perch-Nielsen 1971
Placozygus sigmoides (Bramlette & Sullivan 1961) Romein 1979
Rhabdosphaera gladius Locker 1967
Rhabdosphaera inflata Bramlette & Sullivan 1961
Rhabdosphaera perlonga (Deflandre *in* Grassé, 1952) Bramlette & Sullivan 1961
Rhomboaster bramlettei (Brönnimann & Stradner 1960) Bybell & Self-Trail 1995
Rhomboaster contortus (Stradner 1959) Bybell & Self-Trail 1995
Rhomboaster orthostylus (Shamrai 1963) Bybell & Self-Trail 1995
Scapholithus apertus Hay & Mohler 1967
Sphenolithus anarrhopus Bukry & Bramlette 1969
Sphenolithus conspicuus Martini 1976
Sphenolithus editus Perch-Nielsen 1978
Sphenolithus moriformis (Brönnimann & Stradner 1960) Bramlette & Wilcoxon 1967
Sphenolithus primus Perch-Nielsen 1971
Sphenolithus radians Deflandre *in* Grassé, 1952
Toweius callosus Perch-Nielsen 1971
Toweius eminens (Bramlette and Sullivan 1961) Gartner 1971 var. *eminens*
Toweius eminens (Bramlette & Sullivan 1961) Gartner 1971 var. *tovae* Perch-Nielsen 1971
Toweius occultatus (Locker 1967) Perch-Nielsen 1971
Toweius pertusus (Sullivan 1965) Romein 1979
Transversopontis pulcher (Deflandre *in* Deflandre and Fert, 1954) Perch-Nielsen 1967 (pl. B1, fig. 12)
Transversopontis pulcheroides (Sullivan 1964) Báldi-Beke 1971
Zygodiscus herlyni Sullivan 1964
Zygrhablithus bijugatus (Deflandre *in* Deflandre and Fert, 1954) Deflandre 1959

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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*.

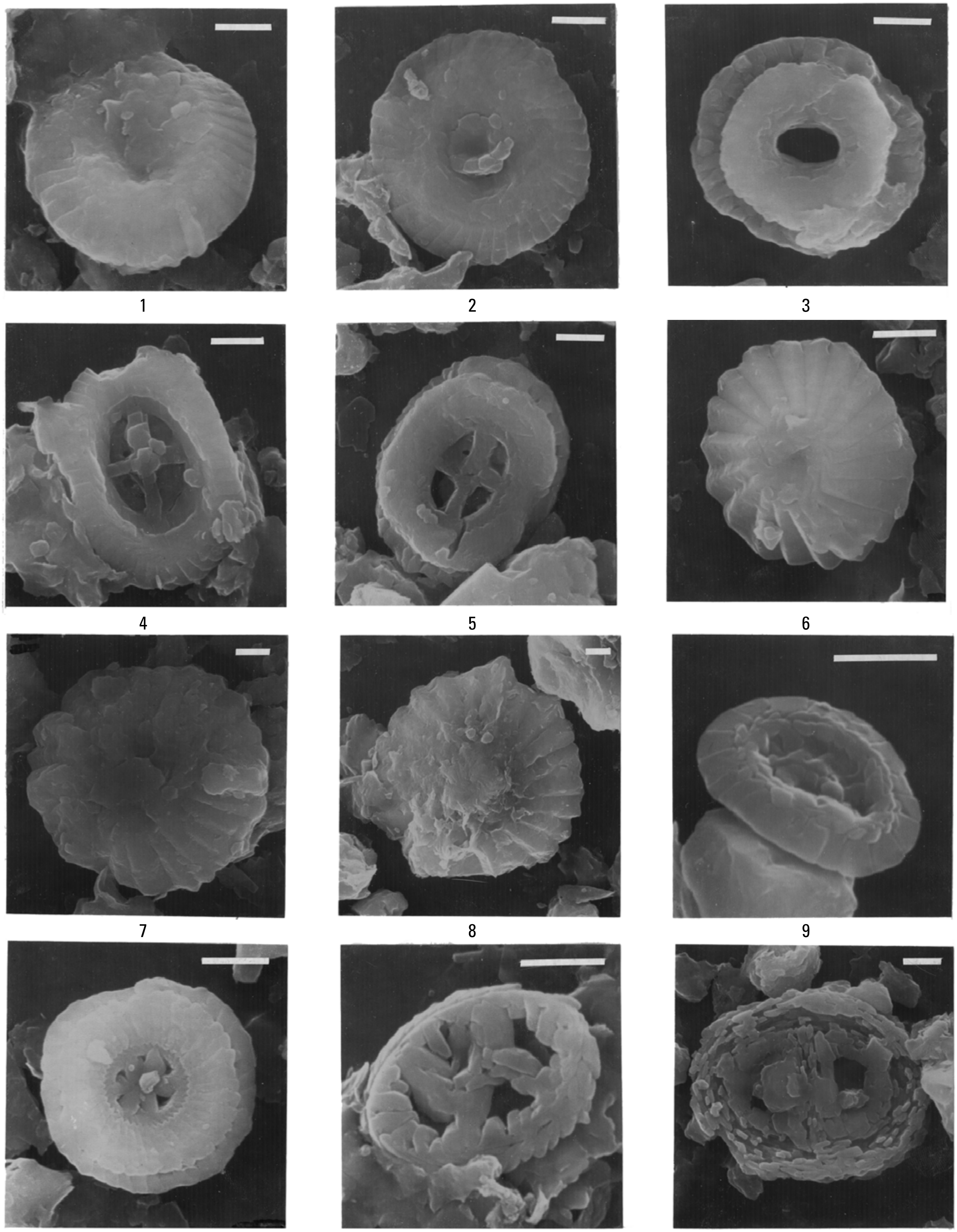
8. *Discoaster salisburgensis*.

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*

Paleocene and Eocene Dinocysts from the Salt Range, Punjab, Northern Pakistan

By Lucy E. Edwards, U.S. Geological Survey

Chapter C of

Regional Studies of the Potwar Plateau Area, Northern Pakistan

Edited by Peter D. Warwick and Bruce R. Wardlaw

Prepared in cooperation with the
Geological Survey of Pakistan,
under the auspices of the
U.S. Agency for International Development,
U.S. Department of State, and the
Government of Pakistan

Bulletin 2078–C

U.S. Department of the Interior
U.S. Geological Survey

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Paleocene and Eocene Dinocysts from the Salt Range, Punjab, Northern Pakistan

By Lucy E. Edwards

Abstract

Dinoflagellate cysts were examined from 12 samples from the Nammal Pass–Nammal Dam composite section and from 3 samples from 2 coreholes in the Salt Range, northern Pakistan. The dinocysts indicate that the age of the Patala Formation in the studied samples is late Paleocene. Samples containing *Apectodinium augustum* (Harland) Lentin & Williams are most probably very late Paleocene in age. The dinocysts indicate that the age of the Nammal Formation at the Nammal Dam section is early Eocene, or possibly younger. The Paleocene-Eocene boundary may possibly be near the sample at 141.5–141.8 feet in the Basharat 34 core, but sample spacing, poor preservation, and the questionable identification of *Wetzeliella astra* Costa et al. make this boundary placement uncertain.

Introduction

Dinoflagellates are single-celled organisms that have both plantlike and animallike characteristics. Paleontologists generally classify them as plants in the division Dinoflagellata. Most dinoflagellates have a complex life cycle, and many produce cysts during some part of this life cycle. Some of these cysts have an organic wall composed of a sporopollenin-like material. These cysts can be recovered as fossils by the same techniques used to recover fossil pollen and spores from sediments. Dinoflagellate cysts, or dinocysts, were included in the U.S. Geological Survey (USGS) paleontological study of material from northern Pakistan (figs. C1, C2).

Paleocene and Eocene dinoflagellate cysts from the northwest European basins and surrounding areas have been studied extensively (see recent compilations by Costa and Manum (1988) and Powell (1988)). Paleocene and Eocene dinocysts and calcareous nannofossils from Pakistan were studied by Köthe (1988), who erected a dinoflagellate zonation and correlated this zonation where possible with the nannofossil zonation of Martini (1971). Other studies resulting in dinocyst occurrence or range charts that depict Paleocene and Eocene sediments are the work of Wilson (1988) for New Zealand and Edwards (1980, 1990) for the southeastern U.S. Atlantic Coastal Plain.

Paleocene sediments containing dinocysts have been reported from southern India (Jain and Garg, 1986). In eastern India, Tripathi (1989) dated samples from the Therria Formation as late Paleocene. However, material from the upper part of the Therria contains *Homotryblium tenuispinosum* Davey & Williams and may actually be of early Eocene age (see discussion below). Jan du Chêne and Adediran (1984) recorded dinocyst occurrences from a section in southwestern Nigeria that they could date as no older than late Paleocene (Zone NP 9 of Martini (1971)), or possibly younger (Zones NP 10 and NP 11 of Martini (1971)).

Williams and Bujak (1985) synthesized published data on worldwide dinocyst ranges and presented these data in the framework of Cenozoic standard calcareous nannofossil and planktic foraminiferal zonations.

Acknowledgments

This work was done as part of the Coal Resources Exploration and Assessment Program (COALREAP), a collaborative program between the U.S. Geological Survey and the Geological Survey of Pakistan. This cooperative program is under the auspices of the U.S. Agency for International Development and the Government of Pakistan. I thank B.R. Wardlaw, W.E. Martin, N.O. Frederiksen, J.M. Self-Trail (USGS, Reston), and I.H. Haydri (Geological Survey of Pakistan) for collecting the samples and providing the stratigraphic framework. I thank V.A.S. Andrle and N.J. Durika (USGS, Reston) for drafting and photographic assistance.

Materials and Methods

Outcrop samples.—Twelve outcrop samples were examined from a composite section at Nammal Pass and Nammal Dam (fig. C3). The Nammal Pass section, lat 32º40.75′ N., long 71º47.19′ E., was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri. Here, the section consists of the coal-bearing Hangu Formation (thickness 138 feet (ft), or 42.1 meters (m)) and the overlying cliff-forming Lockhart Limestone (thickness 159 ft, or 48.5 m). One sample from

Figure C1. Location map showing the Salt Range study area (box) and selected regional features.

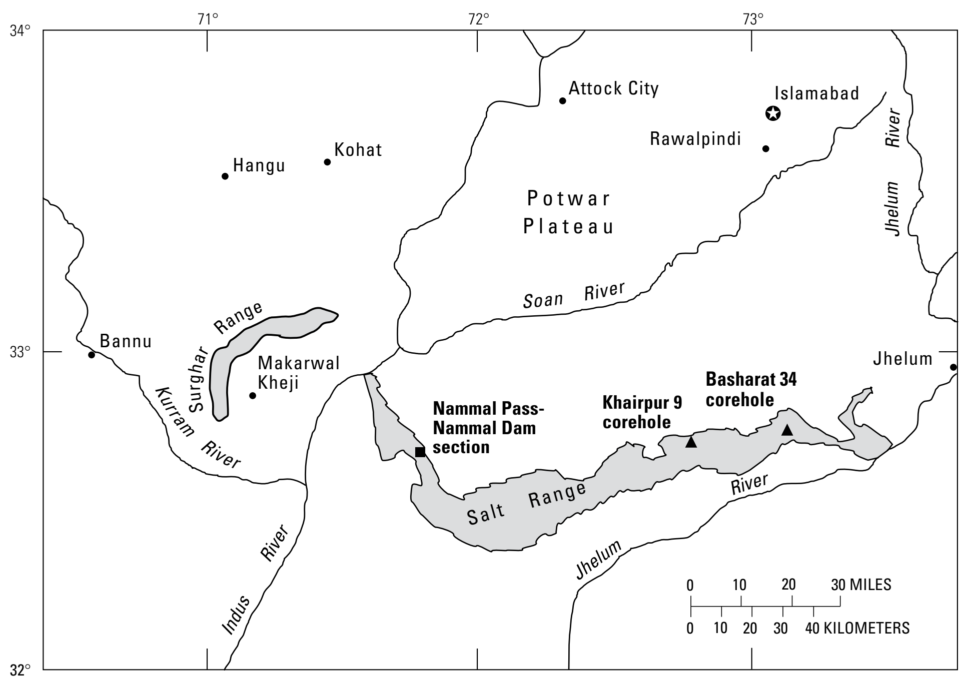

Figure C2. Locations of outcrops (solid square) and coreholes (solid triangles) studied in the Salt Range study area, northern Pakistan.

the Hangu Formation at 129 ft (39.3 m) in the measured section and two samples, R4383A and R4383C, from the Hangu Formation taken by N.O. Frederiksen in mudstone from a coal mine dump at Nammal Pass were examined for dinocysts. The Nammal Dam section was measured by B.R. Wardlaw, W.E. Martin, I.H. Haydri, J.M. Self-Trail, N.O. Frederiksen, and Tariq Masood at lat 32º39.81′ N., long 71º48.05′ E. Five samples from the Patala Formation (thickness 138 ft, or 42.1 m) and four samples from the Nammal Formation (thickness 295 ft, or 89.9 m) were examined for dinocysts. All samples were collected during October–November 1989.

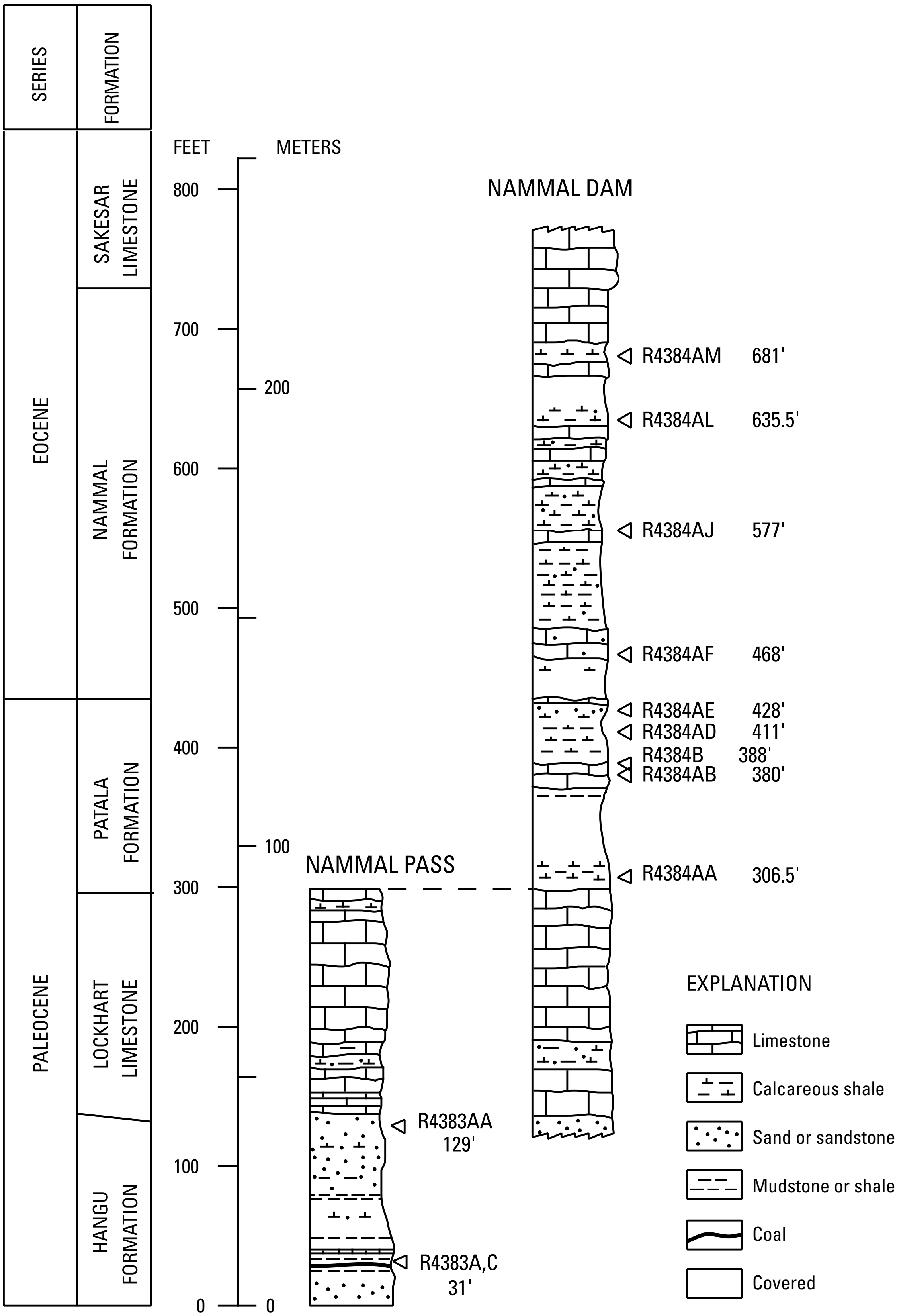

Figure C3. Columnar sections at Nammal Pass and Nammal Dam (simplified from Wardlaw and others, this volume, chap. F) showing positions of samples studied. Height of sample (in feet) above base of section shown after each sample number. See figure C2 for location of sections.

Core samples.—While in Pakistan, Frederiksen and Self-Trail collected samples from seven coreholes drilled by the Geological Survey of Pakistan (GSP) during 1987–1989 and stored at the GSP offices in Lahore. These samples were taken for pollen and spores or for calcareous microfossils and nannofossils, not specifically for dinocysts. However, a few of these samples were also processed for dinocysts.

Processing techniques.—Samples were treated in hydrochloric acid and hydrofluoric acid to remove carbonate and silicate material, respectively. Samples were then oxidized in nitric acid and centrifuged in laboratory detergent to remove fine debris. Sample residues were then stained in Bismark brown, sieved at 10 and 20 micrometers (µm), swirled in a watch glass, and mounted in glycerin jelly for light-microscope observation. One sample, R4372N from the Khairpur 9 corehole (fig. C2), was subjected to $ZnCl_2$ separation and was not stained.

The slide numbers and microscope coordinates of photographed dinoflagellates (pls. C1, C2) locate the specimens on Olympus Vanox microscope 201526 at the U.S. Geological Survey, Reston, Va. On this microscope, the coordinates for the center point of a standard 25.4 × 76.2 mm slide are 27.5, 112.7 (vertical, horizontal axes). The vertical coordinates increase as the stage is moved up, and the horizontal coordinates increase as the slide is moved from left to right. All palynological slides are stored at the U.S. Geological Survey, Reston, Va.

Stratigraphic Palynology

Hangu Formation

Three samples from the Hangu Formation at the Nammal Pass section were examined for dinocysts (figs. C3, C4). Two of these samples yielded very sparse dinofloras. A single, poorly preserved specimen of ?*Apectodinium* sp. suggests, but by no means confirms, a late Paleocene age. A third sample was barren of dinoflagellate cysts.

Lockhart Limestone

No samples from the Lockhart Limestone were studied for dinoflagellate cysts.

Patala Formation

Five samples from the Patala Formation at the Nammal Dam section were studied (figs. C3, C4), as well as one sample from the Patala in the Khairpur 9 corehole (table C1). Preservation is fair to good. *Eocladopyxis peniculata* Morgenroth, *Hystrichokolpoma unispinum* Williams & Downie, *Apectodinium augustum* (Harland) Lentin & Williams, *Hafniasphaera septata* (Cookson & Eisenack) Hansen, and *Ifecysta pachyderma* Jan du Chêne & Adediran are apparently restricted to this formation.

On the basis of the dinocysts, the age of the Patala in the studied samples is late Paleocene. *Apectodinium homomorphum* (Deflandre & Cookson) Lentin & Williams has not been reported from material older than that correlated with calcareous nannofossil Zones NP 7 or NP 8 (Edwards, 1980; Costa and Manum, 1988). Samples containing *A. augustum* are most probably correlative with Zone NP 9.

Nammal Formation

Four samples from the Nammal Formation at the Nammal Dam section (figs. C3, C4) and two samples from the Nammal in the Basharat 34 corehole (table C2) were studied. Preservation is fair to poor. *Homotryblium tenuispinosum sensu lato* and ?*Wetzeliella astra* Costa et al. are apparently restricted to this formation.

The dinocysts indicate that the age of the Nammal Formation at the Nammal Dam section is early Eocene, or possibly younger. The Paleocene-Eocene boundary may possibly be near the sample at 141.5–141.8 ft in the Basharat 34 core, but sample spacing, poor preservation, and the questionable identification of *W. astra* make this boundary placement uncertain.

Discussion

Biostratigraphy

At the Nammal Dam section, the dinoflora shows a distinctive break between the uppermost sample (R4384AE) from the Patala Formation and the lowermost sample (R4384AF) from the Nammal Formation. Samples from the upper part of the Patala have moderately well preserved, relatively diverse dinofloras and contain the distinctive species *Hystrichokolpoma unispinum, Achilleodinium*? sp. I, *Apectodinium augustum*, and *Hafniasphaera septata*. Samples from the Nammal Formation are poorly preserved and have sparse dinofloras lacking these species and containing *Homotryblium tenuispinosum sensu lato*. For the Basharat 34 corehole, only two samples, both from the Nammal Formation, were studied. Here preservation is poor, and so the lowest occurrence of *Homotryblium* sp. may not be stratigraphically significant. This lowest occurrence is seen in the same sample as ?*Wetzeliella astra*.

The lowest stratigraphic occurrence of *W. astra* is commonly used to recognize the Paleocene-Eocene boundary using dinoflagellate cysts (Costa and others, 1978; Morton and others, 1983; Jolley and Spinner, 1989). Other workers (for example, Knox and others, 1983; Powell, 1988) did not find this species to be a reliable marker. For material from central Pakistan, Köthe (1988) used *W. astra* as a marker and defined her Zone Pak D VII on its first occurrence, but noted (Köthe, 1988, p. 11) that she found only one specimen.

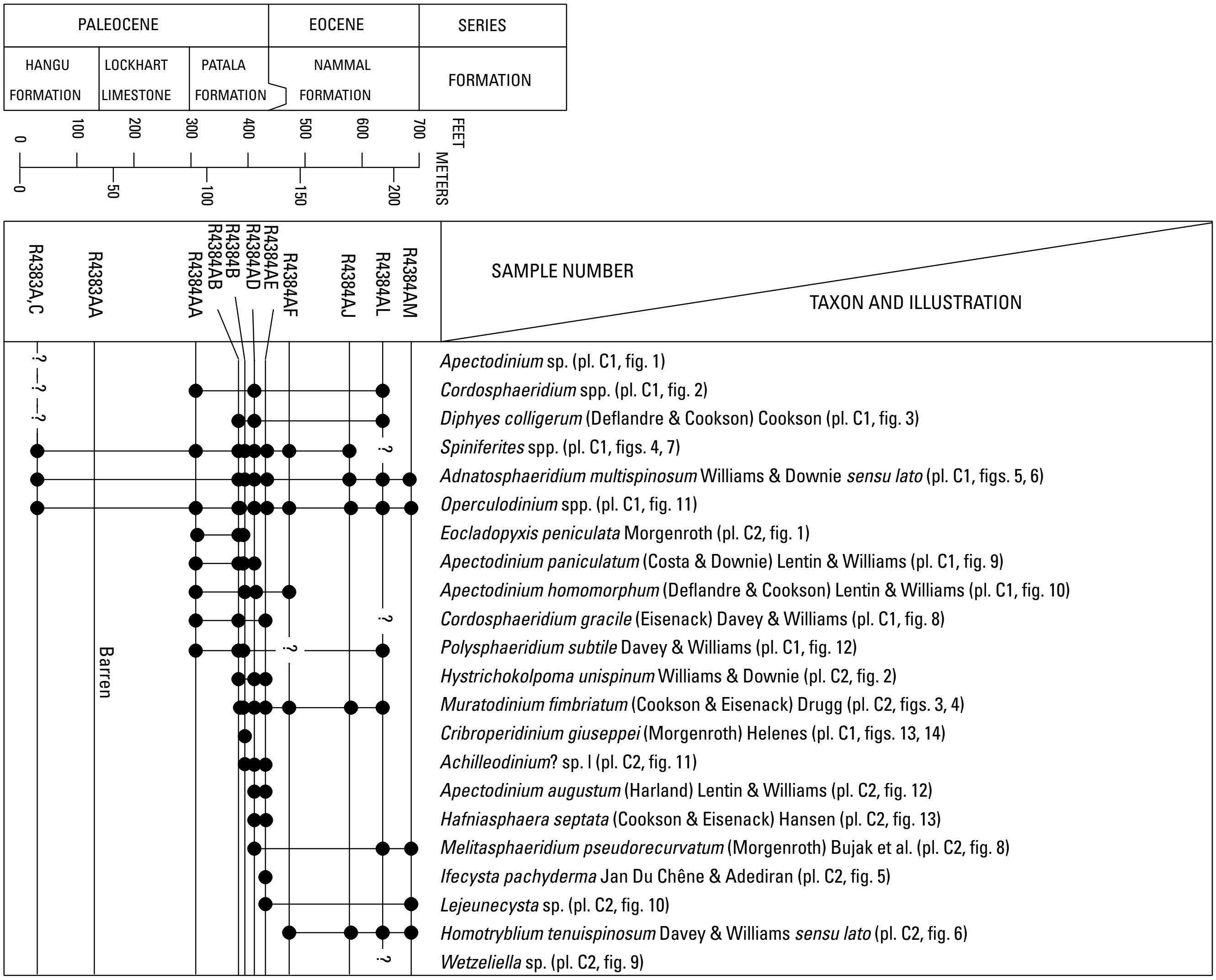

Figure C4. Occurrence and range chart of dinocysts recovered from the Nammal Pass–Nammal Dam composite section. Occurrence queried where uncertain.

Powell (1988) concluded that the highest stratigraphic occurrence of *Apectodinium augustum* should be used as the marker for the Paleocene-Eocene boundary in the central North Sea area. However, indirect correlations using calcareous nannofossils and ash beds (Knox, 1984) coupled with Powell's (1988) data suggest that the highest occurrence of *A. augustum* is actually slightly above the Paleocene-Eocene contact if this contact is placed at the base of Martini's (1971) calcareous nannofossil Zone NP 10.

Within the Eocene, Köthe (1988) used the lowest occurrence of *Homotryblium tenuispinosum* to mark the base of her Zone Pak D VIII and the lowest occurrence of *H. oceanicum* Eaton to mark the base of her Zone Pak D IX. However, on her individual occurrence charts, these species are never found in succession. Williams and Bujak (1985) considered the lowest stratigraphic occurrences of *H. tenuispinosum* and *H. pallidum* Davey & Williams to occur in lower Eocene sediments within calcareous nannofossil Zone NP 10. They showed the lowest occurrences of *H. abbreviatum* Eaton and *H. oceanicum* somewhat higher (within NP 13 and at the base of NP 14, respectively). Costa and Manum (1988) stated that the lowest stratigraphic occurrence of *H. tenuispinosum* is within their highest Paleocene zone, their D 5; however, none of the individual range charts showed this species below the base of their Zone D 6 (lowest Eocene). They reported the lowest occurrences of *H. abbreviatum* in their Zone D 8 (calibrated to NP 12 and part of NP 13) and *H. oceanicum* in their Zone D 9 (calibrated to parts of NP 13 and NP 14). Tripathi (1989) reported *H. tenuispinosum* from upper Paleocene sediments in the upper part of the Therria Formation in Meghalaya, eastern India. He considered these sediments to be Paleocene on the basis of the lowest occurrence of *Apectodinium parvum* (Alberti) Lentin & Williams. Because the reported range of *A. parvum* is late Paleocene to early Eocene (NP 9 to NP 10 according to Jain and Garg (1986); NP 9 to NP 10, but possibly to NP 12 according to Costa and Manum (1988)), and because strati-

Table C1. Dinocysts in sample R4372N from the Khairpur 9 corehole.

[Sample is from the Patala Formation, 30.6–30.9 ft above the base of the Patala. X, present in sample; ?, questionably present]

Taxon	Sample number and depth from surface
	R4372N
	446.6–446.9 ft
Achilleodinium? sp. I	X
Apectodinium homomorphum (Deflandre & Cookson) Lentin & Williams	?
Fibrocysta sp.	?
Operculodinium spp.	X
Polysphaeridium subtile Davey & Williams	?
Spiniferites sp.	X
Thalassiphora pelagica (Eisenack) Eisenack & Gocht	X

Table C2. Dinocysts in two samples from the Basharat 34 corehole.

[Both samples are from the Nammal Formation; sample R4379K is from 81.2–81.5 ft above the base of the Nammal, and sample R4379S is from 19.0–19.3 ft above the base. X, present in sample; ?, questionably present; —, not detected]

Taxon	Sample number and depth from surface	
	R4379S 203.7–204 ft	R4379K 141.5–141.8 ft
Areoligera sp.	—	X
Cribroperidinium giuseppei (Morgenroth) Helenes	—	X
Diphyes colligerum (Deflandre & Cookson) Cookson	—	?
Homotryblium sp.	—	?
Lejeunecysta sp.	—	X
Muratodinium fimbriatum (Cookson & Eisenack) Drugg	—	X
Operculodinium spp.	—	X
Wetzeliella astra Costa et al.	—	?
Polysphaeridium subtile Davey & Williams	X	X
Spiniferites spp.	X	X
Adnatosphaeridium multispinosum Williams & Downie	X	—
Apectodinium hyperacanthum-paniculatum	X	—

graphically lower sediments contain a sparse dinoflora (only one species is shown on their fig. 1), this lowest occurrence should not be considered reliable for correlation, and the Therria sediments may be of Eocene age.

Studied samples from the Nammal Dam section containing *H. tenuispinosum sensu lato* are most probably of early Eocene age. It is unlikely that the lowest occurrence of this species coincides exactly with the base of nannofossil Zone NP 10.

The dinoflora from the Patala Formation is similar to that reported by Jan du Chêne and Adediran (1984) from Nigeria. These authors, too, had difficulty in determining whether their samples are of late Paleocene or early Eocene age.

Paleoenvironment

Given the generally poor dinocyst preservation, little can be said about the paleoenvironments represented by the studied material except that this material probably represents subtropical to tropical paleoenvironments.

Köthe (1988) noted that the first occurrence of *Polysphaeridium subtile* Davey & Williams in Pakistan is older (approximately Zone NP 8) than previously reported (NP 12, according to Williams and Bujak (1985)). However, Caro (1973) also reported this species from the Paleocene of the Spanish Pyrenees. This species may be a direct ancestor (or perhaps a junior synonym; see Lentin and Williams (1989)) of *Polysphaeridium zoharyi* (Rossignol) Bujak et al., a species whose modern distribution is subtropical to tropical and euryhaline (Wall and others, 1977; Harland, 1983). Thus, *P. subtile* may have evolved in lower paleolatitudes.

Muratodinium fimbriatum (Cookson & Eisenack) Drugg also seems to have a diachronous range base: in the Paleocene in more tropical environments such as Pakistan (this report) and the southeastern United States (Edwards, unpub. data), and in the Eocene in less tropical environments such as the eastern United States (Edwards, 1990).

Taxonomic Comments

Genus *Achilleodinium* Eaton
Achilleodinium? sp. I

Plate C2, figure 11

Remarks.—Cyst is subspherical to ellipsoidal, with hollow, tubiform, foleate processes. Processes are intratabular and may occur as a single process per paraplate, as several separate processes per paraplate, or as several proximally joined processes per paraplate. The paracingulum is indicated by aligned processes; the parasulcus is indicated by more slender processes. The antapical process is distinctively shaped and larger than the other processes. Paratabulation is gonyaulacacean, exact formula uncertain due to process fusion. Archeopyle is precingular, type P (3″ only), and the operculum is free.

Occurrence in studied samples.—Patala Formation, Nammal Dam section; Patala Formation, Khairpur 9 corehole.

Genus *Adnatosphaeridium* Williams & Downie
Adnatosphaeridium multispinosum Williams & Downie *sensu lato*

Plate C1, figures 5, 6

Remarks.—This species shows considerable variation in size and process development. Older specimens (like that shown in pl. C1, fig. 6) more commonly are larger and have more robust processes. Younger specimens (like that shown in pl. C1, fig. 5) are more commonly smaller and have more delicate processes. Although two endmembers are illustrated, a wide range of forms is present in many samples.

Occurrence in studied samples.—Hangu Formation, Nammal Pass section; Patala and Nammal Formations, Nammal Dam section; Nammal Formation, Basharat 34 corehole.

Genus *Apectodinium* Lentin & Williams
Apectodinium augustum (Harland) Lentin & Williams

Plate C2, figure 12

Remarks.—This species of *Apectodinium* is distinguished by its reduced apical horn, its long antapical horns, and, especially, its very long lateral horns.

Occurrence in studied samples.—Patala Formation, Nammal Dam section.

Apectodinium homomorphum (Deflandre & Cookson) Lentin & Williams

Plate C1, figure 10

Remarks.—Specimens of the genus *Apectodinium* that do not have prominent apical, lateral, or antapical horns are placed in this species.

Occurrence in studied samples.—Patala and Nammal Formations, Nammal Dam section; Patala Formation, Khairpur 9 corehole.

Apectodinium paniculatum (Costa & Downie) Lentin & Williams

Plate C1, figure 9

Remarks.—Costa and Downie (1976) differentiated this species from *A. quinquelatum* (Williams & Downie) Costa & Downie by its longer lateral horns, but noted that they encountered numerous transitional forms between the two taxa. They stated that *A. paniculatum* differs from *A. hyperacanthum* (Cookson & Eisenack) Lentin & Williams by the absence of a well-developed apical horn and by the shape of the antapical horns. Folded and poorly preserved specimens are difficult to identify to species level. Specimens from the Patala Formation show prominent lateral horns and weakly developed apical horns and are thus placed in *A. paniculatum*. They may, however, be conspecific with some of the forms called *A. quinquelatum* by Köthe (1988). Specimens from the Nammal Formation are designated as *A. hyperacanthum-paniculatum* because the poor preservation precludes unequivocal identification.

Occurrence in studied samples.—Patala Formation, Nammal Dam section; Nammal Formation, Basharat 34 corehole.

?*Apectodinium* sp.

Plate C1, figure 1

Remarks.—A single, poorly preserved specimen was found in sample R4383C from the Hangu coal mine dump at Nammal Pass. If this specimen is an *Apectodinium*, it indicates that the age of this sample is late Paleocene or younger.

Occurrence in studied samples.—Hangu Formation, Nammal Pass section.

Genus *Cordosphaeridium* Eisenack
Cordosphaeridium gracile (Eisenack) Davey & Williams

Plate C1, figure 8

Occurrence in studied samples.—Patala Formation and questionable in Nammal Formation, Nammal Dam section.

Cordosphaeridium spp.

Plate C1, figure 2

Remarks.—This category probably includes *Cordosphaeridium inodes* (Klumpp) Eisenack, *Cordosphaeridium exilimurum* Davey & Williams, *Cordosphaeridium fibrospinosum* Davey & Williams, other representatives of the genus that are too poorly preserved to identify with certainty, and possibly *Amphorosphaeridium*? *multispinosum* (Davey & Williams) Sarjeant.

Occurrence in studied samples.—Patala and Nammal Formations, Nammal Dam section.

Genus *Cribroperidinium* Neale & Sarjeant
Cribroperidinium giuseppei (Morgenroth) Helenes

Plate C1, figures 13, 14

Occurrence in studied samples.—Patala Formation, Nammal Dam section; Nammal Formation, Basharat 34 corehole.

Genus *Diphyes* Cookson
Diphyes colligerum (Deflandre & Cookson) Cookson

Plate C1, figure 3

Remarks.—In several of the observed specimens, it was difficult to determine the exact shape of the antapical process. Thus, it is quite possible that specimens of *Diphyes spinulum* (Drugg) Stover & Evitt have been included here.

Occurrence in studied samples.—Patala and Nammal Formations, Nammal Dam section; questionable in Hangu Formation, Nammal Pass section and Nammal Formation, Basharat 34 corehole.

Genus *Eocladopyxis* Morgenroth
Eocladopyxis peniculata Morgenroth

Plate C2, figure 1

Remarks.—As is typical for this species, most specimens are fragments.

Occurrence in studied samples.—Patala Formation, Nammal Dam section.

Genus *Hafniasphaera* Hansen
Hafniasphaera septata (Cookson & Eisenack) Hansen

Plate C2, figure 13

Remarks.—The unique vacuolar structure of the walls is considered worthy of generic distinction. Thus, the conclusion of Stover and Williams (1987) that the genus *Hafniasphaera* is a junior synonym of *Spiniferites* is rejected.

Occurrence in studied samples.—Patala Formation, Nammal Dam section.

Genus *Homotryblium* Davey & Williams
Homotryblium tenuispinosum Davey & Williams *sensu lato*

Plate C2, figure 6

Remarks.—The Pakistan specimens bear processes that are less flared than typical *Homotryblium tenuispinosum*, but not as cylindrical as *H. oceanicum* Eaton, and should perhaps be considered intermediate between the two endmembers.

Occurrence in studied samples.—Nammal Formation, Nammal Dam section; questionable representatives of the genus *Homotryblium* were found in the Nammal Formation, Basharat 34 corehole.

Genus *Hystrichokolpoma* Klumpp
Hystrichokolpoma unispinum Williams & Downie

Plate C2, figure 2

Remarks.—On specimens in which the paracingular processes could be observed, only one process per paraplate was noted.

Occurrence in studied samples.—Patala Formation, Nammal Dam section.

Genus *Ifecysta* Jan du Chêne & Adediran
Ifecysta pachyderma Jan du Chêne & Adediran

Plate C2, figure 5

Remarks.—The Pakistan forms show the typical apical and antapical hornlike protrusions that are formed by the closely appressed endophragm and periphragm. This species has been reported only from the Paleocene and Eocene (undifferentiated) of Nigeria.

Occurrence in studied samples.—Patala Formation, Nammal Dam section.

Genus *Lejeunecysta* Artzner & Dörhöfer
Lejeunecysta sp.

Plate C2, figure 10

Remarks.—These cysts are rare. They all have a distinctive dark-brown color.

Occurrence in studied samples.—Patala and Nammal Formations, Nammal Dam section; Nammal Formation, Basharat 34 corehole.

Genus *Melitasphaeridium* Harland & Hill
Melitasphaeridium pseudorecurvatum (Morgenroth) Bujak et al.

Plate C2, figure 8

Occurrence in studied samples.—Patala and Nammal Formations, Nammal Dam section.

Genus *Muratodinium* Drugg
Muratodinium fimbriatum (Cookson & Eisenack) Drugg

Plate C2, figures 3, 4

Remarks.—According to Drugg (1970), *Muratodinium fimbriatum* is more or less ovoidal in shape and has apical and antapical projections. *Thalassiphora patula* (Williams & Downie) Stover & Evitt closely resembles and probably intergrades with *M. fimbriatum*. *T. patula* is more spherical and lacks apical and antapical projections. Some of the Pakistan specimens (pl. C2, fig. 3) show only the faintest projections. In the material studied here, there seems to be no consistent stratigraphic relation to horn prominence.

Occurrence in studied samples.—Patala and Nammal Formations, Nammal Dam section; Nammal Formation, Basharat 34 corehole.

Genus *Operculodinium* Wall
Operculodinium spp.

Plate C1, figure 11

Remarks.—A wide variety of spherical forms with nontabular processes was encountered. Many show some evidence of a precingular archeopyle and thus belong to *Operculodinium*.

Occurrence in studied samples.—Hangu Formation, Nammal Pass section; Patala and Nammal Formations, Nammal Dam section; Patala Formation, Khairpur 9 corehole; Nammal Formation, Basharat 34 corehole.

Genus *Polysphaeridium* Davey & Williams
Polysphaeridium subtile Davey & Williams

Plate C1, figure 12

Occurrence in studied samples.—Patala and Nammal Formations, Nammal Dam section; Nammal Formation, Basharat 34 corehole; questionable in Patala Formation, Khairpur 9 corehole.

Genus *Spiniferites* Mantell
Spiniferites spp.

Plate C1, figures 4, 7

Remarks.—Assorted forms assignable to the genus *Spiniferites* were encountered in the samples studied. No attempt was made to assign these often poorly preserved forms to species. Two better preserved specimens are illustrated in plate C1, figures 4 and 7.

Occurrence in studied samples.—Hangu Formation, Nammal Pass section; Patala and Nammal Formations, Nammal Dam section; Patala Formation, Khairpur 9 corehole; Nammal Formation, Basharat 34 corehole.

Genus *Wetzeliella* Eisenack
?*Wetzeliella astra* Costa et al.

Plate C2, figure 7

Remarks.—Several specimens were encountered in a single sample from the Basharat 34 corehole at a depth of 141.5–141.8 ft. The best preserved is illustrated in plate C2, figure 7.

Occurrence in studied samples.—Nammal Formation, Basharat 34 corehole.

?*Wetzeliella* sp.

Plate C2, figure 9

Remarks.—The single poorly preserved specimen illustrated in plate C2, figure 9 has a more prominent pericoel than is generally accepted in the genus *Apectodinium*, and, therefore, it is questionably placed in the genus *Wetzeliella*.

Occurrence in studied samples.—Nammal Formation, Nammal Dam section.

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Plates C1, C2

Plate C1

[All photographs × 500. Sample numbers are followed by the slide number in parentheses]

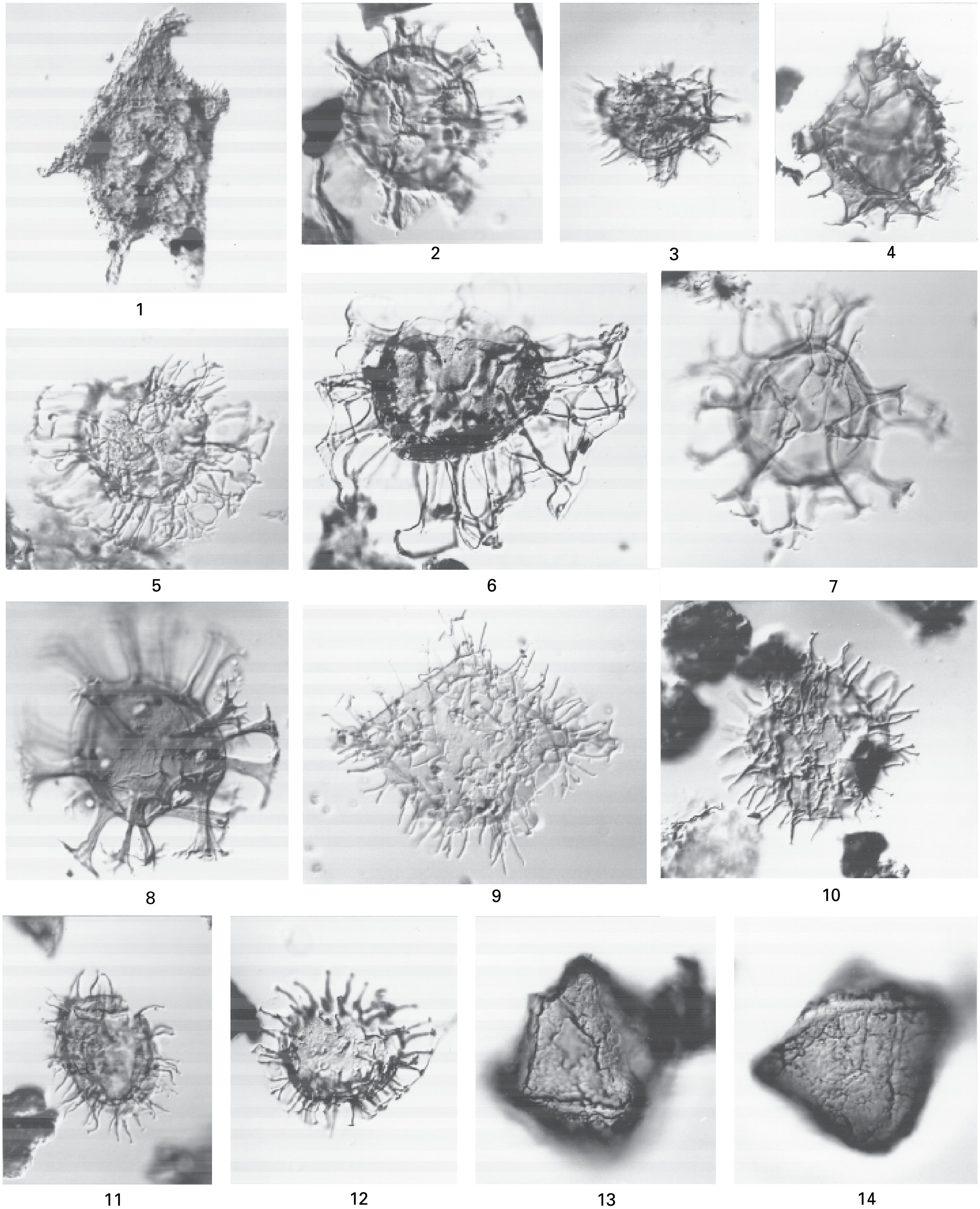
Figures 1–14. Dinocysts from the Hangu, Patala, and Nammal Formations.

1. ?*Apectodinium* sp. Orientation uncertain, sample R4383C (4), Hangu Formation. Slide coordinates 35.8, 75.0.
2. *Cordosphaeridium* sp. Left-lateral view (?), sample R4384AA (4), Patala Formation. Slide coordinates 21.1, 89.6.
3. *Diphyes colligerum* (Deflandre & Cookson) Cookson. Orientation uncertain, sample R4384AD (3), Patala Formation. Slide coordinates 32.9, 80.2.
4. *Spiniferites* sp. Right-lateral view at midfocus, R4384AF (4), Nammal Formation. Slide coordinates 27.3, 80.5.

5, 6. *Adnatosphaeridium multispinosum* Williams & Downie *sensu lato*.
   5. Orientation uncertain, sample R4384AJ (3), Nammal Formation. Slide coordinates 33.0, 106.6.
   6. Dorsal view (?) at midfocus, sample R4384B (2), Patala Formation. Slide coordinates 19.8, 82.3.

7. *Spiniferites* sp. Antapical view of apex, sample R4384AE (3), Patala Formation. Slide coordinates 36.4, 79.1.
8. *Cordosphaeridium gracile* (Eisenack) Davey & Williams. Orientation uncertain, sample R4384AB (4), Patala Formation. Slide coordinates 18.1, 92.9.
9. *Apectodinium paniculatum* (Costa & Downie) Lentin & Williams. Ventral view (?) at midfocus, sample R4384AA (4), Patala Formation. Slide coordinates 30.6, 77.7.
10. *Apectodinium homomorphum* (Deflandre & Cookson) Lentin & Williams. Ventral view (?) at midfocus, sample R4384AF (4), Nammal Formation. Slide coordinates 35.0, 78.0.
11. *Operculodinium* sp. Antapical view of apex, sample R4384AF (4), Nammal Formation. Slide coordinates 37.1, 102.8.
12. *Polysphaeridium subtile* Davey & Williams. Oblique antapical view of hypocyst, sample R4384B (2), Patala Formation. Slide coordinates 28.4, 81.8.

13, 14. *Cribroperidinium giuseppei* (Morgenroth) Helenes. Oblique right-lateral views, sample R4384AB (4), Patala Formation. Slide coordinates 22.5, 86.0.
   13. Focus on epicyst.
   14. Focus on hypocyst.



Dinocysts from the Hangu, Patala, and Nammal Formations

Plate C2

[All photographs × 500. Sample numbers are followed by the slide number in parentheses]

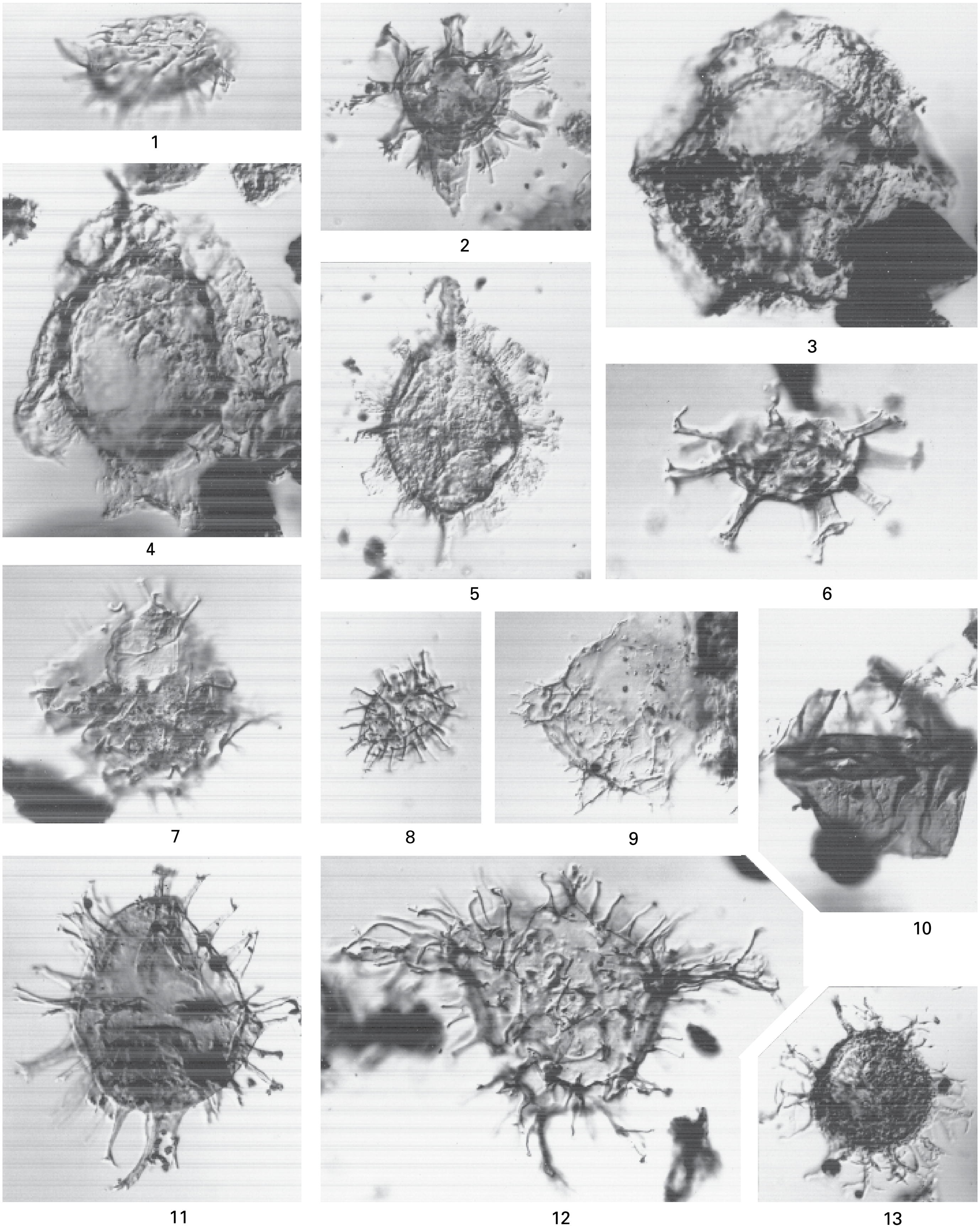
Figures 1–13. Dinocysts from the Patala and Nammal Formations.

1. *Eocladopyxis peniculata* Morgenroth. Interior view of fragment, sample R4384AB (4), Patala Formation. Slide coordinates 32.2, 73.6.
2. *Hystrichokolpoma unispinum* Williams & Downie. Orientation uncertain, sample R4384AD (3), Patala Formation. Slide coordinates 25.4, 81.1.

3, 4. *Muratodinium fimbriatum* (Cookson & Eisenack) Drugg.

 3. Dorsal view of dorsal surface, sample R4384AD (3), Patala Formation. Slide coordinates 18.2, 88.0.
 4. Ventral view (?) at midfocus, sample R4384AF (4), Nammal Formation. Slide coordinates 31.9, 89.1.

5. *Ifecysta pachyderma* Jan du Chêne & Adediran. Ventral view of ventral surface, sample R4384AE (3), Patala Formation. Slide coordinates 32.6, 103.4.
6. *Homotryblium tenuispinosum* Davey & Williams *sensu lato*. Left-lateral view (?), sample R4384AL (3), Nammal Formation. Slide coordinates 28.1, 85.9.
7. ?*Wetzeliella astra* Costa et al. Dorsal view of dorsal surface, sample R4379K (3), Nammal Formation. Slide coordinates 27.4, 106.3.
8. *Melitasphaeridium pseudorecurvatum* (Morgenroth) Bujak et al. Orientation uncertain, sample R4384AD (3), Patala Formation. Slide coordinates 36.8, 93.3.
9. ?*Wetzeliella* sp. Ventral view (?) at midfocus, sample R4384AL (3), Nammal Formation. Slide coordinates 19.7, 98.8.
10. *Lejeunecysta* sp. Ventral view at midfocus, sample R4384AE (3), Patala Formation. Slide coordinates 21.0, 85.2.
11. *Achilleodinium*? sp. I. Left-lateral view, sample R4384B (3), Patala Formation. Slide coordinates 19.1, 87.0.
12. *Apectodinium augustum* (Harland) Lentin & Williams. Dorsal view of dorsal surface, sample R4384AD (3), Patala Formation. Slide coordinates 26.4, 110.4.
13. *Hafniasphaera septata* (Cookson & Eisenack) Hansen. Right-lateral view, sample R4384AD (3), Patala Formation. Slide coordinates 34.1, 103.5.



Dinocysts from the Patala and Nammal Formations

Spore-Pollen Biostratigraphy and Paleoecology of Mesozoic and Lower Tertiary Samples from the Surghar and Salt Ranges, Northern Pakistan

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Chapter D of

Regional Studies of the Potwar Plateau Area, Northern Pakistan

Edited by Peter D. Warwick and Bruce R. Wardlaw

Prepared in cooperation with the
Geological Survey of Pakistan,
under the auspices of the
U.S. Agency for International Development,
U.S. Department of State, and the
Government of Pakistan

Bulletin 2078–D

U.S. Department of the Interior
U.S. Geological Survey

Contents

Plates

[Plates follow Appendix D1]

Figures

Table

Spore-Pollen Biostratigraphy and Paleoecology of Mesozoic and Lower Tertiary Samples from the Surghar and Salt Ranges, Northern Pakistan

By N.O. Frederiksen, T.P. Sheehan, and V.A.S. Andrle

Abstract

The conglomerate at the base of the Basharat drill hole 34 (eastern Salt Range), thought to represent the Tobra Formation (Permian), contained Permian pollen grains and spores that may be indigenous or may be reworked; thus, the age of this conglomerate is uncertain.

Two samples from the lower part of Lumshiwal Nala (Makarwal coal field, Surghar Range), probably from the Lumshiwal Formation, were assigned Late Jurassic to Early Cretaceous and middle Cretaceous (approximately Aptian to Albian) ages, respectively.

Rocks from the shallow subsurface of the Kuraddi section in the western Salt Range, thought to be possibly from the Paleocene Hangu Formation, contained spores and pollen grains probably of Jurassic to Early Cretaceous age; therefore, these samples were probably from the Mesozoic Datta Formation.

Rocks mapped as the Hangu Formation at Lumshiwal Nala (Surghar Range) and Nammal Pass (western Salt Range) are Paleocene in age. All analyzed samples of the Patala Formation from the Salt Range appear to be late Paleocene in age and contain pollen assemblages similar to those of the Lakhra Formation of Sindh Province. The Patala assemblages are no older than those from the uppermost part of the Bara Formation of Sindh Province. Paleocene coal beds in the Hangu and Patala Formations were undoubtedly deposited in or near brackish water because dinoflagellate cysts and brackish-water palm pollen of the genus *Spinizonocolpites* were found in the associated detrital rocks.

Two samples from the Nammal Formation (lower Eocene(?)) of the Basharat drill hole 34 (eastern Salt Range) had low-diversity spore and pollen assemblages that did not include any species known to be restricted to the Eocene, although some new species were present that might be so restricted.

Introduction

Lower and middle Eocene rocks of the Surghar and Salt Ranges (figs. D1, D2) were deposited entirely in marine environments and can generally be given an age assignment using marine megafossils or microfossils. However, some of the Mesozoic and Paleocene formations of the region are predominantly nonmarine; although marine fossils have been found in these formations in certain areas, many outcrops lack such fossils. Spores and pollen are therefore most useful in providing ages and correlations of mainly nonmarine units. Previously published Tertiary spore and pollen work in the region includes a description of some late Paleocene or Eocene species from Dandot, in Jhelum District, Punjab, by Vimal (1952) and a description of many Paleocene species from northern and southern Pakistan by Frederiksen (1994).

In the present study of spores and pollen from the Surghar and Salt Ranges, 1 sample was analyzed from the Tobra Formation(?) (Permian(?)), 2 from the Lumshiwal Formation (Mesozoic), 7 from rocks thought at least tentatively to represent the Hangu Formation (Paleocene), 26 from the Patala Formation (mainly or entirely Paleocene), and 2 from the Nammal Formation (Eocene(?)). Spore-pollen species mentioned in the text and figures are listed in appendix D1. Many taxa studied are shown in plates D1–D4.

Acknowledgments

This work was done as part of the Coal Resources Exploration and Assessment Program (COALREAP), a collaborative program between the U.S. Geological Survey and the Geological Survey of Pakistan. This cooperative program is under the auspices of the U.S. Agency for International Development and the Government of Pakistan. Most samples discussed in this paper were collected by Frederiksen; however, many of the Patala samples from the central and eastern Salt Range were collected by P.D. Warwick. We appreciate the helpful reviews of L.E. Edwards, J.E. Fassett, and B.R. Wardlaw.

Previously Reported Ages of Formations

The Lumshiwal Formation of the Surghar Range (table D1) contains very few marine fossils but was thought by Fatmi

Figure D1. Location map showing the Salt Range study area (box) and selected regional features.

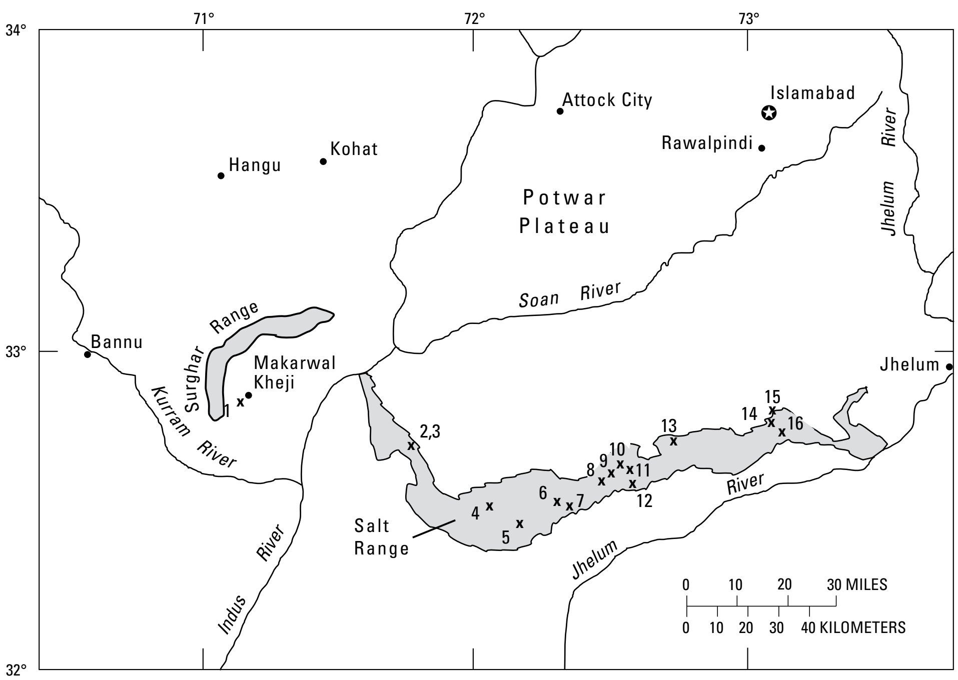

Figure D2. Map of the Salt Range study area in northern Pakistan showing sample localities discussed in this report. 1, Lumshiwal Nala; 2, Nammal Pass section; 3, Nammal Dam section; 4, Kuraddi section; 5, sample R4264; 6, sample R4262; 7, Arara section; 8, sample R4242M; 9, sample R4242K; 10, sample R4242J; 11, Nila Wahan section; 12, sample R4242L; 13, drill hole 9 in Khairpur area; 14, drill hole 34 in Basharat area; 15, sample R4242E; and 16, sample R4242D.

Table D1. Some stratigraphic units in Sindh Province and in the Surghar and Salt Ranges, Pakistan.

[No stratigraphic correlations between units in the two regions are implied]

Sindh Province	Surghar and Salt Ranges
Tertiary—Paleocene and Eocene	Tertiary—Paleocene and Eocene
Laki Formation	Nammal Formation
Ranikot Group	Patala Formation
Sohnari Formation	Lockhart Limestone
Lakhra Formation	Hangu Formation
Bara Formation	Jurassic and Cretaceous
Khadro Formation	Lumshiwal Formation
	Chichali Formation
	Samana Suk Formation
	Datta Formation

(1972, p. 323) to be probably Aptian(?) to middle Albian in that region. In other areas the Lumshiwal Formation is thought to contain strata ranging from Upper Jurassic to Albian (Fatmi, 1972), but in general, the age of the formation and the ages of different levels within the formation are poorly known.

The Hangu Formation and its presumed correlative, the Dhak Pass Formation, contain foraminifers in some areas of the Salt and Surghar Ranges, and these fossils have suggested an early Paleocene age (Cheema and others, 1977). Most samples from the Hangu and Dhak Pass Formations examined for calcareous nannofossils and dinoflagellates by Köthe (1988) were barren of these fossils, but several samples contained sparse calcareous nannofossil and dinoflagellate assemblages that were assigned to the upper Paleocene by these authors. L.E. Edwards (this volume, chap. C) assigned rare dinoflagellates from two samples probably of the Hangu Formation at Nammal Pass (fig. D2, locality (loc.) 2) provisionally to the upper Paleocene. In summary, (1) the Hangu and Dhak Pass Formations appear to contain mainly nonmarine strata (or at least it has been difficult to obtain marine fossils from these formations), and therefore the ages of the formations are not well known in many areas; and (2) no effort seems to have been made to reconcile early Paleocene ages for the Hangu and Dhak Pass Formations based on foraminifers with late Paleocene ages based on dinoflagellates and calcareous nannofossils. Ages of coal beds in the Hangu and Dhak Pass are poorly known on the basis of marine fossils.

The Patala Formation is considered to be upper Paleocene in most areas but extending into the lower Eocene in a few places, on the basis of mollusks, foraminifers, ostracodes, calcareous nannofossils, and dinoflagellates (Cheema and others, 1977; Köthe, 1988). According to L.M. Bybell and J.M. Self-Trail, L.E. Edwards, and T.G. Gibson (this volume, chaps. B, C, and E), the uppermost part of the Patala at Nammal Dam (general area of fig. D2, locs. 2, 3) is uppermost Paleocene. Furthermore, the Lockhart Limestone, which underlies the Patala Formation, is also upper Paleocene (Cheema and others, 1977; Köthe, 1988; Edwards, this volume, chap. C). Therefore, the entire Patala is probably upper Paleocene in most places. However, few fossils have been obtained from strata associated with coal beds within the Patala. In the present study, most samples from the Patala Formation are from detrital rocks closely associated with coal beds.

The lower part of the Nammal Formation at Nammal Dam has been assigned a late Paleocene age on the basis of planktic foraminifers (Gibson, this volume, chap. E, and references therein), but an early Eocene age on the basis of calcareous nannofossils (Bybell and Self-Trail, this volume, chap. B). In the Basharat corehole 34 (fig. D2, loc. 14), the Paleocene-Eocene boundary may fall within the middle part of the formation on the basis of dinoflagellates (Edwards, this volume, chap. C). However, at Nammal Dam (fig. D2, loc. 3), the lowest part of the Nammal Formation may be lower Eocene (Edwards, this volume, chap. C).

Determination of Spore-Pollen Ages

In this paper, the means of determining spore-pollen ages for samples from the Salt and Surghar Ranges has been to compare species found in these regions (1) with species found in the upper Paleocene of Sindh Province (Frederiksen, 1990) and (2) with species found by palynologists who have worked on Mesozoic and lower Tertiary sections in India (many publications describe the palynology of Indian material). However, many spore-pollen species found in the samples from the Salt and Surghar Ranges but not in Sindh Province remained unidentified because of time limitations. An important weakness in previous knowledge is that no spore-pollen assemblages from the lower Paleocene of the Indian subcontinent have been described, although assemblages of this age are presently under investigation in India (R.K. Kar, Birbal Sahni Institute of Palaeobotany, Lucknow, India, oral commun., 1989). Early Paleocene assemblages from India would have been especially useful for comparison with samples assigned to the Hangu Formation of the Salt and Surghar Ranges, which, as noted above, is thought to be lower Paleocene at least in some areas.

Figure D3 is a range chart for 27 pollen species and species groups in the upper Paleocene of the Lower Indus coal region, Sindh Province. The chart is based on pollen occurrences in 75 samples from 8 coreholes: UAL–2, UAL–13, UAJ–1, DH–18, UAK–5, UAK–7, UAT–8, and UAT–9 (Frederiksen, 1990). Stratigraphic units shown in figure D3 (see also table D1) are those of corehole UAL–13, the longest and most complete core. This core section was transformed into a single composite section for the upper Paleocene of the Lower Indus coal region by correlating it with all the other cores (using the graphic correlation charts of Frederiksen (1990)).

The species and species groups in figure D3 were stratigraphically the most significant pollen forms found in the Lower Indus samples, although many of these are new species, and therefore, their true stratigraphic ranges are not yet certain. Figure D3 does not include forms that ranged throughout the upper

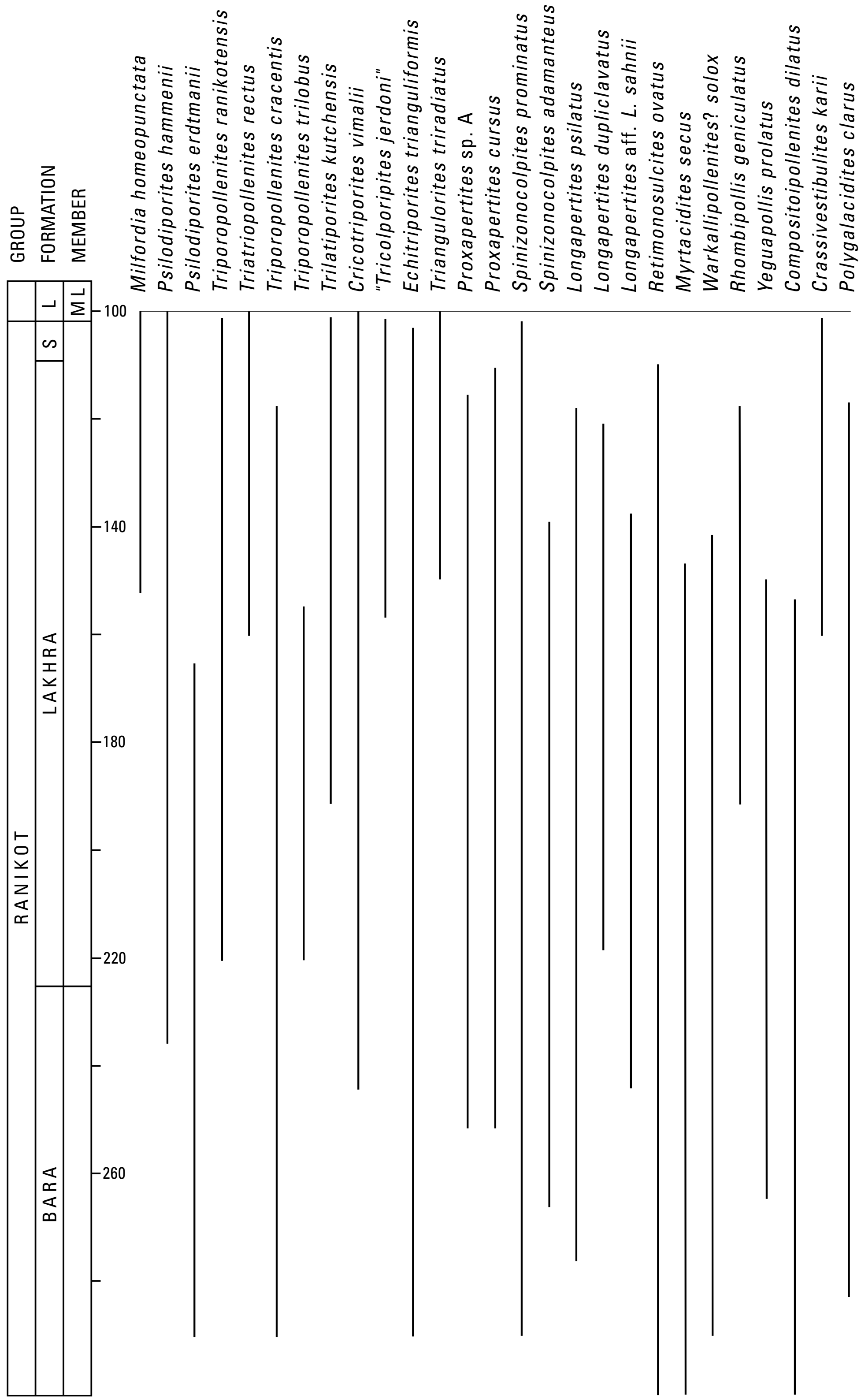

Figure D3. Range chart for 27 stratigraphically significant pollen species and species groups in a composite section for the upper Paleocene of the Lower Indus coal region, Sindh Province (data from Frederiksen, 1990). Stratigraphic units shown are those of corehole UAL–13, and each composite thickness unit represents 1 m of thickness in UAL–13. Stratigraphic nomenclature from Outerbridge and others (1991). L, Laki Formation; ML, Meting Limestone Member; S, Sohnari Formation.

Paleocene section in the Lower Indus region, nor does it include rare forms whose true range tops and bases are poorly known.

Besides the species known from the Lower Indus region, five additional early Tertiary taxa were tabulated for the samples from the Salt and Surghar Ranges. These species, and their ranges as known from India, are as follows.

Dandotiaspora dilata—apparently confined to the Paleocene (Ambwani and Kar, 1988)

Dandotiaspora telonata (pl. D3, fig. 2)—mainly Paleocene, but ranges up into the Eocene (Ambwani and Kar, 1988)

Lakiapollis ovatus (see *L.* aff. *L. ovatus* in pl. D4, fig. 1)—Paleocene to middle and upper(?) Eocene (Venkatachala and others, 1988)

Retitribrevicolporites matanomadhensis (pl. D4, fig. 4)—Paleocene to middle Eocene (Kar, 1985)

Acrostichum spp. (pl. D3, fig. 1)—This genus is interesting because (1) it is the only modern fern genus that can live consistently in brackish-water environments (it is pantropical), and (2) large abundances of *Acrostichum* spores are said to be characteristic of early Paleocene spore-pollen assemblages of India (R.K. Kar, oral commun., 1989). Because of some evidence that the Hangu Formation is at least partly early Paleocene in age, it was of interest to see whether *Acrostichum* spores were abundant in Hangu samples. However, spores identified as belonging to this genus are very rare to absent in all Paleocene and Eocene samples examined for the present report. On the other hand, there is some question whether the characteristic verrucate to coarsely granulate ornamentation found in modern *Acrostichum* spores (Nayar and others, 1964; Kremp, 1967; Thanikaimoni, 1987) is preserved very well in the fossil state. For example, Anderson and Muller (1975, p. 295) reported that *Acrostichum* spores from the Miocene and Holocene of Borneo had, "in the fossil state, a smooth exine." Thanikaimoni (1987, pl. 43, figs. 785–788) illustrated two fossil *Acrostichum* spores from Sri Lanka, one of which has a rough exine (ornamentation or a result of corrosion?) and the second of which has a smooth exine except for fine pitting, which is probably due to corrosion. In summary, it appears that most fossil *Acrostichum* spores are not easy to identify with certainty unless they are associated with obvious mangrove pollen; therefore, the rarity of obvious *Acrostichum* spores in the Paleocene of Pakistan apparently does not necessarily mean that these spores are actually rare in the samples.

Palynological Methods

Palynological samples were prepared by means of standard acid maceration. All samples underwent heavy liquid separation using $ZnCl_2$ having a specific gravity of 1.45. This unusually low specific gravity was necessary in order to remove the abundant dark woody particles from the residues and to increase the richness of the residues in the spores and pollen. The float fraction was screened on a 10-micrometer (µm) nylon sieve and mounted in glycerine jelly. When spores and pollen were present in a sample, they were usually fairly to very well preserved. Slide designations in captions for plates D1–D4 show the sample number with the slide number in parentheses. The coordinates listed in the plate descriptions locate the specimens on Leitz microscope 871956 at the U.S. Geological Survey (USGS), Reston, Va. On this microscope, the coordinates for the center point of a standard 25.4 × 76.2 mm slide are 38.8 × 102.5 (horizontal × vertical axes); the horizontal coordinates increase toward the right edge of the stage, and the vertical coordinates increase toward the front of the stage. All slides are stored at the USGS in Reston, Va.

Sample Analyses

Makarwal Coal Field

The Makarwal coal field is in the Mianwali District, Surghar Range (fig. D2, loc. 1). Palynology samples examined from this area are from Lumshiwal Nala, lat 32°51.49′ N., long 71°08.83′ E., and include samples from the Lumshiwal, Hangu, and Patala Formations (table D1). In the Makarwal coal field, Danilchik and Shah (1987, p. 17) measured 285 feet (ft) of Lumshiwal Formation in its type section, where it underlies the Hangu Formation. This type section for the Lumshiwal Formation is in Miranwal Nala, 1.7 kilometers (km) north of Lumshiwal Nala.

Palynology sample R4381A.—Field no. NF89P–1, carbonaceous shale at base of stream channel, thought to be probably Mesozoic in age or possibly from the Paleocene Hangu Formation. The stratum from which this sample was taken is probably from the Lumshiwal Formation, and apparently it lies below the measured section for the uppermost part of the Lumshiwal Formation and the Hangu Formation in Lumshiwal Nala that was described by Danilchik and Shah (1987, p. 19). The sample probably is from the same horizon as Warwick sample K–SH–1, examined by Khan (1990). Sample R4381A contains a rich spore-pollen assemblage, including *Callialasporites dampieri* (pl. D2, fig. 1), *C. segmentatus*, *C. trilobatus*, *Corollina*, *Exesipollenites*, *Araucariacites*, *Contignisporites fornicatus*, a large variety of *Gleicheniidites* types, and rare dinoflagellate cysts and *Veryhachium* acritarchs. Age is Late Jurassic or Early Cretaceous, in agreement with Khan's (1990) age determination for sample K–SH–1. As noted above, the Lumshiwal Formation in the Surghar Range was thought, on the evidence of very sparse marine fossils, to be Aptian(?) to Albian. In the Makarwal coal field, the Lumshiwal Formation is underlain by the Upper Jurassic to Lower Cretaceous (Neocomian) Chichali Formation; however, no Chichali was mapped in the area of Lumshiwal Nala (Danilchik and Shah, 1987). Therefore, in the area of Lumshiwal Nala, the Lumshiwal Formation appears to include strata of Chichali (Late Jurassic to Early Cretaceous) age.

Palynology sample R4381B.—Field no. NF89P–2, underclay below Hangu(?) coal. The sample contained only rare palynomorphs, and no age determination could be made.

Palynology sample R4381C.—Field no. NF89P–3, siltstone above the coal bed that is underlain by the clay of sample R4381B. Sample R4381C contained *Klukisporites*, *Densoisporites* (pl. D2, fig. 3), *Contignisporites glebulentus* (pl. D2, figs. 5, 6), *Coptospora kutchensis* (pl. D2, fig. 4), *Matonisporites*, and *Callialasporites segmentatus* (pl. D2, fig. 2). No dinoflagellate cysts were seen. Age is probably middle Cretaceous, approximately Aptian to Albian. There is confusion as to whether this sample comes from the same horizon as Warwick sample SH–MK–HT–1, examined by Khan (1990). Khan (1990) reported a possible Paleogene age for sample SH–MK–HT–1, which would be in conflict with the middle Cretaceous age determined for sample R4381C. However, it is possible that the coal bed near Khan's sample is the Makarwal main coal bed of Danilchik and Shah (1987, p. 19), which was considered to be in the Hangu Formation. Sample R4381C may come from the Lumshiwal Formation, possibly from the upper part of the formation, near a coal bed that is about 25 ft below the Makarwal main coal bed (Danilchik and Shah, 1987, p. 17). The doubt about sample positions and ages needs to be resolved by future collecting in the section.

Palynology sample R4381D.—Field no. NF89P–4, Hangu Formation higher in stream channel than sample R4381C. The sample contained only sparse pollen grains, few spores, and rare dinoflagellate cysts. Some variety of spore-pollen forms was present, but we are not familiar with most of them. Figure D4 lists the forms that also occur in the upper Paleocene of Sindh Province. These forms all have long ranges or are so rare that the ranges are poorly known. Age is Paleocene.

Palynology sample R4381E.—Field no. NF89P–5, carbonaceous shale associated with coal in the lower part of the Hangu Formation. The sample contained many species of angiosperm pollen, but we are not familiar with most of them. Spores are not abundant; rare dinoflagellate cysts are present. Figure D4 lists the pollen forms that also occur in the upper Paleocene of Sindh Province. These forms all have long ranges or are so rare that the ranges are poorly known, but they probably all extend well down into the Bara Formation in Sindh Province. No Late Cretaceous species (listed, for example, by Venkatachala and Sharma (1974) and Baksi and Deb (1980)) have been seen in this sample or the next lower one (R4381D). Age is Paleocene.

Sample	*Triatriopollenites dubius*	*Cricotriporites vimalii*	*Echitriporites trianguliformis*	*Triangulorites triradiatus*	*Proxapertites* sp. A	*Proxapertites assamicus*	*Proxapertites operculatus*	*Spinizonocolpites prominatus*	*Spinizonocolpites adamanteus*	*Longapertites retipilatus*	*Tricolpites reticulatus*	*Cupanieidites granulatus*	*Polycolporopollenites calvus*	*Retistephanocolpites* spp.	*Dandotiaspora dilata*
R4381G	?	X	.	.	X	X	X	.	.	X	P	X	.	X	.
R4381E	.	.	X	X	.	X	X	X	X	X	.	.	.	.	.
R4381D	.	.	.	.	.	X	X	X	.	X	.	.	X	.	X

Figure D4. Analyses of spore-pollen assemblages from the Hangu (samples R4381D, E) and Patala (sample R4381G) Formations of Lumshiwal Nala in the Makarwal coal field. X, present; P, probably present; ?, possibly present.

Palynology sample R4381F.—Field no. NF89P–6, transition zone between the Lockhart Limestone and the Patala Formation. Nearly barren of spores and pollen; rare dinoflagellate cysts are present.

Palynology sample R4381G.—Field no. NF89P–6A, Patala Formation at 403 ft in the measured section of Wardlaw and others (this volume, chap. F). Like the Paleocene Hangu samples, this sample contained many species that are unfamiliar to us. Figure D4 lists the pollen forms that also occur in the upper Paleocene of Sindh Province. These forms generally have long ranges or are so rare that the ranges are poorly known, but two species, *Cricotriporites vimalii* and *Proxapertites* sp. A, have known range bases in the upper part of the Bara Formation in Sindh Province. Furthermore, the two samples from the lower part of the Hangu Formation, R4381D and E, are more similar to each other than they are to the Patala sample R4381G. In short, the age of R4381G is presumably late Paleocene.

Palynology sample R4381H.—Field no. NF89P–7, lower part of Patala Formation at 275 ft in the measured section of Wardlaw and others (this volume, chap. F). This sample was nearly barren of palynomorphs.

Nammal Pass Section

Three samples thought to be from the Hangu Formation were collected from a coal mine dump near the road over Nammal Pass in the western Salt Range (fig. D2, loc. 2). This locality is near the base of the Nammal Pass measured section of Wardlaw and others (this volume, chap. F), at lat 32°40.75′ N., long 71°47.19′ E. Two samples from this mine dump contained sparse dinoflagellates possibly of late Paleocene age (Edwards, this volume, chap. C).

Two of the three samples collected were analyzed for spores and pollen (fig. D5): R4383A, field no. NF89P–10, gray mudstone; and R4383B, field no. NF89P–11, coal. The samples had relatively few spores, but they did contain a considerable variety of angiosperm pollen; however, most of the pollen grains represented new species, different from the pollen species known from the upper Paleocene (Ranikot Group) of Sindh Province and from the Patala Formation of the Salt Range. Age is Paleocene but older than typical Patala samples. Sample R4383A (roof mudstone) contained the pollen genus *Spinizonocolpites*, representing the brackish-water palm genus *Nypa*, as well as fragments of dinoflagellate cysts; sample R4383B (coal) contained *Spinizonocolpites*. Thus, the Hangu

Sample	*Psilodiporites hammenii*	*Triatriopollenites dubius*	*Cricotriporites vimalii*	*"Tricolporipites jerdoni"*	*Echitriporites trianguliformis*	*Triangulorites triradiatus*	*Proxapertites* sp. A	*Proxapertites assamicus*	*Proxapertites operculatus*	*Proxapertites emendatus*	*Spinizonocolpites prominatus*	*Spinizonocolpites adamanteus*	*Longapertites psilatus*	*Longapertites retipilatus*	*Longapertites discordis*	*Longapertites* sp. F	*Tricolpites reticulatus*	*Myrtaciidites secus*	*Warkallipollenites? medius*	*Callophyllumpollenites* cf. *C. rotundus*	*Compositoipollenites dilatus*	*Cupanieidites flacccidiformis*	*Retistephanocolpites* spp.	*Acrostichum* sp.	*Dandotiaspora telonata*	*Retitribrevicolporites matanomadhensis*
R4384A–C	•	•	X	•	•	•	•	•	•	•	•	•	X	•	•	•	•	•	•	•	•	•	X	•	•	X
R4385C–E	•	X	X	X	•	•	X	X	•	X	X	•	•	•	X	•	X	X	•	•	P	X	X	?	X	X
R4386E	•	X	•	•	•	•	•	X	X	•	X	•	•	X	•	•	•	•	•	•	•	•	X	•	?	•
R4387B, C	X	•	X	X	•	X	•	X	X	•	X	•	•	•	X	X	•	•	•	X	•	X	X	?	X	•
R4383A, B	X	•	•	•	X	•	X	•	X	X	X	X	•	X	X	•	•	•	X	•	•	•	X	•	•	•

Figure D5. Analyses of spore-pollen assemblages from the Hangu Formation of Nammal Pass (samples R4383A, B) and from the Patala Formation of the Nammal Dam (samples R4384A–C), Arara (samples R4385C–E), Kuraddi (sample R4386E), and Nila Wahan (samples R4387B, C) sections. X, present; P, probably present; ?, possibly present.

coal and its roof mudstone at this locality were deposited in brackish water.

Nammal Dam Section

The Nammal Dam section is located at lat 32°39.81′ N., long 71°48.05′ E. in the western Salt Range (fig. D2, loc. 3). Three samples were examined from the Patala Formation at this locality: R4384A, field no. NF89P–13, lowest dark beds of the Patala; R4384B, field no. NF89P–14, 91 ft above the base of the Patala; and R4384C, field no. NF89P–15, 10 ft higher than sample NF89P–14.

Each of these samples contained only sparse spores and pollen grains, and analyses of the three samples are combined in figure D5. Age is late Paleocene(?). All three samples contained dinoflagellate cysts; thus, the beds were deposited in brackish-water to marine environments.

Kuraddi Section

The Kuraddi section is located 0.5 km south of the village of Kuraddi in the western Salt Range; the base of the section is at lat 32°31.67′ N., long 72°03.43′ E. (fig. D2, loc. 4; section 31 of Warwick and Shakoor (1988); section 8 of Wardlaw and others (this volume, chap. F)). The following palynology samples were examined: from the Patala Formation, R4386E, field no. NF89P–26; and from the Hangu Formation(?), R4386A, field no. NF89P–22; R4386B, field no. NF89P–23; and R4386C, field no. NF89P–24.

The three samples thought perhaps to be from the Hangu Formation were from blocks of mudstone on a pile of coal mine spoil. These samples all had the same palynomorph assemblage, characterized by (1) a high dominance (>90 percent) of the gymnosperm pollen genus *Corollina* (pl. D1, figs. 10, 11) and (2) a low diversity of other constituents, which were mainly fern spores. No dinoflagellate cysts were seen. The following spore-pollen species were identified: "*Dictyophyllidites pectinataeformis*" of Venkatachala (1969, pl. D1, fig. 12), *Concavisporites* cf. *C. jurienensis*, *Matonisporites crassiangulatus* (pl. D1, fig. 8), *Microreticulatisporites* cf. *M. telatus*, *Cingulatisporites* cf. *C. foveolatus* (pl. D1, fig. 7), *C. pseudoalveolatus* (pl. D1, fig. 9), *Cingulatisporites* spp. (pl. D1, figs. 3, 4), *Clavifera*? spp. (pl. D1, figs. 5, 6), *Ischyosporites* aff. *I. crateris*, *Baculatisporites comaumensis*, *Lycopodiacidites* aff. *L. subtriangulus*, *Acanthotriletes* cf. *A. levidensis*, and *Inaperturopollenites turbatus* (pl. D1, fig. 12). Age is Jurassic or Early Cretaceous, perhaps most likely Neocomian. It is apparent that these samples were from rocks mapped by Gee (1981) near Kuraddi as the Datta Formation; Gee considered the Datta to be Lower Jurassic.

Sample R4386E (Patala Formation) contained relatively few identified species (fig. D5). Age is presumably late Paleocene. The assemblage from this mudstone sample contained the brackish-water palm genus *Spinizonocolpites*.

Samples from the Central and Eastern Salt Range

Samples from the Patala Formation of the central and eastern Salt Range that yielded useful palynological data are in figure D6 and below.

Palynology sample R4264.—Field no. SH–S30–2, central Salt Range coal field, lat 32°27.75′ N., long 72°11.58′ E., the Punjab, Khushab District (fig. D2, loc. 5). Material studied is a grab sample of shale of the Patala Formation. Age is late Paleocene, correlative with the Lakhra Formation and apparently with the middle part of the Lakhra Formation. The sample contained some dinoflagellate cysts.

Palynology sample R4262.—Field no. SH–ARR–HM–RT, central Salt Range coal field, lat 32°32.83′ N., long 72°20.92′ E., the Punjab, Khushab District, Hayak Ul Mir Coal Co. mine (fig. D2, loc. 6). Material studied is a grab sample of coal roof shale of the Patala Formation. Age is late Paleocene, correlative with the Lakhra or Sohnari Formation. No dinoflagellate cysts were seen, but the presence of *Spinizonocolpites* (brackish-water palm) pollen suggests brackish-water deposition.

Palynology sample R4242M.—Field no. SH–P–KB–6B, central Salt Range coal field, lat 32°36.67′ N., long 72°28.75′ E., the Punjab, Khushab District, Karam Buksh and Co. mine 6B (fig. D2, loc. 8). Material studied is a grab sample of coal roof shale of the Patala Formation. Age is late Paleocene, correlative with the Lakhra Formation. The sample contained rare dinoflagellate cysts.

Palynology sample R4242K.—Field no. SH–PJ–PCP–1, central Salt Range coal field, lat 32°37.75′ N., long 72°31.00′ E., the Punjab, Khushab District, Punjmin-PCP mine 1 (fig. D2, loc. 9). Material studied is a grab sample of coal roof shale of the Patala Formation. Age is late Paleocene, correlative with the Lakhra or Sohnari Formation. The sample contained rare dinoflagellate cysts.

Palynology sample R4242J.—Field no. SH–M–SAL–1, central Salt Range coal field, lat 32°39.42′ N., long 72°33.42′ E., the Punjab, Chakwal District, S.A. Latif and Co. mine (fig. D2, loc. 10). Material studied is a grab sample of coal roof shale of the Patala Formation. Age is late Paleocene, correlative with the Lakhra Formation. The sample contained some dinoflagellate cysts.

Palynology sample R4242L.—Field no. SH–P–KC–12, central Salt Range coal field, lat 32°35.50′ N., long 72°35.58′ E., the Punjab, Khushab District (fig. D2, loc. 12). Material studied is a grab sample of coal roof shale of the Patala Formation. Age is late Paleocene, correlative with the Lakhra Formation. The sample contained rare dinoflagellate cysts.

Palynology sample R4242E.—Field no. SH–CGAS–HCC–3, eastern Salt Range coal field, lat 32°48.83′ N., long 73°06.42′ E., the Punjab, Jhelum District, Hasnain Coal Co. mine (fig. D2, loc. 15). Material studied is a grab sample of coal roof shale of the Patala Formation. Age is late Paleocene, correlative with the Lakhra Formation or uppermost part of the Bara Formation. The sample contained sparse dinoflagellate cysts.

Sample	*Psilodiporites hammenii*	*Triporopollenites trilobus*	*Triatriopollenites dubius*	*Cricotriporites vimalii*	*"Tricolporipites jerdoni"*	*Echitriporites trianguliformis*	*Proxapertites* sp. A	*Proxapertites assamicus*	*Proxapertites operculatus*	*Proxapertites emendatus*	*Spinizonocolpites prominatus*	*Longapertites psilatus*	*Longapertites punctatus*	*Longapertites retipilatus*	*Longapertites discordis*	*Longapertites* aff. *L. sahnii*	*Longapertites* sp. F	*Retimonosulcites ovatus*	*Matanomadhiasulcites maximus*	*Brevitricolpites vadosus*	*Myrtaceidites secus*	*Porocolpopollenites* aff. *P. ollivierae*	*Callophyllumpollenites* aff. *C. rotundus*	*Compositoipollenites dilatus*	*Cupanieidites flacciformis*	*Cupanieidites granulatus*	*Polygalacidites clarus*	*Retistephanocolpites* spp.	*Acrostichum* sp.	*Dandotiaspora dilata*	*Dandotiaspora telonata*	*Lakiapollis ovatus*	*Retitribrevicolporites matanomadhensis*
R4242D	.	.	X	X	.	X	.	X	.	.	X	X	X	X	.	X	X	.	X	X	.	.	.	.	.	X	.	X	.	.	X	.	.
R4242E	X	.	.	X	.	.	.	X	P	?	X	.	.	X	.	X	X	.	.	.	X	.	.	X	?	X	.	X	X	.	X	X	X
R4242J	X	X	.	X	P	.	.	X	X	X	.	.	X	X	.	.	X	.	X	.	.	.	.	.	X	.	.	.	.	X	X	.	.
R4242K	P	.	X	X	.	.	.	X	X	X	X	.	.	X	X	.	X	.	.	.	.	.	X	.	X	X	.	X	X	X	X	.	.
R4242L	.	.	X	X	X	.	X	X	X	X	X	.	.	X	X	.	X	X	X	.	.	.	.	.	X	.	.	X	.	X	X	.	X
R4242M	?	.	.	X	X	.	.	X	X	X	X	.	X	X	X	.	X	.	.	.	X	.	X	.	X	.	.	X	.	X	X	?	X
R4262	P	.	.	X	X	.	.	X	X	X	X	.	.	X	.	.	X	.	X	.	.	X	.	.	.	.	.	X	.	.	X	X	.
R4264	X	.	X	X	X	.	.	.	X	X	X	.	.	X	.	.	X	.	.	.	X	X	.	.	X	.	X	X	.	.	X	.	.

Figure D6. Analyses of spore-pollen assemblages from the Patala Formation of various sections in the central and eastern Salt Range. X, present; P, probably present; ?, possibly present.

Palynology sample R4242D.—Field no. SH–ARA–MC5, eastern Salt Range coal field, lat 32°44.83′ N., long 73°08.25′ E., the Punjab, Jhelum District, Munawer Corp. mine 5 (fig. D2, loc. 16). Material studied is a grab sample of coal roof shale of the Patala Formation. Age is late Paleocene, correlative with the Lakhra Formation. The sample contained sparse dinoflagellate cysts.

Arara Section

The Arara section is located 3.2 km southeast of the village of Arara, its base at lat 32°32.16′ N., long 72°23.54′ E. (fig. D2, loc. 7; section 29 of Warwick and Shakoor (1988); section 10 of Wardlaw and others (this volume, chap. F)). Five siltstone, shale, and mudstone samples were collected from a pile of coal mine spoil in the Patala Formation at this locality. Combined analyses of three of these palynology samples are given in figure D5: R4385C, field no. NF89P–18; R4385D, field no. NF89P–19; and R4385E, field no. NF89P–20.

This set of samples was relatively rich in angiosperm pollen species known from the upper Paleocene of Sindh Province. The samples contained pollen of the brackish-water palm genus *Spinizonocolpites*.

Nila Wahan Section

The Nila Wahan section is located at a north point dividing major drainages to Nila Wahan Gorge, 2 km southeast of the village of Bhal; the base of the Lockhart Limestone is at lat 32°38.67′ N., long 72°35.75′ E. (fig. D2, loc. 11; section 20 of Warwick and Shakoor (1988); section 13 of Wardlaw and others (this volume, chap. F)). Three mudstone samples were collected from a pile of coal mine spoil in the Patala Formation at this locality; combined analyses of two of these palynology samples are given in figure D5: R4387B, field no. NF89P–28; and R4387C, field no. NF89P–29.

These samples contained a fair number of angiosperm pollen species known from the upper Paleocene of Sindh Province. No dinoflagellate cysts were found, but pollen of the brackish-water palm genus *Spinizonocolpites* was present.

Drill Hole 9, Khairpur Area

Drill hole 9 in the Khairpur area is at lat 32°44.67′ N., long 72°47.00′ E. (fig. D2, loc. 13). Only samples processed for palynomorphs are listed below; samples marked with an asterisk were barren or contained only rare palynomorphs. Depths are in feet below ground surface. Analyses of three usable spore-pollen assemblages from the Patala Formation are given in figure D7.

Nammal Formation

Four palynology samples were processed from the Nammal Formation: R4372C*, 210.5–210.7 ft; R4372D*, 301.0–301.4 ft; R4372E*, 335.3–335.6 ft; and R4372F*, 405.7–406.0 ft.

Patala Formation

Palynology sample R4372J, 421.1–421.5 ft, is of late Paleocene age, correlative with the Lakhra Formation or the uppermost part of the Bara Formation. Palynology sample R4372N, 446.6–446.9 ft, contained only sparse spores and pollen grains but did contain dinoflagellate cysts. Palynology sample R4372O, 457.9–458.0 ft, is probably of late Paleocene age and contained rare dinoflagellate cysts. Palynology sample

Sample	*Cricotriporites vimalii*	"*Tricolporipites jerdoni*"	*Proxapertites assamicus*	*Proxapertites operculatus*	*Proxapertites emendatus*	*Spinizonocolpites prominatus*	*Longapertites psilatus*	*Longapertites punctatus*	*Longapertites retipilatus*	*Longapertites discordis*	*Longapertites* aff. *L. sahnii*	*Longapertites* sp. F	*Matanomadhiasulcites maximus*	*Porocolpopollenites* aff. *P. ollivierae*	*Cupanieidites* aff. *C. flabelliformis*	*Cupanieidites flacciformis*	*Retistephanocolpites* spp.	*Acrostichum* sp.	*Dandotiaspora dilata*	*Dandotiaspora telonata*	*Retitribrevicolporites matanomadhensis*
R4372J	X	•	X	•	•	•	X	X	•	•	P	•	•	X	•	•	X	P	•	•	•
R4372O	X	P	X	X	X	X	•	X	X	X	•	X	•	•	•	X	X	P	•	X	X
R4372Q	X	•	X	X	•	X	•	X	X	X	•	•	X	•	X	X	X	•	X	X	•

Figure D7. Analyses of spore-pollen assemblages from the Patala Formation of drill hole 9, Khairpur area. X, present; P, probably present.

R4372Q, 465.3–465.7 ft, is of late Paleocene age. No dinoflagellate cysts were seen, but the presence of genus *Spinizonocolpites* (brackish-water palm) pollen suggests at least brackish-water deposition. Also processed were palynology samples R4372K*, 431.7–432.2 ft; R4372R*, 476.2–476.4 ft; and R4372S*, 479.4–479.5 ft.

Lockhart Limestone

Four palynology samples were processed from the Lockhart Limestone: R4372T*, 483.3–483.4 ft; R4372V*, 488.8–489.3 ft; R4372W*, 500.0–500.3 ft; and R4372Y*, 512.7–513.3 ft.

Drill Hole 34, Basharat Area

Drill hole 34 in the Basharat area of the eastern Salt Range is at lat 32°46.87′ N., long 73°05.95′ E. (fig. D2, loc. 14). Only samples processed for palynomorphs are listed below; samples marked with an asterisk were barren or contained only rare palynomorphs. Depths are in feet below ground surface.

Palynology samples from the Nammal Formation are R4379A*, 86.0–86.2 ft; R4379B, 94.0–94.2 ft; R4379C*, 96.9–97.1 ft; R4379D, 106.0–106.2 ft; R4379K*, 141.5–141.8 ft; R4379O*, 171.1–171.4 ft; R4379P*, 181.7–181.9 ft; and R4379S*, 203.7–204.0 ft.

Palynology samples from the Patala Formation are R4379U*, 224.2–224.3 ft; R4379X, 245.6–245.9 ft; R4379Y, 257.0–257.3 ft; R4379Z, 266.9–267.1 ft; R4379AB*, 286.0–286.2 ft; and R4379AD*, 305.7–306.0 ft.

Palynology sample R4379AE, 326.8–327.0 ft, is from the Tobra(?) Formation.

Sample R4379AE, near the base of the drill hole, was a conglomerate thought by the well-site geologists to be from the Tobra Formation (Permian). This sample contained dark-brown, well-preserved Permian pollen grains and spores (pl. D1, figs. 1, 2) that could be either indigenous or reworked. There were also a few monosulcate gymnosperm grains of *Ginkgo*-cycad-cycadeoid type, which are probably Permian or Mesozoic. Light-brown palynomorphs were also present that seemed to be younger than Permian. Most of these were smooth inaperturate grains of unknown affinity (that is, it is unknown whether they represent gymnosperm pollen or marine palynomorphs), but no obvious dinoflagellate cysts were present. However, these smooth inaperturate grains might be contaminants in the coarse-grained rock. In short, the age of the sample could be Permian or younger.

Analyses of three usable spore-pollen assemblages from the Patala Formation and two from the Nammal Formation are given in figure D8. The three Patala samples from the Basharat drill hole contained the richest spore-pollen flora of any Patala samples examined for this report, no doubt partly because the site of deposition was close to the land area that was the source of the spores and pollen grains, and partly because these were unweathered core samples in which the spores and pollen were unusually well preserved. These Patala samples correlate with the Lakhra Formation of Sindh Province, but they contain quite a few pollen species that do not range as high as the top of the Lakhra (*Proxapertites* sp. A; *Longapertites psilatus*, *L. dupliclavatus*; *L.* aff. *L. sahnii*; *Myrtacidites secus*; *Rhombipollis geniculatus*; *Polygalacidites clarus*). Sparse dinoflagellate cysts were found in two of the Patala samples, and all three also contained brackish-water *Spinizonocolpites* pollen; thus, the samples appear to have been deposited in brackish water.

Sample	*Psilodiporites hammenii*	*Triporopollenites cracentis*	*Triatriopollenites dubius*	*Cricotriporites vimalii*	*Echitriporites trianguliformis*	*Proxapertites* sp. A	*Proxapertites assamicus*	*Proxapertites operculatus*	*Proxapertites cursus*	*Proxapertites emendatus*	*Spinizonocolpites prominatus*	*Clavainaperturites* cf. *C. clavatus*	*Longapertites psilatus*	*Longapertites retipilatus*	*Longapertites discordis*	*Longapertites dupliclavatus*	*Longapertites* aff. *L. sahnii*	*Longapertites* sp. F	*Matanomadhiasulcites maximus*	*Brevitricolpites vadosus*	*Tricolpites reticulatus*	*Myrtacidites secus*	*Warkallipollenites? medius*	*Rhombipollis geniculatus*	*Porocolpopollenites* aff. *P. ollivierae*	*Callophyllumpollenites* aff. *C. rotundus*	*Cupanieidites* aff. *C. flabelliformis*	*Cupanieidites flacciformis*	*Cupanieidites granulatus*	*Polygalacidites clarus*	*Retistephanocolpites* spp.	*Dandotiaspora dilata*	*Dandotiaspora telonata*	*Lakiapollis ovatus*	*Psilodiporites bengalensis*	*Retitribrevicolporites matanomadhensis*
R4379B	.	.	.	.	.	.	X	X	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	X
R4379D	X	.	.	X	.	.	X	X	.	X	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.
R4379X	.	.	X	X	.	.	X	X	.	.	X	X	X	.	X	.	.	X	.	.	.	.	X	.	.	.	.	X	.	.	X	.	.	.	.	X
R4379Y	.	P	X	X	.	.	X	X	.	X	X	X	X	X	.	X	X	X	.	X	.	X	X	.	X	X	X	X	X	X	X	X	.	X	X	X
R4379Z	.	.	X	X	P	X	X	X	X	X	X	.	X	.	.	.	.	.	X	.	.	.	X	X	.	.	.	X	X	.	X	.	X	.	.	.

Figure D8. Analyses of spore-pollen assemblages from the Patala Formation (samples R4379X, Y, Z) and Nammal Formation (samples R4379B, D) of drill hole 34, Basharat area. X, present; P, probably present.

Samples R4379B and D were the only samples from the Nammal Formation examined for this report that contained more than a few spores and pollen grains. In this drill hole, in the eastern part of the Salt Range, the Nammal includes a sequence of pyritic, sparsely fossiliferous, dark-gray shale nearly 20 ft thick, and the two pollen-bearing samples came from this shale sequence. Sparse dinoflagellates in the sequence indicated that the Paleocene-Eocene boundary may fall near sample R4379K (Edwards, this volume, chap. C), which would mean that our spore-pollen samples R4379B and D would be early Eocene in age.

Spores and pollen grains are fairly abundant in the two samples (pl. D4, figs. 11–15), but the taxonomic diversity of these fossils is low (figs. D8, D9). Some species were found that were not known from the Patala Formation or from the upper Paleocene of Sindh Province, but the main characteristic of the Nammal assemblages was the high dominance by a few species of pollen, apparently from wind-pollinated plants, mainly of the genera *Proxapertites* and *Retistephanocolpites*. At least partly because of the low pollen diversity in the Nammal samples, no species known to be restricted to the Eocene were found in these samples. Rare dinoflagellate cysts were found in one of the Nammal samples (R4379B), but pollen of the genus *Spinizonocolpites* (brackish-water palm) was not seen in either sample from this formation.

Discussion and Conclusions

This report concerns spore-pollen analyses of 38 Permian(?), Mesozoic, and lower Tertiary samples from the Surghar and Salt Ranges. These samples consist of 1 from the Tobra(?) Formation (Permian or younger), 2 from the Lumshiwal Formation (Mesozoic), 7 from rocks thought at least tentatively to belong to the Hangu Formation (Paleocene), 26 from the Patala Formation (probably Paleocene), and 2 from the Nammal Formation (Eocene(?)).

The conglomerate at the base of the Basharat drill hole 34 (eastern Salt Range), thought by the well-site geologists to represent the Tobra Formation (Permian), contained dark-brown Permian pollen grains and spores (indigenous or reworked?), but it also contained light-brown palynomorphs that may be Mesozoic or may be contaminants. Therefore, the age of this conglomerate is uncertain.

Of the two samples from the lower part of Lumshiwal Nala (Makarwal coal field, Surghar Range), probably from the Lumshiwal Formation, one was assigned a Late Jurassic to Early Cretaceous age and the other was assigned a middle Cretaceous (approximately Aptian to Albian) age.

Four Paleocene samples were analyzed from strata assigned to the Hangu Formation. Two of these samples were from Lumshiwal Nala in the Surghar Range, and two were from Nammal Pass in the western Salt Range. Two dinoflagellate assemblages from the Hangu Formation at Nammal Pass (same mine dump as samples examined here for spores

Formation	Nammal Fm.	Patala Fm.	Hangu Fm.
Psilodiporites hammenii	X	X	X
Triporopollenites cracentis	•	P	•
Triporopollenites trilobus	•	X	•
Triatriopollenites dubius	•	X	•
Cricotriporites vimalii	X	X	•
"Tricolporipites jerdoni"	•	X	•
Echitriporites trianguliformis	•	X	X
Triangulorites triradiatus	•	X	X
Proxapertites sp. A	•	X	X
Proxapertites assamicus	X	X	X
Proxapertites operculatus	X	X	X
Proxapertites cursus	•	X	•
Proxapertites emendatus	X	X	X
Spinizonocolpites prominatus	•	X	X
Spinizonocolpites adamanteus	•	•	X
Clavainaperturites cf. *C. clavatus*	•	X	•
Longapertites psilatus	•	X	•
Longapertites punctatus	•	X	•
Longapertites retipilatus	X	X	X
Longapertites discordis	•	X	X
Longapertites dupliclavatus	•	X	•
Longapertites aff. *L. sahnii*	•	X	•
Longapertites sp. F	•	X	•
Retimonosulcites ovatus	•	X	•
Matanomadhiasulcites maximus	•	X	•
Brevitricolpites vadosus	•	X	•
Tricolpites reticulatus	X	X	•
Myrtacidites secus	•	X	•
Warkallipollenites? *medius*	•	X	X
Rhombipollis geniculatus	•	X	•
Porocolpopollenites aff. *P. ollivierae*	•	X	•
Callophyllumpollenites aff. *C. rotundus*	•	X	•
Compositoipollenites dilatus	•	X	•
Cupanieidites aff. *C. flabelliformis*	•	X	•
Cupanieidites flaccidiformis	•	X	•
Cupanieidites granulatus	•	X	•
Polygalacidites clarus	•	X	•
Polycolporopollenites calvus	•	•	X
Retistephanocolpites spp.	X	X	X
Acrostichum sp.	•	X	P
Dandotiaspora dilata	•	X	X
Dandotiaspora telonata	•	X	•
Lakiapollis ovatus	•	X	•
Psilodiporites bengalensis	•	X	•
Retitribrevicolporites matanomadhensis	X	X	•

Figure D9. Composite analyses of spore-pollen assemblages from the Hangu, Patala, and Nammal Formations of the Surghar and Salt Ranges. The only species listed are those that were also tabulated from the Ranikot Group and lower part of the Laki Formation in Sindh Province (Frederiksen, 1990), in addition to several species from the Surghar and Salt Ranges. X, present; P, probably present.

and pollen) were assigned a possible late Paleocene age by Edwards (this volume, chap. C). The spore-pollen samples contained a considerable variety of angiosperm pollen, but most of the pollen grains represented new species, different from species of the upper Paleocene of Sindh Province and at least to some degree different from species in the Patala Formation of the Salt Range. The disparity between the Hangu and Patala assemblages is shown in figure D9, where the Hangu assemblages appear to have a low diversity only because so many of the Hangu species are new. Some new species in the Hangu Formation might range up into the Patala Formation in this region, but the new species have not been studied to determine their stratigraphic ranges.

Paleocene coal beds in the Hangu Formation were undoubtedly deposited in or near brackish water because dinoflagellate cysts and pollen of the brackish-water palm genus *Spinizonocolpites* were found in the associated detrital rocks. Three samples tentatively attributed to the Hangu Formation were also examined from the shallow subsurface of the Kuraddi section in the western Salt Range. These samples were found to be Jurassic or Lower Cretaceous and therefore were probably from the Datta Formation (Mesozoic).

Twenty-six samples of the Patala Formation were studied from 15 localities, ranging geographically from the Surghar Range to the eastern Salt Range. The main coal bed in the Patala Formation is mostly in the lower or middle part of the formation (Warwick and Shakoor, 1988), which is upper Paleocene from evidence of marine fossils in underlying and overlying rocks. The uppermost part of the Patala is mostly upper Paleocene but has been assigned to the lower Eocene in a few places on the basis of marine fossils.

Spore-pollen assemblages from the Patala Formation were similar (in some cases, very similar) to assemblages from the upper Paleocene Lakhra Formation of Sindh Province. However, the spore-pollen assemblages could not be used to prove conclusively that all of the Patala samples studied for this report were late Paleocene in age. Practically no information is available from Sindh Province about changes in spore-pollen assemblages across the Paleocene-Eocene boundary, and as far as we know, no papers have been published on the palynology of this boundary in India.

Nearly all the Patala samples contained pollen of the brackish-water palm genus *Spinizonocolpites* and (or) dinoflagellate cysts. Thus, the Patala samples all or nearly all formed in brackish water, and the coal beds, with which most of the samples were associated, undoubtedly formed near the sea.

Only two samples from the Nammal Formation had usable spore-pollen assemblages; these samples were from drill hole 34 in the Basharat area of the eastern Salt Range. The samples may be lower Eocene on the basis of dinoflagellate assemblages from this corehole (Edwards, this volume, chap. C). These spore-pollen assemblages were characterized by high dominance and low diversity and were not definitive as to a late Paleocene or early Eocene age.

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Appendix D1. Alphabetical List of Species Mentioned in this Report

[An asterisk denotes an informal species name used by Frederiksen (1990). Plate and figure citations refer to illustrations in the present paper]

Acanthotriletes cf. *A. levidensis* Balme 1957
Acrostichum sp.; pl. D3, fig. 1

Baculatisporites comaumensis (Cookson 1953) Potonié 1956
Brevitricolpites vadosus Frederiksen 1994

Callialasporites dampieri (Balme 1957) Dev 1961; pl. D2, fig. 1
Callialasporites segmentatus (Balme 1957) Dev 1961; pl. D2, fig. 2
Callialasporites trilobatus (Balme 1957) Dev 1961
Callophyllumpollenites aff. *C. rotundus* Sah & Kar 1974; pl. D3, fig. 12
Cingulatisporites cf. *C. foveolatus* Couper 1958; pl. D1, fig. 7
Cingulatisporites pseudoalveolatus Couper 1958; pl. D1, fig. 9
Cingulatisporites spp.; pl. D1, figs. 3, 4
Clavainaperturites cf. *C. clavatus* van der Hammen & Wymstra 1964
Clavifera? spp.; pl. D1, figs. 5, 6
Compositoipollenites dilatus Frederiksen 1994
Concavisporites cf. *C. jurienensis* Balme 1957
Contignisporites fornicatus Dettmann 1963
Contignisporites glebulentus Dettmann 1963; pl. D2, figs. 5, 6
Coptospora kutchensis Venkatachala 1969; pl. D2, fig. 4
Cordaitina sp.; pl. D1, fig. 2
Corollina spp.; pl. D1, figs. 10, 11
Couperipollis sp.; pl. D2, fig. 8
Crassivestibulites karii Frederiksen 1994
Cricotriporites vimalii (Sah & Dutta 1966) Frederiksen 1994
Cupanieidites aff. *C. flabelliformis* Venkatachala & Rawat 1972
Cupanieidites flaccidiformis Venkatachala & Rawat 1972; pl. D4, fig. 6
Cupanieidites granulatus Jain, Kar & Sah 1973
Cupanieidites sp.; pl. D4, fig. 7
Cupuliferoipollenites sp.; pl. D4, fig. 16

Dandotiaspora dilata Sah et al. 1971
Dandotiaspora telonata Sah et al. 1971; pl. D3, fig. 2
Densoisporites sp.; pl. D2, fig. 3
Dictyophyllidites pectinataeformis (Bolkhovitina 1953) Dettmann 1963
"Dictyophyllidites pectinataeformis" of Venkatachala (1969, pl. D1, fig. 12)

Echitriporites trianguliformis van Hoeken-Klinkenberg 1964; pl. D2, fig. 7

Genus? sp., rugulate, oblate, tricolpate; pl. D4, fig. 3
Genus? sp., psilate-punctate spheroidal tricolporate; pl. D4, fig. 8

Inaperturopollenites turbatus Balme 1957; pl. D1, fig. 12
Ischyosporites aff. *I. crateris* Balme 1957

Klukisporites sp.

Lakiapollis ovatus Venkatachala & Kar 1969
Lakiapollis aff. *L. ovatus*; pl. D4, fig. 1
Lakiapollis cf. *L. ovatus*; pl. D4, fig. 2
Longapertites discordis Frederiksen 1994; pl. D3, fig. 9
Longapertites dupliclavatus Frederiksen 1994
Longapertites psilatus Frederiksen 1994
Longapertites punctatus Frederiksen 1994
Longapertites retipilatus Kar 1985; pl. D4, fig. 12
Longapertites aff. *L. sahnii* Rao & Ramanujam 1978
Longapertites sp. F*
Lunatisporites sp.; pl. D1, fig. 1
Lycopodiacidites aff. *L. subtriangulus* Venkatachala et al. 1969

Matanomadhiasulcites maximus (Saxena 1979) Kar 1985; pl. D3, fig. 8
Matonisporites crassiangulatus (Balme 1957) Dettmann 1963; pl. D1, fig. 8
Microreticulatisporites cf. *M. telatus* Balme 1957
Milfordia homeopunctata (McIntyre 1965) Partridge in Stover & Partridge 1973
Myrtacidites secus Frederiksen 1994; pl. D3, fig. 11

Cf. *Nyssoidites (Nyssa) ingentipollinius* (Traverse 1955) Potonié 1960 of Jain and others (1973); pl. D4, fig. 5

Polycolporopollenites calvus Frederiksen 1994
Polygalacidites clarus Sah & Dutta 1966
Porocolpopollenites aff. *P. ollivierae* (Gruas-Cavagnetto 1976) Frederiksen 1983
Proteacidites? sp.; pl. D3, fig. 5
Proxapertites assamicus (Sah & Dutta 1966) Singh 1975; pl. D3, fig. 7
Proxapertites cursus van Hoeken-Klinkenberg 1966
Proxapertites emendatus (Sah & Dutta 1976) Kar & Kumar 1986; pl. D3, fig. 6
Proxapertites operculatus (van der Hammen 1954) van der Hammen 1956; pl. D4, fig. 11
Proxapertites sp. A*

Psilodiporites bengalensis (Varma & Rawat 1963) Venkatachala & Rawat 1972; pl. D3, fig. 4
Psilodiporites erdtmanii (Varma & Rawat 1963) Venkatachala & Rawat 1972
Psilodiporites hammenii Varma & Rawat 1963

Retimonosulcites ovatus (Sah & Kar 1970) Kar 1985
Retistephanocolpites spp.; pl. D3, fig. 10
Retitrescolpites sp. B*
Retitribrevicolporites matanomadhensis (Venkatachala & Kar 1969) Kar 1985; pl. D4, fig. 4
Rhombipollis geniculatus Frederiksen 1994

Spinizonocolpites adamanteus Frederiksen 1994
Spinizonocolpites prominatus (McIntyre 1965) Stover & Evans 1973

Tetracolporopollenites sp.; pl. D4, fig. 10
Triangulorites sp. A*
Triangulorites triradiatus (Saxena 1979) Kar 1985
Triatriopollenites dubius (Venkatachala & Rawat 1972) Frederiksen 1994; pl. D3, fig. 3
Triatriopollenites rectus Frederiksen 1994
Tricolpites reticulatus Couper 1953; pl. D4, fig. 14
Tricolpites sp.; pl. D4, fig. 15
"Tricolporipites jerdoni" Biswas 1962
Tricolporopollis decoris Dutta & Sah 1970; pl. D4, fig. 9
Trilatiporites kutchensis Venkatachala & Kar 1969; pl. D4, fig. 13
Triporopollenites cracentis Frederiksen 1994
Triporopollenites ranikotensis Frederiksen 1994
Triporopollenites trilobus Frederiksen 1994

Warkallipollenites? *medius* Frederiksen 1994
Warkallipollenites? *solox* Frederiksen 1994

Yeguapollis prolatus Frederiksen 1994

Plates D1–D4

Plate D1

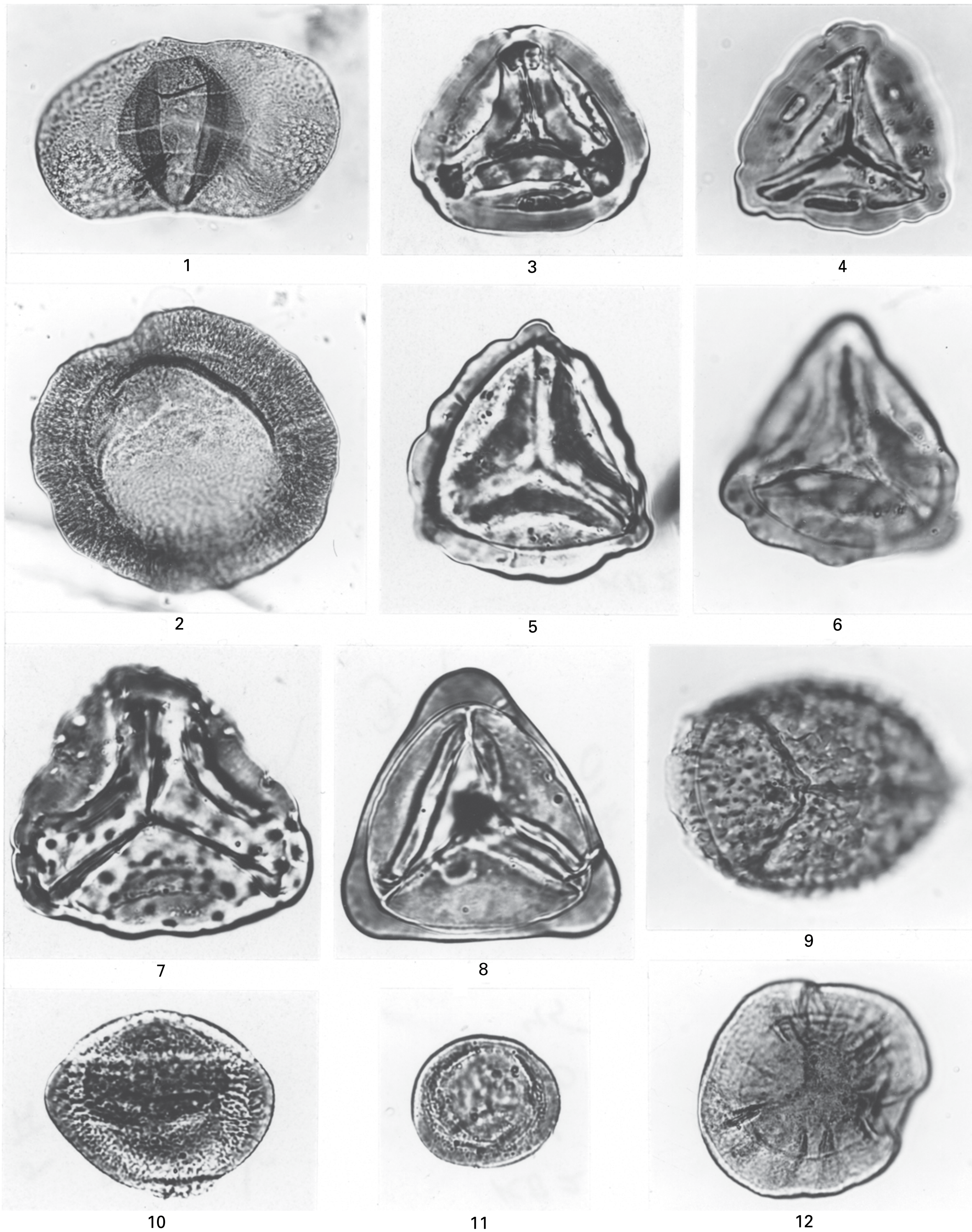
[Magnification × 1,000 unless otherwise noted; see scale in pl. D2]

Figures 1, 2. Permian gymnosperm pollen from the Basharat drill hole 34, eastern Salt Range.

1. *Lunatisporites* sp.; slide R4379AE(1), coordinates 50.7 × 104.6. Maximum dimension 93 µm.
2. *Cordaitina* sp.; slide R4379AE(1), coordinates 60.2 × 105.4. Maximum dimension 95 µm.

3–12. Jurassic or Early Cretaceous spores and gymnosperm pollen from the Kuraddi section, western Salt Range.

3. *Cingulatisporites* sp.; slide R4386C(4), coordinates 48.5 × 104.3.
4. *Cingulatisporites* sp.; slide R4386A(4), coordinates 40.1 × 106.6.
5. *Clavifera*? sp.; slide R4386C(4), coordinates 60.3 × 99.7.
6. *Clavifera*? sp.; slide R4386C(4), coordinates 47.9 × 98.3.
7. *Cingulatisporites* cf. *C. foveolatus* Couper 1958; slide R4386C(4), coordinates 49.4 × 109.4.
8. *Matonisporites crassiangulatus* (Balme 1957) Dettmann 1963; slide R4386B(3), coordinates 55.6 × 106.2.
9. *Cingulatisporites pseudoalveolatus* Couper 1958; slide R4386C(4), coordinates 43.0 × 97.7.
10. *Corollina* sp., equatorial view; slide R4386A(4), coordinates 44.4 × 105.4.
11. *Corollina* sp., polar view; slide R4386A(2), coordinates 49.1 × 104.7.
12. *Inaperturopollenites turbatus* Balme 1957; slide R4386B(3), coordinates 67.4 × 99.4. Maximum dimension 75 µm.



Permian and Jurassic or Early Cretaceous Spores and Gymnosperm Pollen from the Salt Range

Plate D2

[Magnification × 1,000; see scale]

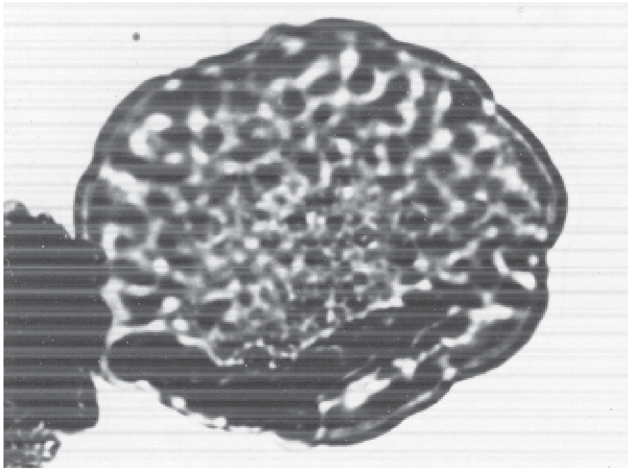
Figures 1–6. Late Jurassic or Early Cretaceous (fig. 1) and probably middle Cretaceous, approximately Aptian to Albian (figs. 2–6) spores and gymnosperm pollen from Lumshiwal Nala, Makarwal coal field, Surghar Range.

1. *Callialasporites dampieri* (Balme 1957) Dev 1961; slide R4381A(1), coordinates 51.0 × 96.1.
2. *Callialasporites segmentatus* (Balme 1957) Dev 1961; slide R4381C(1), coordinates 39.9 × 111.9.
3. *Densoisporites* sp.; slide R4381C(1), coordinates 40.8 × 101.9.
4. *Coptospora kutchensis* Venkatachala 1969; slide R4381C(1), coordinates 41.3 × 109.6.

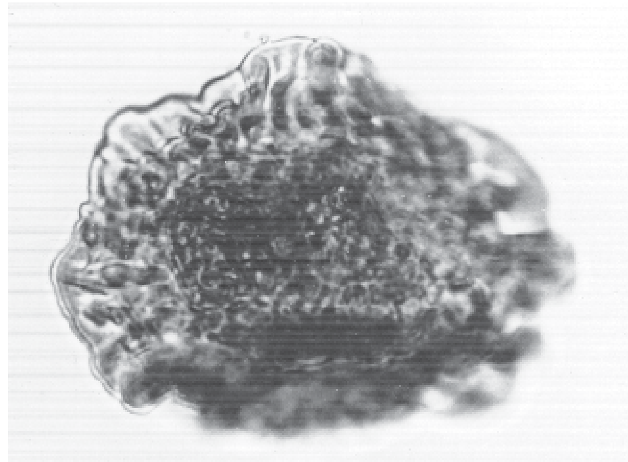
5, 6. *Contignisporites glebulentus* Dettmann 1963; slide R4381C(1), coordinates 41.6 × 107.5.

7, 8. Paleocene angiosperm pollen from the Hangu Formation, Nammal Pass section, western Salt Range.

7. *Echitriporites trianguliformis* van Hoeken-Klinkenberg 1964; slide R4383B(1), coordinates 49.7 × 99.7.
8. *Couperipollis* sp.; slide R4383A(2), coordinates 54.4 × 106.4.



1



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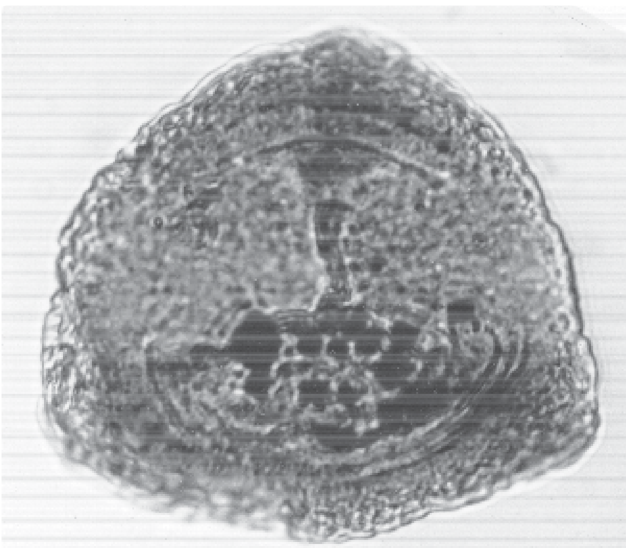

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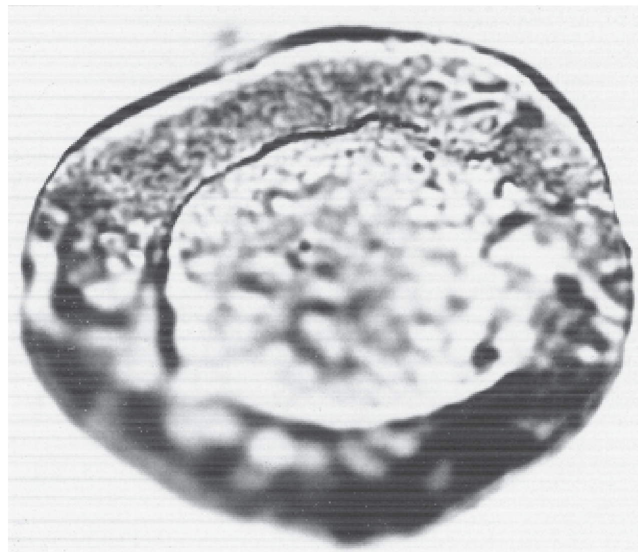

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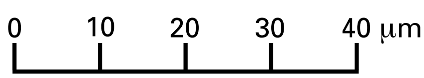

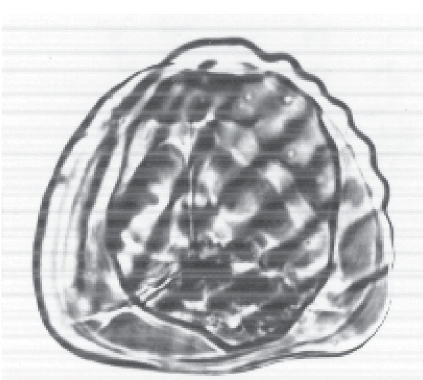

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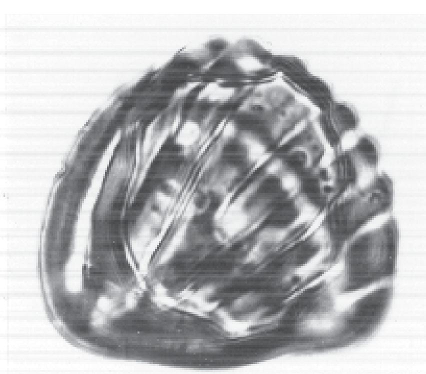

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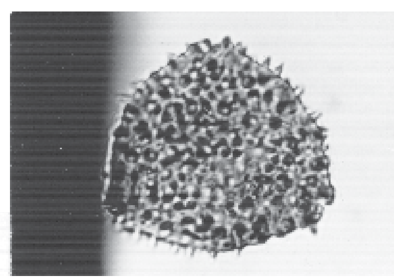

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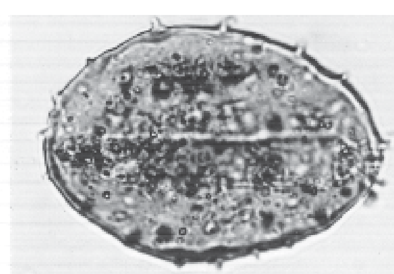


8

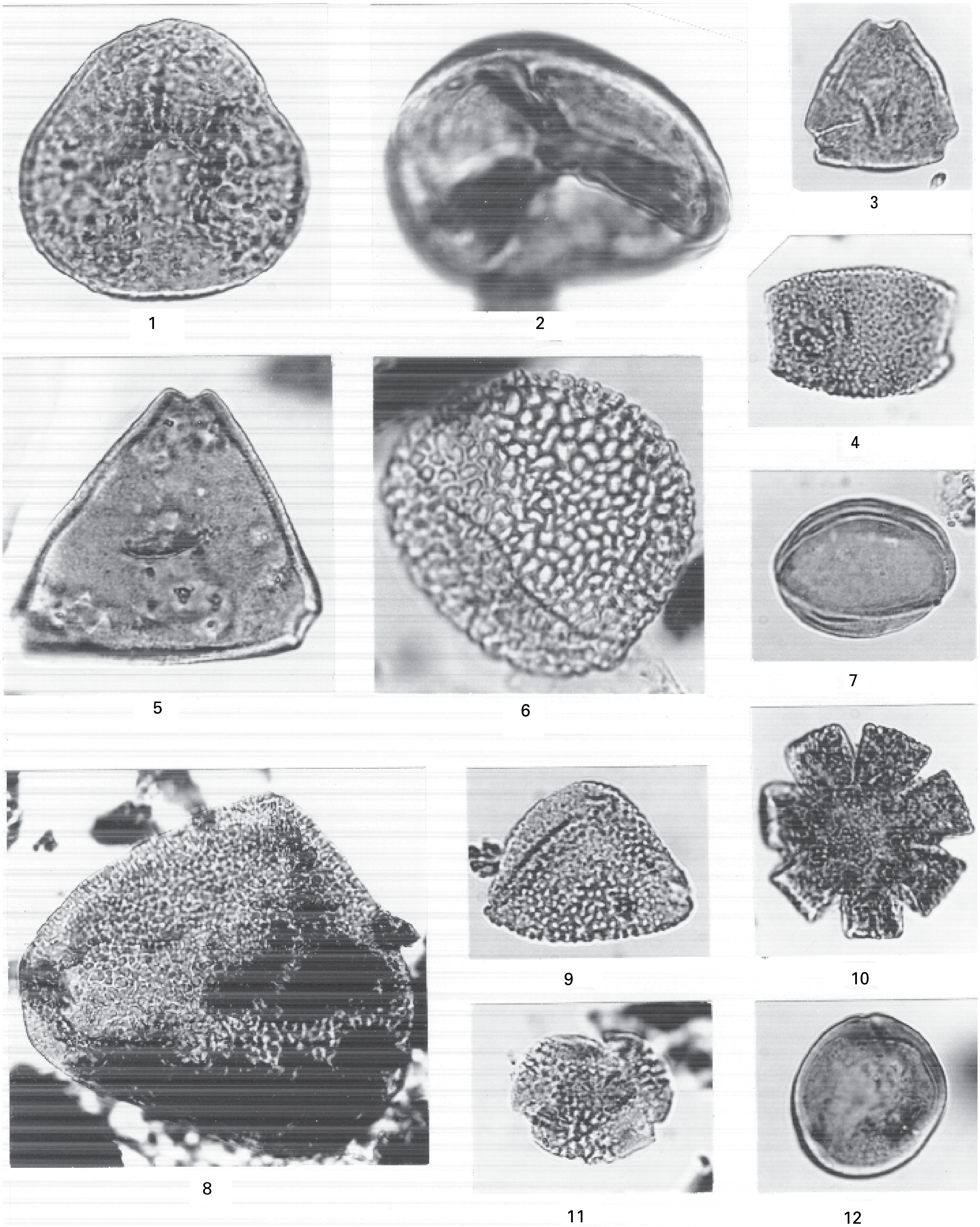
Late Jurassic or Early Cretaceous, Probably Middle Cretaceous, and Paleocene Spores and Pollen from the Surghar and Salt Ranges

Plate D3

[Magnification × 1,000 unless otherwise noted; see scale in pl. D2]

Figures 1–12. Spores and angiosperm pollen from the Patala Formation of the Salt Range.

1. *Acrostichum* sp.; slide R4242K(4), coordinates 51.3 × 97.9.
2. *Dandotiaspora telonata* Sah et al. 1971; slide R4372O(2), coordinates 52.8 × 104.6.
3. *Triatriopollenites dubius* (Venkatachala & Rawat 1972) Frederiksen 1994; slide R4242L(3), coordinates 49.5 × 106.7.
4. *Psilodiporites bengalensis* (Varma & Rawat 1963) Venkatachala & Rawat 1972; slide R4379Y(1), coordinates 39.8 × 112.0.
5. *Proteacidites*? sp.; slide R4262(4), coordinates 38.4 × 107.9.
6. *Proxapertites emendatus* (Sah & Dutta 1966) Kar & Kumar 1986; slide R4242K(4), coordinates 51.1 × 106.4.
7. *Proxapertites assamicus* (Sah & Dutta 1966) Singh 1975; slide R4385E(2), coordinates 35.1 × 100.9.
8. *Matanomadhiasulcites maximus* (Saxena 1979) Kar 1985; slide R4379Z(2), coordinates 52.1 × 95.2. Maximum dimension 168 µm.
9. *Longapertites discordis* Frederiksen 1994; slide R4242M(3), coordinates 51.9 × 104.9.
10. *Retistephanocolpites* sp.; slide R4379Y(1), coordinates 34.6 × 96.8.
11. *Myrtacidites secus* Frederiksen 1994; slide R4379Z(2), coordinates 54.0 × 110.5.
12. *Callophyllumpollenites* aff. *C. rotundus* Sah & Kar 1974; slide R4379Y(1), coordinates 52.0 × 98.0.



Spores and Angiosperm Pollen from the Patala Formation of the Salt Range

Plate D4

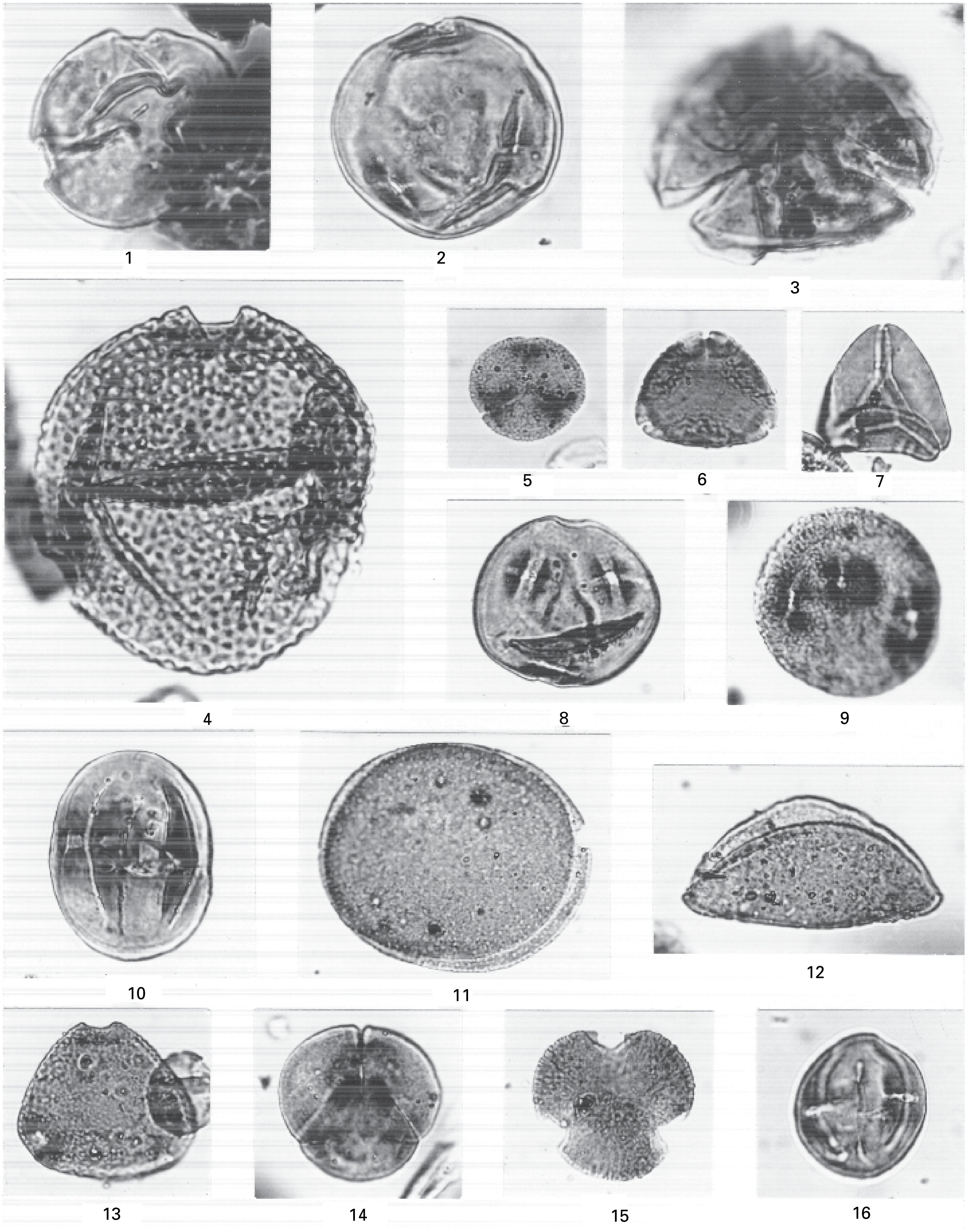
[Magnification × 1,000; see scale in pl. D2]

Figures 1–10. Angiosperm pollen from the Patala Formation of the Salt Range.

1. *Lakiapollis* aff. *L. ovatus* Venkatachala & Kar 1969; slide R4242E(3), coordinates 61.5 × 107.1.
2. *Lakiapollis* cf. *L. ovatus* Venkatachala & Kar 1969; slide R4372O(2), coordinates 55.3 × 106.6.
3. Genus? sp., rugulate, oblate, tricolpate; slide R4379Z(2), coordinates 50.2 × 92.6.
4. *Retitribrevicolporites matanomadhensis* (Venkatachala & Kar 1969) Kar 1985; slide R4379Y(1), coordinates 44.7 × 98.6.
5. Cf. *Nyssoidites* (*Nyssa*) *ingentipollinius* (Traverse 1955) Potonié 1960 of Jain and others (1973); slide R4379X(2), coordinates 55.6 × 97.0.
6. *Cupanieidites flaccidiformis* Venkatachala & Rawat 1972; slide R4379X(2), coordinates 61.6 × 106.6.
7. *Cupanieidites* sp.; slide R4262(4), coordinates 41.5 × 95.2.
8. Genus? sp., psilate-punctate spheroidal tricolporate; slide R4379X(2), coordinates 48.0 × 107.4.
9. *Tricolporopollis decoris* Dutta & Sah 1970; slide R4379X(2), coordinates 56.5 × 94.6.
10. *Tetracolporopollenites* sp.; slide R4372O(1), coordinates 34.5 × 111.8.

11–16. Angiosperm pollen from the Nammal Formation of the Salt Range.

11. *Proxapertites operculatus* (van der Hammen 1954) van der Hammen 1956; slide R4379B(1), coordinates 50.0 × 107.5.
12. *Longapertites retipilatus* Kar 1985; slide R4379B(1), coordinates 54.9 × 95.2.
13. *Trilatiporites kutchensis* Venkatachala & Kar 1969; slide R4379D(1), coordinates 53.8 × 103.2.
14. *Tricolpites reticulatus* Couper 1953; slide R4379D(1), coordinates 53.8 × 103.2.
15. *Tricolpites* sp.; slide R4379D(1), coordinates 65.4 × 98.9.
16. *Cupuliferoipollenites* sp.; slide R4379K(1), coordinates 37.1 × 99.1.



Angiosperm Pollen from the Patala and Nammal Formations of the Salt Range

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

By Thomas G. Gibson, U.S. Geological Survey

Chapter E of

Regional Studies of the Potwar Plateau Area, Northern Pakistan

Edited by Peter D. Warwick and Bruce R. Wardlaw

Prepared in cooperation with the
Geological Survey of Pakistan,
under the auspices of the
U.S. Agency for International Development,
U.S. Department of State, and the
Government of Pakistan

Bulletin 2078–E

U.S. Department of the Interior
U.S. Geological Survey

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

By Thomas G. Gibson

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.

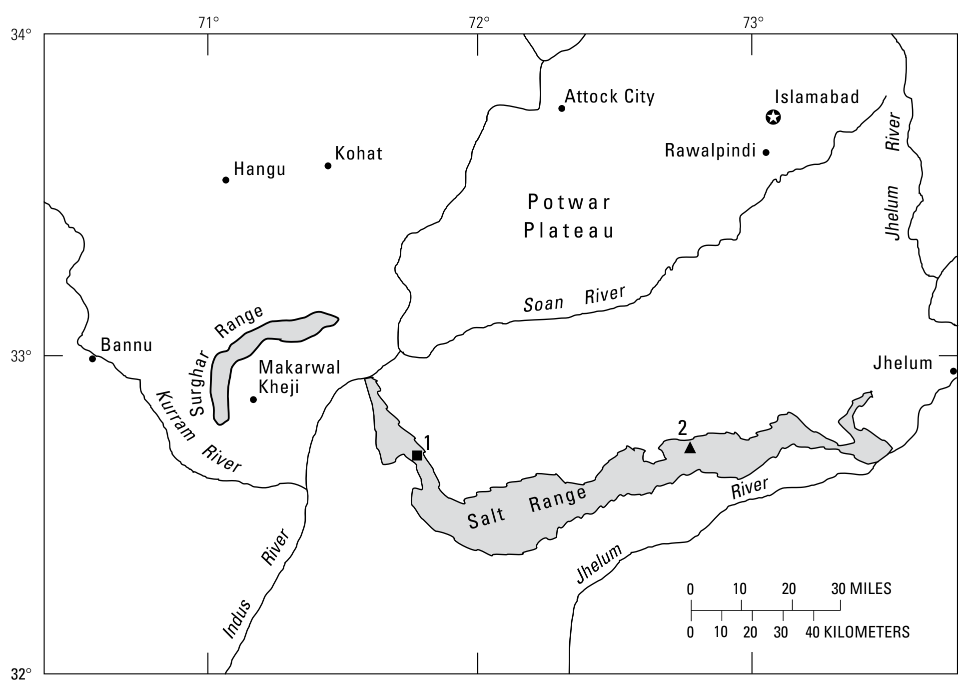

Figure E2. The Salt Range study area in northern Pakistan showing locations of the sections studied: 1, Nammal Dam section; 2, Khairpur 9 corehole.

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.

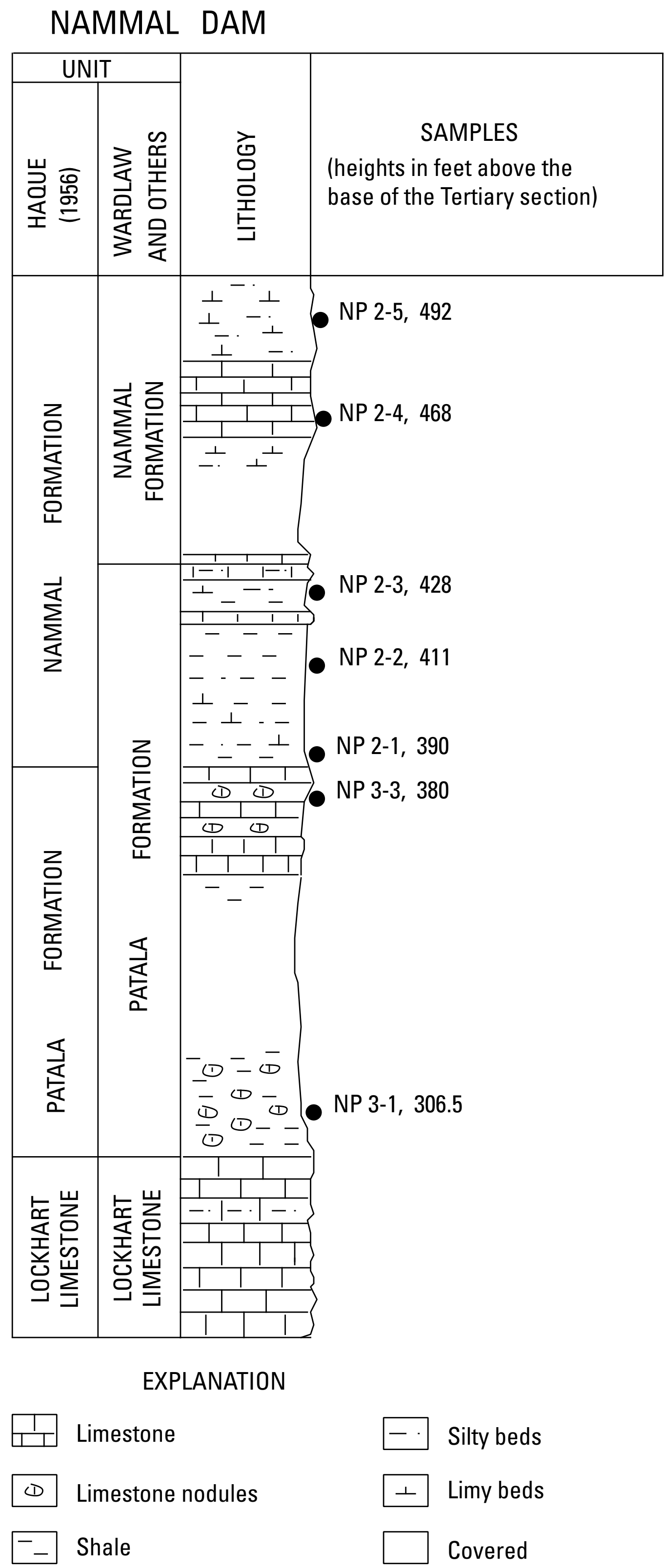

Figure E3. Lithologic section in Nammal Gorge at Nammal Dam measured by Wardlaw and others (this volume, chap. F) showing location of samples (solid circles) studied. Inferred relation of this section with section given by Haque (1956) is shown at left. See figure E2 for location.

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

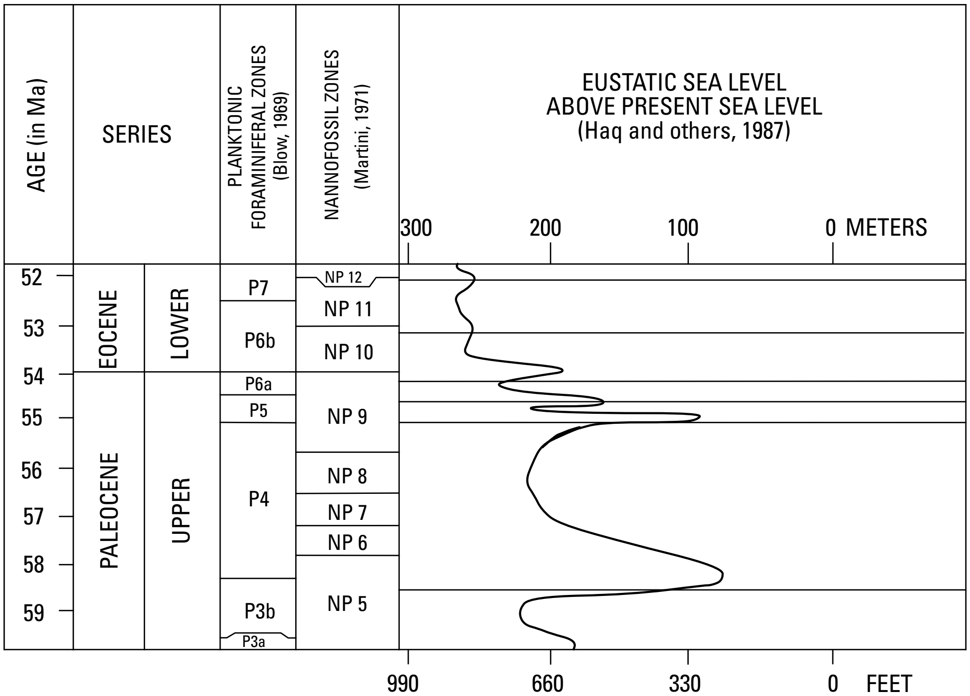

Figure E4. Age relations of planktonic foraminiferal zones, calcareous nannofossil zones, and eustatic sea-level changes.

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			Planktonic percentage*	No. of smaller benthonic species	tau values**
		Smaller benthonics	Larger benthonics	Planktonics			
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).

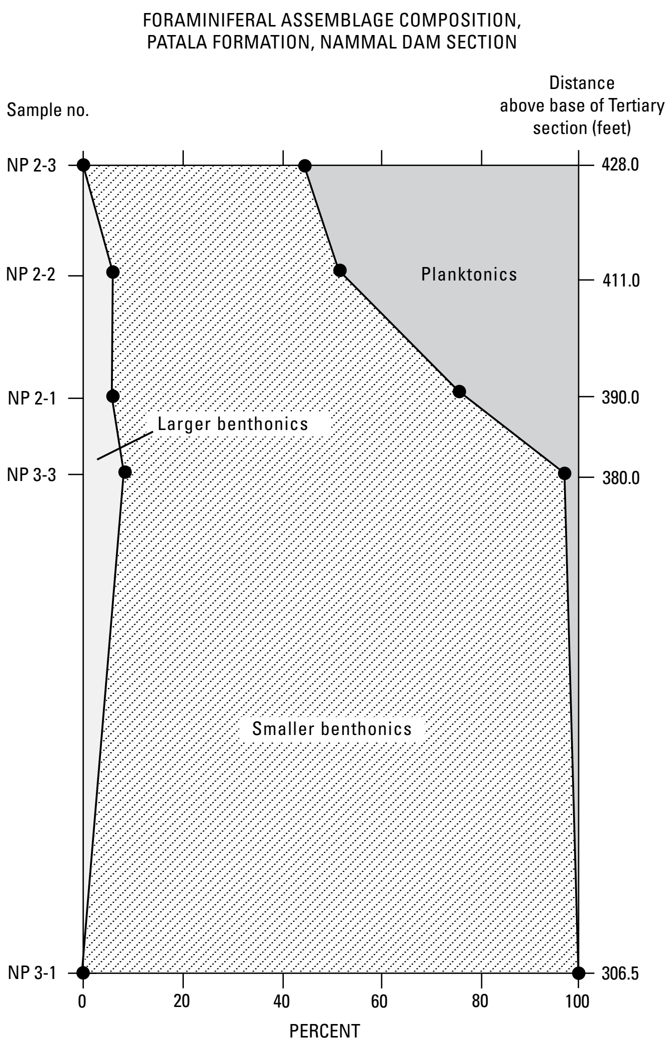

Figure E5. Upward increase in the proportion of planktonic foraminifers and the changes in abundance in the smaller and larger benthonic foraminifers in samples from the Patala Formation at the Nammal Dam section. Data plotted are in table E1.

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

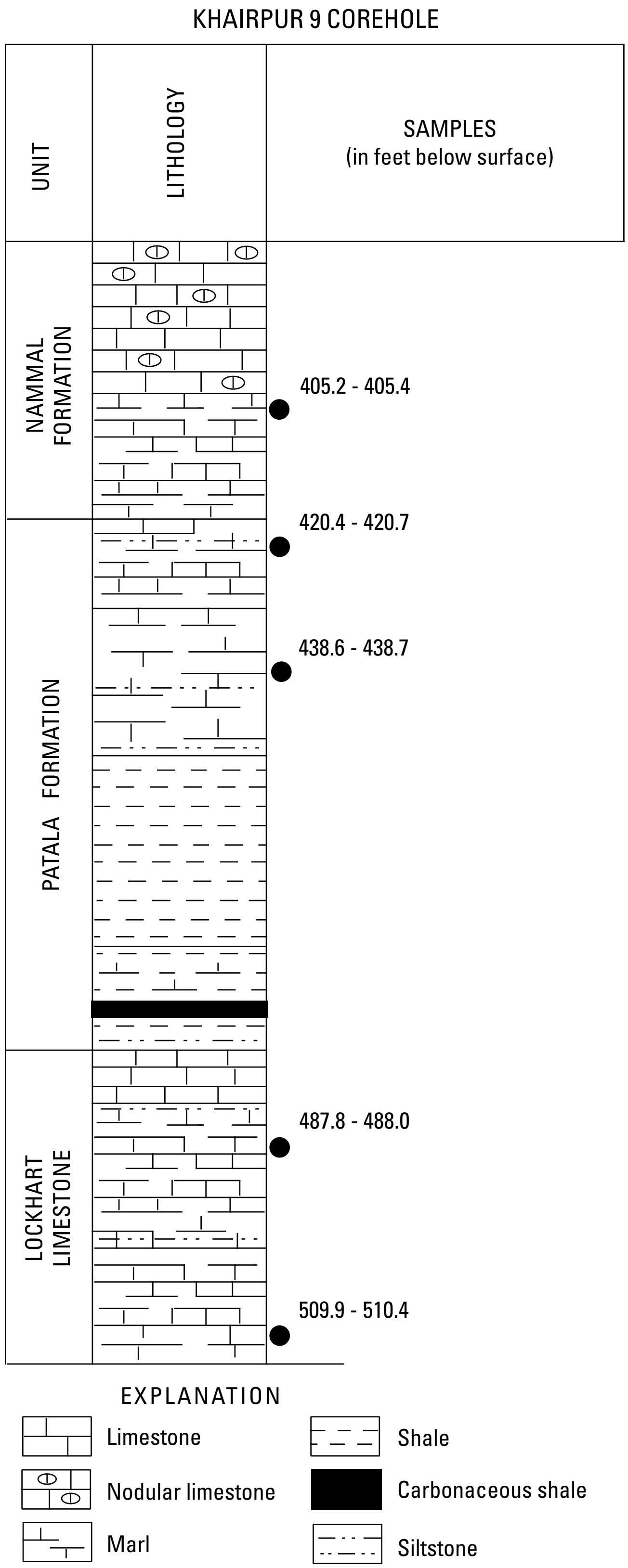

Figure E6. Lithologic section of examined part of the Khairpur 9 corehole and location of samples (solid circles). Total depth of corehole is 514 ft; samples are shown in feet below surface. See figure E2 for location.

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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Stratigraphic Analysis of Paleocene and Lower Eocene Rocks Adjacent to the Potwar Plateau, Northern Pakistan

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Chapter F of

Regional Studies of the Potwar Plateau Area, Northern Pakistan

Edited by Peter D. Warwick and Bruce R. Wardlaw

Prepared in cooperation with the
Geological Survey of Pakistan,
under the auspices of the
U.S. Agency for International Development,
U.S. Department of State, and the
Government of Pakistan

Bulletin 2078–F

U.S. Department of the Interior
U.S. Geological Survey

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Stratigraphic Analysis of Paleocene and Lower Eocene Rocks Adjacent to the Potwar Plateau, Northern Pakistan

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Abstract

The Paleocene and lower Eocene rocks of the area adjacent to the Potwar Plateau represent deposition along the northeast margin or shelf of the Pakistan-India plate and within a trough developed between the shelf and the Afghanistan plate. The Salt Range displays outcrops that represent gradual transition from marginal trough deposition in the northwest to shore deposition in the southeast. Shelf deposition is represented by three transgressive-regressive packages: one in the upper Paleocene (NP 6–NP 9, Paleogene nannofossil zones), one in the lowest Eocene (NP 10–NP 11), and one in the lower Eocene (NP 11–NP 14).

Coal deposits in the Hangu Formation are associated with oxysol and shoreface deposits, suggesting that they formed in tropical, everwet, nearshore environments. Coal deposits in the Patala Formation are associated with marine carbonates and siltstones and poorly developed soils with various clay mineralogies, suggesting that they formed in subtropical, seasonal, nearshore environments. The distribution of lithofacies further suggests that the coal deposits of the Patala Formation formed in a back-bay swamp shoreward of a barrier sand.

Introduction

The lithofacies and stratigraphy of the upper Paleocene to lower Eocene sequence composing the Hangu Formation, Lockhart Limestone, Patala Formation, Nammal Formation, Margala Hill Limestone, and base of the Sakesar Limestone were studied to determine the tectonic, eustatic, and climatic controls for the deposition of Paleocene and Eocene coals in the regions adjacent to the Potwar Plateau. This work was part of a collaborative study of the coal resources of Pakistan conducted by the U.S. Geological Survey (USGS) and the Geological Survey of Pakistan (GSP) under the auspices of the U.S. Agency for International Development (USAID). This work was specifically part of the Potwar Regional Framework Assessment Project of the Coal Resources Exploration and Assessment Program (COALREAP) of Pakistan. The study consisted of the measurement and description of Paleocene to lower Eocene rocks at 19 surface sections and in the cores of 7 boreholes; the locations of the sections and boreholes are shown on plate F1. Field work was conducted in January, February, October, and November 1989; a final field check was conducted in June 1991.

Warwick and Wardlaw (1992) suggested that the Paleocene and Eocene rocks of northern Pakistan were deposited in a northeast-trending trough developed between the Pakistan-India plate and the Afghanistan plate (fig. F1). Deposition within this trough was affected by structural activity (uplift) and resultant clastic sediment input from the Afghanistan plate and by possible closure of the northern end of the trough as early as the late Paleocene (Warwick and Wardlaw, 1992). Most of the sections studied for this paper are on the fringe of the Pakistan-India plate and show little direct effect of Afghanistan tectonism. However, sections in the Murree Hills, the Kala Chitta Range, and the Attock-Cherat Range (pl. F1) are north of the Main Boundary Thrust (MBT) on various thrust fault blocks and provide some of the evidence for northern closure of the trough (Warwick and Wardlaw, 1992).

The units of interest for this study are the Paleocene Hangu Formation and Lockhart Limestone, the Paleocene and Eocene Patala Formation, and the Eocene Nammal Formation, Sakesar Limestone, and Margala Hill Limestone. Most of the measured sections stopped in the Sakesar Limestone. A detailed analysis of the Sakesar can be found in Jurgan and others (1988). The Hangu Formation and Patala Formation are coal bearing but not throughout their entire extent. For a general description of the stratigraphic units exposed within the Potwar Plateau region, refer to Shah (1977).

Acknowledgments

We would like to thank everyone in the Pakistan USAID mission who helped us with many logistical problems and the many members of the Geological Survey of Pakistan (GSP) and the Hydrocarbon Development Institute of Pakistan for their aid. Specifically, we thank Ned Noble, U.S. Geologi-

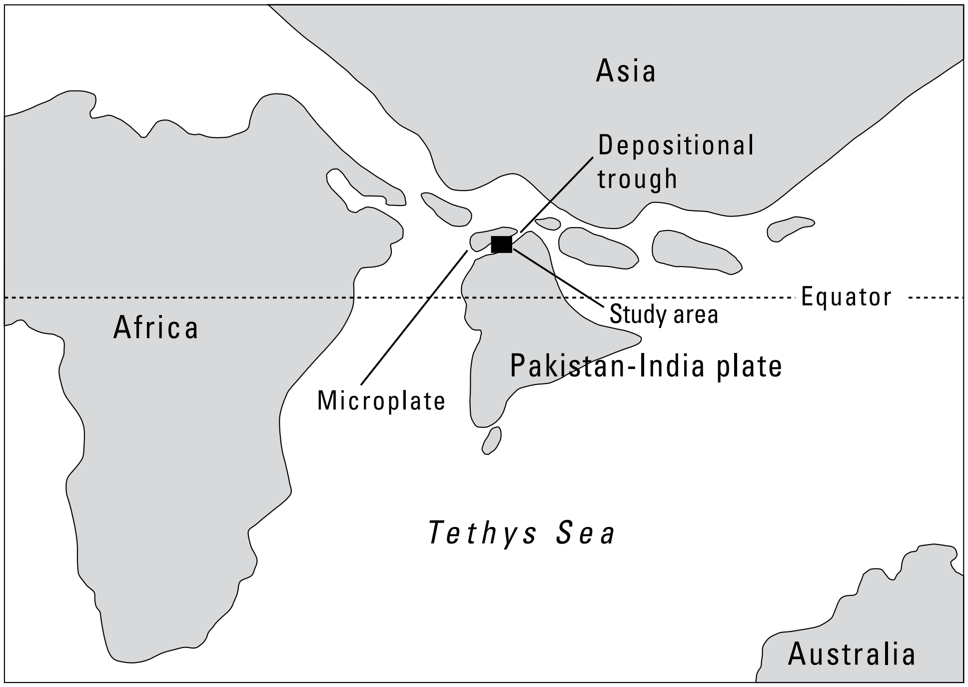

Figure F1. Late Paleocene continental configuration of the Pakistan-India plate and a microplate showing a Paleocene–Eocene depositional trough (modified from Scotese and others, 1988). The microplate is part of the Afghanistan plate.

cal Survey (USGS) resident team leader, and Peter Warwick, project chief for the Potwar Regional Framework Assessment Project. We also acknowledge help in the field provided by Peter D. Warwick, Norman O. Frederiksen, and Jean M. Self-Trail of the USGS and by Tariq Masood, Shahid Javed, Tariq Shakoor, and Amad Hussain of the GSP. The Lockhart Limestone section at Nammal Dam was measured and collected by J.R. SanFilipo and E.M. Brouwers of the USGS.

Section Descriptions

1. *Murree Hills.*—This section was measured by B.R. Wardlaw, W.E. Martin, I.H. Haydri, and J.M. Self-Trail in October 1989. The area is intensely folded. The Patala Formation is folded upon itself several times and undoubtedly represents a duplicated or triplicated thickness. It is mostly covered. The Lockhart and Margala Hill Limestones are fairly well exposed. The section of the Margala Hill Limestone was terminated where the Margala Hill is folded back upon itself. The section is located on the Dunga Gali road, north of Murree; its base is at lat 33°59.1′ N., long 73°23.82′ E., Survey of Pakistan map 43 G/5 (a sheet in the third edition series of 1:50,000-scale topographic maps published in 1987 by the Survey of Pakistan).

The Lockhart Limestone forms a small cliff consisting of wavy- and nodular-bedded skeletal lime mudstones to tight wackestones. The upper part of the Lockhart is interbedded limestones and limy siltstones, forming transitional lithologies to the overlying Patala Formation. The Patala is poorly exposed and is commonly observed in tight folds made up of very limy skeletal siltstone and silty skeletal lime mudstone. The Margala Hill Limestone forms a small cliff made up of two limestone ledges separated by a slightly recessive, very nodular limy siltstone (or marl). The lower limestone ledge consists of skeletal lime mudstone that is wavy bedded to slightly nodular bedded and contains thin silty partings. The upper ledge consists of slightly wavy-bedded skeletal wackestone and silty interbeds.

2. *Kala Chitta Range.*—This section was measured by B.R. Wardlaw, W.E. Martin, and Shahid Javed in October 1989. The base of the Lockhart is located at lat 33°39.02′ N., long 72°22.8′ E., and the base of the Patala is located at lat 33°39.29′ N., long 72°23.11′ E., Survey of Pakistan map 43 C/6. The section consists of cliff-forming Lockhart Limestone disconformably overlying the covered Cretaceous Kawagarh Formation. The top of the Lockhart is repeated at least three times by reverse faults. The true thickness was estimated and then corrected by comparing it with an additional section (unfaulted) measured at Surg (section 3). The top of the Lockhart forms a dip slope that was followed up a saddle, where the overlying Patala Formation and Margala Hill Limestone are exposed. The Margala Hill Limestone is overlain by the Bhadrar beds of Jurgan and Abbas (1991).

The Lockhart Limestone generally consists of medium wavy beds and contains some nodular-bedded horizons of tight skeletal wackestone; it forms many cliffs. The Patala is poorly exposed except for well-exposed limestone nodules and nodular- and wavy-bedded, silty skeletal wackestones.

Skeletal limy siltstone (marl) is commonly exposed above and below the limestone beds, suggesting that most of the Patala is made up of this lithology. The Margala Hill Limestone is made up of a sequence of well-exposed limestone ledges and poorly exposed to covered swales. The ledges are generally skeletal wackestone that are nodular bedded with scattered wavy beds near the base becoming more wavy bedded near the top. The swales are generally represented by scattered limestone nodules, probably in a covered marl. The middle part of the formation appears to lack limestone ledges and forms a very large covered interval. The uppermost limestone ledge in the Margala Hill Limestone, underlying the Bhadrar beds of Jurgan and Abbas (1991), is recrystallized and has common calcite veins, indicating a significant exposure surface at the top.

3. *Surg (Kala Chitta Range).*—This section was measured by P.D. Warwick and I.H. Haydri in October 1989. The section consists of Cretaceous units disconformably overlain by the Lockhart Limestone and part of the Patala Formation and ends in a very tight fold repeating the section. The base of the section is located at lat 33°42.99′ N., long 72°15.94′ E., Survey of Pakistan map 43 C/6.

The Lockhart Limestone appears very similar here to that exposed in the previous section, consisting mostly of wavy-bedded skeletal wackestone. Packstone appears to be a little more common in this section. The Patala is tightly folded but well exposed in this fold and consists of limy mudstone, shale, thin limestone lenses, and common limestone nodules. The lenses are lime mudstone, and the nodules are lime mudstone to wackestone.

4. *Cherat Range.*—This section was measured in a tight syncline in a very folded sequence in the middle of the Cherat Range by B.R. Wardlaw, W.E. Martin, I.H. Haydri, P.D. Warwick, Amad Hussain, and Shahid Javed in October 1989. The base of the section is located at lat 33°51.64′ N., long 71°54.09′ E., Survey of Pakistan map 38 O/13. The section consists of the Hangu Formation overlying the Precambrian Dathner Formation and followed by a thick Lockhart Limestone, overlain unconformably by the "red" Patala facies of Warwick and Wardlaw (1992).

The Hangu Formation has a bauxite overlain by a thin lateritic soil at its base. A variously developed coal bed (0.3–1.0 meter (m) thick) immediately overlies the exposure surface represented by the laterite. This sequence appears to be repeated depositionally at least once. Most of the Hangu is covered, but small portions in gullies are exposed. The scattered exposures appear to represent most of the formation and are pieced together and displayed in the columnar section (pl. F1). Most of the Hangu is represented by mudstones and shale, occasionally bauxitic or lateritic, or is fossiliferous. A thin carbonaceous shale is in the upper part, and a thin coal bed (0.1–0.3 m thick) is very near the top of the formation.

The Lockhart Limestone is made up of three well-exposed limestone units separated by two covered intervals. The lower limestone is a small ledge of alternating wavy-bedded skeletal lime mudstone and calcareous mudstone that contains scattered limestone nodules capped by clean quartz sandstone containing siliceous cement. The intervening covered interval is completely covered. The middle limestone unit consists of alternating wavy and nodular beds of skeletal lime mudstone. The upper covered interval has scattered limestone nodules in its lower part. The upper limestone unit forms a prominent cliff. The lower part of the upper unit contains nodular-bedded muddy skeletal lime mudstone and scattered wavy beds. The upper part becomes less muddy and completely wavy bedded. The contact with the red-colored siltstones of the overlying "red" Patala facies is unconformable. The red Patala facies (see discussion in "Stratigraphic Interpretation" section) is poorly exposed except for a few ledges of conglomeratic siltstone. The conglomerate clasts are pebble to cobble size and of mixed lithology, generally chert and limestone. Abraded and poorly preserved scattered larger foraminifers are present as pebbles.

5. *Lumshiwal Nala (Makarwal).*—This section was measured by B.R. Wardlaw, W.E. Martin, I.H. Haydri, J.M. Self-Trail, and N.O. Frederiksen in October 1989. The upper part, which is entirely cliff, was climbed and measured by Wardlaw, Martin, and Haydri. The base of the section consists of coal-bearing Hangu Formation overlying carbonaceous-rich and apparently coal-bearing Cretaceous Lumshiwal Formation (see Frederiksen and others, this volume, chap. D). The contact appears to be at the base of the major coal bed, and samples were collected along the contact for paleontology to resolve the age relations. The Hangu is overlain by the Lockhart Limestone; thick, well-exposed, generally marine Patala Formation; Nammal Formation (limestone facies); and very thick, cliff-forming Sakesar Limestone that appears to be at least doubled in thickness by faulting. The base of the section is located at lat 32°51.49′ N., long 71°8.83′ E., Survey of Pakistan map 38 P/1. The general stratigraphy of the area was reported by Danilchik and Shah (1987).

The Hangu Formation is dominated by sandstone but contains a thick coal bed (3 m) and carbonaceous shale at its base. The sandstone is poorly to well sorted, containing subrounded quartz grains, scattered carbonaceous smears, mottling, crossbedding of limonite tracers, flaser crossbedding, and shaly stringers. Above an upper coaly bed, the sandstone is generally calcareous, consisting of common mollusks, scattered limestone nodules, faint crossbedding, and burrows, probably representing shoreface facies.

The Lockhart Limestone is dominated by nodular tight skeletal wackestone with shale partings that become thicker near the top. The base and top of the unit are limy siltstones or shales and common limestone nodules. The upper part of the unit appears to be transitional with the overlying Patala Formation. The contact is drawn where shale is more common than nodules above and nodules more common than shale below. The Patala Formation is dominated by fossiliferous calcareous siltstone and scattered intervals of limestone nodules and scattered nodular limestone beds. The Nammal Formation consists of flat-bedded, sparsely skeletal lime mudstone that becomes finely skeletal wackestone at its top. The overlying

Sakesar Limestone is thick, wavy to nodular bedded, cherty, skeletal limestone (wackestone and packstone). Very little of the Sakesar Limestone was examined because it forms a shear cliff.

6. *Nammal Pass.*—This section is located near the road over Nammal Pass in the western Salt Range and was measured in two parts. The first part (the first (northern) traverse, fig. 1, Editors' Preface of this volume) was also measured in two parts. The lower part consists of the coal-bearing Hangu overlying the Jurassic Datta Formation and was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in October 1989; the upper part consists of the top bed of the Hangu Formation and the cliff-forming Lockhart Limestone and was measured by Wardlaw, Martin, and Haydri in February 1989. It is located just above the road, with the base at lat 32°40.75′ N., long 71°47.19′ E., Survey of Pakistan map 38 P/14. The second part was measured 0.6 km to the southeast on a nearby saddle and consists of the top of the Lockhart Limestone, Patala Formation, and Nammal Formation; the base of the second part was at lat 32°40.44′ N., long 71°47.58′ E., Survey of Pakistan map 38 P/14. The Hangu Formation forms a small cliff at the base of the measured section and is made up of a sequence dominated by sandstones containing a coal-bearing carbonaceous shale near its base and several paleosols and gypsiferous mudstones and shales in its middle part.

The Lockhart Limestone overlies very fossiliferous sandstones at the top of the Hangu Formation. The sandstones are rich in mollusks, contain calcareous cement, and represent nearshore marine deposition within the Hangu. The Lockhart Limestone forms a rubbly cliff and was measured up a steep ravine and dry waterfall. The Patala Formation and overlying recessive marl facies of the Nammal Formation are generally not exposed and commonly form talus-covered slopes. Along the measured section, the units are partly exposed. The upper part of the Nammal and overlying Sakesar Limestone form steep cliffs that make the crest of the range. The Lockhart Limestone consists of a lower part of alternating recessive and cliff-forming units that are completely exposed; a middle part of cliff-forming, thick nodular packstones to wackestones; and an upper part of alternating recessive and cliff-forming units.

The Patala Formation consists of a basal fossiliferous siltstone and thick sequence of marine shales. The Nammal Formation consists of a thick lower unit that is mostly covered, slope-forming, recessive limy siltstone (or marl), and beds of silty packstone to lime mudstone are exposed. The recessive beds are generally exposed above and below the limestone beds. The upper part of the Nammal is exposed in a very steep cliff of wavy- to flat-bedded lime mudstones to packstones and was measured at Nammal Dam, where it was more accessible.

7. *Nammal Dam.*—This section was measured by B.R. Wardlaw, W.E. Martin, I.H. Haydri, J.M. Self-Trail, N.O. Frederiksen, and Tariq Masood in October 1989. The Lockhart Limestone was measured by J.R. SanFilipo in February 1990. Wardlaw and Martin revisited the section in June 1991. The section consists of a relatively well-exposed Patala Formation overlying a cliff-forming dip slope of Lockhart Limestone and overlain by well-exposed Nammal Formation, and cliff-forming Sakesar Limestone. This section is the same as that measured by the Hydrocarbon Development Institute of Pakistan (HDIP) and reported on by Köthe (1988) as the Nammal Gorge section and appears to be the same as that reported by Haque (1956; see discussion in "Stratigraphic Interpretation" section). The base of the Patala is located at lat 32°39.81′ N., long 71°48.05′ E., Survey of Pakistan map 38 P/14. The base of the Lockhart and the top beds of the Hangu measured by SanFilipo are in the gorge of the stream some 500 m northeast of the base of the Patala section.

The Lockhart Limestone measured by J.R. SanFilipo and collected for paleontology by E.M. Brouwers appears very similar to that described at Nammal Pass (compare sections 6 and 7, pl. F1). The Lockhart overlies a fossiliferous (mollusk-rich) sandstone at the top of the Hangu, just as it does at Nammal Pass.

The Patala Formation generally consists of dark-gray shales and glauconitic skeletal wackestones and packstones. The formation can be divided into three units: lower, middle, and upper. The lower unit is largely dark-gray shale that has common lime mudstone nodules in its lower half. The middle unit, forming a limestone ledge, consists of medium-bedded glauconitic, sandy skeletal wackestone at its base, becoming alternating wavy and nodular beds of glauconitic skeletal packstone at its top. The upper unit is dark-gray shales containing thin limy mudstones rich in planktic foraminifers and one bed of argillaceous lime mudstone. The unit is capped by a very limy sandstone.

The Nammal Formation is divided into two units: the lower marl facies and the upper limestone facies. These units are referred to as facies because they show a great deal of variation away from the Nammal Pass-Nammal Dam area. The lower marl facies is made up of very limy siltstone (marl), which forms swales broken by several limestone ledges of skeletal lime mudstone to wackestone. The base of the formation is drawn at the sharp irregular contact between the top sandstone of the Patala and an overlying thin bed of fine skeletal wackestone. Above the wackestone, only marls are found in the swales, and below the sandstone, only shales are found in the swales. It is unfortunate that the beds immediately overlying this contact are covered, but there is a marked change in color of the soil (lighter), similar to that formed on the marl higher in the section. This change in color appears consistent for a great distance and is quite mappable from the Nammal Dam section to the Nammal Pass section. This formation contact is based on a mappable change in lithologies and not on proposed faunal zones.

The upper limestone facies of the Nammal forms a cliff of flat-bedded, silty to sandy, skeletal lime mudstone to wackestone. The facies is made up of less fossiliferous lime mudstone at its base and becomes more skeletal, thicker bedded, and wackestone dominated in its upper part.

A coarsely nodular-bedded Sakesar Limestone overlies in marked contrast to the relatively flat beds of the limestone facies of the Nammal Formation.

8. *Kuraddi.*—This section is located 0.5 kilometer (km) south of the village of Kuraddi, on the south limb of a tight anticline that is disrupted by two faults that repeat a minor amount of the section near the base. The base is at lat 32°31.67′ N., long 72°03.43′ E., Survey of Pakistan map 43 D/2 (section 31 of Warwick and Shakoor (1988)). The Lockhart Limestone and the Patala and Nammal Formations were measured in February 1989 and the Hangu Formation was measured in October 1989, both instances by B.R. Wardlaw, W.E. Martin, and I.H. Haydri. The Patala was re-collected for paleontology by J.M. Self-Trail, N.O. Frederiksen, and Tariq Masood in October 1989. A poorly exposed carbonaceous shale overlying the Permian Amb Formation exposed in the core of the anticline was being mined in October 1989. This carbonaceous shale was not previously reported and appears to be Jurassic or Cretaceous (see Frederiksen and others, this volume, chap. D).

The sequence at Kuraddi is nearly completely exposed. A thin Lockhart Limestone overlies lateritic and bauxitic soils in the upper part of the Hangu Formation. The Lockhart is duplicated by faulting that exactly repeats the section bed for bed. The lower part of the sandstone unit within the Patala is also repeated; this observation is only demonstrable by mapping out all the unit contacts between several stream drainages.

The Hangu Formation consists largely of laterite and lateritic sandstones, and prominent bands of kaolinite occur in its upper part. The Lockhart Limestone consists of alternating beds of sandy, limy, skeletal siltstone and medium-bedded sandy skeletal wackestone that is locally rich in bryozoans and contains common echinoid spines and a *"Crepidula"*-like gastropod. The Patala Formation consists of a basal unit of finely interbedded, laminated fine sandstone and shale (or mudstone) that is overlain by a cliff-forming burrowed sandstone. Most of the remainder of the formation consists of alternating limy skeletal siltstones and shales. The siltstones are locally rich in larger foraminifers. The siltstone-bearing interval occurs below and above a dark-gray shale that is slightly carbonaceous.

The Nammal Formation shows a gradational contact with the underlying Patala Formation. This relation is typical in the Salt Range from this section eastward, where the contact is exposed. Skeletal siltstones at the top of the Patala grade into silty, skeletal limestones at the base of the Nammal. Commonly, the same dominant fossils carry through the contact. In the case of the Kuraddi section, the fossils are larger foraminifers and mollusks. The Nammal Formation consists of two cliff-forming skeletal wackestone to packstone units separated by a slightly recessive unit of silty, skeletal wackestone to lime mudstone. A recessive unit of *Fasciolites* marl makes up the top of the Nammal below the Sakesar Limestone.

9. *Kathwai.*—This section is located 2.3 km nearly due south of the village of Kathwai; the base is at lat 32°27.75′ N., long 72°11.42′ E., Survey of Pakistan map 43 D/3 (section 30 of Warwick and Shakoor (1988)). The section was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in February 1989.

The Lockhart Limestone is poorly exposed; only the upper limestone beds break through the soil-covered slope. Shale, sandstone, and thin lateritic soils of the Hangu Formation overlying the Triassic Mianwali Formation are found scattered in small isolated outcrops below the Lockhart Limestone.

The Lockhart Limestone consists of alternating beds of limy siltstone (marl) and medium beds of silty packstone containing larger foraminifers. The Patala Formation is poorly exposed except for the sandstone in the lower part of the unit (this is the same sandstone unit identified as the "Dilliwala" sandstone complex of the Patala Formation by Warwick and Shakoor, this volume, chap. I). The contact between the Patala and Nammal is not exposed. The Nammal Formation consists of a lower covered recessive unit (marl(?)) that is inferred on the basis of regional relations. The exposed portion of the Nammal consists of a steep, cliff-forming, nodular skeletal wackestone overlain by a recessive unit of limy siltstone (marl) and skeletal wackestone to packstone, which is below a large cliff of the Sakesar Limestone.

10. *Arara.*—This section is located 3.2 km southeast of the village of Arara; the base is at lat 32°32.16′ N., long 72°23.54′ E., Survey of Pakistan map 43 D/6 (section 29 of Warwick and Shakoor (1988)). The section was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in February 1989 and was remeasured by Wardlaw, Martin, Haydri, and J.M. Self-Trail in October 1989.

The Arara section is generally poorly exposed throughout the area and is mostly covered with talus from cliffs of the Nammal Formation and Sakesar Limestone. Most of the sequence is exposed on a nose near the Rashid Tedi Mine. Here the Lockhart Limestone overlies a thick lateritic soil (4.6 m) that represents the entire Hangu Formation. The Hangu disconformably overlies the Permian Warchha Sandstone.

The Lockhart Limestone consists of a lower unit of medium- to thick-bedded, silty, skeletal packstone with common echinoid spines and an upper unit of limy siltstone (marl), scattered limestone nodules, and common whole echinoid (sea biscuit) fossils preserved. The abundance of echinoid spines and of delicate whole fossils implies that these burrowing sediment feeders are in place and may be greatly responsible for the burrowed nodular limestone so common in the Paleocene and Eocene units of the Salt Range.

The lower sandstone unit of the Patala Formation ("Dilliwala" sandstone complex) directly overlies the Lockhart Limestone. The remainder of the Patala is generally not exposed, except for a portion in and around the small coal mines throughout the area.

The contact between the Nammal and Patala Formations is not exposed. The exposed portion of the Nammal consists of a lower cliff-forming unit and an upper recessive unit that forms a small ledge beneath the cliffs of the Sakesar Limestone.

11. *Pail-Khushab Road.*—This section is located 0.6 km north of a major switchback in the northern escarpment; the base of the Lockhart is at lat 32°35.83′ N., long 72°27.25′ E., Survey of Pakistan map 43 D/6 (section 28 of Warwick and

Shakoor (1988)). The section was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in February (Lockhart Limestone and the Patala and Nammal Formations) and October (Hangu Formation) 1989.

Most of the Lockhart Limestone and Nammal Formation is exposed as two very steep cliffs separated by a talus-covered slope representing the Patala and lower part of the Nammal Formation. The Lockhart Limestone overlies a thick cliff-forming sandstone at the top of the Hangu Formation.

The Hangu Formation consists of the aforementioned sandstone and an underlying lateritic sandstone and thick bauxite (3 m). The base of section is in a dense thicket, where the bauxite overlies Permian sandstone, probably of the Amb Formation.

The Lockhart Limestone consists of, in ascending order, a mudstone, a sequence of alternating cliff-forming nodular skeletal wackestone to packstone and slightly recessive silty nodular lime mudstone to packstone, followed at the top by thick-bedded (flat) skeletal packstone. Except for exposures in and about small coal mines, the Patala is covered by abundant coarse talus from the overlying steep cliffs of the Nammal Formation and Sakesar Limestone. The contact between the Nammal and Patala Formations is not exposed. The exposed Nammal consists of a steep cliff-forming lower unit of nodular skeletal packstone to wackestone and an upper unit that forms a steep slope of recessive limy, skeletal siltstone (marl) containing skeletal wackestone nodules. The Sakesar Limestone forms a sheer cliff above with a sharp contact with the upper unit of the Nammal.

12. *Dhaman.*—This section is located 0.6 km southwest of the village of Dhaman; its base is at lat 32°37.42′ N., long 72°29.25′ E., Survey of Pakistan map 43 D/6 (section 23 of Warwick and Shakoor (1988)). The section was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in February 1989.

The Lockhart Limestone overlies a thin lateritic soil and thick-bedded sandstone that make up the Hangu Formation. The Hangu lies on the Permian Amb Formation. The Lockhart Limestone is not exposed at its base; the lowermost part is probably mudstone similar to section 11. The exposed Lockhart consists of limy mudstone (marl) containing muddy, skeletal wackestone nodules grading upward to limy siltstone (marl) containing skeletal wackestone nodules.

The base of the Patala Formation is not exposed but is probably shale similar to that exposed above the locally mined coal bed. The exposed part of the Patala consists of a thin coal bed (see Warwick and Shakoor, this volume, chap. I for thickness and description) and dark-gray shale overlain by limy, skeletal siltstone containing a few beds of silty, skeletal wackestone and a thin mudstone at the top.

The Nammal Formation is well exposed and consists of a basal recessive unit of skeletal wackestone and limy siltstone (marl). This unit is overlain by a precarious cliff-forming sequence of sandy dolostone and thick-bedded nodular skeletal wackestone alternating with very nodular silty skeletal wackestone and limy siltstone (marl). The very nodular intervals form loose, rubbly, steep slopes between the cliffs of the thick-bedded limestone. The contact with the overlying cliffs of the Sakesar Limestone is sharp and undulating.

13. *Nila Wahan.*—This section is located at the north point dividing major drainages to Nila Wahan Gorge, 2 km southeast of the village of Bhal; the base of the Lockhart is located at lat 32°38.67′ N., long 72°35.75′ E., Survey of Pakistan map 43 D/10 (section 20 of Warwick and Shakoor (1988)). B.R. Wardlaw, W.E. Martin, and I.H. Haydri measured the Lockhart Limestone and the Patala and Nammal Formations in February 1989 and the Hangu Formation in October 1989. J.M. Self-Trail and N.O. Frederiksen sampled the section in October 1989.

The Hangu Formation disconformably overlies the Permian Sardhai Formation and consists mostly of sandstone and scattered interbeds of shale, sandy siltstone, and laterite. The uppermost bed is micaceous sandstone.

The Lockhart Limestone consists of a lower recessive unit that grades from a limy mudstone containing skeletal lime mudstone, to wackestone nodules, to a limy siltstone containing skeletal wackestone, to packstone nodules. Bryozoans are common in the upper part. A middle ledge-forming unit consists of nodular skeletal packstone to wackestone containing common "*Crepidula*"-like gastropods and echinoid spines; larger foraminifers are abundant at the top. An upper recessive unit consists of sandy skeletal wackestone and limy siltstone that contains common oysters near the top. The uppermost unit consists of thick- to medium-bedded (flat) skeletal packstone to wackestone containing bryozoan and echinoid spine fragments. The uppermost unit is richly glauconitic.

The Patala Formation is poorly exposed, consisting of a lower unit of shale, a coal bed near the top, and an upper unit of skeletal, limy siltstone. The contact between the Patala and Nammal is not exposed, but beds representing the lowermost part of the Nammal are exposed and consist of skeletal wackestone and limy siltstone (marl). Most of the lower part of the formation is covered. The well-exposed part of the Nammal consists of alternating recessive and ledge-forming units that start in a recessive unit at the base and end in a recessive unit at its top. A thin, friable sandy dolostone occurs at the base of the second recessive unit. The contact with the cliffs of the overlying Sakesar Limestone is sharp.

14. *Sohai River Gorge.*—This section is located on a steep cliff on the east side of the gorge near the head of Sohai River (Sardahi) Gorge, 1.7 km southwest of the village of Khandoyah; the base of the section is at lat 32°43.92′ N., long 72°43.42′ E., Survey of Pakistan map 43 D/10 (base of section in carbonaceous shale of Hangu and nodular limestone of Lockhart is the same as section 19 of Warwick and Shakoor (1988) measured as Patala and Nammal in that paper). The section was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in February 1989.

The Lockhart Limestone overlies pisolitic laterite, carbonaceous shales, a coal bed (0.3 m thick), and siltstones of the Hangu Formation just above the river. Beds of the Permian Sardhai Formation are exposed in the river.

The Lockhart Limestone consists of a lower unit of foraminifer-rich, skeletal wackestone to very limy skeletal mudstone, followed by a thin micaceous very fine sandstone to siltstone; a cliff-forming unit of slightly nodular sandy, muddy, foraminifer-rich, skeletal wackestone containing mudstone and shale partings; and an upper steep recessive unit of mostly very limy, foraminiferous mudstone, limestone nodules, and stringers of silty, foraminiferous wackestone. The upper unit grades into mudstones, siltstones, and shales that form the basal unit of the Patala Formation.

The Patala Formation is well exposed and consists of a lower unit that is mostly shale and two coal beds (0.1 and 0.2 m thick) that grade into a middle unit of mudstone. The upper part consists of a thin calcareous sandstone and a sandy, limy, abundantly foraminiferous siltstone that grades into sandy, limy siltstone containing common silty, foraminiferous wackestone nodules of the lower part of the Nammal Formation.

The Nammal Formation consists of a lower recessive unit described above, the upper part of which becomes covered by talus from the sheer cliff of the overlying unit of the Nammal. The base of the cliff is massive, containing undulating irregular breaks. The lowermost part is lime mudstone that grades into skeletal wackestone that becomes more nodular (wavy bedded) but still massive. A massive sandy dolostone bed marks the center of the cliff and the end of our steady handholds and footholds. The remainder of the outcrop (cliff) could not be measured. Along a goat trail on the other side of the canyon, we estimated the remaining thicknesses and described the units. Two steep recessive units divided by a small cliff mark the upper part of the formation below the sheer cliff of the Sakesar.

15. *Khairpur 9 borehole.*—This borehole is located at lat 32°44.67′ N., long 72°47.00′ E., Survey of Pakistan map 43 D/14. It was drilled April–May 1987 (Alam and others, 1987), and initial core descriptions are by M. Anwar (written commun., 1989). N.O. Frederiksen and J.M. Self-Trail collected the core and modified the core description in October 1989. The Paleocene and lower Eocene section was reinterpreted by B.R. Wardlaw in 1990. The core was reexamined by B.R. Wardlaw and W.E. Martin in June 1991.

16. *Khokhar Bala 10 borehole.*—This borehole is located at lat 32°45.88′ N., long 72°48.83′ E., Survey of Pakistan map 43 D/13. It was drilled in June 1987 (Alam and others, 1987), and initial core descriptions are by M. Anwar and S.T.A. Mashhadi (written commun., 1989). N.O. Frederiksen and J.M. Self-Trail collected the core and modified the core description in October 1989. The Paleocene and lower Eocene section was reinterpreted by B.R. Wardlaw in 1990. The core was reexamined by B.R. Wardlaw and W.E. Martin in June 1991.

17. *Dalwal 6 borehole.*—This borehole is located at lat 32°43.33′ N., long 72°52.72′ E., Survey of Pakistan map 43 D/14. It was drilled in January 1987 (Alam and others, 1987), and initial core descriptions are by S.T.A. Mashhadi and M. Anwar (written commun., 1989). N.O. Frederiksen and J.M. Self-Trail collected the core and modified the core description in October 1989. The Paleocene and lower Eocene section was reinterpreted by B.R. Wardlaw in 1990. The core was reexamined by B.R. Wardlaw and W.E. Martin in June 1991.

18. *Chitti Dhan.*—This section is located 4.3 km northwest of the village of Dandot on the south side of Gandhala Ravine; the base of the section is at lat 32°41.17′ N., long 72°55.83′ E., Survey of Pakistan map 43 D/14 (section D–1 of Hussain and Javed as reported by Warwick and Shakoor (1988)). The section was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in February 1989.

The Lockhart Limestone is absent at Chitti Dhan, but marine, fossiliferous sandy siltstone at the base of the Patala represents the lateral equivalent of the limestone. These siltstones overlie variegated mudstones that are assigned to the Hangu Formation. The limestones of the Lockhart pinch out between the Sohai River Gorge and the Chitti Dhan section. The Hangu Formation unconformably overlies sandstones of the Permian Warchha Sandstone.

The lower part of the Patala Formation is partly exposed and consists of shales and a thin coal bed (0.2 m). The upper part of the formation is covered but interpreted to be alternating fossiliferous siltstones and shales.

Most of the Nammal is exposed and consists of a thick recessive unit at the base, a middle ledge-forming unit that has a calcareous sandstone at its base, and a covered recessive unit, probably limy mudstone at the top. The upper recessive unit is covered by very coarse talus of the overlying Sakesar Limestone.

19. *Dandot 14 borehole.*—This borehole is located at lat 32°39.92′ N., long 72°56.12′ E., Survey of Pakistan map 43 D/14. It was drilled in February–March 1988, and initial core descriptions are by S.T.A. Mushhadi, M. Anwar, and H. Hussain (written commun., 1989). N.O. Frederiksen and J.M. Self-Trail collected the core and modified the core description in October 1989. The Paleocene and lower Eocene section was reinterpreted by B.R. Wardlaw in 1990. The core was reexamined by B.R. Wardlaw and W.E. Martin in June 1991.

20. *Katas 3 borehole.*—This borehole is located at lat 32°43.70′ N., long 72°58.23′ E., Survey of Pakistan map 43 D/14. It was drilled in March 1987 (Alam and others, 1987), and initial core descriptions are by T. Shakoor and S. Javed (written commun., 1989). N.O. Frederiksen and J.M. Self-Trail collected the core and modified the core description in October 1989. The Paleocene and lower Eocene section was reinterpreted by B.R. Wardlaw in 1990. The core was reexamined by B.R. Wardlaw and W.E. Martin in June 1991.

21. *Basharat.*—This section is located in hills north of the village of Basharat, 2 km to the north-northeast, with the base of section at lat 32°48.00′ N., long 73°06.00′ E., Survey of Pakistan map 43 H/1 (section 17 of Warwick and Shakoor (1988)). The section was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in February 1989.

The Basharat section represents a barely exposed thicket-covered slope. It does exhibit well the base of the Patala and the underlying unit. The beds immediately underlying the Patala are assigned to the Hangu Formation and consist of conglomeratic silty angular quartz sandstone and quartz pebble conglomerate overlain by lateritic soil. Below the Hangu are coarsely conglomeratic beds of the Permian Tobra Formation.

The base of the Patala consists of shales and a coal bed (approximately 0.3 m thick). The remainder of the section is not exposed except for a ledge-forming limestone of the Nammal Formation and a few limestone nodules immediately below the Sakesar Limestone.

22. *Basharat 34 borehole.*—This borehole is located at lat 32°46.87′ N., long 73°05.95′ E., Survey of Pakistan map 43 H/1. It was drilled in February 1989, and initial core descriptions are by Mashhadi and others (1990). N.O. Frederiksen and J.M. Self-Trail collected the core and modified the core description in October 1989. The Paleocene and lower Eocene section was reinterpreted by B.R. Wardlaw in 1990. The core was reexamined by B.R. Wardlaw and W.E. Martin in June 1991.

23. *Sikkiwala Kas.*—This section is located in a big cliff on the north side of the main canyon at the confluence of the major tributary, 1.1 km southeast of Dhok Bhusa; the base of the section is at lat 32°47.58′ N., long 73°12.98′ E., Survey of Pakistan map 43 H/1 (section 11 of Warwick and Shakoor (1988)).

The beds immediately below the Patala Formation consist of (in ascending order above the Cambrian Baghanwala Formation) sandy, poorly sorted, well-rounded, multilithic conglomerate of the Permian Tobra Formation; conglomeratic (quartz pebble) sandstone and siltstone, relatively clean angular quartz sandstone, and laterite, assigned to the Hangu Formation.

The Patala Formation is very thin and consists of oyster-rich limy siltstone that grades upward into oyster-rich silty limestone of the Nammal Formation.

The Nammal Formation consists of a succession of three recessive units alternating with three ledge- or cliff-forming units. The middle ledge-forming unit consists of silty skeletal wackestone immediately overlain by very silty nummulitic (foraminiferous) packstone. A similar ledge at about the same stratigraphic horizon is identified at Ara. The uppermost bed of the Nammal Formation at the top of a sheer cliff face is overlain by conglomeratic sandstone of the Miocene Murree Formation of the Rawalpindi Group. The uppermost bed of the Nammal shows a thin weathering rind at its top, which contains voids that are filled with iron-stained chert.

24. *Ara 22 borehole.*—This borehole is located at lat 32°45.47′ N., long 73°11.93′ E., Survey of Pakistan map 43 H/1. It was drilled in November 1988, and initial core descriptions are found in Mashhadi and others (1990). N.O. Frederiksen and J.M. Self-Trail collected the core and modified the core description in October 1989. The Paleocene and lower Eocene section was reinterpreted by B.R. Wardlaw in 1990. The core was reexamined by B.R. Wardlaw and W.E. Martin in June 1991.

25. *Ara.*—This section is located on the escarpment immediately southeast of the Ara rest house, with the base of the section at lat 32°44.42′ N., long 73°13.00′ E., Survey of Pakistan map 43 H/2 (section 6 of Warwick and Shakoor (1988)). The section was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in February 1989.

The beds immediately below the Patala Formation consist of, in ascending order, conglomeratic angular quartz sandstone, shale, and conglomeratic angular quartz sandstone that becomes less conglomeratic upward. All of these beds are assigned to the Hangu Formation and disconformably overlie the multilithic conglomerate of the Permian Tobra Formation.

The Patala Formation consists of a 0.3-m coal bed (Warwick and Shakoor, 1988), carbonaceous shale and siltstone, and a siltstone unit that becomes limier and oyster-rich upward, grading into oyster-rich silty lime mudstone at the base of the Nammal Formation.

The Nammal Formation consists of a succession of two ledge-forming limestones alternating with two largely covered recessive units. The recessive units display numerous limestone nodules (mostly skeletal lime mudstone) that are probably subcrops. The upper ledge-forming limestone has already been mentioned as being similar to that at Sikkiwala Kas. The uppermost limestone nodules of the Nammal, below sandstones of the Murree Formation, display paleoweathering features similar to the top of the section at Sikkiwala Kas.

26. *Alberoni.*—This section is located approximately 2.3 km east of Baghanwala Fort “Alberoni”; the base of the section is at lat 32°43.92′ N., long 73°15.08′ E., Survey of Pakistan map 43 H/6 (section 3 of Warwick and Shakoor (1988)). The section was measured by B.R. Wardlaw, W.E. Martin, and I.H. Haydri in February 1989.

The generally eastward thinning Paleocene section is exposed at Alberoni and is nearing the eastern end of the outcrop belt, where the Paleocene and Eocene rocks are eroded away, and the Miocene Murree Formation overlies the Cambrian Baghanwala Formation. The rocks immediately below the Patala Formation are conglomeratic angular quartz sandstone and thin, relatively clean quartz sandstone that both display coal streaks and are assigned to the Hangu Formation. The Hangu disconformably overlies the multilithic conglomerates and conglomeratic sands of the Permian Tobra Formation.

The Patala Formation consists of a lower unit of poorly exposed shale, a coal bed that is locally thick (up to 1.2 m), and an upper unit of alternating mudstone and limy skeletal siltstone that becomes dominantly siltstone with abundant oyster shells near the top. This grades into loose skeletal wackestone with abundant oyster shells at the base of the Nammal Formation.

The Nammal Formation is not very well exposed and has thinned to less than 9 m beneath the upper Eocene unconformity below the Rawalpindi Group (Murree Formation). The Nammal is represented by a mostly recessive unit that is silty skeletal wackestone nodules in limy siltstone (marl); the lower part has abundant echinoid spines, and the upper part is mostly represented by subcrops. The uppermost beds are overlain by a possible soil profile at the base of the sandstone of the Murree Formation.

Paleontologic Control

Paleontologic control for the upper Paleocene to lower Eocene units is sparse. Many of the units are marginal-marine to shallow-marine deposits but lack abundant planktic forms that would be age diagnostic. Pollen and spores are commonly abundant in carbonaceous shales, but these lithologies are not common in the section. The remainder (most) of the section appears to be well oxidized, and oxidation has eliminated pollen and spores from the rocks, especially in surface sections. The common diagenetic overprint appears to have recrystallized or removed many planktic forms. Ostracodes appear to be common to most sections, but these abundant faunas have not been adequately studied. Nevertheless, enough fossil control exists for a preliminary model. Of importance are the paleontologic studies of this volume (chapters B, C, D, and E) that establish the ages of a regional reference section at Nammal Dam. These studies basically corroborate earlier studies of Köthe (1988). The foraminifer study of Afzal and Daniels (1991) is also important in that it shows a nearly continuous succession of planktic foraminifers for the latest Paleocene and early Eocene at Khairabad in the northern Salt Range. The flora reported by Edwards (this volume, chap. C) from the Basharat core that yielded an early Eocene age for the Nammal Formation (early NP 10?) and the disparate ages indicated by floras from a section near Ara reported by Köthe (1988) are very important. Köthe's (1988) material is not well constrained stratigraphically in her presentation. The difficulty of identifying the Patala Formation and differentiating it from the Hangu Formation in the eastern Salt Range is a problem that probably was not addressed for her study. Regardless, the dinoflagellate floras reported from the Patala by Köthe (1988) that indicate probable NP 8 and NP 10 ages indicate a significant hiatus in the unit she identifies as Patala.

In the course of fieldwork, we noticed that the first abundant occurrence of the larger foraminifer *Fasciolites globosa* appeared to be a useful marker for comparing sections. There is no particular reason that the abundant first occurrence of this foraminifer should be a time marker, but we continue to utilize it as a "datum" for interpreting our sections throughout the Salt Range. The paleontologic data from the studies in this volume and from previous work on the various units of the Salt Range are summarized in figure F2. The ages of units from our Nammal Pass and Nammal Dam sections are reviewed in more detail in the "Stratigraphic Interpretation" section below.

Lithofacies

Eleven general lithofacies are recognized for this study (figs. F3 and F4).

Facies 1.—Oxysol, sand, and mud of the Hangu Formation consist of laterites, lateritic soils, and bauxites interbedded with a variety of generally dirty sands, commonly with clay and coal streaks, and muds, micaceous in places. Coal beds in the sections studied are common to those that are "basinal," occurring within the depositional trough (Warwick and Wardlaw, 1992) rather than along its margin and are associated with oxysols or muds. Coal beds are common within the Hangu on the Kohat Plateau and are associated with sands (Khan, 1992).

Facies 2.—Shoreface sand of the Hangu Formation is silty to clean, bioturbated, generally medium sand containing scattered to common mollusks and calcareous cement, generally occurring in the upper part of the Hangu in "basinal" settings (fig. F3).

Facies 3.—Skeletal lime sand of the Lockhart, Margala Hill, and Sakesar Limestones is skeletal wackestone to packstone, generally containing larger foraminifers; in addition, dasyclad and red algae, bryozoans, mollusks, and other foraminifers are common accessories. Lime mudstone is rare, and the beds are typically wavy to nodular.

Facies 4.—Foraminiferous lime mud of the Lockhart Limestone is skeletal lime mudstone to wackestone, containing common planktic foraminifers in the foraminifer constituents and is "basinal" in distribution (Warwick and Wardlaw, 1992).

Facies 5.—Sand of the Patala Formation is medium- to fine-grained, bioturbated, well-sorted, subrounded quartz, containing silica cement. It has a limited distribution, generally marking the western limit of coal-bearing Patala Formation and represents barrier sands (Warwick and Shakoor, 1988, and this volume, chap. I, and sections 8–10 in fig. F4).

Facies 6.—Mud and shale of the Patala Formation represent a variety of generally fine-grained clastic sediments that are rooted, carbonaceous, coal-bearing, fossiliferous, marginal-marine swamp deposits (Frederiksen and others, this volume, chap. D). Warwick and Shakoor (this volume, chap. I) report local sandstone lenses within this facies that either were not observed or were assigned to the Hangu in this report.

Facies 7.—Skeletal silt of the Patala Formation is foraminifer- and mollusk-bearing skeletal limy siltstone, to silty lime mudstone, to packstone, commonly distributed in the upper part of the Patala Formation in the Salt Range (fig. F4). Sparsely skeletal sand, mud, and shale are rare constituents.

Facies 8.—Marine shale and marl of the Patala Formation are finely skeletal, dark-gray to olive-drab shale, marly shale, and marl containing common planktic foraminifers. Fine sand is common locally as sandstone or as a common constituent in shale and marl.

Facies 9.—Marl and nodular limestone of the Nammal Formation and Margala Hill Limestone are interbedded with marl and nodular skeletal lime mudstone to packstone. The marl commonly contains limestone nodules.

Facies 10.—Flat-bedded limestone of the Nammal Formation is skeletal lime mudstone, cherty in places, containing common planktic foraminifers. It is equivalent to the foraminiferous lime mud facies of the Lockhart Limestone but differs in that it is flat bedded compared with the typically wavy- to nodular-bedded Lockhart. It also represents a "basinal" facies like its equivalent in the Lockhart.

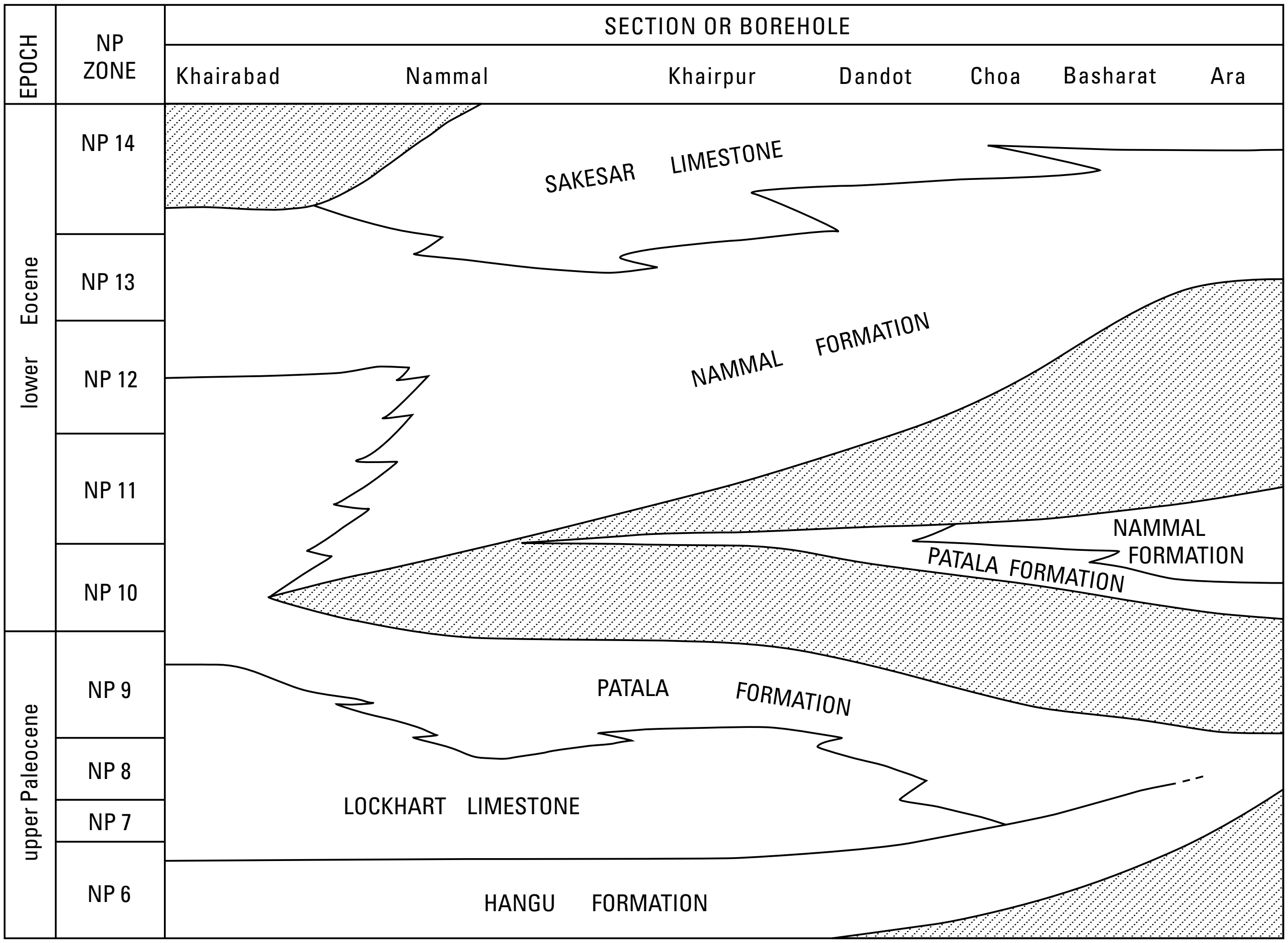

Figure F2. General age (shown as nannofossil zones) of units in the Salt Range from sections using faunas or floras as controls, from Khairabad to Ara. Nannofossil zones based on data from Köthe (1988) and Edwards (this volume, chap. C); sections from Köthe with additional data on the Nammal section and the Khairpur and Basharat boreholes from Edwards. Stripes indicate hiatus.

Facies 11.—The red beds of the "red" Patala facies are red siltstone and mudstone containing sandy conglomeratic beds and conglomerate of chert and limestone pebbles and abraded larger foraminifers. This facies has a limited distribution, found only at the Cherat section of this study. Warwick and Wardlaw (1992) reported this facies elsewhere (Kohat Pass) and discussed its significance in some detail.

Stratigraphic Interpretation

The Murree Hills and Kala Chitta Range sections (sections 1 and 2) are similar to those of the Salt Range (sections 6–26) (pl. F1). The Hangu Formation is missing at the base of sections 1 and 2; the Nammal Formation and Sakesar Limestone are not recognized as separable map units and are thus included in the equivalent Margala Hill Limestone. The Murree Hills section is highly folded. In the Kala Chitta Range section, the Margala Hill Limestone is overlain by the Bhadrar beds of Jurgan and Abbas (1991). These beds have been previously mapped as part of the Chorgali Formation (see Qureshi, 1992) and have also been reported overlying the Sakesar Limestone in the Salt Range. Jurgan and Abbas (1991) rightfully pointed out that these nodular limestones are indeed the same unit in both the Kala Chitta Range and Salt Range but are not the Chorgali Formation, which is a dolostone and shale unit representing deposition in a restricted environment in its type area. Therefore, Jurgan and Abbas (1991) referred to the unit as the Bhadrar beds, which they included as the top unit of the Sakesar Limestone.

The Cherat Range section (fig. F3, section 4) has the Hangu Formation and Lockhart Limestone at its base but differs from other sections by its somewhat enigmatic red beds overlying the Lockhart. The red beds, described as facies 11, have reworked, abraded, larger foraminifers in conglomeratic beds. No other fossils are apparent. Meissner and others (1974), in a section nearby at Dag, assigned the red beds to the Mami Khel Clay (=Kuldana Formation) because they are overlain by the Kohat Formation. Similarly, Ahmad Hussain, Said Rahim, Tariq Shakoor, and Abdul Latif (GSP, written commun., 1990) assigned this unit to the Patala Formation because

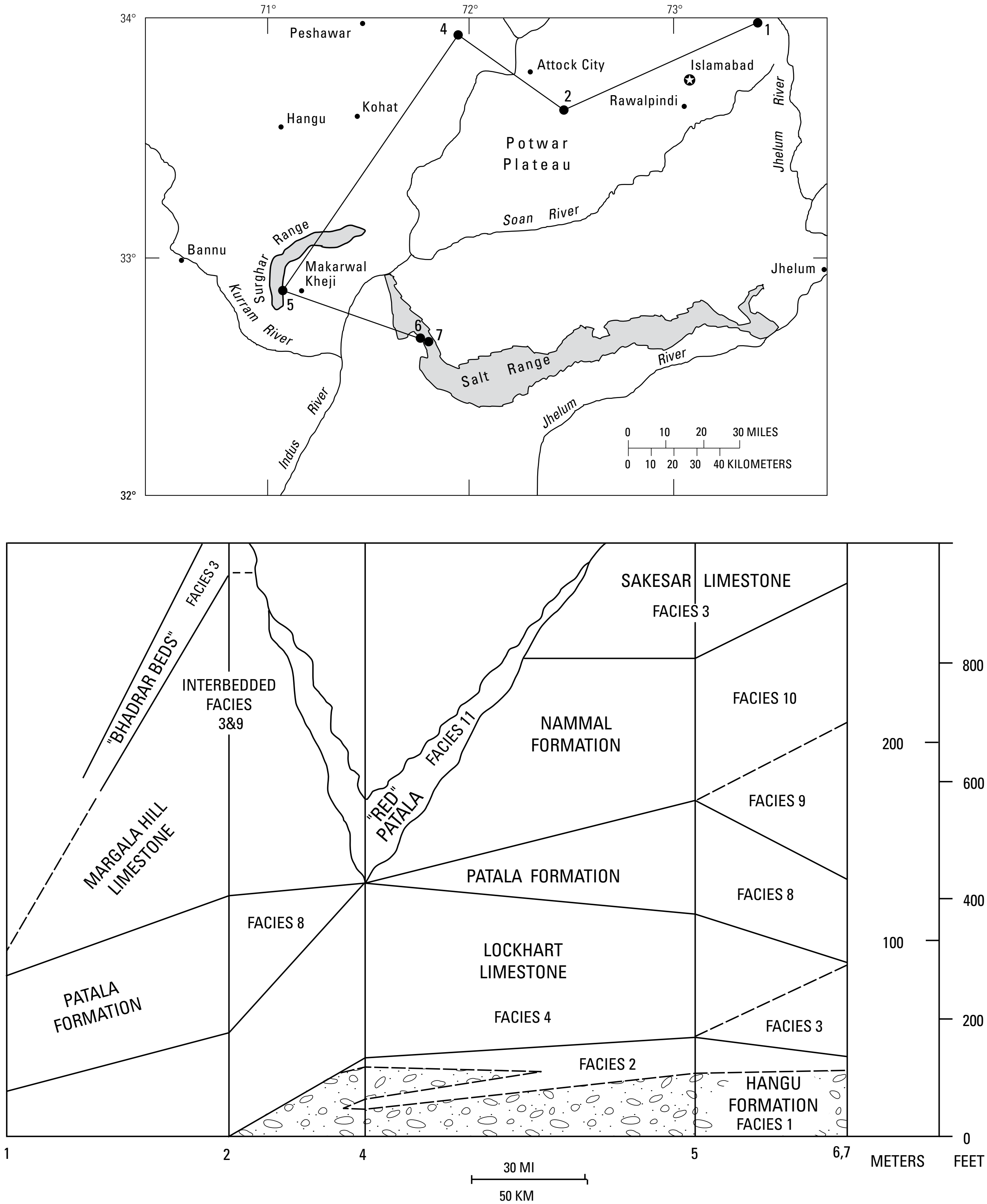

Figure F3. Fence diagram of sections displaying general stratigraphy in the area adjacent to the Potwar Plateau and showing lithofacies present in each unit. Heights are given in feet and meters above the base of the Tertiary section. The inset map shows the location of sections: 1, Murree Hills; 2, Kala Chitta Range; 4, Cherat Range; 5, Lumshiwal Nala (Makarwal); 6, 7, Nammal Pass and Nammal Dam.

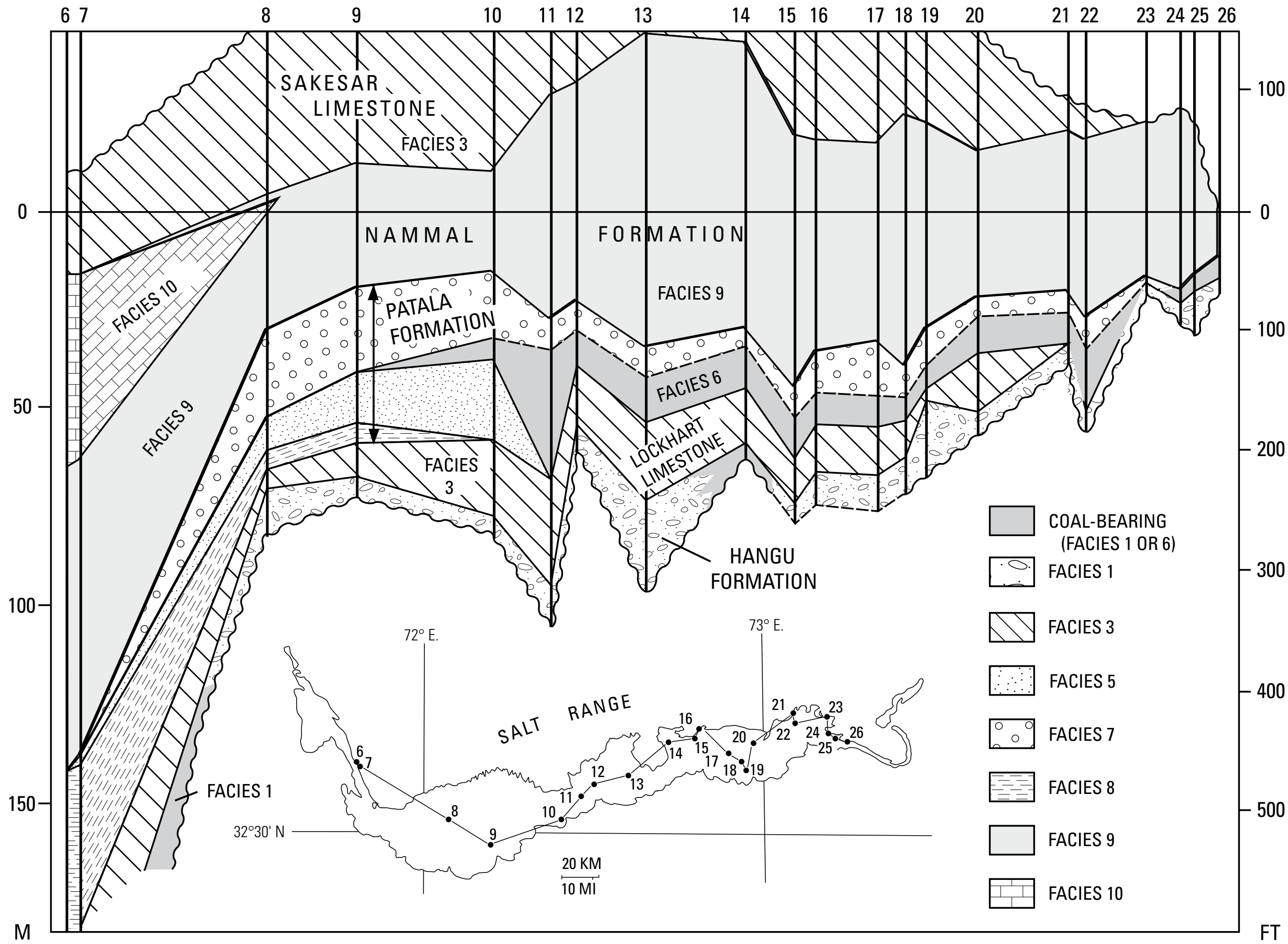

Figure F4. Fence diagram of sections in the Salt Range showing relation of facies to datum of *Fasciolites* acme zone. The inset map shows the locations of sections: 6, Nammal Pass; 7, Nammal Dam; 8, Kuraddi; 9, Kathwai; 10, Arara; 11, Pail-Khushab Road; 12, Dhaman; 13, Nila Wahan; 14, Sohai River Gorge; 15, Khairpur 9 borehole; 16, Khokhar Bala 10 borehole; 17, Dalwal 6 borehole; 18, Chitti Dhan; 19, Dandot 14 borehole; 20, Katas 3 borehole; 21, Basharat; 22, Basharat 34 borehole; 23, Sikkiwala Kas; 24, Ara 22 borehole; 25, Ara; 26, Alberoni. The location of the Salt Range is shown in the inset map of figure F3.

it overlies the Lockhart Limestone. The Kuldana Formation generally overlies the Bhadrar beds in the Kala Chitta Range and the upper part of the Panoba Shale or Shekhan Limestone in the Kohat area (see Warwick and Wardlaw, 1992), not the Lockhart Limestone. The Patala Formation does not consist of red beds. We, therefore, refer to these beds as the “red” Patala facies (following Warwick and Wardlaw, 1992) and suggest that they probably represent a new unit that is neither Patala nor Kuldana.

The Hangu Formation is coal bearing at the Cherat Range, Makarwal, Nammal, and Sohai River Gorge sections (sections 4, 5, 6, 7, and 14). In the Cherat Range, it is made up largely of mudstone and a few thick laterites near its base. The unit is dominated by sandstone at both Makarwal and Nammal, and several thin lateritic soils occur at the Nammal sections. The formation at all three of the above localities grades into a marine facies in the upper part, generally represented by shoreface sands and abundant mollusks. This shoreface facies is thickest at Makarwal (fig. F3, section 5, facies 2). The Hangu coal bed at Sohai River Gorge overlies a laterite and underlies shales and siltstones that are micaceous in places. This coal is slightly enigmatic; the other Hangu coals appear to reflect deposition in a topographic trough at initial Paleocene transgressions (they are all centered in the depositional trough of Warwick and Wardlaw, 1992). The coal bed of the Sohai River Gorge perhaps also reflects a topographic low at the time of initial transgression.

The Patala Formation is dominated by marine siltstones and shales throughout the area represented by the sections of figure F3 and does not contain coal.

Some differences exist concerning the thickness and quality of exposure of the section in the gorge at Nammal Dam (Gibson, this volume, chap. E). We have examined the entire area and find the best exposure to be at the location where we measured the section. The area Gibson (this volume, chap. E) alludes to as a better section has Lockhart slumped over the entire lower part of the Patala and no exposure of that part of the section. The remainder is a little less exposed than the section we measured. We also conclude that our section is the same as that measured by Haque (1956) and by HDIP and reported on by Köthe (1988) and Jurgan and others (1988). First, the HDIP section is painted along the same traverse as ours and, as pictured in internal reports, is the same as ours. Unfortunately, only the upper part of the section is reported on by Jurgan and others (1988, see fig. F5). The entire section sampled for Köthe's (1988) report has not yet been illustrated. Second, Haque's (1956) section shows all the subtle units of ours (fig. F5), and so we feel they are from the same place. Haque (1956) exaggerated the thickness by not correcting adequately for the dip. Calculating the map distance and dip shown by Haque (1956) for the sections (Gibson's traverse or ours) clearly demonstrates that Haque's columnar section is at least 500 ft (152 m) too thick for the rocks as mapped. In addition, we feel that Haque's (1956) illustration of complete exposure is more a matter of artistic license (or drafting style) than substantive reality.

Haque (1956) reported *Morozovella velascoensis* and associated foraminifers from the Nammal Formation, though his illustrated forms are all from the Patala Formation. This planktic foraminifer and associated fauna are diagnostic of the latest foraminifer zone of the late Paleocene. Gibson (this volume, chap. E) documents the last occurrence in his material within the Patala Formation. A sample that is equivalent to Haque's highest occurrence (sample NP2–4) was barren of planktic foraminifers and contained a fair but poorly preserved nannofossil flora (Bybell and Self-Trail, this volume, chap. B), and a few dinoflagellate cysts that indicated an early Eocene age (Edwards, this volume, chap. C).

In an effort to resolve the potential conflict in age interpretations, B.R. Wardlaw and W.E. Martin resampled the interval in question (samples NP4–1 and NP4–2; see this volume, chap. B). Sample NP4–1 yielded abundant nannofossils and indicates an Eocene age (NP 11, chap. B). Similarly, Köthe (1988) reported an early Eocene age (NP 11) on the basis of nannofossils and dinoflagellates for the lower part of the Nammal Formation from the HDIP section at Nammal Gorge. Therefore, because recovery of foraminifers from this interval could not be duplicated and the interval clearly yields Eocene floras, we have to discount the reported but unsubstantiated occurrence of foraminifers diagnostic of the late Paleocene from this lowest part of the Nammal Formation reported by Haque (1956) in an exaggerated section and championed by Gibson (this volume, chap. E).

Compilation of the age data available for the Nammal section (this volume, chaps. B–E and Köthe (1988)) is shown in figure F6. Also shown is the agreement of the section at Makarwal with that composited for the Nammal area (Hangu Formation and Lockhart Limestone from the Nammal Pass section, Patala and Nammal Formations from the Nammal Dam section). Clearly, the upper part of the Patala Formation can be seen as a lateral equivalent of the marl facies of the Nammal Formation, probably representing a more offshore facies. This relation resolves the problem (Bybell and Self-Trail, this volume, chap. B) with the Eocene ages for the Patala reported by Köthe (1988) in the Kohat Plateau. In a transitional section from Nammal to Makarwal in the northern Salt Range identified as Khairabad-east, Afzal and Daniels (1991) reported a nearly continuous planktic foraminifer succession (converted to nannofossil zone equivalents for comparison) from NP 9 in the uppermost part of the Lockhart Limestone (transitional to Patala), NP 9–NP 12 for the Patala Formation, and NP 12–NP 14 for the Nammal Formation. More important, the *Morozovella subbotinae subbotinae*/*Morozovella velascoensis acuta* Zone is restricted to samples from the lower 30 ft (9 m) of the Patala Formation and the upper 5 ft (1.5 m) of the Lockhart Limestone. These data suggest that the apparent hiatus at the unconformity dividing the Patala and Nammal Formations at Nammal is not present in more offshore, basinal sections.

Sequence Stratigraphy

The deposition of Paleocene and lower Eocene rocks of the area within and adjacent to the Potwar Plateau was in three transgressive-regressive (T–R) packages, or sequences, on the shelf (fig. F7) that merge into one major T–R package in the depositional trough or "basin" (fig. F7). The dividing sequence boundaries (unconformities) disappear in "basinal" settings westward in the middle of the depositional trough (fig. F1). The major T–R package in the basin corresponds to deposition from NP 6 to NP 13 probably at a time between the major drops in sea level in late NP 5 and NP 13 (see fig. F8). Brief periods of nondeposition may reflect intervening lowstands, but that is uncertain from the data available. The three T–R packages represented on the shelf of the Pakistan-India plate do not correspond as well to the eustatic changes in sea level, suggesting that tectonic and climatic factors were important to their deposition.

The first T–R package consists of the Hangu Formation, Lockhart Limestone, and lower part of the Patala Formation. Where the Hangu was deposited on a shelf, it is represented by facies 1 (oxysol, sand, and mud) and rare coal beds. Where it was deposited in the trough, the Hangu is coal bearing and has a marine shoreface sand, which suggests that the depositional trough was marginally marine and was dominated by sands, oxysols, and swamps in a probable tropical setting. This initial transgressive deposition of marginal-marine environments in the "basin" and more terrestrial environments on the shelf was then overlain by the carbonates of the Lockhart Limestone. The Lockhart Limestone contains foraminiferous muds where it was deposited in the trough and foraminiferous sands where it was deposited on the shelf from start to end, implying relatively rapid transgression over an inherited topography that differentiated the facies distribution. Maximum transgression is represented by the onlap of marine shales of the Patala Formation onto the shelf (NP 9, late Paleocene). On the shelf, the Patala Formation is coal-bearing mud and shale and a barrier sand. Warwick and Shakoor (this volume, chap. I) detail

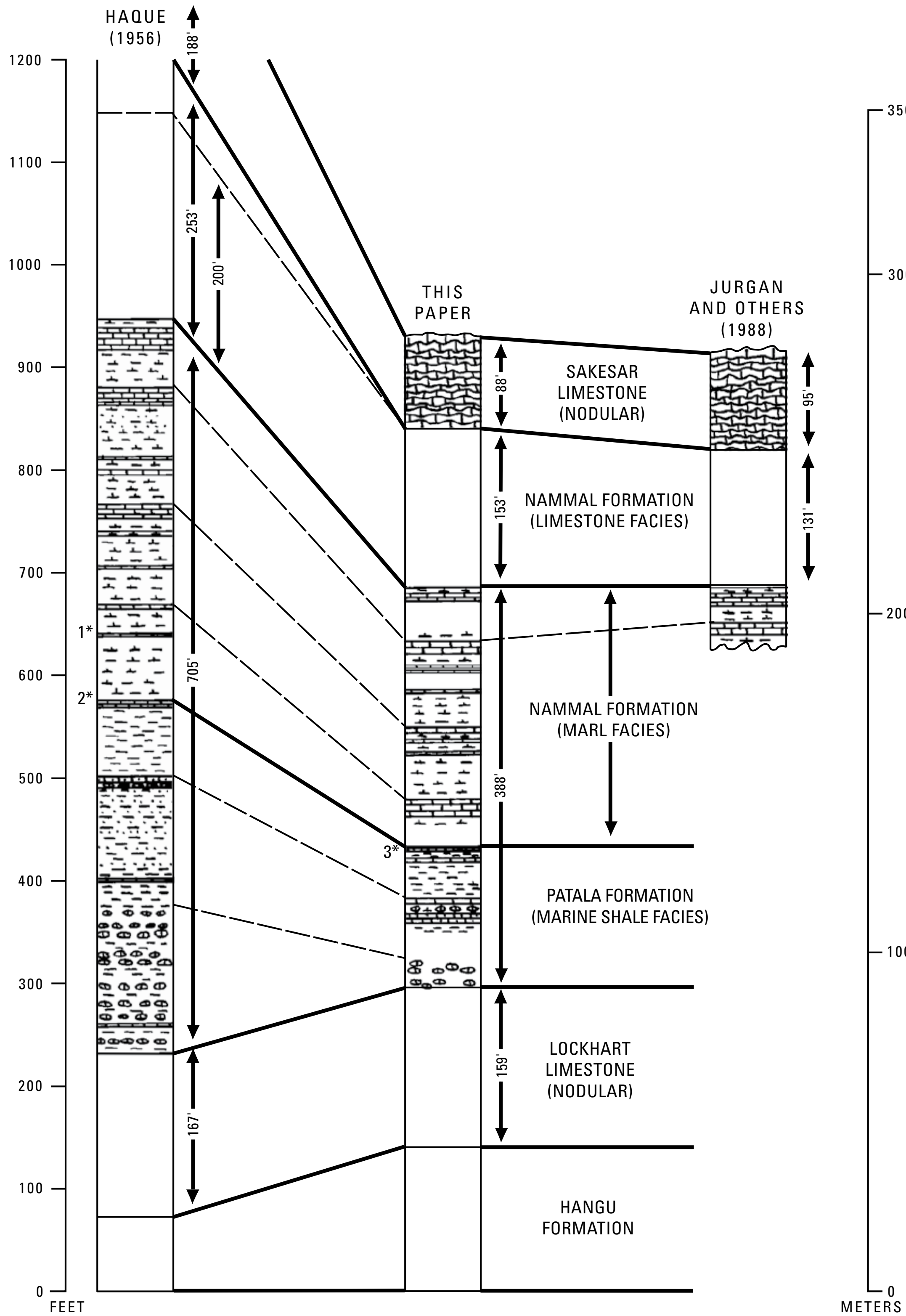

Figure F5. Comparison of measured sections of Nammal Dam/Nammal Gorge from Haque (1956), Jurgan and others (1988), and this paper. Lithic symbols the same as shown on plate F1. Solid lines represent formation or facies boundaries; dashed lines represent correlation lines, 1* is location of highest reported occurrence of *Morozovella velascoensis* reported by Haque (1956), 2* is location from which figured specimens of *Morozovella velascoensis* were taken by Haque (1956), and 3* is location of highest occurrence of *Morozovella velascoensis* reported in Gibson's material (this volume, chap. E).

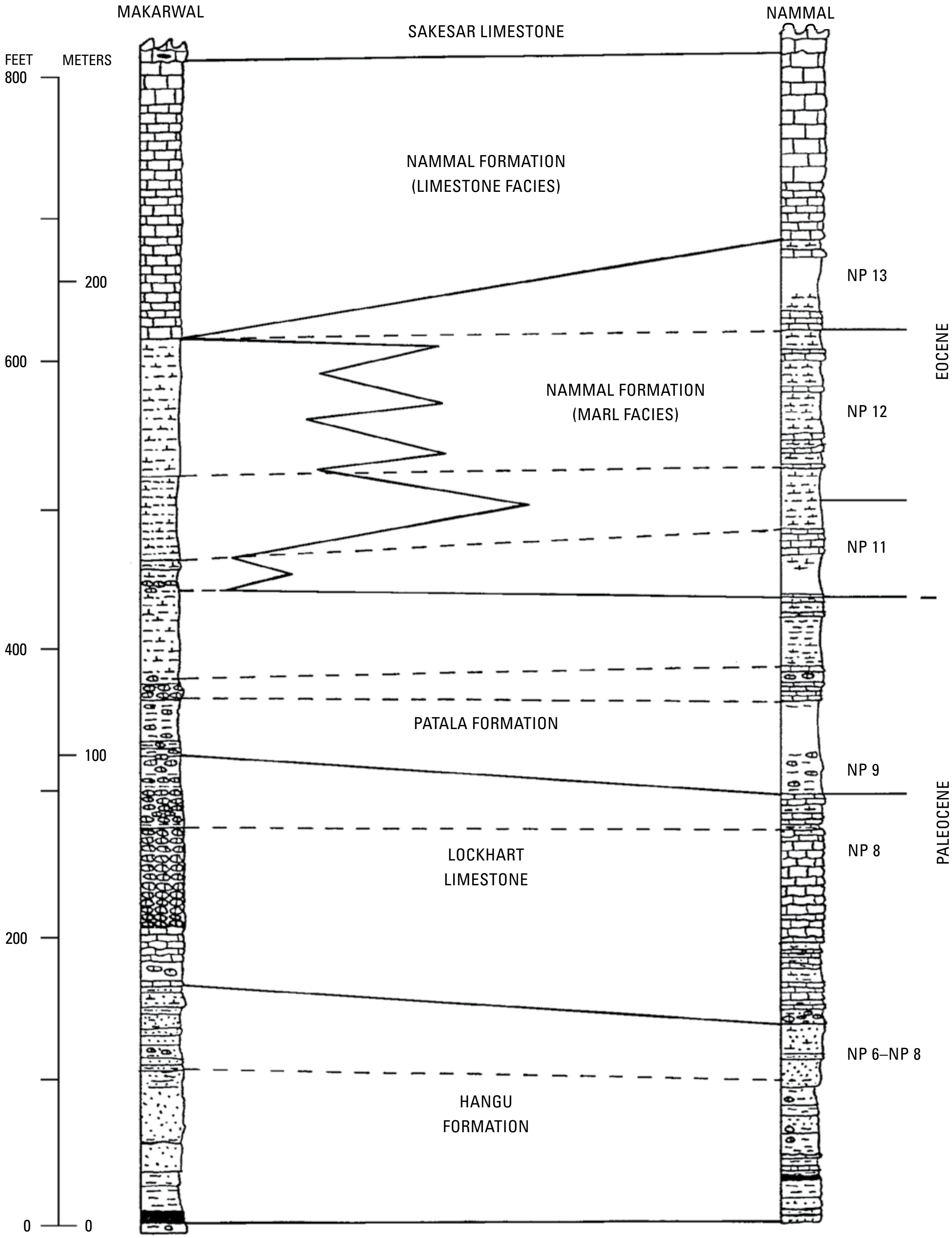

Figure F6. Comparison of formations and lithologies of sections and inferred age (in nannofossil zones) at Makarwal and Nammal Dam, showing facies relation of Patala and Nammal Formations. Solid lines represent formation or facies boundaries; dashed lines represent correlation lines. Lithic symbols are the same as those shown on plate F1. Nannofossil zones are based on data from Köthe (1988) and chapters B–E of this volume.

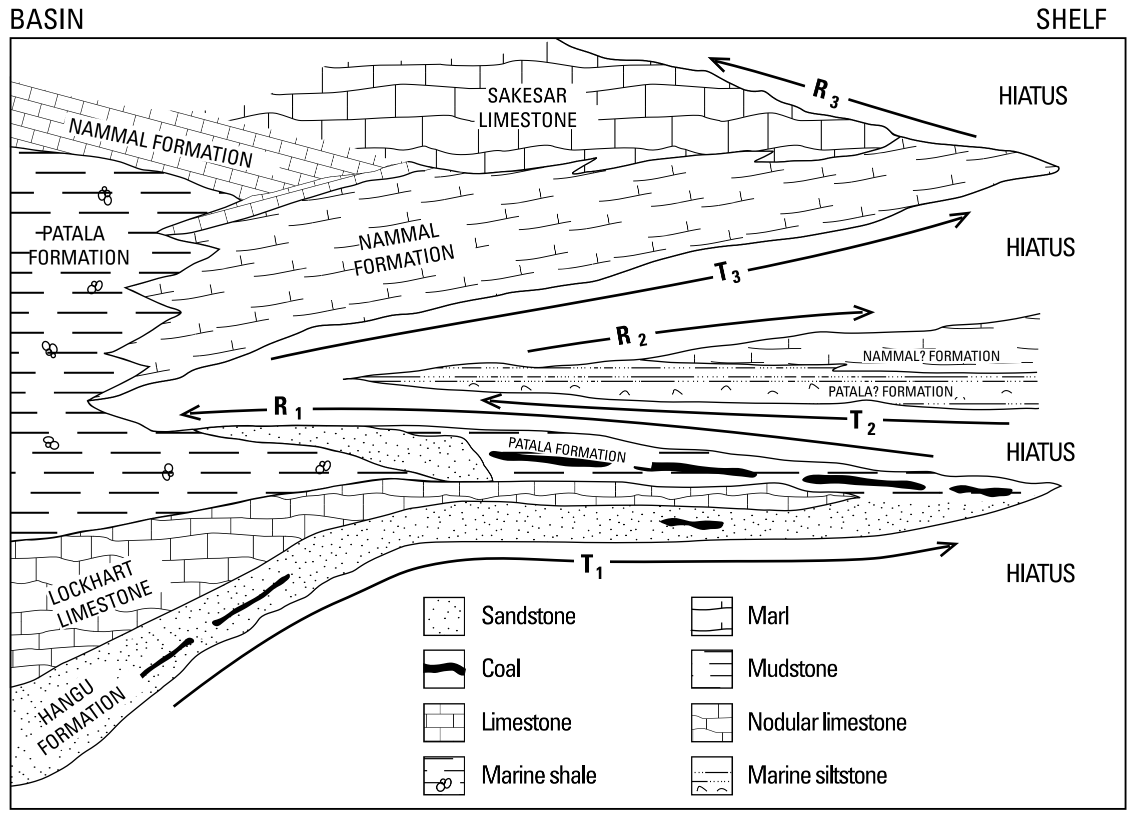

Figure F7. Model of Paleocene and lower Eocene depositional packages within and near the Potwar Plateau. T, transgression; R, regression.

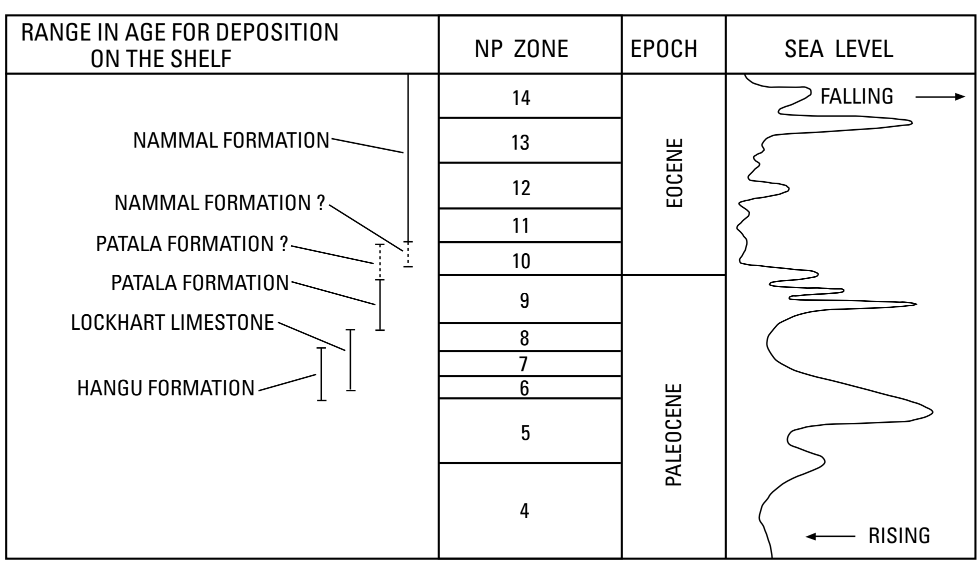

Figure F8. Eustatic sea-level changes (from Haq and others, 1987) compared with probable range in age of deposition of Paleocene and Eocene units on the shelf and nannofossil zones. Nannofossil zones based on data from Köthe (1988) and Edwards (this volume, chap. C).

the distribution of these units and the coal beds. The coal beds resulted from marginal-marine (brackish) swamps (see Frederiksen and others, this volume, chap. D) shoreward of the barrier sands in large back bays that occupied the shelf. The coal beds are in close association with kaolinite and illite clays (Whitney and others, 1990) and suggest deposition in a subtropical setting. Having carbon tied up in coal and carbonates in close proximity strongly suggests seasonality. The back-bay and barrier environments prograded out over marine units in the regressive phase at the end of this package. A significant unconformity cuts through the Patala on the shelf.

The diachroneity of the transgressive units of T–R packages 1 and 3 suggests transgression from a general west to east or northwest to southeast direction (fig. F7). However, the diachroneity of the transgressive unit of T–R package 2 is very different (figs. F2 and F7), suggesting transgression from the northeast. The time of transgression of T–R package 2 appears to be earliest Eocene (NP 10). Warwick and Wardlaw (1992) postulated northern closure of the depositional trough in the late Paleocene, and deposition of T–R package 2 could be related to this closure and cutoff of access from the trough and onlap from the north-northeast from the "Tethyan" sea.

T–R package 2 consists of the upper part of the Patala Formation (facies 7, skeletal silt) and lower part of the Nammal Formation (part of facies 9, marl) and was deposited only on the shelf. Deposition was in a very shallow marine environment, and oysters are common to both the Patala and Nammal in this package. Packstones containing larger foraminifers to grainstones replete with nummulitid foraminifers are not uncommon in the Nammal Formation, perhaps supporting the "Tethyan" influence of the T–R package. Warwick and Shakoor (this volume, chap. I) identify a unit, the Sidhandi shale bed within the Nammal Formation in the eastern Salt Range. This unit was not exposed in any of our surface sections. It may be represented in the boreholes. Warwick and Shakoor (chap. I) observed it in small mines of the aluminum-rich clays (kaolinite) of the unit. It is possible that this unit represents a soil profile at the top of T–R package 2. The Sidhandi shale bed may be equivalent to the sandy dolostone or calcareous sand (Wardlaw and others, 1990) found in the sections at Sohai River Gorge, Nila Wahan, and Dhaman (pl. F1) in the central Salt Range. The sand and sandy dolostone are part of a weathering profile. The timing of this T–R package seems to coincide with the eustatic sea-level rise in the early Eocene (NP 10, fig. F8). Closure of the northern end of the trough and cutoff of influence of the trough on the deposition of this package may represent a short interval where the eustatic signal was the major driving force in deposition.

T–R package 3 consists of the Nammal Formation and Sakesar Limestone on the shelf. The T–R package appears to represent a return of influence from the trough and transgression from the west or northwest and a masked eustatic influence or signal. Maximum transgression is represented by the onlap of lime mudstones of the Nammal Formation (NP 13(?)). Regression is represented by the same facies (lime mudstone) prograding out into the trough (at Makarwal), followed by Sakesar Limestone deposition. Deposition was generally shallow marine except for the lime mudstone containing common planktic foraminifers that suggests offshore deposition. The lack of coals or carbonaceous shale in T–R packages 2 and 3 suggests the combined influence of a more marine setting (lacking swamps) and further migration of the Pakistan-India plate into more northern latitudes less conducive to swamp (and coal) formation.

Conclusions

Paleocene and lower Eocene sediments found in and adjacent to the Potwar Plateau represent deposition in a "basinal" setting within the center of a trough developed between the Afghanistan and Pakistan-India plates and in a "shelfal" setting along the margin of the Pakistan-India plate. Shelf deposition is represented by three transgressive-regressive packages: the first in the upper Paleocene (NP 6–NP 9), the second in the lowest Eocene (NP 10–NP 11), and the third in the lower Eocene (NP 11–NP 14).

Coal within the Salt Range is present in the Hangu Formation, where it is intimately related with oxysols and shoreface deposits. Coal is common in the regressive sedimentation of the Patala Formation, representing swamp and pervasive back-bay deposition. Outside the Salt Range, coal deposition appears limited to the lower part of the initial transgressive package of the Hangu Formation in marginal-marine environments. The coals of the Hangu are intimately related with oxysols and are of a generally better quality than those of the Patala, probably resulting from deposition in tropical, everwet conditions. The coals of the Patala are intimately related with marine sediments or poorly developed soils commonly containing various clay mineralogies (kaolinite and illite) and probably resulting from deposition in seasonal, subtropical conditions. This change in quality of the coals and depositional setting appears to be related to the movement of the Pakistan-India plate north through climatic zones.

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Environmental Geology of the Islamabad-Rawalpindi Area, Northern Pakistan

By Iqbal M. Sheikh, Geological Survey of Pakistan
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Chapter G of

Regional Studies of the Potwar Plateau Area, Northern Pakistan

Edited by Peter D. Warwick and Bruce R. Wardlaw

Prepared in cooperation with the
Geological Survey of Pakistan,
under the auspices of the
U.S. Agency for International Development,
U.S. Department of State, and the
Government of Pakistan

Bulletin 2078–G

U.S. Department of the Interior
U.S. Geological Survey

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Environmental Geology of the Islamabad-Rawalpindi Area, Northern Pakistan

By Iqbal M. Sheikh, Mustafa K. Pasha, Van S. Williams, S. Qamer Raza, and Kanwar S.A. Khan

Abstract

Islamabad, the capital of Pakistan, is a planned city constructed since about 1960 at the foot of the Margala Hills just north of the old city of Rawalpindi. Rapid growth of both Islamabad and Rawalpindi to a combined population near 1.3 million has made ever-increasing demands on natural resources and caused adverse effects on the environment. To maintain the quality of the capital, municipal authorities need information on the physical environment to guide future development. Major environmental concerns are (1) availability of building materials, (2) environmental degradation from extraction and processing of building materials, (3) availability of surface and ground water, (4) pollution of water by waste disposal, (5) geologic hazards, and (6) engineering characteristics of soil and rock. This report summarizes information on the environmental geology of the Islamabad area that has been collected by a cooperative project of the Geological Survey of Pakistan and the U.S. Geological Survey, supported by the U.S. Agency for International Development.

Many of the interpretations in this report are based on the geologic map of the Islamabad-Rawalpindi area at 1:50,000 scale that was compiled by the first three authors of this report and released separately (Williams and others, 1999, U.S. Geological Survey Open-File Report 99–0047). A 1:100,000-scale map plate included with this report shows environmental map units that are based on the geology, landforms, and slopes; resources of construction materials; engineering conditions; and geologic hazards. This approach is one example of how geologic information can be organized to aid urban planning in the south Asia region.

Introduction

The metropolitan area of Islamabad-Rawalpindi lies between longs 72°45′ and 73°30′ E. and lats 33°30′ and 33°50′ N. in the Islamabad District, the Rawalpindi District of the Punjab, and the Abbottabad District of North-West Frontier Province, Pakistan (figs. G1 and G2, pl. G1). Islamabad is the national capital and the hub for all governmental activities; Rawalpindi is an older and much larger city and is a center of industrial, commercial, and military activity.

Rawalpindi lies along the ancient trade route from Persia and Europe across the Khyber Pass to India (fig. G1). The area has been a cultural meeting place and invasion route for millennia and was visited by Alexander the Great, Genghis Khan, the Moghul conquerors, and other prominent historical figures. Rawalpindi itself was settled around 1765 and grew to importance during the late 1800's, when it became an important staging ground for the British Afghan campaigns. Today it remains the site of a major military cantonment and headquarters of the Pakistan Armed Forces.

Islamabad is a planned city in a beautiful setting at the foot of the mountains immediately north of Rawalpindi, constructed to serve as capital of the newly independent country of Pakistan. Construction began in the early 1960's, following extensive surveys and planning. Since then, rapid growth of both Islamabad and Rawalpindi to a combined population estimated at 1.3 million has made ever-increasing demands on natural resources and caused adverse effects on the environment. As of 1981, the population of Islamabad was estimated as 201,000 and that of Rawalpindi as 806,000 (Survey of Pakistan, 1982). To maintain the quality of the capital, municipal authorities need information on the physical environment to guide future development.

Potential environmental problems are (1) providing additional resources of ground water, (2) extensive pollution of surface water and of ground water by improperly disposed solid waste, (3) continued availability of geologic construction materials, (4) effects of mining of limestone, sand, gravel, and clay, (5) potential subsidence of building foundations caused by instability of loess, (6) control of gully erosion, (7) danger of debris flows from the mountain canyons and floods along the streams, and (8) earthquake hazards. This report is a summary of earth science information in the Islamabad area that can be applied to these problems.

This report is based on a geologic map of the area at a scale of 1:50,000 (Williams and others, 1999) and an environmental geologic map at a scale of 1:100,000 (pl. G1) that delineates (1) environmental units that are based on geology, landforms, and slopes, (2) resources of construction materials, and (3) engineering conditions and geologic hazards. These

Figure G1. Location map showing the Islamabad-Rawalpindi study area (box) and selected regional features.

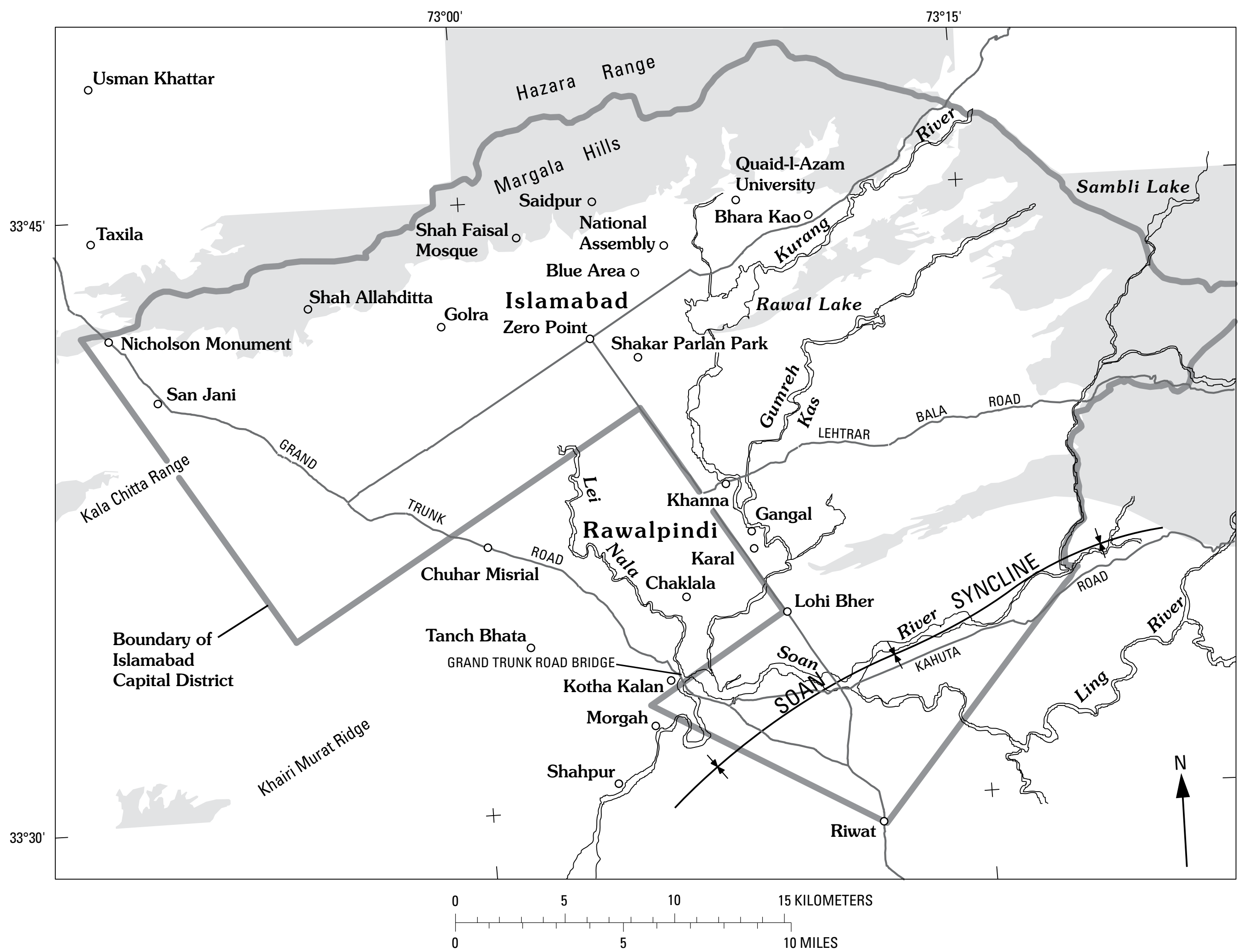


Figure G2. Location map of Islamabad-Rawalpindi study area showing cultural and geographic places mentioned in the report. Mountainous areas are shaded.

data are compiled on the 1:50,000-scale topographic map of "Islamabad and Surroundings" (Survey of Pakistan, 1985), which delimits the study area. Figure G2 locates cultural and geographic places within the study area that are mentioned in the text.

Tables G1, G2, and G3, which define and describe the units shown on the environmental geologic map (pl. G1), summarize the characteristics of the geologic materials in the Islamabad-Rawalpindi study area. Table G1 describes lithology and landform; table G2 describes engineering properties, hazards, and hydrology; and table G3 describes resources and land-use considerations. This information has been derived from geologic and topographic maps, aerial photographs, satellite images, laboratory testing of geologic samples, and review of previous studies. All of this information has been collected and synthesized by a cooperative project of the Geological Survey of Pakistan (GSP) and the U.S. Geological Survey (USGS), supported by the U.S. Agency for International Development (USAID). Figure G3 shows the sources of the basic geologic mapping.

Acknowledgments

This work was supported by the U.S. Agency for International Development. The various agencies and individuals who generously allowed us access to unpublished data include the Capital Development Authority, National Engineering Services of Pakistan, the National Logistic Cell, the Pakistan Army, Syed Najmul Hasan of the National Highways Board, and the Pakistan Department of Meteorology. Akram Bhatti of the Geological Survey of Pakistan and many of his colleagues who have been working in the Islamabad area for many years contributed greatly to this report by sharing their observations and work in progress.

Climate

Records for the Islamabad station of the Pakistan Department of Meteorology (written commun., 1988) (fig. G4) indicate a monsoonal climate of rainy hot summers and cool dry winters; precipitation is characteristic of the semiarid zone of Pakistan. The monsoon rains usually start in June, peak in August, and end by September. A much smaller winter monsoon peaks in March. The four monsoon summer months always have some precipitation, but any of the other months can be completely dry. Annual rainfall of only 249.1 millimeters (mm) was recorded in 1982. The high of 1,732 mm was recorded in 1983. The average for 1931–87 was 1,055 mm. The maximum recorded temperature was 45.9 degrees Celsius (°C) in June 1972, and the minimum was –3.9°C in one January before 1961. Freezing temperatures are rare and have been recorded only in November, December, and January. There is no record of snow (Pakistan Department of Meteorology, written commun., 1988).

Hydrology

The Soan and Kurang Rivers are the main streams draining the area. Their primary tributaries are the Ling River, draining northwestward into the Soan; Gumreh Kas, draining westward into the Kurang from the area between the Kurang and Soan; and Lei Nala, draining southward into the Soan from the mountain front and urban areas. The Kurang and Soan Rivers are dammed at Rawal and Sambli Lakes, respectively, to supply water for the urban area. Extensive forest reserves in the headwaters of the Kurang and Soan Rivers benefit the quality and quantity of supply. A supplemental network of municipal and private wells as deep as 200 meters (m) produces ground water primarily from Quaternary alluvial gravels. The altitude of the water table decreases from about 600 m at the foot of the Margala Hills to less than 450 m near the Soan River, so that the saturated zone generally lies 2–20 m below the natural ground surface (Ashraf and Hanif, 1980). Lei Nala carries most of the liquid waste from Rawalpindi and contributes greatly to the pollution of the Soan River below their confluence. Solid-waste disposal practices threaten the quality of ground-water reserves.

Landforms

General Terrain

The terrain in the metropolitan area of Islamabad-Rawalpindi consists of plains and mountains whose total relief exceeds 1,175 m. Three general physiographic zones trend generally east-northeast. The northern part of the metropolitan area lies in the mountainous terrain of the Margala Hills, a part of the lower and outer Himalayas, which also includes the Hazara and Kala Chitta Ranges (fig. G2). The Margala Hills, which reach 1,600-m altitude near Islamabad, consist of many ridges of Jurassic through Eocene limestones and shales that are complexly thrusted, folded, and generally overturned.

South of the Margala Hills is a southward-sloping piedmont bench underlain primarily by folded sandstones and shales of the Rawalpindi Group (Miocene). Although the relief of the piedmont area is generally low and dominated by extensive plains of windblown silt, the piedmont area also includes many ridges and valleys that have been buried by alluvial deposits from the hills. Buried ridges of sandstone are generally covered by interbedded sandy silt and limestone gravel that locally exceed 200 m in thickness; these deposits, in turn, have been dissected and then buried under a layer of eolian loess and reworked silt that locally exceeds a thickness of 40 m. The gravel and loess are especially

Table G1. Geology and geomorphology of environmental map units shown on plate G1.

Environmental unit (pl. G1) Symbol	Unit name	Geologic unit[1]	Lithology	Landform
		Loose sediment		
S	Stream-channel alluvium.	Quaternary stream-channel alluvium.	Unconsolidated, channel-crossbedded, moderately sorted channel and bar deposits of sand and gravel.	Streambeds, low islands, and bars within braided or meandering stream channels.
F	Flood-plain alluvium.	Quaternary flood-plain alluvium.	Unconsolidated, channel-crossbedded, moderately sorted channel and bar deposits of sand and gravel, overlain by relatively thin veneer of silt, clay, and organic material.	Stream flood plains. Low stream terraces having very gentle slopes.
T	Stream-terrace alluvium.	Quaternary stream and fan terraces.	Unconsolidated, channel-crossbedded, moderately sorted channel and bar deposits of sand and gravel, overlain by relatively thin veneer of silt, clay, and organic material.	Stream and fan terraces. Stream terraces are former flood plains now above the general level of flooding because of lowering of the streambed, uplift, or decrease in stream size. Gently sloping with steep slopes along eroded margins.
A	Fan alluvium	Quaternary fan alluvium.	Primarily unconsolidated sand and gravel of a mixture of the lithologies found in the tributary watershed. The surface may be covered with thin soil of silt and clay. Poorly sorted and bedded. Debris-flow deposits are common.	Alluvial fans. Sediments deposited where streams emerge from confining valleys and shift radially. Slopes less than 15% except in gullies or eroded margins. Usually the major stream flowing across the fan is braided.
P	Undissected windblown silt.	Quaternary Potwar Clay.	Thick, massive loess. Well-sorted grains of eolian silt held together in an openwork pattern by films of clay and carbonate. Low bulk density. Commonly reworked by water, so crossbedded channel fills of sand and gravel are present.	Loess plains. The depositional surface forms gently rolling low hills sloping less than 15%, mantling a more rugged, buried topography. Steep at eroded margins and gullies. Patches in valley bottoms within mountains.
B	Dissected windblown silt	Quaternary Potwar Clay.	Loess. Well-sorted grains of eolian silt held together in an openwork pattern by films of clay and carbonate. Low bulk density. Commonly reworked by sheet wash and small streams, so crossbedded channel fills of sand and gravel are present.	Loess badlands and gullies. A dense network of steep-sided gullies eroding silt deposits so that the depositional surface is destroyed and most land slopes steeply.
		Weak rock		
H	Undissected, unconsolidated or very weakly consolidated mudstone and sandstone.	Chinji, Nagri, and Dhok Pathan Formations of the Siwalik Group.	Unconsolidated or very weakly consolidated mudstone and sandstone. Moderately bedded and sorted.	Gentle hill slopes with angular clasts. Gently sloping table lands with wide benches and low steps between levels. Covered with a residual soil formed from weathering of the underlying rock.
X	Crystalline gravel conglomerate.	Soan Formation of the Siwalik Group.	Rounded cobbles as large as 30 cm in diameter of metamorphic and igneous rocks from a distant source in a sandy matrix. Weakly cemented to noncemented.	Gentle hill slopes with rounded clasts. Moderately sloping, rolling hills with steep slopes at eroded margins. May cap ridges or hogbacks.
G	Eroded, unconsolidated or very weakly consolidated sandstone, mudstone, and conglomerate.	Siwalik Group and Lei Conglomerate.	Unconsolidated or very weakly consolidated sedimentary rock. Moderately bedded and sorted.	Bedrock badlands and gullies. Steep to moderate hill slopes covered by sparse soil and vegetation.

Table G1. Geology and geomorphology of environmental map units shown on plate G1.—Continued

Environmental unit (pl. G1) Symbol	Unit name	Geologic unit[1]	Lithology	Landform
		Moderately strong rock		
C	Limestone gravel conglomerate.	Lei Conglomerate	Subangular cobbles of Eocene limestone as large as 30 cm. Matrix of reworked eolian silt. Conglomerate is thickly interbedded with sandy silt beds.	Moderately sloping, rolling hills and plains. Eroded into steeper slopes near the Soan River.
M	Interbedded sandstone and shale.	Murree and Kamlial Formations of the Rawalpindi Group.	Consolidated sandstone beds that are relatively resistant to erosion interbedded with less resistant, poorly consolidated rocks such as claystone.	Rocky ridges and pinnacles. Moderate to steep hill slopes with stairstep alternation of cliffs and benches.
L	Limestone	Surghar, Makarwal, and Cherat Groups.	Thickly bedded, gray, fossiliferous marine limestone and dolomite interbedded with minor shale and sandstone. Intensely folded, faulted, and sheared in the Margala Hills.	Steep rocky hill slopes. Cliffs and benches in mountains.

[1]See Williams and others, 1999.

Table G2. Engineering properties, hazards, and hydrology of environmental map units shown on plate G1.

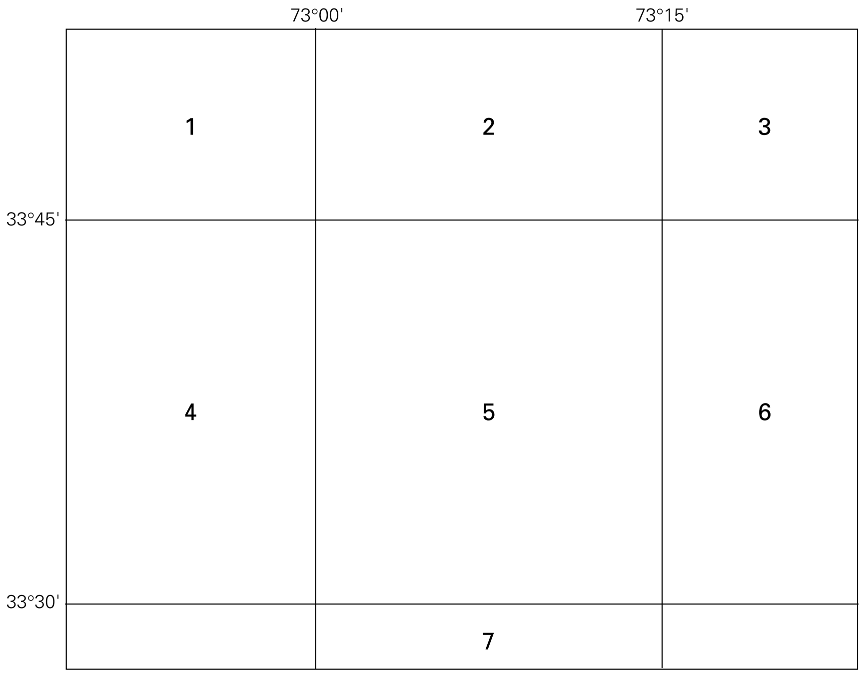
Environmental unit (pl. G1) Symbol	Unit name	Engineering properties	Limitations and hazards	Surface and ground water
		Loose sediment		
S	Stream-channel alluvium.	Low to moderate bearing capacity. Subject to subsidence, liquefaction, failure of cutbanks, stream erosion. High water table. Easy to moderate excavation.	Flooding, erosion of banks, depositional burial, subsidence under load, liquefaction during earthquakes.	Surface water, good ground water at shallow depth, high permeability, poor drainage. Any disturbance affects quality of surface and ground water.
F	Flood-plain alluvium.	Low to moderate bearing capacity. Subject to subsidence, liquefaction, failure of cutbanks, stream erosion. High water table. Easy to moderate excavation.	Flooding, erosion of banks, depositional burial, subsidence under load, liquefaction during earthquakes.	Surface water, good ground water at shallow depth, high permeability, poor drainage. High permeability and shallow ground water make flood-plain alluvium unfavorable for waste disposal.
T	Stream-terrace alluvium.	Moderate bearing capacity. Subject to slumping along edge. Moderate to easy excavation.	Lower terrace flooding. Undercutting by stream erosion. Liquefaction during earthquakes.	Surface water and shallow ground water available. High permeability and shallow ground water make stream-terrace alluvium unfavorable for waste disposal.
A	Fan alluvium	Moderate bearing capacity. Moderate to easy excavation.	Debris flows, sheet floods, and gully erosion. Liquefaction during earthquakes.	Surface water and shallow ground water available. High permeability and shallow ground water make fan alluvium unfavorable for waste disposal.
P	Undissected wind-blown silt.	Moderate bearing capacity when dry, but may lose most strength when wet under load or subject to earthquake shear. Easy excavation. Very erodible.	Very erodible by streams or wind. May collapse under structures when wet. May collapse into flowing landslides under earthquake shock. Excavated caves may collapse under earthquake shock.	Rapid runoff and high sediment yield degrade surface streams. Generally yields little ground water but may contain gravel aquifers.

Table G2. Engineering properties, hazards, and hydrology of environmental map units shown on plate G1.—Continued

Environmental unit (pl. G1) Symbol	Unit name	Engineering properties	Limitations and hazards	Surface and ground water
		Loose sediment—Continued		
B	Dissected windblown silt.	Moderate bearing capacity when dry, but may lose most strength when wet under load or subject to earthquake shear. Easy excavation. Unstable slopes. Very erodible.	Very erodible by streams or wind. May collapse under structures when wet. May collapse into flowing landslides under earthquake shock. Gullies subject to flash floods. Excavated caves may collapse under earthquake shock.	Rapid runoff and high sediment yield degrade surface streams. Generally yields little ground water but may contain gravel aquifers.
		Weak rock		
H	Undissected, unconsolidated or very weakly consolidated mudstone and sandstone.	Low bearing capacity. Unstable slopes subject to creep and earthflow. Very erodible by water or wind. May include expansive clays. Easy excavation.	Erosion, slope failure, subsidence under load, expansive soils.	Sandy units may be good aquifers. Artesian pressure is possible.
X	Crystalline gravel conglomerate.	Moderately high bearing capacity. Natural slopes are well drained and relatively stable but will not support steep cut slopes unless cemented. Excavation may be difficult.	Poor agricultural soil, poor moisture-holding capacity.	High infiltration rate and transmissivity make the unit a good ground-water recharge medium and aquifer. Surface streams are likely to be small and widely spaced. Surface soil is dry and difficult to irrigate. Unsuitable for waste disposal.
G	Eroded, unconsolidated or very weakly consolidated sandstone, mudstone, and conglomerate.	Low bearing capacity. Unstable slopes subject to creep and earthflow. Very erodible by water or wind. May include expansive clays. Easy excavation.	Erosion, slope failure, mudflows, flash floods, subsidence under load, expansive soils.	Sandy units may be good aquifers. Artesian pressure is possible.
		Moderately strong rock		
C	Limestone gravel conglomerate.	Moderately high bearing capacity. Natural slopes are well drained and relatively stable but will not support steep cut slopes unless cemented. Excavation may be difficult.	Poor agricultural soil	High infiltration rate and transmissivity make the unit a good ground-water recharge medium and aquifer. Surface streams are likely to be small and widely spaced. Unsuitable for waste disposal.
M	Interbedded sandstone and shale.	Shales are weak, but thick sandstones have moderate bearing capacity. Slopes are unstable because erosion of the shale undermines the stronger sandstones. Where dip is toward the slope, sandstone may slide on the shale. Excavation difficult.	Block-slip landslides on dip slopes. Rockfall and rotational block slides on slopes opposite to dips. Debris flows.	Surface water may be difficult to obtain in rugged areas. Sandstones may be favorable as aquifers but require mechanical drilling; shales are unfavorable. Artesian conditions may exist.
L	Limestone	Good bearing capacity but may have concealed cavities subject to collapse; moderately stable slopes where dip is into slope. Subject to block slip on dip slopes. High fracture permeability makes the unit unfavorable for waste disposal. Difficult excavation.	Dip slope landslides, ground collapse	Good ground-water recharge medium and aquifer. Flow rates are high and filtration low, so pollution spreads rapidly. Few surface streams cross the limestone, but large springs may occur near the base.

Table G3. Resources and land-use considerations of environmental map units shown on plate G1.

Environmental unit (pl. G1) Symbol	Environmental unit (pl. G1) Unit name	Resources	Land-use considerations
		Loose sediment	
S	Stream-channel alluvium	Gravel, sand	No major structures affected by flooding. Regulate extraction of sand and gravel to minimize disturbance of stream equilibrium and degradation of water quality. No disposal of toxic waste.
F	Flood-plain alluvium	Gravel, sand, some brick clay, farming soil.	Minimize residential use, preserve for cropland. Favorable for irrigation but may be subject to high ground water. Protect structures from shifting channels. No major structures affected by flooding.
T	Stream-terrace alluvium	Gravel, sand, silty clay, farming soil	Lower terraces subject to same limitations as flood plains. Higher terraces suitable for many uses but unfavorable for waste disposal. Risk from stream erosion must be controlled or avoided.
A	Fan alluvium	Gravel, sand, silty clay, farming soil	Fan surfaces suitable for many uses, but unfavorable for waste disposal. Potential debris flows affecting the apical area must be controlled or avoided.
P	Undissected windblown silt	Good source of brick clay. Good farming soil. Can be carved into caves for lodging or livestock.	Erosion of gullies must be controlled, building foundations protected from excessive wetting. Vegetation should be protected, farmers should use measures to prevent soil erosion.
B	Dissected windblown silt	Possible source of brick clay. Can be carved into caves for lodging or livestock. Can be graded and compacted into suitable building sites.	Attempt reclamation by revegetation and protection from erosion. Farming and grazing should be restricted. At critical locations, erosion control structures and dams may be necessary.
		Weak rock	
H	Undissected, unconsolidated or very weakly consolidated mudstone and sandstone.	Sand or clay	Suitable for most uses with proper design of structures.
X	Crystalline gravel conglomerate.	Good source of gravel for aggregate	Near urban areas, planning should allow for sequential land use. Value of aggregate resource should be evaluated before residential development is permitted. Residential use can be postponed until mining and reclamation are completed.
G	Eroded, unconsolidated or very weakly consolidated sandstone, mudstone, and conglomerate.	Sand or clay	Unsuitable for most uses because of rapid erosion and poor soil. Has potential for reclamation because the topography can be modified with earth-moving equipment.
		Moderately strong rock	
C	Limestone gravel conglomerate.	Good source of gravel for aggregate	Near urban areas, planning should allow for sequential land use. Value of the aggregate resource should be considered before residential development is permitted. Residential use can be postponed until mining and reclamation are completed.
M	Interbedded sandstone and shale.	Sandstone building stone	Care must be taken to avoid destabilizing slopes during construction. Design foundations to avoid differential settlement problems.
L	Limestone	Important source of crushed aggregate, feedstock for cement manufacture. Some limestones form oil reservoirs at depth.	Makes excellent watershed, especially when vegetation can be maintained. Mining on dip slopes may be dangerous.



SOURCES OF GEOLOGIC MAPPING

1 Bhatti and others (in press)
2 Pasha and Bhatti (in press)
3 Akhtar and others (in press)
4 Akhtar and Bhatti (in press)
5 Naeem and Bhatti (1985)
6 Kauser (in press)
7 Akhtar and Bhajawa (in press)

Figure G3. Sources of geologic mapping data for this report.

important to the environmental geology because they form most of the building foundations and because gravel is the primary ground-water aquifer. West of Rawalpindi, plains of thick, easily eroded loess are extensively dissected into shallow badland valleys. East of Rawalpindi, the folded ridges of Rawalpindi Group rocks rise above the alluvial cover to form prominent hills. Urban development is concentrated in the piedmont bench area, which is little dissected in its northern part, where Islamabad is located, but is more deeply dissected toward the south near the Soan River, where Rawalpindi is located.

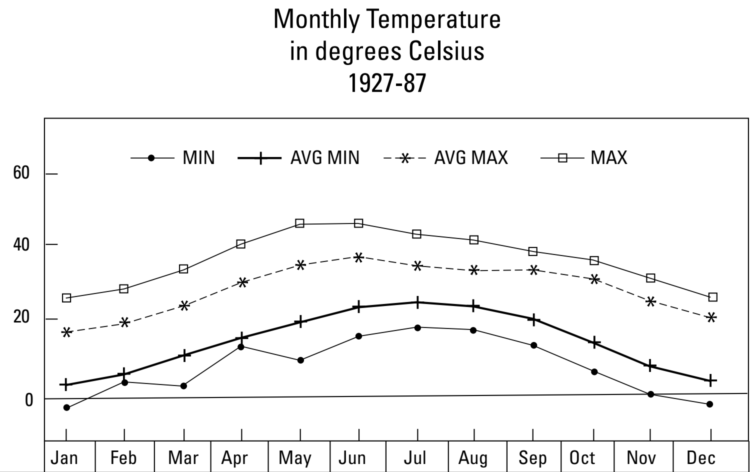
In the southernmost part of the area, the Soan River valley extends generally along the axis of the Soan syncline at an altitude of about 425 m. The Soan is incised more than 40 m below the level of extensive silt-covered plains north and south of the river. Southeast of Rawalpindi, upstream from the Grand Trunk Road bridge, the Soan channel and flood plain extend 1.5 kilometers (km) across the valley floor. Elsewhere, the valley bottom is much narrower. Beds of fluvial sandstone, mudstone, and conglomerate of the Siwalik Group of Neogene to Pleistocene(?) age underlie the southern area and crop out along the many steep-sided stream valleys that dissect the land. The beds dip steeply on the north limb of the syncline north of the Soan River, and more gently on the south limb. The piedmont bench and Soan valley make up the northern edge of the Potwar Plateau (see Warwick, this volume, chap. A, fig. A2), which extends southwestward for 150 km.

Descriptive Outline of Landforms

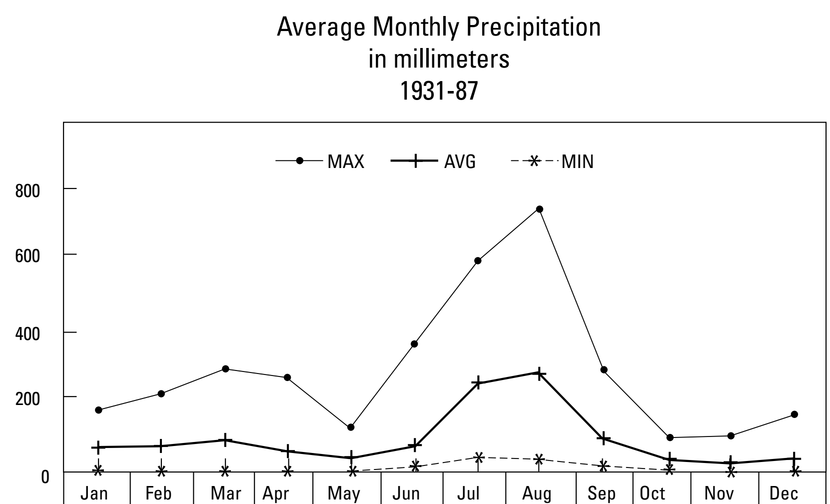
Landforms mapped (pl. G1) in the Islamabad-Rawalpindi area can be subdivided into those constructed by deposition of sediment and those carved by erosion. Each landform has a characteristic range of slopes, soil types, and active geologic processes that may limit its suitability for various uses.

Depositional Landforms

Streambeds, low islands, and bars.—Low land in valley bottoms that is generally covered and reshaped by flowing water each year. These features are formed by braided



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MIN	-3.9	3.4	2.2	13.0	8.9	15.0	18.0	17.2	13.3	6.4	-0.2	-2.8
AVG MIN	2.5	5.5	10.2	15.1	19.0	23.7	24.6	23.6	20.5	14.0	7.2	3.1
AVG MAX	17.0	19.1	23.8	29.8	35.1	37.1	34.9	33.3	33.3	30.9	25.1	20.0
MAX	26.1	28.3	33.3	40.6	45.6	45.9	43.3	41.4	38.1	36.1	31.0	26.0



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MAX	167	209	282	265	116	344	580	730	282	95	96	152
AVG	61	70	81	52	34	59	239	277	92	24	16	29
MIN	0	0	0	0	0	3.6	30.7	28.1	9.4	0	0	0

Figure G4. Temperature and precipitation data for Islamabad. Data from Pakistan Department of Meteorology (written commun., 1988).

or meandering streams. The surface is generally sand and gravel, and there is little or no soil development. The surface is unstable and lacks vegetation except for quick-growing grass. Slopes are less than 4 percent.

Stream flood plains.—Low benches slightly above the stream channels in valley bottoms. They are above water level most of the year but are commonly flooded whenever the streams overtop their banks. The surface is generally fine sand, silt, and clay with a relatively high organic content and fertile soil. Slopes are less than 4 percent.

Stream and fan terraces.—Lower terraces form wide benches along the sides of modern stream valleys similar to flood plains, but the terraces are higher above the stream and are seldom flooded. Higher terraces form gravel-capped ridges and flat-topped hills that never flood. Terraces are dissected relict flood plains; uplift of the old depositional surface and erosional lowering of streambeds have left the terrace surfaces above the reach of most floods. The highest terraces are along the mountain front in stream valleys and alluvial fans and generally are preserved where limestone gravel that was cemented by calcium carbonate from ground water forms hard layers resistant to erosion. Under the terrace surface, a thin layer of fine-textured soil generally overlies channel deposits of sand and gravel. The terrace surfaces generally slope less than 10 percent, but erosional scarps on the side of the terrace slope steeply.

Alluvial fans.—Fan-shaped bodies of gravel-rich alluvium deposited near the mountain front where streams emerge from steep canyons. Streams on the fan surface commonly shift their courses laterally; floods and debris flows episodically cover parts of the fan surface with water and thick layers of sediment. The time interval between major debris flows may be tens of years, so the hazard is commonly underestimated. Cemented limestone gravel in the alluvium may make excavation difficult. Slopes are less than 15 percent.

Loess plains.—Plains and gently sloping hills of fine silt and clay built up from airborne dust burying preexisting hills and valleys. The landscape has also been smoothed by thin sheets of rainwater flowing across the surface. The soil is fertile and easily tilled but is easily eroded by water and wind. The geologic formation underlying these plains is the Quaternary Potwar Clay. Slopes are less than 15 percent.

Erosional Landforms

Loess badlands and gullies.—Steep-sided but generally shallow ravines eroded in soft loess (windblown silt and clay of the Potwar Clay). These gullies tend to grow and coalesce through headward erosion. Growth of loess badlands can be controlled, and some of the land can be reclaimed through conservation measures. Loess badlands are especially extensive south and west of Rawalpindi.

Bedrock badlands and gullies.—Areas of generally parallel, deep ravines eroded in steeply dipping soft mudstone and sandstone of the Siwalik Group. Most of the gullies have formed along the strike of weakly consolidated beds separated by ridges of resistant, cemented sandstone. This landform develops from loess badlands and gullies when streams cut down through the base of the loess into steeply dipping bedrock. Such terrain is extensive west of Riwat on either side of the Soan River. Bedrock badlands are more difficult to reclaim than loess badlands. Slopes are 50–100 percent.

Gentle hill slopes with angular clasts.—Rolling hills generally sloping more than 15 percent but less than 75 percent. Some ledges of rock may crop out, but the surface generally is covered with thin soil of sand, clay, and broken rock derived from weathering of the underlying bedrock. This type of slope is generally found on low hills underlain by sandstones of the Rawalpindi and Siwalik Groups.

Gentle hill slopes with rounded clasts.—Rolling hills generally sloping more than 15 percent but less than 100 percent. Some ledges of rock may crop out, but the surface generally is covered with thin sandy soil derived from weathering of the underlying rock; the soil contains rounded cobbles from a distant source. This type of slope is generally found on low hills underlain by conglomerates of the Soan Formation (Pliocene and lower Pleistocene(?)) or Lei Conglomerate (middle Pleistocene).

Rocky ridges and pinnacles.—Low hills, abundant rock outcrops, and thin sandy soil formed primarily on resistant, steeply dipping sandstone beds of the Kamlial Formation (lower and middle Miocene). The beds typically erode into a band of parallel, low sandstone walls. Excavation and agriculture are difficult. Average slope is less than 15 percent but may include vertical rock walls several meters high.

Steep, rocky hill slopes.—Mountain slopes 20 percent to vertical, and many rock ledges. Parts of rock slopes are covered by boulders and finer rock debris; soil is sufficient in places to support partial cover. Includes most of the Margala Hills, where Paleocene marine limestones have been deeply eroded.

Geology

The dominant factor controlling the geology of the Islamabad-Rawalpindi area is the convergence of the Pakistan-India and Eurasian tectonic plates and the collision between the plates that began about 20 million years ago. This process produced complex structure and stratigraphy in the Islamabad-Rawalpindi area that have been studied by many Pakistani and foreign geologists. Most of the individual quadrangle maps comprising the study area have been mapped by the Geological Survey of Pakistan (fig. G3), although many have not yet been published. This mapping has been interpreted and compiled by the first three authors of this report into a map at 1:50,000 scale (Williams and others, 1999) of the same area covered by plate G1. Plate G1 shows some of the information on the geologic map, but many geologic units of various ages have been grouped together on the basis of their physical properties, and much of the structural detail has been omitted. This discussion of the geology of the Islamabad-Rawalpindi area will be best understood by reference to the geologic map (Williams and others, 1999).

Descriptive Outline of Rock Units

The sedimentary rocks of the Islamabad area record a long period of gentle geologic fluctuations and slow deposition while the Pakistan-India tectonic plate drifted northward across the Indian Ocean, followed by much more vigorous tectonic processes and rapid deposition in the shorter period since the Pakistan-India and Eurasian plates converged. Consequently, the 150-million-year (m.y.) period from deposition of the Samana Suk Formation (Middle Jurassic) to the beginning of deposition of the Murree Formation (lower Miocene) is represented by only about 675 m of primarily marine sedimentary rocks, whereas the last 20 m.y. are represented by more than 7,572 m of continental sedimentary rock (fig. G5).

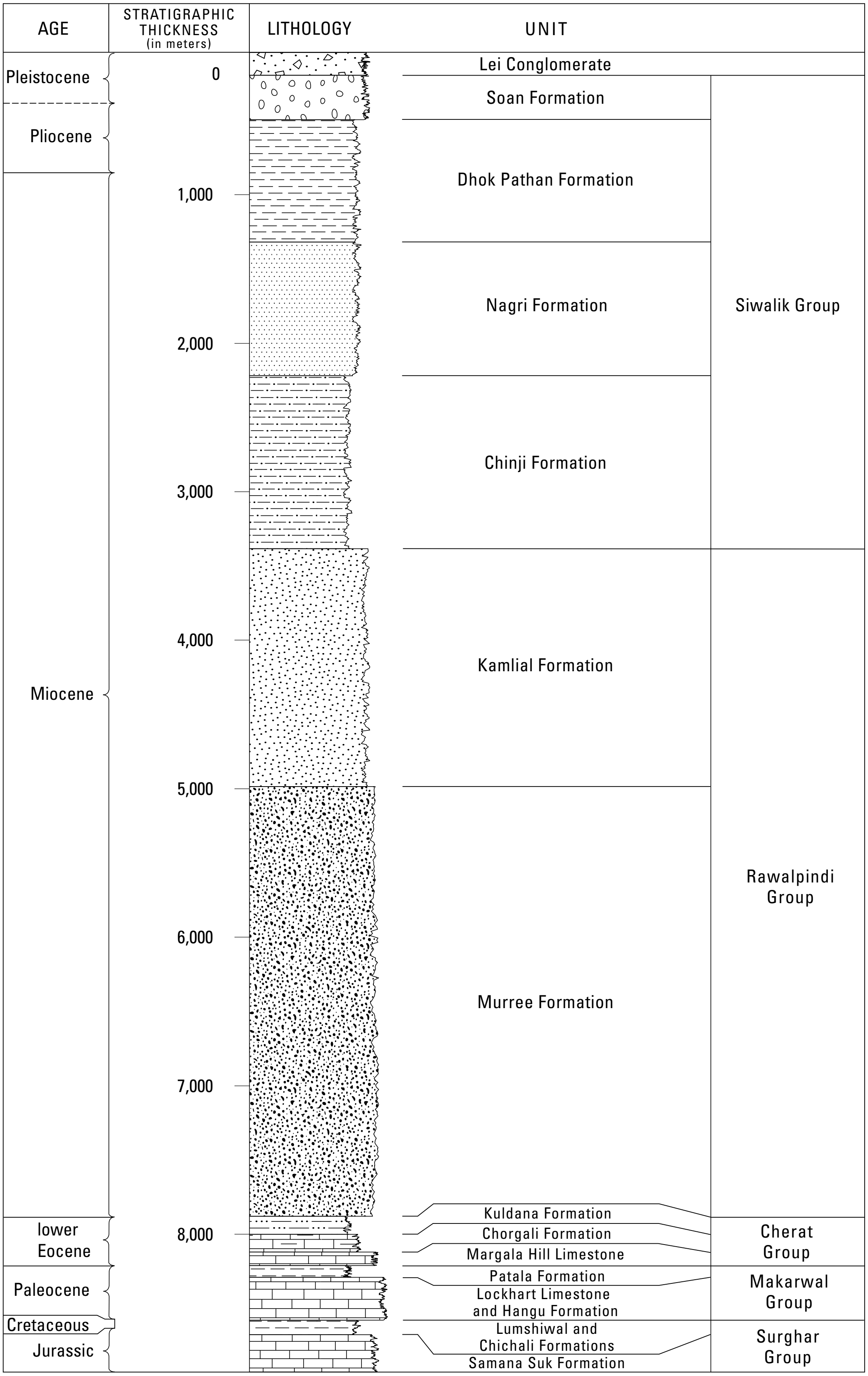


Figure G5. Generalized composite stratigraphic section of consolidated rocks in the Islamabad-Rawalpindi study area. See text for exact ages and generalized lithologic descriptions. Dashed boundaries are approximate.

During the uplift and structural deformation of the last 1.5 m.y., erosion has dominated over deposition, so that the only sediments preserved are thin, discontinuous bodies of alluvium and eolian silt.

Surghar Group (Jurassic and Lower Cretaceous)

Samana Suk Formation (Middle Jurassic).—Fossiliferous limestone and subordinate marl. The limestone is dark gray, brownish gray, and mottled yellowish orange; medium to thick bedded; micritic to oolitic and pelletal; and at places shelly; it has dolomitic and sandy beds. The marl is light olive gray to greenish gray, laminated, thinly bedded, and splintery. The unit forms escarpments and steep slopes. The exposed thickness ranges from 200 to 250 m. Contact with the overlying Chichali Formation is unconformable. The base is not exposed.

Chichali Formation (Upper Jurassic and Lower Cretaceous).—Shale and sandstone. The shale is dark gray, brownish gray, and dark olive gray; splintery; thinly bedded; and calcareous; it contains ferruginous and phosphatic nodules. The sandstone is dull greenish gray, thin to medium bedded, fine grained, and glauconitic. Subordinate thin limestone bands are dark gray. The unit contains belemnites and ammonoids. The unit conformably underlies the Lumshiwal Formation. The measured thickness is 34–50 m. The age is Late Jurassic (Tithonian) to Early Cretaceous (Neocomian).

Lumshiwal Formation (Lower Cretaceous).—Marine sandstone and subordinate limestone and shale. The sandstone is dark brown and greenish gray, is thin to thick bedded, and consists of quartz and glauconite. The shale is silty and glauconitic. The limestone is yellowish orange, arenaceous, shelly, thinly bedded, and hard and contains ammonoids and brachiopods. The limestone is intercalated with marl in places. The Lumshiwal Formation unconformably underlies the Hangu Formation. The Upper Cretaceous Kawagarh Formation, which overlies the Lumshiwal Formation immediately north of the map boundary, was eroded from the map area before deposition of the Hangu Formation. The Lumshiwal erodes into steep slopes and escarpments. The thickness is 10–50 m.

Makarwal Group (Paleocene)

Hangu Formation.—Continental claystone, sandstone, and intercalated shale. The claystone and shale are red, brown, and greenish gray; thinly laminated to thin bedded; silty; sandy; hematitic; and bauxitic. The sandstone is reddish brown and grayish black, thin to thick bedded, brittle, oolitic, ferruginous, and quartzitic. The Hangu Formation consists of highly weathered sediments deposited in a humid, tropical, continental environment. The thickness ranges from 2 to 8 m. The unit conformably underlies the marine Lockhart Limestone.

Lockhart Limestone.—Marine limestone and subordinate marl and shale. The limestone is pale gray to dark gray, medium grained, thick bedded, in part nodular, hard, bituminous, and fossiliferous. The marl is grayish black and fossiliferous. The shale is olive gray to greenish gray and has weakly developed cleavage. The thickness ranges from 70 to 280 m. The unit conformably underlies the Patala Formation.

Patala Formation.—Shale and subordinate limestone and marl. The shale is greenish gray to brownish gray, thinly laminated, splintery, and calcareous; it grades into siltstone and sandstone. The limestone is gray to light gray, thinly bedded, and fossiliferous. The marl is dark gray and fossiliferous. The Patala Formation represents primarily marine deposition. The measured thickness is 70–80 m. The unit is conformable with the overlying Margala Hill Limestone.

Cherat Group (Lower Eocene)

Margala Hill Limestone.—Marine limestone and subordinate marl and shale. The limestone is dark gray to pale gray, medium to thick bedded, nodular, and fossiliferous. The marl is gray to brownish gray and hard. The shale is greenish gray and reddish brown and splintery. The measured thickness ranges from 60 to 90 m. The unit is conformable with the overlying Chorgali Formation.

Chorgali Formation.—Marine shale, limestone, and marl. The formation is divisible into lower and upper parts. The lower part consists of shale that is olive green and greenish orange; splintery; and intercalated with lenticular thin limestone beds and coquina beds composed of large foraminifers. The upper part consists of limestone that is gray to light gray and white to grayish yellow, thin to medium bedded, flaggy, cherty, and fossiliferous. The marl is light gray to gray and thinly bedded. The measured thickness ranges from 30 to 120 m. The unit is conformable with the overlying Kuldana Formation.

Kuldana Formation.—Marine and continental claystone, marl, limestone, and minor sandstone. The claystone is variegated in color and has gypsum intercalations. The marl is pale gray to brownish gray, is thin to medium bedded, and contains fibrous gypsum. The limestone is white to very pale brown. The sandstone is brownish gray, fine grained, and calcareous. The measured thickness is 60–120 m. The unit unconformably underlies the Murree Formation.

Rawalpindi Group (Miocene)

Murree Formation (lower Miocene).—Continental sandstone and claystone. The sandstone is reddish gray to purple gray, fine to medium grained, thick bedded, micaceous, crossbedded, jointed, and calcareous. The claystone is purple to dark red and contains mottled lenses of pseudoconglomerate. Epidote is common in the sandstone of the Murree Formation. The measured thickness ranges from 2,000 to 2,895 m in the area. The contact with the overlying Kamlial Formation is conformable.

Kamlial Formation (lower and middle Miocene).—Sandstone and claystone. The sandstone is purple, gray, and dark brick red; medium to coarse grained; thick bedded; micaceous; jointed; and calcareous. The Kamlial Formation contains interbeds of hard purple claystone; some claystone beds are weathered and have yellow mottles. These weathered beds resemble conglomerate. The unit is distinguished from the underlying Murree Formation by its spheroidal weathering. Measured thicknesses range from 1,200 to 1,600 m. The upper contact beneath the Chinji Formation is conformable. Near the village of Chinji, 115 km southwest of Islamabad, the base was dated by fission-track dating of volcanic ash at about 18.3 million years ago (Ma) (Johnson and others, 1985).

Siwalik Group (Neogene and Pleistocene(?))

Chinji Formation (middle and upper Miocene).—Claystone and sandstone. The claystone is brick red, friable, hard, and intercalated with sandstone. The sandstone is dark gray to brownish gray, medium to thick bedded, soft, and crossbedded. The thickness ranges from 880 to 1,165 m. The upper contact with the Nagri Formation is conformable. Near the type locality, the base was dated by fission-track dating of volcanic ash at about 14.3 Ma (Johnson and others, 1985).

Nagri Formation (upper Miocene).—Sandstone and subordinate claystone and conglomerate. The sandstone is gray, greenish gray, and brownish gray; medium to coarse grained, thick bedded; crossbedded; and calcareous and has a salt-and-pepper pattern that is produced by magnetite and ilmenite. The claystone is brown, reddish gray, and orange and is sandy or silty. The thickness is 500–900 m. Contact with overlying Dhok Pathan Formation is conformable. Near the type locality, the base was dated by fission-track dating of volcanic ash at about 10.8 Ma (Johnson and others, 1985).

Dhok Pathan Formation (upper Miocene and Pliocene).—Sandstone and claystone containing lenses of conglomerate in the upper part. The sandstone is light gray, fine to medium grained, medium bedded, and crossbedded. The claystone is orange red and chocolate brown, hard, and compact. The measured thickness is 500–825 m. The unit is overlain unconformably by the Soan Formation. Near the type locality, the base was dated by fission-track dating at about 8.5 Ma (Johnson and others, 1985).

Soan Formation (Pliocene and lower Pleistocene(?)).—Conglomerate and subordinate interbeds of sandstone, siltstone, and claystone. The conglomerate clasts range in size from pebbles to boulders and consist of about 80 percent rounded quartzite, about 10 percent fine-grained volcanic trap rock, and 10 percent metamorphic rocks and sedimentary rocks of the Siwalik Group. Clasts are cemented in a calcareous sandy matrix. The sandstone is greenish gray, coarse grained, and soft. The claystone is orange, brown, pale pink, and soft. The exposed thickness is 200–300 m. The upper contact beneath the Lei Conglomerate and younger sediments is an unconformity older than 1.6±0.18 Ma (Johnson and others, 1982). The base locally rests on an unconformity dated by fission-track dating of a volcanic ash at 1.9±0.4 Ma (Raynolds, 1980, p. 190).

Surficial Units (Pleistocene and Holocene)

Lei Conglomerate (middle Pleistocene).—Carbonate-cemented cobble conglomerate consisting of 93 percent subangular limestone clasts intercalated with and grading laterally into weakly consolidated silt, sand, and clay. Other clasts are 5 percent older Siwalik Group sedimentary rocks, 2 percent quartzite, and trace amount of igneous rocks (Gill, 1951; Raynolds, 1980). The Lei Conglomerate is generally flat lying, but locally it is folded and faulted. It overlies rocks of the Siwalik and Rawalpindi Groups upon an angular unconformity. At Shahpur (lat 33°30.8′ N., long 73°04′ E.), fine overbank sediments are preserved beneath an erosional disconformity at the base of the conglomerate and above the angular unconformity. Volcanic ash from sediments older than the Lei Conglomerate and younger than the Soan Formation has been dated by the fission-track method at 1.6±0.18 Ma, representing a local maximum age for the Lei Conglomerate (Johnson and others, 1982).

The Lei Conglomerate is interpreted as an alluvial basin-fill sequence of coarse, angular gravel derived from the uplifting Margala Hills to the north interbedded with finer sediment derived from sandstone and shale of the Rawalpindi Group and windblown silt. The unit was deposited along the axis of the subsiding Soan syncline. Cemented conglomerate beds are resistant to erosion and form ledges and hills. Uncemented conglomerate beds are the most important ground-water aquifer in the area. The exposed thickness is 106 m, but drill hole FC–12 southwest of Saidpur (fig. G2) penetrated more than 152 m of interbedded clay (72 percent) and gravel (28 percent) (Ashraf and Hanif, 1980). In this drill hole, the average thickness of gravel beds is 6 m and that of clay beds is 14 m.

Potwar Clay (Pleistocene and Holocene).—Windblown silt and clay and subordinate amounts of alluvial gravel. Sediment is light brown to gray, very fine grained, hard, compact, and calcareous. The windblown sediment averages 71–74 percent silt-size and 15–16 percent clay-size material. The unit is 14–18 percent calcium carbonate. The mineral composition is predominantly quartz, but subordinate amounts of feldspar and clay minerals are present, such as kaolinite and illite (Rendell, 1988, p. 392). The well-developed vertical partings and lack of bedding suggest that much of the sediment is atmospheric dust, but stratification of some of the sediment indicates partial reworking by surface wash and streams. Locally, the silt is intercalated with crossbedded lenses of sand and gravel and with the Lei Conglomerate.

Thermoluminescence ages of loess from the Potwar Clay in the Riwat area range from 20 thousand to 132 thousand years ago (ka) from near the surface to 11-m depth and are greater than 170 ka for more deeply buried loess beneath a gravel facies. Calculated accumulation rates range from 6 to 27 centimeters per thousand years (cm/1,000 yr) (Rendell, 1988, p. 393). The silt and clay beds are very erodible; hence, deep, steep-sided gullies and badlands are extensive. The Potwar Clay is subject to loss of bearing strength when wet. Its thickness is highly varied, depending on the relief of the underlying unconformity. The exposed thickness is 1–35 m. Similar deposits intercalated with the Lei Conglomerate extend to a depth of 152 m (Ashraf and Hanif, 1980).

Terrace alluvium (Pleistocene and Holocene).—Gravel, clay, and silt locally cemented by calcium carbonate. Clast-supported boulders, cobbles, and pebbles of sedimentary rocks enclose a sandy and clayey matrix. These former stream-channel and flood-plain deposits no longer receive sediment because subsequent downcutting by streams has left them high above flood level. Repeated episodes of uplift or climate change and erosion have left terrace deposits at several levels. The terrace-alluvium unit resembles the Lei Conglomerate but is younger and retains its depositional form. The unit is divided into older and younger subunits.

Older terrace alluvium (Pleistocene).—Terrace alluvium whose depositional surface is more than 5 m above modern flood level. The older terrace-alluvium unit is generally preserved as discontinuous remnants of gravel capping ridges and flat-topped hills. The maximum thickness is about 3 m.

Younger terrace alluvium (upper Pleistocene and Holocene).—Terrace alluvium whose depositional surface is less than 5 m above modern flood level. The younger terrace alluvium generally forms benches along the sides of modern stream valleys. The thickness is about 3 m.

Alluvium and windblown silt, undifferentiated (upper Pleistocene and Holocene).—Eolian silt and stream-channel, flood-plain, terrace, and slope-wash alluvium intermixed in small areas that cannot be depicted separately at the map scale. Such deposits typically occupy small depressions in the Margala Hills and are less than 10 m thick.

Flood-plain and fan alluvium (Holocene).—Moderately bedded and sorted sand and gravel channel and debris-flow deposits overlain by a thin veneer of sandy silt and clay from overbank flooding and slope-wash deposition. The flood-plain and fan alluvium was typically deposited adjacent to streams or in fan-shaped bodies at the mouth of canyons or gullies. The maximum thickness beneath flood plains is about 6 m, and that beneath fans is about 20 m.

Stream-channel alluvium (Holocene).—Unconsolidated gravel, sand, and silt that is subject to stream transport each year. The stream-channel alluvium is poorly to moderately sorted and contains low-angle crossbedding. The alluvium is generally without soil or vegetation. It forms low islands and bars within braided and meandering stream channels. The maximum thickness is about 3 m.

Geologic History

Sedimentary rocks exposed in the Islamabad area (fig. G1) record 150 m.y. of geologic history from the Middle Jurassic to the Quaternary. The period from about 150 to 24 Ma was characterized by slow, primarily marine deposition and little tectonic activity; that from 24 to 1.9 Ma by rapid, voluminous, continental deposition and slow subsidence; and that since 1.9 Ma by intense tectonism, extensive erosion, and subordinant local deposition dominated by coarse clastic continental sediment.

The oldest rocks exposed in the study area are Jurassic marine limestone and dolomite that were deposited on a continental shelf along the northern edge of the continental part of the Pakistan-India tectonic plate as it migrated northward before converging with the Eurasian plate. The oolitic, biomicritic, and intrasparitic types of limestone in the Samana Suk Formation indicate different amounts of energy in the various carbonate depositional environments. A short break in deposition during the Late Jurassic is represented by the unconformity between the Samana Suk and Chichali Formations. From the Late Jurassic to the Early Cretaceous, anaerobic bottom conditions and chemically reducing environments accompanied deposition of the glauconitic shale and sandstone of the Chichali Formation. During the Early Cretaceous, conditions changed to a slightly saline, shallow-water, reducing environment when the glauconitic sandstone of the Lumshiwal Formation was deposited. The calcareous facies of the Lumshiwal Formation are nearshore shallow-water deposits. Emergence of the area above sea level during the mid-Cretaceous is indicated by the unconformity between the Lumshiwal and Kawagarh Formations north of the map area (the Kawagarh is missing from the study area). During the early Late Cretaceous, the sea transgressed again, and the limestone and marl of the Kawagarh Formation were deposited in shallow- to deep-marine water.

During the Late Cretaceous to Paleocene, the area rose again above sea level. The exposed surface of the marine Kawagarh Formation was first eroded and then buried beneath highly weathered continental sediments of the Hangu Formation. In the map area, the Kawagarh was entirely removed; thus, the Hangu unconformably lies on the Lumshiwal Formation. Intense lateritic and bauxitic weathering of the Hangu Formation reflects the equatorial latitude of the Pakistan-India tectonic plate during the Paleocene. Following deposition and weathering of the Hangu, marine conditions returned and persisted through the early Eocene. Calcareous and argillaceous sediments of the Lockhart Limestone, Patala Formation, Margala Hill Limestone, and Chorgali Formation were deposited during this time. This marine depositional sequence was followed by alternate marine and continental environments during which the Kuldana Formation was deposited. During the middle Eocene, initial contact of the Pakistan-India plate with Asia elevated the region above sea level and produced the unconformity beneath the continental Murree Formation.

By Miocene time, the sea had completely receded south of the map area, and during the Miocene and Pliocene, very thick continental deposits of the Rawalpindi and Siwalik Groups accumulated in the subsiding Himalayan foredeep region. These deposits consist of sediments eroded from highlands to the north that were uplifted and deformed by tectonic forces in the zone of convergence. The south margin of the deformed zone migrated southward into the Islamabad area, where it first caused coarser sedimentation but eventually so deformed and uplifted the area that deposition drastically decreased and erosion became the predominant sedimentary process. The tectonic migration that began during the Eocene continues to the present. The estimated average rate of southward migration during the Pliocene was 3 cm/1,000 yr, and the average accumulation of mud, sand, and gravel in the subsiding foredeep region was about 28 cm/1,000 yr (Raynolds, 1980, p. 191).

During the Pliocene, sedimentation was controlled by an eastward-flowing river system (Raynolds, 1980). The conglomerate of the Soan Formation that was deposited by that river system during the late Pliocene consisted chiefly of quartzite and metamorphic clasts eroded from the Himalayan core and is similar to clasts in modern Indus River (pl. A1) gravels. Local sedimentation stopped between 3 Ma and 1 Ma, when the Hazara fault zone developed, when limestone of the Margala Hills was thrust up along the north border of the study area, and when the sandstone and mudstone of the Rawalpindi and Siwalik Groups were folded and faulted throughout the area. The eastward-flowing river system was disrupted and superseded by the much smaller, southward-flowing Soan River system, and locally derived limestone gravel became the dominant component of the Lei Conglomerate; this conglomerate accumulated most thickly over the Soan Formation and other upturned Siwalik Group rocks along the axis of the subsiding Soan syncline at the southern edge of the map area.

During the Quaternary, climatic fluctuations along with tectonic uplift caused periodic incision of the drainage south of the Margala Hills and alternate periodic accumulations of silt and alluvial gravel from the Margala Hills, which filled the valleys and spread laterally to form wide plains of low relief. A great influx of windblown silt probably was blown from the braided outwash channel that originated in the highly glaciated headwaters of the Indus River (pl. A1). This eolian silt formed the thick deposits of loess that mantle the landscape and contribute to the burial of preexisting valleys. Loess deposition was probably most rapid during the glacial maximums, but it continues despite the present interglacial climate because very large glaciers still exist in the Indus River basin and contribute large amounts of fine-grained sediment, which causes the Indus to form a braided channel below the mountain front 50 km long and 10 km wide (Warwick, this volume, chap. A, pl. A1, fig. A2). Calculated rates of loess accumulation during the period from 170 to 20 ka range from 6 to 27 cm/1,000 yr (Rendell, 1988, p. 393).

Strongly developed soils are scarce in the Islamabad area, perhaps because of the seasonally dry climate and the lack of stable surfaces caused by alternation of erosion and loess deposition. Some paleosols, however, are preserved within the loess.

Pleistocene stream and fan-terrace deposits along the mountain front, preserved as much as 30 m above present drainage levels, reflect stream incision and provide a measure of continued tectonic uplift of the piedmont zone since their deposition. Distant tectonic events may also have affected the balance of aggradation and degradation. Tectonic tilting and uplift across the course of the Indus River (McDougall, 1989) near the gorge at Kalabagh, 200 km to the west (pl. A1, fig. A2), have caused major shifts in the course of the Indus and affected the base level of the Soan River (pl. A1).

Active tectonism across the area continues in the form of folding, thrust faulting, and seismicity. A very large earthquake in A.D. 25 destroyed the Buddhist community at Taxila, about 25 km west-northwest of Islamabad. The most recent damaging earthquake (Modified Mercalli intensity VII) was in the area centered along the Gumreh Kas (stream) about 7 km northeast of Rawalpindi (fig. G6) in February 1977 and had a Richter magnitude of 5.8.

Geologic Structure

The Islamabad-Rawalpindi area can be divided into three structural zones, trending generally east-northeast, that reflect compression and movement oriented S. 20° E.:

1. In the north, the mountainous Margala Hills consist of Jurassic through Eocene limestone and shale that are complexly folded and thrust along the Hazara fault zone. Uplift of these mountains probably formed a major topographic barrier during the last 1 m.y.

2. South of the mountains, a southward-sloping piedmont bench, the piedmont fold belt, is underlain primarily by truncated folds in the sandstone and shale of the Rawalpindi Group.

3. In the southernmost part of the area, the Soan River flows generally along the axis of the Soan syncline.

Cross sections *A–A″*, *A′–A″*, and *B–B′* (figs. G7–G9) depict interpretations of the geologic structure slightly modified from previous interpretations shown in sections by Naeem and Bhatti (1985) and Pasha and Bhatti (in press).

Hazara Fault Zone

Islamabad is on the south margin and leading edge of the Hazara fault zone. All the faults in the map area, except those south of Rawalpindi, are part of this fault zone. This zone consists of an arc of thrusted and folded rocks about 25 km wide and 150 km long that is convex to the south and extends west-southwestward away from the Himalayan syntaxis. More than 20 individual thrust sheets have been identified across the 25-km-wide zone north of Islamabad, but only 5 major thrusts lie within the map area. In the Islamabad area, some of the thrust faults are slightly oblique to the front of the Margala Hills; hence, they project west-southwestward beneath the cover of the piedmont fold belt. The extensions of these faults are prominent north of Fetehjang, 25 km west of Rawalpindi, where they form the south margin of the Kala Chitta Range, which is an en echelon extension of the structural pattern of the Margala Hills.

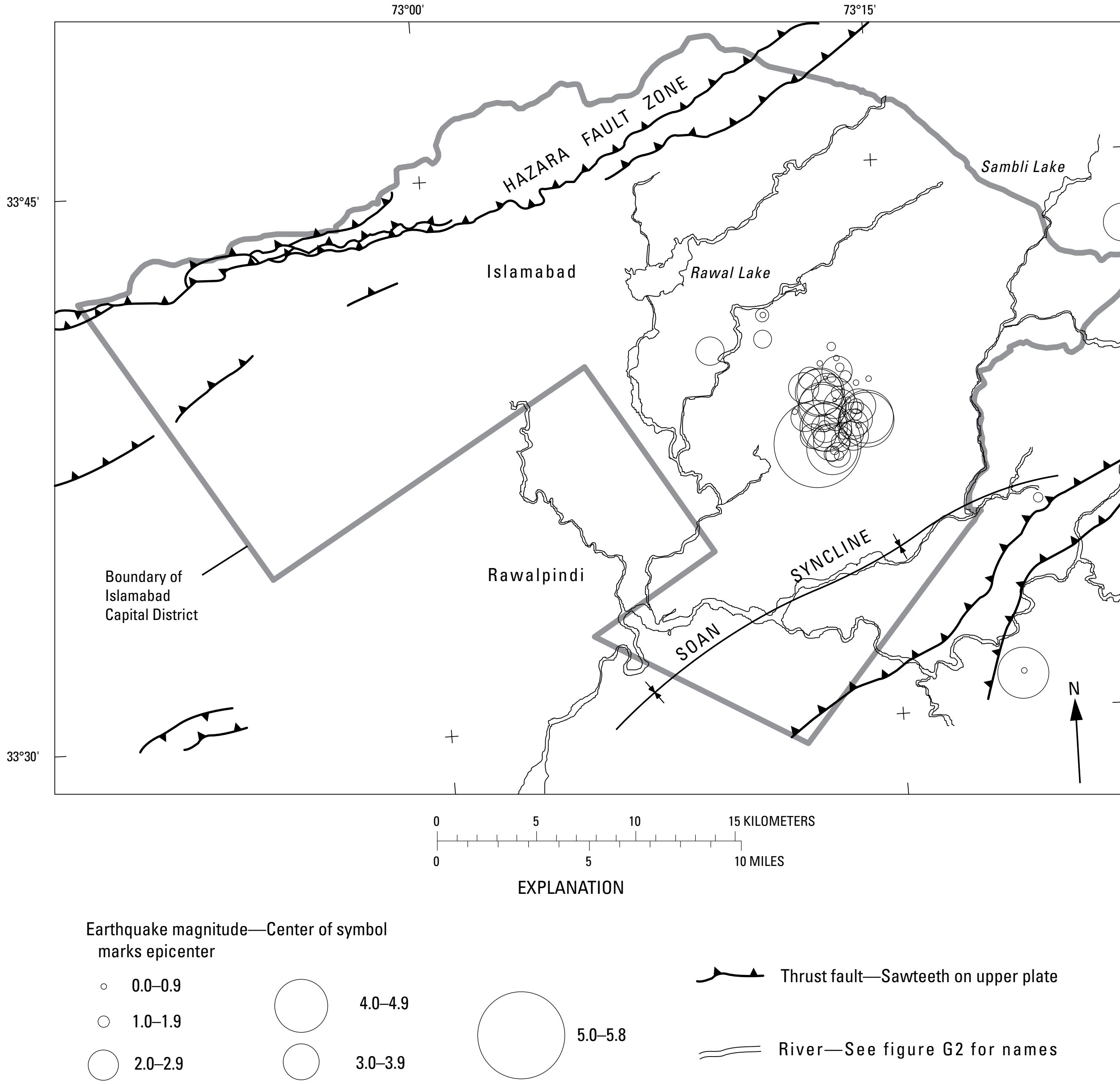


Figure G6. Earthquake magnitudes between January 26, 1977, and April 30, 1978 (from Adhami and others, 1980), and potentially active faults in the Islamabad-Rawalpindi study area. Centers of circles are epicenters, and radii of circles are proportional to magnitude.

The thrust and fold structure of the Margala Hills immediately north of Islamabad is complex (fig. G8). The Margala Hills consist of at least five principal thrust sheets that repeat the pre-Miocene marine section. The structurally lowest sheet dips generally northward at about 30°, and the higher thrust sheets dip progressively more steeply, so that the northernmost and structurally highest are overturned and dip southward at about 85°. The thrusts have most commonly broken through the beds within or just beneath the Samana Suk Formation, although almost all pre-Miocene units are cut at some place in the study area. Higher in the section, thrusts are common at the base of the Margala Hill Limestone (probably within the shale of the Patala Formation) and within the overlying Chorgali Formation.

According to interpretations shown in cross sections *A–A″*, *A′–A″* (figs. G7 and G8), and *B–B′* (fig. G9), beds within the thrust sheets are commonly not parallel to the bounding faults, but instead are intensely folded, both isoclinally and disharmonically. Beds within the thick thrust sheet composing most of the south slope of the Margala Hills are generally in stratigraphic order, but repetition through internal folding has tectonically thickened the section to five times normal thickness. Tight folds that originally were probably overturned southward now appear to be overturned northward because of northward rotation of the entire thrust sheet during the formation of lower, younger thrusts. Northward decreases in rock age combined with southward dips produce an impression of overturning of the section and general horizontal axis rotation of about 120° to the north. Only about half the beds, however, are presently overturned, although those that appear to be upright were probably overturned during an earlier phase of the deformation and have been turned upright by later northward rotation. The geometry suggests that the locus of thrust ramping has migrated southward through time, and the formation of each successive ramp has rotated the overlying thrust sheet back toward the north.

Steeply dipping Pleistocene gravel sparsely exposed south of the mountain front indicates that the structurally lower thrusts may have the potential for renewed movement; it is likely that tectonically generated stresses would be absorbed by movement along low-dipping faults before a stress level high enough to reactivate the higher, overturned thrusts would be reached. Therefore, the overturned thrusts are unlikely to have substantial recurrent movement and are not shown in figure G6.

Piedmont Fold Belt

The faults and folds in the piedmont fold belt south of the mountain front probably have high potential activity, although definitive exposures are sparse and discontinuous. The Pleistocene Lei Conglomerate, overlying the sandstone of the Murree Formation (lower Miocene), is folded in the broad anticline at Shakar Parian Park (fig. G2) in Islamabad. The Lei Conglomerate also is tilted 80° southward along a thrust fault in the Kuldana Formation (lower Eocene) north of Golra, about 17 km northwest of Rawalpindi. The fault at Golra may be an eastward projection of the southward overthrusting of the mountain front along the south face of the Kala Chitta Range, a major range that begins about 25 km west of Rawalpindi and extends westward south of the Margala Hills. Major faults bounding the Khalri Murat Range (figs. A2, G2), about 15 km south of the Kala Chitta Range (figs. A2, G1), may also extend northeastward toward Rawalpindi, concealed beneath Quaternary eolian and alluvial deposits.

Soan Syncline

The Soan syncline is an asymmetric, faulted fold of regional extent, plunging west-southwestward, in which fluvial sandstone, claystone, and conglomerate of the Siwalik Group dip 60°–85° toward the axis of the syncline on the north limb and 45°–70° on the south limb. The maximum width of the syncline in the map area is about 11 km, but the fold extends 100 km to the southwest. About 38 km southwest of the map area, the maximum width is 22 km. Along the south limb, two splays of a northwest-dipping thrust fault, at least 32 km long, trend generally parallel to the fold axis. The throw on the north splay is greater than that on the south splay, and the north splay displaces about 1,600 m of the Kamlial Formation (middle and lower Miocene).

Seismic data (Baker and others, 1988; Pennock and others, 1989; Burbank and Beck, 1991) suggest that the north limb of the syncline is underlain at depth by a northward backthrust over an antiformal stack of sedimentary rocks repeated by complex southward thrust faulting. Such a backthrust has not been identified in outcrop, perhaps because the area is generally covered by Quaternary deposits. If such an interpretation is correct, most tectonic shortening across the Soan syncline would be absorbed by thrust faults beneath the syncline. The surface block containing the syncline would behave as a pop-up structure, accounting for the relatively simple deformation in the syncline as compared with the surrounding terrain.

Adhami and others (1980) have interpreted tilted Quaternary conglomerate along the south side of the Soan River east of the Grand Trunk Road and a bedrock shear zone that seems to wedge into Holocene alluvium along the Ling River near Kahuta (0.8 km east of the east border of the study area) (pl. A1) as indicating continued folding and faulting along the Soan syncline through the late Pleistocene.

Geologic Hazards

Seismic Risk

The Islamabad-Rawalpindi area lies in a tectonically active zone, where faulting, folding, and earthquakes have been frequent in the recent geologic past. Quaternary deposits are tectonically deformed throughout the map area. In A.D. 25, the Buddhist monasteries at Taxila, 25 km west-northwest of Islamabad, were destroyed by an earthquake estimated at Modified Mercalli intensity IX. More recently, a Richter magnitude 5.8 earthquake on February 14, 1977, centered 7 km northeast of Rawalpindi (fig. G6), caused damage indicating Modified Mercalli intensity VII near the epicenter (Adhami and others, 1980).

The focus of the 1977 earthquake was estimated to be at 14- to 18-km depth and could not be definitely associated with any of the known surface faults in the map area. Although earthquake shaking is not confined to areas near surface faults, the risk of surface rupture is greater where the surface has been broken previously. Only those faults estimated as most likely to rupture during earthquakes are shown in figure G6, along with epicenters and magnitude of earthquakes in the Islamabad area between January 26, 1977, and April 30, 1978, from data of Adhami and others (1980, p. 72–81).

Studies by National Engineering Services of Pakistan (NESPAK) indicated that a realistic seismic factor for building design should probably be higher than that indicated on

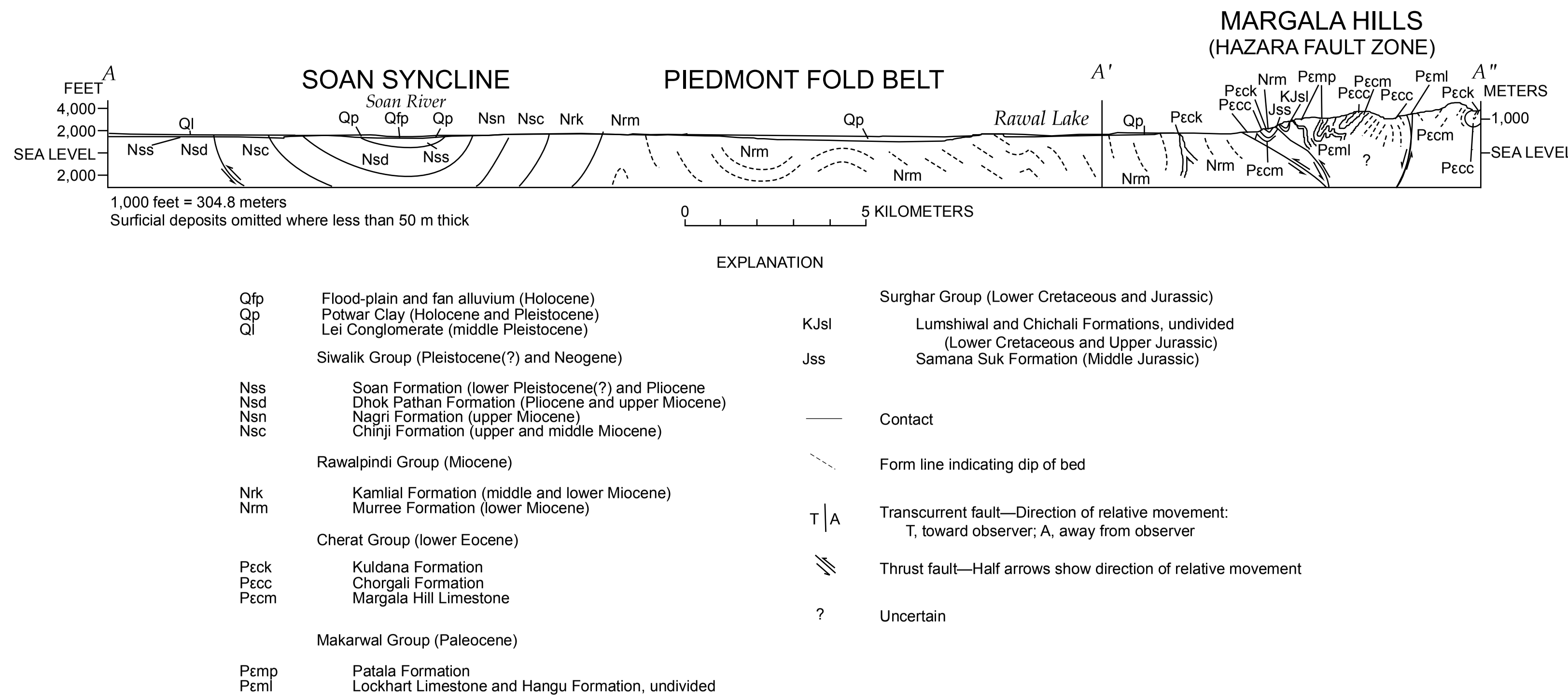


Figure G7. Geologic cross section *A–A″* in the Islamabad-Rawalpindi study area (modified from Williams and others, 1999, whose section was modified from those by Naeem and Bhatti (1985) and Pasha and Bhatti (in press)). See plate G1 for location.

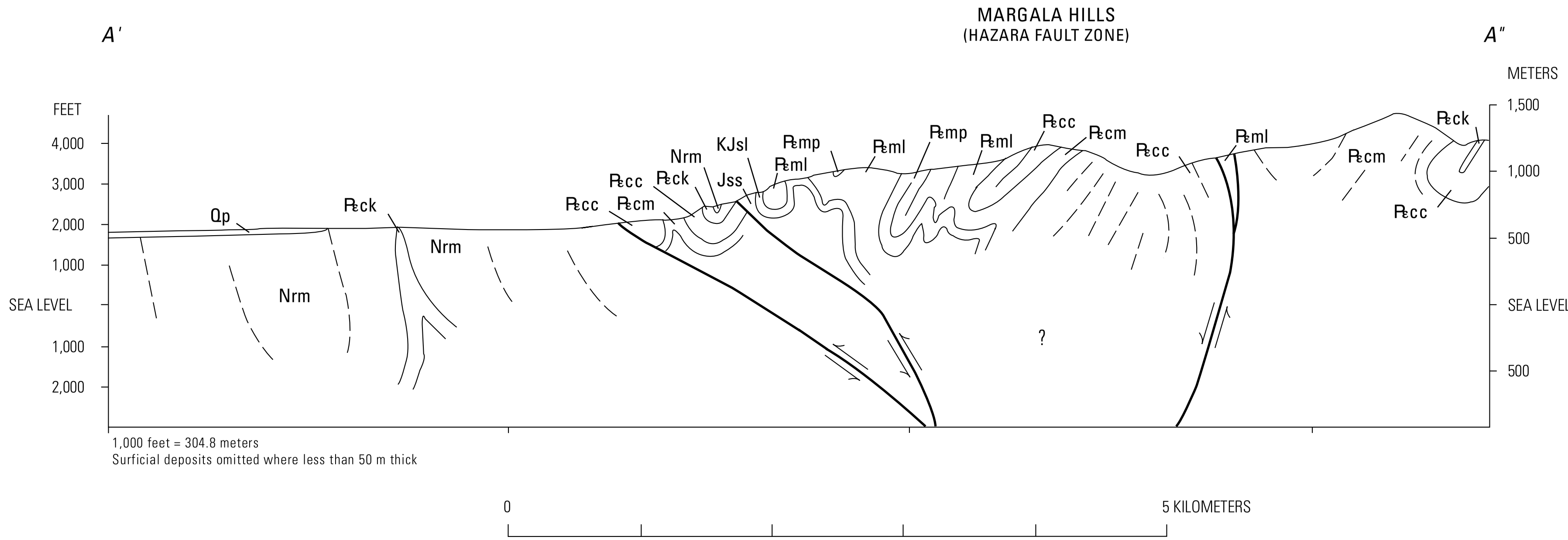


Figure G8. Enlargement of the north end (*A′–A″*) of the geologic cross section *A–A″* in the Islamabad-Rawalpindi study area (modified from Williams and others, 1999, whose section was modified from those by Naeem and Bhatti (1985) and Pasha and Bhatti (in press)). See figure G7 and plate G1 for location; see figure G7 for explanation of geology.

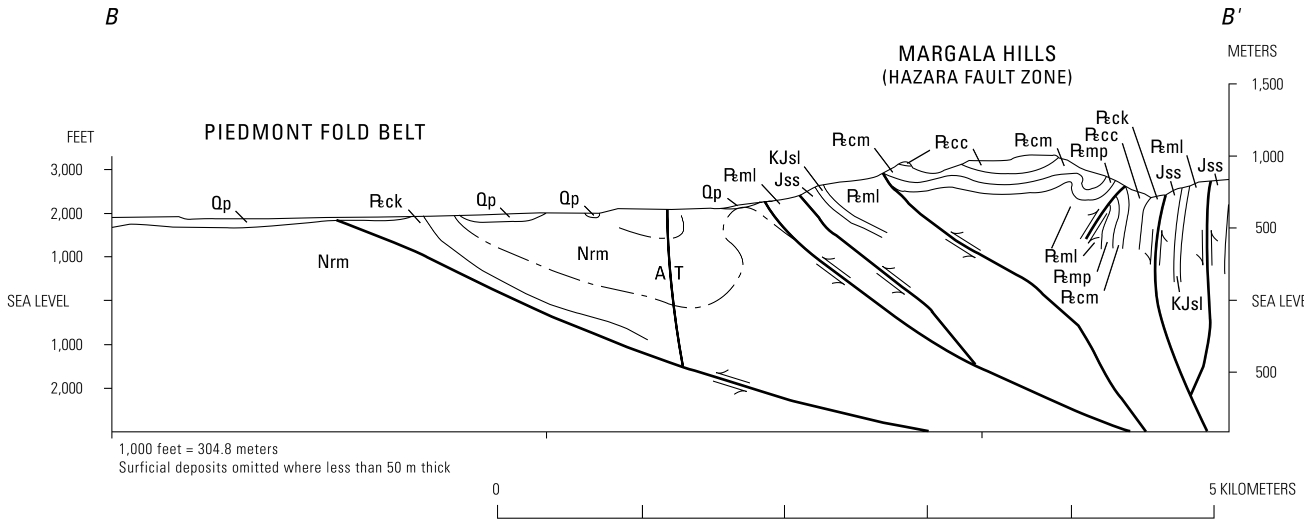


Figure G9. Geologic cross section *B–B′* in the Islamabad-Rawalpindi study area (modified from Williams and others, 1999). See plate G1 for location and figure G7 for explanation of geology.

the seismic zoning map of Pakistan (Adhami and others, 1980, p. 133). They recommended design for 0.125-*g* (gravitational acceleration) horizontal acceleration for ordinary structures, and for 0.2 *g* without collapse for important structures. For sensitive structures, site-specific designs are required that take into account the strength of the underlying soil and bedrock and the distance from probable earthquake sources (Adhami and others, 1980, p. 137).

NESPAK (Adhami and others, 1980, p. 131) estimated that each year there is a 50 percent chance of a Richter magnitude 4 earthquake, an 8.33 percent chance of magnitude 5, a 1.67 percent chance of magnitude 6, a 0.26 percent chance of magnitude 7, and a 0.11 percent chance of magnitude 7.5 (recurrence intervals of 2, 12, 66, 380, and 912 years, respectively). A complicating factor in estimating probable seismic accelerations in the Islamabad area is the irregularity of the bedrock surface buried beneath Quaternary silt and gravel. Capital Development Authority (CDA) test hole 18, 1.8 km south of the zero-point road intersection in Islamabad (fig. G2, pl. G1), penetrated more than 140 m of unconsolidated gravel and clay (probably including interbedded conglomerate and silt of the Lei Conglomerate) without reaching bedrock (fig. G10). Depths to bedrock exceeding 100 m are common over much of the area, even close to outcrops. In the southern part of the area, Siwalik Group bedrock is commonly near the surface, but it is little stronger than the alluvial cover. Thick, unconsolidated deposits tend to amplify earthquake shocks, and uncompacted eolian silt, such as parts of the Potwar Clay, may collapse or even liquefy if the bonds between the grains are destroyed.

Flooding

Lei Nala heads in the Margala Hills and passes through the center of Rawalpindi, where homes and lives have been lost to flooding in low-lying areas. Although the stream is relatively small, it is entrenched, so floodwaters are confined to the narrow flood-plain zone at the valley bottom. This confinement increases the depth and suddenness of flooding in the small area affected but protects most of the population, who live above flood level. If continued losses are to be minimized, land use in the affected areas may have to be changed. Wide flood plains along the Soan River above the Grand Trunk Road bridge are subject to flooding but are not densely populated. Expansion of residential or industrial development onto the Soan flood plain should be carefully controlled, although dams on tributaries to the Soan help to reduce potential problems.

Debris Flows

Debris flows issuing from mountain canyons onto alluvial fans at the mountain front create another flooding hazard that is less easily recognized than most conventional flood hazards. Infrequent, extreme precipitation events may trigger such flash floods of mud, boulders, and water, but during the periods between events, sediment accumulates in the mountain canyons, and the longer the time between flushing events, the more violent may be the final release. Deposits from such events seem to occur in northern Islamabad in parts of municipal blocks F6, E8, F8, E9, F9, and E10 (block grid of master plan of Islamabad, Survey of Pakistan, 1982).

General Engineering Characteristics

Foundation conditions in Islamabad and Rawalpindi vary greatly. The bedrock surface consists mostly of folded and faulted sandstone and claystone of the Rawalpindi Group, some soft sandstone and claystone from the Kuldana Formation, harder limestone from the Chorgali Formation toward

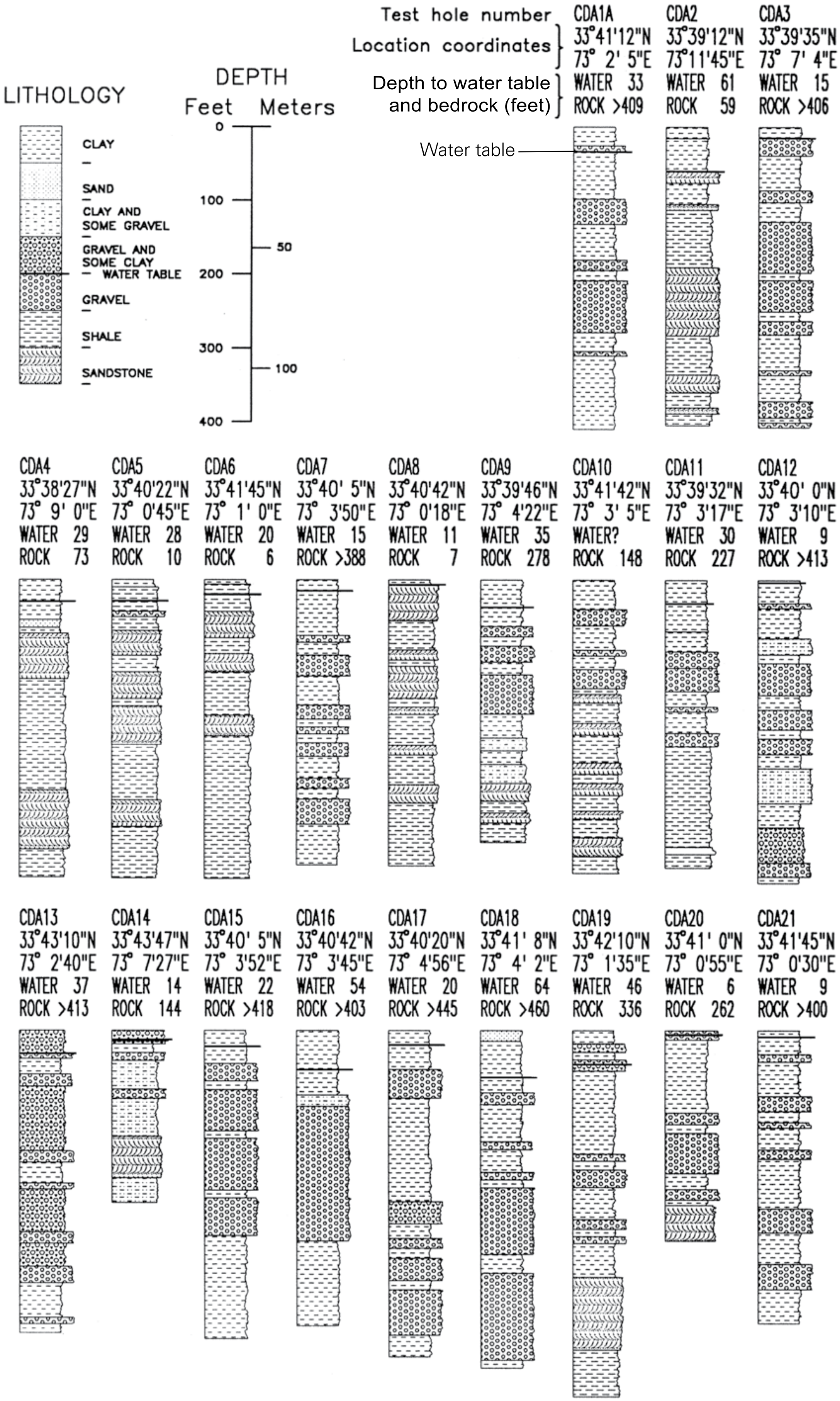


Figure G10. Logs of the Capital Development Authority (CDA) hydrologic test holes around Islamabad. See plate G1 for locations of test holes (plotted without CDA prefix). Data from Ashraf and Hanif (1980).

the north, and some Siwalik Group sandstone and claystone toward the south. These rocks have been deformed and eroded into a highly irregular surface, and they have been partly buried beneath alternating layers of silt and sandy, locally cemented, limestone gravel in the Lei Conglomerate, Potwar Clay, and younger stream deposits. The Pleistocene deposits generally lie flat, but locally they also are tectonically deformed. Between bedrock outcrops, a flat plain of silt may conceal bedrock ridges just below the surface, hard, cemented limestone conglomerate, or loose silt and gravel more than 100 m thick.

In general, all the natural foundation materials are weak, including the bedrock. The exceptions are the limestone beds of the Chorgali Formation, some cemented sandstone beds in the Murree and Kamlial Formations of the Rawalpindi Group, and the cemented limestone gravel in the Lei Conglomerate and stream-terrace deposits. The uncompacted eolian silt covering many upland surfaces has moderate bearing capacity when dry, but it is subject to sudden loss of strength and collapse when wetted under loads of about 1–3 kilograms per square centimeter (kg/cm^2) (Rendell, 1985, p. 766). The silt is very easily excavated, but where cemented gravel lies close to the surface, excavation may be much more difficult and expensive than anticipated (Khan and others, 1987).

Table G4 tabulates the range of values and averages for various physical properties of soil and rock samples from the Islamabad-Rawalpindi area as generalized categories of sandstone, mudstone, gravel, sand, and silt plus clay. Categories for unconsolidated samples signify the particle-size range making up the greatest weight percent of the sample. Most of the samples are poorly sorted, so some of the gravel samples contain as much as 18 percent silt and clay, and some of the samples classified as silt plus clay contain as little as 40.5 percent silt and clay. Liquid limit, plastic limit, and plastic index are determined on the portion of the sample finer than 0.42 mm, so the values reported for gravels reflect properties of the matrix sand, silt, and clay. This tabulation does not represent a systematic areal collection but is a random collection of all the available data that could be located (74 samples), supplemented with analyses of 11 samples collected specifically for this study (3–01 to 3–11, pl. G1).

Samples from building sites of the Pakistan Overseas Foundation office building (pl. G1, 1–1) and the Pakistan Engineering Council (pl. G1, 2–1) near the Blue Area in central Islamabad (fig. G2) provided data on water content, bulk density, specific gravity, liquid limit, plastic limit, plastic index, consolidation, direct shear, unconfined compression, point load, organic-matter content, sulfate content, pH, percent gravel, percent sand, and percent silt plus clay. Samples 3–01 to 3–03 (pl. G1) of loess surface soil from Islamabad and Riwat provided data on water content, specific gravity, liquid limit, plastic limit, plastic index, organic-matter content, sulfate content, sodium chloride content, total dissolved solids, optimum moisture content, maximum dry density, percent gravel, percent sand, and percent silt plus clay. Sample 3–04 from a brick clay pit (pl. G1) provided data on organic-matter content, sulfate content, total dissolved solids, percent gravel, percent sand, and percent silt plus clay. Samples 3–05 to 3–09 of building sand from Lawrencepur (50 km northwest of Islamabad) provided data on specific gravity, organic-matter content, sulfate content, sodium chloride content, total dissolved solids, percent gravel, percent sand, and percent silt plus clay. Samples 3–10 and 3–11 (pl. G1, 3–10) are crushed limestone from a quarry near Nicholson Monument (fig. G2). They were analyzed for data on specific gravity, abrasion resistance, moisture absorption, percent gravel, percent sand, and percent silt plus clay.

A series of 21 hydrologic test holes drilled by the Capital Development Authority across Islamabad (pl. G1) provides information on depth to bedrock, depth to the water table, and some physical properties of subsurface materials. Samples from these holes were measured to determine natural water content, dry bulk density, specific gravity, porosity, permeability, percent gravel, percent sand, and percent silt plus clay. Logs of these holes are summarized in figure G10; they were constructed from information in the report of Ashraf and Hanif (1980).

The rest of the physical properties data is from route studies along roads outside the study area, but in the same geologic materials that occur in the study area. These provided data on specific gravity, liquid limit, plastic limit, plastic index, California bearing ratio, optimum moisture content, maximum dry density, percent gravel, percent sand, and percent silt plus clay. There is no certainty that the data from the 85 samples summarized in table G4 are typical of the Islamabad-Rawalpindi area, but they do indicate part of the range of possible values.

Most of the large structures in Islamabad and Rawalpindi are less than 10 stories high, although some higher than 20 stories have been completed and others are under construction (pl. G1), primarily in the Blue Area (fig. G2), near the National Assembly building. The minarets of Shah Faisal Mosque are also very tall, slender structures, and the main building is massive. All the tall structures are underlain by silt, conglomerate, and bedrock of folded Murree sandstone and mudstone.

Waste Disposal

Disposal of the large quantities of liquid and solid waste generated by the combined populations of more than 1.3 million people in Rawalpindi and Islamabad is a major problem that presently causes extensive pollution of ground water, surface water, and air. Islamabad has one of the most modern sewage treatment plants in Pakistan; sewage is carried by pipes to a disposal plant just north of Rawalpindi, where it is treated and the relatively clean effluent passes into a tributary of Lei Nala. Immediately downstream, however, waste water of all types enters Lei Nala as it passes through Rawalpindi. On the south side of Rawalpindi, Lei Nala enters the Soan River as a putrid stream covered with brown foam. Toxic waste may

Table G4. Physical properties of geologic materials in the Islamabad-Rawalpindi study area.

[Samples are described in the text under "General Engineering Characteristics." wt %, weight percent; g/cm^3, grams per cubic centimeter; kg/cm^2; kilograms per square centimeter; deg, degrees; —, no data available]

Property	Sand-stone	Mud-stone	Gravel	Sand	Silt plus clay
Water content (wt %)					
Average	8.90	7.73	5.70	7.07	15.19
Maximum	15.12	12.88	8.70	13.67	29.20
Minimum	1.40	2.40	4.59	4.65	1.74
No. of samples	6	6	8	25	11
Dry bulk density (g/cm^3)					
Average	1.79	1.97	1.69	1.62	1.64
Maximum	2.52	2.45	2.00	1.69	2.00
Minimum	1.42	1.47	1.56	1.53	1.40
No. of samples	8	6	8	25	8
Specific gravity					
Average	2.58	2.64	2.65	2.63	2.64
Maximum	2.66	2.70	2.70	2.72	2.73
Minimum	2.46	2.57	2.57	2.56	2.47
No. of samples	5	3	10	30	9
Porosity (%)					
Average	40.21	39.86	37.85	38.32	41.82
Maximum	42.19	42.63	39.39	40.44	43.22
Minimum	38.13	38.11	37.43	36.41	39.92
No. of samples	5	3	7	25	3
Permeability (darcies)					
Average	1.62	1.51	8.64	11.74	.20
Maximum	5.36	2.37	20.51	30.61	.44
Minimum	.14	.69	.32	.38	.04
No. of samples	5	3	8	25	3
Silt plus clay content (%)					
Average	—	—	4.78	9.20	80.50
Maximum	—	—	18.00	35.20	99.00
Minimum	—	—	.00	1.40	40.50
No. of samples	—	—	13	37	14
Liquid limit (% water)					
Average	—	—	20.00	31.00	33.70
Maximum	—	—	21.00	35.00	40.00
Minimum	—	—	19.00	25.00	23.00
No. of samples	—	—	2	4	10
Plastic limit (% water)					
Average	—	—	14.50	20.75	21.00
Maximum	—	—	15.00	24.00	26.00
Minimum	—	—	14.00	17.00	16.00
No. of samples	—	—	2	4	10
Plastic index					
Average	—	—	5.50	10.25	12.70
Maximum	—	—	6.00	13.00	20.00
Minimum	—	—	5.00	6.00	7.00
No. of samples	—	—	2	4	10

Property	Sand-stone	Mud-stone	Gravel	Sand	Silt plus clay
Consolidation:					
Void ratio (%)					
Average	—	—	—	—	0.603
Maximum	—	—	—	—	.650
Minimum	—	—	—	—	.570
No. of samples	—	—	—	—	3
Compression index					
Average	—	—	—	—	0.15
Maximum	—	—	—	—	.20
Minimum	—	—	—	—	.10
No. of samples	—	—	—	—	3
Direct shear:					
Cohesion (kg/cm^2)					
Average	—	—	—	—	0.29
Maximum	—	—	—	—	.30
Minimum	—	—	—	—	.28
No. of samples	—	—	—	—	2
Angle of friction (deg)					
Average	—	—	—	—	11.50
Maximum	—	—	—	—	18.00
Minimum	—	—	—	—	5.00
No. of samples	—	—	—	—	2
Unconfined compression:					
Unconfined compressive strength (kg/cm^2)					
Average	109.50	31.96	6.20	—	2.41
Maximum	315.00	90.27	6.20	—	8.40
Minimum	6.00	1.09	6.20	—	.60
No. of samples	3	3	1	—	5
Strain at failure (%)					
Average	0.95	—	1.20	—	5.12
Maximum	1.00	—	1.20	—	9.10
Minimum	.90	—	1.20	—	1.40
No. of samples	2	—	1	—	5
Point load (kg/cm^2)					
Average	57.50	41.50	—	—	—
Maximum	57.50	63.00	—	—	—
Minimum	57.50	14.00	—	—	—
No. of samples	1	3	—	—	—
Organic-matter content (%)					
Average	—	—	—	0.04	0.59
Maximum	—	—	—	.05	1.83
Minimum	—	—	—	.01	.16
No. of samples	—	—	—	5	6
Sulfate (%)					
Average	—	—	—	0.001	0.039
Maximum	—	—	—	.001	.114
Minimum	—	—	—	.001	.001
No. of samples	—	—	—	5	6

Table G4. Physical properties of geologic materials in the Islamabad-Rawalpindi study area.—Continued

Property	Sand-stone	Mud-stone	Gravel	Sand	Silt plus clay
Sodium chloride (%)					
Average	—	—	—	0.002	0.047
Maximum	—	—	—	.005	.137
Minimum	—	—	—	.001	.002
No. of samples	—	—	—	5	3
Total dissolved solids (%)					
Average	—	—	—	0.091	0.446
Maximum	—	—	—	.120	.748
Minimum	—	—	—	.065	.175
No. of samples	—	—	—	5	4
pH					
Average	6.5	—	7.6	—	7.0
Maximum	6.5	—	7.6	—	7.0
Minimum	6.5	—	7.5	—	7.0
No. of samples	1	—	2	—	2
California bearing ratio unsaturated					
Average	—	—	—	38.23	—
Maximum	—	—	—	57.40	—
Minimum	—	—	—	15.20	—
No. of samples	—	—	—	6	—
California bearing ratio saturated					
Average	—	—	—	18.92	—
Maximum	—	—	—	38.10	—
Minimum	—	—	—	6.60	—
No. of samples	—	—	—	6	—
Optimum moisture content (%)					
Average	—	—	—	10.28	15.87
Maximum	—	—	—	10.81	16.60
Minimum	—	—	—	8.71	15.00
No. of samples	—	—	—	4	3
Maximum dry density (g/cm^3)					
Average	—	—	—	2.33	1.82
Maximum	—	—	—	3.08	1.86
Minimum	—	—	—	2.08	1.78
No. of samples	—	—	—	4	3

be part of the mixture, as Lei Nala passes through industrial areas, and the Rawalpindi area lacks an organized facility for disposal of toxic waste.

Solid waste is also dumped into Lei Nala and at various sites in the surrounding countryside (pl. G1). These sites are generally unsuitable for agriculture, either because of bedrock outcrops or because of gullies in the silt. The waste is spread, burned, and, in some places, covered with a thin layer of soil. These practices represent an attempt to reclaim waste land, and in a few places, crops are planted over the buried waste. Air pollution results from the burning in either case, but potential problems with pollution of surface and ground water are more severe in the bedrock outcrop areas. There is no impermeable barrier between the waste and the exposed bedding planes of steeply dipping permeable sandstone of the Murree Formation, so leachate from the waste can move rapidly into the ground-water flow system. Also, steep slopes in bedrock areas combined with lack of adequate cover material and drainage control structures allow leachate to move rapidly into surface streams. During the summer monsoon, leaching of waste is accelerated by precipitation averaging more than 250 mm/month and maximum temperatures averaging more than 34°C. Control of ground-water pollution is important because municipal and private wells are used extensively in Islamabad and Rawalpindi to supplement supplies from the Rawal and Sambli Lakes.

Potentially favorable sites for waste disposal near Rawalpindi exist in exhausted clay pits within the Potwar Clay. Compacted clay-rich silt has low permeability, and areas of silt suitable for cover can usually be found. When properly engineered, filled, and covered, the reclaimed pits may be suitable for low-intensity uses such as agriculture, storage yards, or parks and recreation.

Urban Mineral Resources

The most important mineral resources in the Islamabad-Rawalpindi urban area are construction materials: limestone for cement; aggregate for concrete; sand for mortar; and clay for bricks, tiles, and pottery. All of these resources are quite abundant and have been heavily exploited. Most aggregate is quarried and crushed from limestone bedrock or dug from alluvial gravel in modern and ancient stream deposits. General-purpose sand is taken locally from modern streambeds, and higher quality sand is brought in from pits at Lawrencepur, about 50 km northwest of Islamabad. Brick clay is dug from pits scattered around the Islamabad-Rawalpindi area wherever the surficial cover of Potwar Clay (primarily windblown silt) is sufficiently thick and clay rich.

Aggregate

Aggregate is in heavy demand in the Islamabad-Rawalpindi area for use in concrete construction and road building. There are two principal sources. Most of the supply is obtained by quarrying and crushing limestone from the Margala Hills, but a secondary source is alluvial gravel, either taken directly from the stream channel or dug from terrace deposits. Other potential sources are little exploited.

Table G5 lists the locations and estimated quantity of important aggregate resources. The areas of outcrop were measured from the environmental geologic map (pl. G1), but the estimated reserve (in metric tons) was calculated by using assumptions about thickness and bulk density. The symbols in table G5 appear on plate G1 to identify the areas measured in each category. Those symbols consist of the basic environmental geologic map unit letter symbol plus a number that is appended to indicate the resource area. For example, the letter C indicates the areas of Lei Conglomerate outcrop not included in aggregate-reserve calculations; on plate G1, sym-

Table G5. Estimated reserves of aggregate in the Islamabad-Rawalpindi study area.

[Assumptions used to calculate reserves are explained in the text in the "Aggregate" section. Areas of reserves are shown on plate G1. Availability: a, already active; b, potentially available; c, beneath superior agricultural land; d, beneath urban development; e, beneath protected parkland or reserved forest; f, beneath important structures]

Map symbol (pl. G1)	Availability	Area (ha)	Reserve (millions of metric tons)	Location
			Limestone bedrock	
L1	b	142	103.8	NE end of Khairi Murat Ridge.
L2	b	369	270.2	NE end of Kala Chitta Range.
L3	a	668	488.5	Margala Hills near Grand Trunk Road.
L4	b	231	168.7	Margala Hills E of Sang Jani and W of Shah Allahditta.
L5	a	282	206.5	Margala Hills N of Shah Allahditta.
L6	b	898	657.2	Margala Hills E of Shah Allahditta and W of quarries near Islamabad.
L7	b	87	63.7	Small low foothills just W of Islamabad.
L8	a	736	538.0	Margala Hills NW of Islamabad.
L9	e	5,155	3,770.9	Margala Hills N of Islamabad.
L10	b	1,879	1,374.5	Margala Hills NE of Islamabad.
Subtotal		10,447	7,642.0	
			Limestone gravel from the Lei Conglomerate	
C1	e	79	7.5	Shakar Parian Park.
C2	b	197	21.6	Isolated outcrops SW of Rawalpindi.
C3	d	1,271	338.0	Large outcrops N of Soan River.
C4	b	655	71.9	Scattered outcrops S of Soan River.
C5	b	1,410	1,546.8	Thick hill SE of Soan River.
Subtotal		3,612	1,985.8	
			Crystalline conglomerate of the Soan Formation	
X1	b	308	84.5	N of Soan River.
X2	b	998	273.9	S of Soan River.
Subtotal		1,306	358.4	
			Terrace gravel	
T1	b	594	45.9	W of Shah Allahditta.
T2	b	169	13.1	Along stream bank at Sang Jani-Grand Trunk Road.
T3	f	163	12.6	Near National Assembly building.
T4	b	916	70.8	E of Islamabad.
T5	f	331	25.5	At Quaid-l-Azam University.
Subtotal		2,173	167.9	
			Flood-plain sand and gravel	
F1	c	218	21.9	Soan River flood plain below Grand Trunk Road bridge.
F2	c	11	1.1	Soan River flood plain above Grand Trunk Road bridge.
Subtotal		229	23.0	
			Unmined stream-channel sand and gravel	
S1	b	247	12.4	Above Rawal Lake.
S2	b	92	4.6	Gumreh Kas.
S3	b	90	4.5	Soan River below Grand Trunk Road bridge.
S4	b	573	28.8	Soan River above Grand Trunk Road bridge.
Subtotal		1,002	50.3	
			Actively mined stream-channel sand and gravel	
S5	a	194	9.7	Below Rawal dam.
S6	a	219	11.0	Soan River near Grand Trunk Road bridge where mined.
Subtotal		413	20.7	
Grand total		19,182	10,248.1	

bols C1–C5 also appear, because part of unit C was subdivided into five geographic areas for calculating aggregate reserves. Location is a critical factor in the economics of aggregate resources, because of the low value of the product relative to the transportation cost. Assumptions used to calculate the reserves in table G5 are discussed below for each potential source of aggregate:

1. Limestone bedrock. The reserve tonnage of limestone bedrock was calculated by assuming mining to an average depth of 30 m and a bulk density of 2.4 g/cm^3. The steeply dipping limestone beds extend to a great depth, and mining to depths greater than 30 m is possible. Environmental impact, mine safety, and economics are the primary limitations on production of aggregate from limestone, rather than the extent of the raw material.

2. Limestone gravel from the Lei Conglomerate. The Lei Conglomerate was estimated to have an average minable thickness of 6 m and a bulk density of 1.8 g/cm^3. It is not much used as a source of aggregate at present, perhaps because the limestone gravel commonly is cemented and interbedded with silt.

3. Crystalline conglomerate of the Soan Formation. The crystalline conglomerate of the Soan Formation was estimated to have an average minable thickness of 7.5 m and a bulk density of 1.8 g/cm^3. This unit is a possible source of high-strength aggregate but may prove difficult to crush because it contains clasts of strong crystalline rock.

4. Terrace gravel. Terrace gravels were estimated to have an average minable thickness of 3 m and a bulk density of 1.7 g/cm^3. They are widely distributed along the mountain front, but because individual deposits are scattered, reserves at any one locality are generally small. Many deposits are covered by urban development and major structures. Northeast of Islamabad, at Bhara Kao, some of the larger terrace deposits are presently being mined.

5. Flood-plain sand and gravel. Flood-plain alluvium along the Soan River was estimated to have an average minable thickness of 6 m and a bulk density of 1.7 g/cm^3, but little of it has been mined. The land is fertile and easily irrigated and, consequently, is quite valuable for agriculture. If pumping or dredging is required, the high water table beneath the flood plain may make excavation more expensive than for other sources of aggregate.

6. Stream-channel sand and gravel. Stream-channel alluvium was estimated to have an average minable thickness of 6 m and a bulk density of 2.0 g/cm^3. The thickness estimate is nearly meaningless because material removed during the dry season is replaced by deposition during the monsoon. Alluvium is generally not mined under water but is excavated from dry bars exposed during the dry season. The bulk density estimate is high because of many cobbles of crystalline rocks.

Limestone is quarried mostly from the Lockhart Limestone and Samana Suk Formation but may also be obtained from the Margala Hill Limestone. Most of the quarries are at the foot of the Margala Hills, where access is easy and where mining and crushing are facilitated by the extensive shearing that has accompanied thrust faulting (pl. G1). Two samples of Lockhart Limestone from the quarries at soil sample site 3–10 (pl. G1), near Nicholson Monument, have an average Los Angeles abrasion test value of 22.79 percent loss for 500 revolutions. The average apparent specific gravity of the crushed rock is 2.69, and the average absorption is 0.625 percent.

Immediately north of Islamabad, mining at the mountain front is prohibited within reserved forests that protect the scenic backdrop of the capital. The greatest concentration of limestone quarries in the metropolitan area extends along the mountain front from the forest boundaries westward for about 20 km. On either side of the Grand Trunk Road at Nicholson Monument, 15 km northwest of Rawalpindi, quarries are nearly continuous, and very little of the hill slopes remains undisturbed. Dust pollution there seriously restricts visibility, and the closeness of uncoordinated mining operations increases the substantial hazard to the miners.

Control of the mining area is split between Rawalpindi and Islamabad administrative authorities and the Punjab Provincial Government. The Capital Development Authority controls about 600 hectares (ha) on either side of the Grand Trunk Road at Nicholson Monument, where about 217 crushers are working. The limestone is crushed on a single-shift basis, and about 36 metric tons per day is the average production of each crusher, which means total production of aggregate from this area is about 2.5 million metric tons per year.

In the Punjab Provincial Government area, an automatic crusher and 40 hand-fed crushers are in operation. The hand-fed crushers produce almost the same tonnage as described for the Capital Development Authority areas, but the automatic plant, at Shah Allahditta, produces about 91 metric tons per day, which is used to feed the adjacent cement factory.

The alluvial gravel is commonly quite coarse and the clasts are well rounded, so crushing is needed to optimize size and increase angularity. Most of the crushers are scattered along the Soan River and its tributaries, where they take gravel directly out of the streambed or dig it from terraces. The main production centers have five crushers on the Soan River near the Grand Trunk Road bridge, six on terraces at Bhara Kao, and five along the Kurang River below Rawal Lake and above the Baroher Kahuta Road. Potential undesirable effects of stream-channel mining are excessive siltation and degradation of water quality downstream and accelerated erosion of streambeds and banks upstream.

Sand

Of about 1,500 ha leased for sand production as of 1989, 90 percent is along the Soan River and along the Haro River at Usman Khattar, and 10 percent is in the Kotha Kalan and

Morgah areas. Other localities supplying Rawalpindi and Islamabad are south of the area along the Grand Trunk Highway near Gujar Khan (pl. A1 of Warwick, this volume, chap. A). Sand from Lawrencepur, about 50 km to the northwest, is cleaner, coarser, and more angular than the local sand, and it has the quality required for multistory construction. At Lawrencepur, the sand is about 7 m thick beneath 70 cm of loessic silt. Five samples of sand (3–05 to 3–09) collected for this study from Lawrencepur sand pits averaged 94 percent sand, 4 percent silt, and 2 percent gravel. They contain some iron particles and average 0.376 percent organic matter, 0.09 percent total dissolved solids, 0.00084 percent sulfate, and 0.0012 percent sodium chloride. The average apparent specific gravity is 2.77, and average absorption is 0.916 percent.

Brick Clay

The Potwar Clay, used for making bricks, is a thick blanket of wind-deposited dust that has settled and accumulated over thousands of years and now covers most of the gently sloping parts of the Islamabad-Rawalpindi metropolitan area and extensive parts of the Potwar Plateau. It is widely exposed and covers about 30 percent of the total map area. It consists of silt, clay, and sand. Silt and sand predominate at some places, whereas clay predominates at others. Brick kilns are widely spread across the Islamabad-Rawalpindi area wherever the clay content of the Potwar Clay (loessic silt and clay) is sufficient for making bricks (pl. G1). A sample (3–04, pl. G1) taken for this study from an operating clay pit contained 79 percent clay, 20 percent silt, and 1 percent sand, although most Potwar Clay deposits in the Islamabad area probably average about 75 percent silt and 15 percent clay-size particles (Rendell, 1988, p. 392). Kaolinite and illite are the most common clay minerals, but most of the fine particles are quartz. The brick clay sample had 0.2 percent organic material, 0.64 percent total dissolved solids, and 0.114 percent sulfur dioxide content.

Although all of the digging of clay and the molding, stacking, and firing of bricks are done by hand, the number of kilns is so large that production is sufficient for the substantial requirements of the Islamabad-Rawalpindi metropolitan area. About 375 brick kilns (Brick Kilns Association of Rawalpindi, written commun., 1989) are scattered in areas where the loess is especially fine and rich in clay. The localities listed in table G6 produce significant quantities of bricks for Islamabad and Rawalpindi, although some are outside the study area. The number and exact location of brick kilns fluctuate constantly, but concentrations of brick kilns that were observed in the study area are shown on plate G1.

There is no system for regulating or leasing clay pits and brick kilns. Wherever the clay deposits are of sufficient thickness and quality, the owner of the land may dig a pit and construct a brick kiln. Each kiln and the surrounding clay pit occupy about 10,000 square meters (m^2); each operation has an average production life of about 10 years. Bricks are produced in cycles lasting about 3 months. About 300,000 bricks are produced in each run, and about 12 million over the life of the pit.

Table G6. Number of brick kilns operating in major clay-mining areas in or near the Islamabad-Rawalpindi study area.

[Brick Kilns Association of Rawalpindi (written commun., 1989). For locations, see figure G2]

Location	Number of kilns
Chaklala	30
Tarnool[1] (16 km W)	45
Chuhar Misrial	8
Karal	5
Lohi Bher	10
Taxila	100
Tanch Bhata	25
Khanna	8
Chakri[1] (53 km SW)	5
Lehtrar Bala Road	13
Gangal	20
Fatehjang[1] (40 km WSW)	50

[1]Located outside but near the study area. Distances and directions are from the zero-point road intersection in Islamabad (fig. G2).

Generally, two sizes of bricks are manufactured. For walls, the brick size is 22 cm by 11 cm, which weighs about 2.5 kilograms (kg). For ceilings, the brick size is 15 cm by 30 cm, weighing about 3 kg.

In the metropolitan area, about 375,000 m^2 (37.5 ha) of land per year is consumed for the manufacture of bricks (Rawalpindi Industries Department, written commun., 1989). This land is not necessarily lost to other uses because abandoned clay pits may be reclaimed for residential use or for solid-waste disposal followed sequentially by agricultural, forestry, or parkland use.

Brick kilns are fired with subbituminous coal trucked to the Islamabad-Rawalpindi area from near Quetta (fig. G1). Each truck carries about 20 metric tons, and 14–15 trucks are needed for each kiln run of about 275,000 bricks, or about 1 kg of coal per brick (Brick Kilns Association of Rawalpindi, written commun., 1989). About 450,000 metric tons of coal per year is thus burned in the Islamabad-Rawalpindi area for brick production, and the sulfurous smoke emitted by the many primitive kilns surrounding Rawalpindi is an important factor in degrading the quality of air.

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Resource Evaluation of Selected Minerals and Industrial Commodities of the Potwar Plateau Area, Northern Pakistan

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Rafiullah Khan, Geological Survey of Pakistan

Chapter H of

Regional Studies of the Potwar Plateau Area, Northern Pakistan

Edited by Peter D. Warwick and Bruce R. Wardlaw

Prepared in cooperation with the
Geological Survey of Pakistan,
under the auspices of the
U.S. Agency for International Development,
U.S. Department of State, and the
Government of Pakistan

Bulletin 2078–H

U.S. Department of the Interior
U.S. Geological Survey

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Resource Evaluation of Selected Minerals and Industrial Commodities of the Potwar Plateau Area, Northern Pakistan

By Harald Drewes, Zaki Ahmad, and Rafiullah Khan

Abstract

A part of northern Pakistan was reviewed by a multidisciplinary team to provide a broad geological synthesis in connection with a study of the coal resources of the country. This review was designed to help the earth-resource explorationists and planners, as well as to provide a means for mutual training in team studies and in some geological specialties. An integral part of this synthesis is a survey of the distribution and assessment of the development potential of certain metals and industrial commodities.

Because knowledge of the distribution and potential of most industrial commodities had been published (Zaki Ahmad, comp., 1969, Geological Survey of Pakistan Records, v. 15, pt. 3), the primary task involved compilation of available data. This effort showed that the quality of the basic data was mixed. An improved means of recording data on site, using modern topographic maps, for systematic check of the accuracy of basic commodity identification and summary geologic description would greatly benefit future assessment efforts of Pakistan's resources.

Data on the occurrence of metallic mineral resources were meager and provided one opportunity for a reconnaissance study to contribute to a resource evaluation. Most rocks of the Potwar Plateau area proved to lack the degree of induration suitable for vein deposits, but a vein system does cut the older, more indurated rocks of the northernmost part of the study area. Enough of these veins carry anomalous amounts of the base metals copper, lead, zinc, and mercury; the precious metal silver; and the indicator metals arsenic and cadmium to illustrate that hydrothermal systems are present, particularly in Proterozoic phyllites. The transition of the vein system to aplite sheets links the anomalous abundance of metals to granitic stocks as a possible source of metal-bearing fluids, as well as of heat to drive the hydrothermal systems. This suggestion, however, is based on a cursory field study and remains unsupported by geophysical data of the sort commonly applied to seek out likely sites of blind stocks.

The results of this resource study corroborate the knowledge that industrial commodities such as salt, gypsum, cement rock, and certain clays are present in abundance and that the potential for their further development is excellent. Basic stratigraphic principles can be applied to exploration because these commodities are contained in particular formations. The presence of many other industrial commodities, such as bauxite, glass sand, other clays, and hematite iron ores, is also well known, but these are present in marginal quantity or quality or do not have a ready market. The development of these commodities is likely, at least for certain limited applications (for example, bauxite is unlikely to occur in sufficient quality and quantity to provide the basis for an aluminum industry, yet it may serve as an additive in the cement industry). The link between commodity conditions and industrial economy was explained by Ahmad (1969).

The resource potential for metallic minerals, particularly for copper, lead, zinc, and silver, is low over most of the region and remains unknown in the southernmost part, which is extensively covered by alluvium. Over most of the central Potwar Plateau region, geological and geophysical data are sufficient to assign a low potential for mineral resources at a high degree of confidence. A low-potential rating is given only a low degree of confidence in the northernmost part of the study area, where geochemical reconnaissance is incomplete and geophysical data are nonexistent. In other words, there is a possibility in this northernmost terrane of turning up additional favorable evidence that could lead to the designation of some tracts as having a moderate or even good potential.

Introduction

The Potwar Plateau study of Pakistan (figs. H1, H2) was designed to demonstrate the effectiveness of a team approach to analysis of regional coal basins, as currently practiced by the U.S. Geological Survey. Although the focus remained on coal-related studies, a more general study of resource potential was added. Counterpart scientists of the Geological Survey of Pakistan participated in the study to gain hands-on training.

This chapter is a product of a cooperative program between the Geological Survey of Pakistan and the U.S.

Figure H1. Location of the Potwar Plateau study area (box).

EXPLANATION

Alluvium (Quaternary)—Deposits of basins or lowlands

Sedimentary and metasedimentary rocks (Quaternary to Proterozoic)—Mainly rocks of the foothills; also present in the Himalayas

Granite (Pliocene to Jurassic)—Mainly rocks of the high Himalayas; small bodies in the foothills

Diorite (Tertiary? to Mesozoic)—Rocks of the high Himalayas

Amphibolite (Mesozoic?)—Includes ophiolite; rocks of the high Himalayas

Thrust fault—Dotted where concealed, sawteeth on upper plate

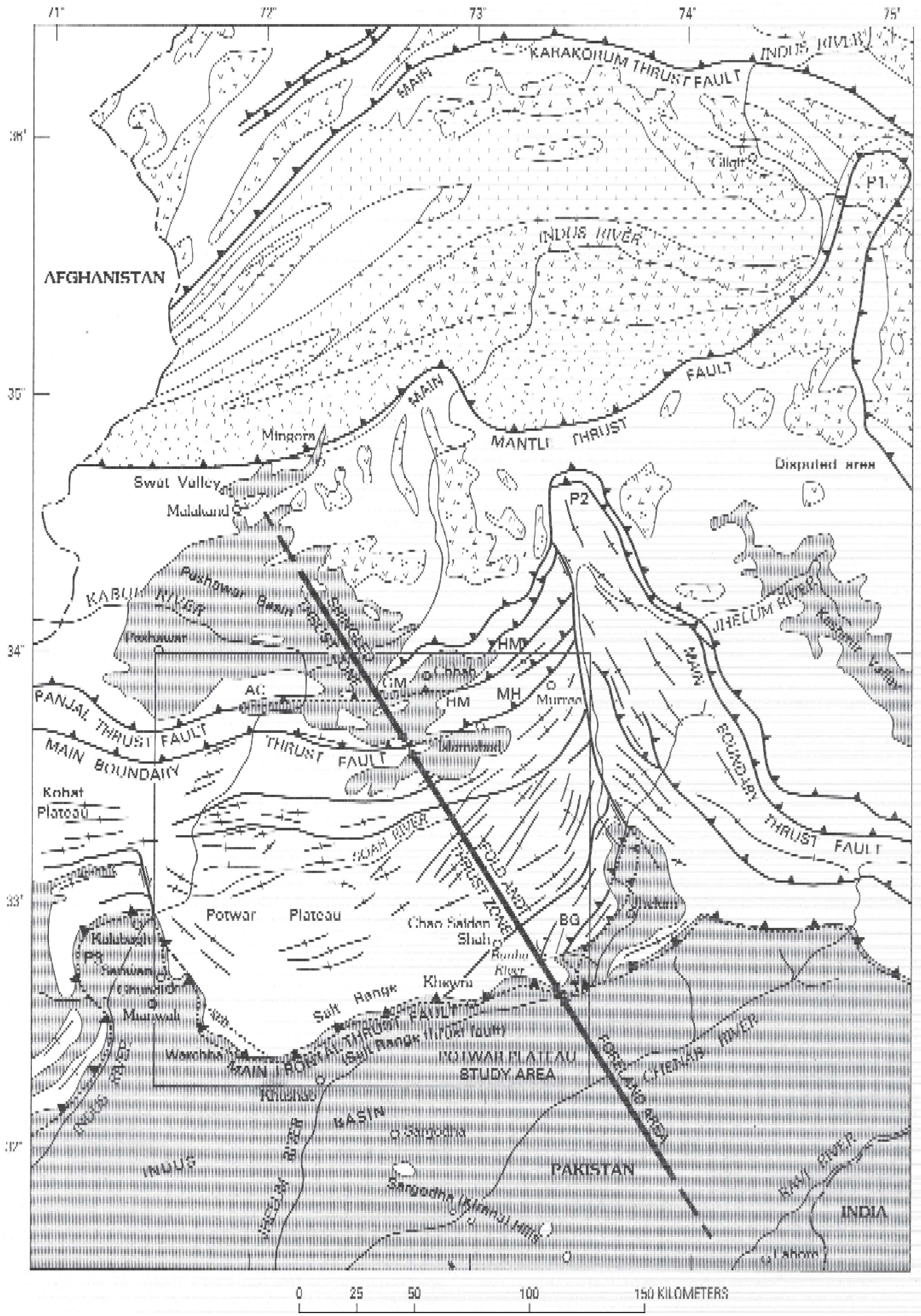
Strike-slip fault—Dotted where concealed or where it becomes a concealed (blind) oblique-slip ramp. Arrow couple shows relative movement

Fold axis

P1 **Pivot point**—Approximate site of vertical pivot axis for syntax; showing, by number, order of inception

Tectonic zones and foreland area—Discussed in text; dashed where extent remains undetermined

Figure H2 (above and facing page). Geologic setting of the Potwar Plateau study area (box). Sites: AC, Attock-Cherat Range; BG, Bunha River gap; GM, Gandghar Range; HM, Hazara Range; MH, Margala Hills. Figure from Drewes, 1995, figure 2, on which the geology was adapted from Kazmi and Rana (1982) and unpublished geologic mapping compiled by M.A. Bhatti, Feroz-ud-din, J.W. McDougall, P.D. Warwick, and Harald Drewes (1991–94).


71°
72°
73°
74°
75°
36°
35°
34°
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32°
AFGHANISTAN
KARAKORUM THRUST FAULT
MAIN
INDUS RIVER
Gilgit
P1
MAIN MANTLE THRUST FAULT
Mingora
Swat Valley
Malakand
Disputed area
P2
KABUL RIVER
Peshawar Basin
Peshawar
JHELUM RIVER
HM
Chhab
GM
HM
MH
Murree
AC
PANJAL THRUST FAULT
MAIN BOUNDARY THRUST FAULT
Islamabad
MAIN BOUNDARY THRUST FAULT
Kohat Plateau
SOAN RIVER
FOLD AND THRUST ZONE
Potwar Plateau
Chao Saidan Shah
BG
Jhelum
Kalabagh
P3
Mianwali
Salt Range
Khewra
MAIN FRONTAL THRUST FAULT
(Salt Range thrust fault)
POTWAR PLATEAU STUDY AREA
FORELAND AREA
CHENAB RIVER
Khushab
INDUS BASIN
Sargodha
INDUS RIVER
PAKISTAN
Sargodha (Kirana) Hills
RAVI RIVER
INDIA
Lahore
0 25 50 100 150 KILOMETERS

Geological Survey (USGS), sponsored by the Government of Pakistan and the U.S. Agency for International Development (USAID). Funding was provided by USAID through project 391–0478; Energy Planning and Development Project, Coal Resource Assessment Component 2a; and Participating Agency Service Agreement (PASA) 1PK–0478–P–IC–5068–00.

Project Aims and Logistic Restraints

This chapter offers a review of the known and potential distribution of selected metallic minerals and industrial commodities in the Potwar Plateau area, Pakistan. Under Pakistani policies, the development of oil, gas, and uranium energy resources is the responsibility of agencies other than the Geological Survey of Pakistan; therefore, these commodities were not studied, although oil field sites are indicated for general information on plate H1, the commodity distribution map.

Reconnaissance field checks were made of sedimentary deposits (or sedimentary-hosted hydrothermal deposits(?)) and vein-hosted hydrothermal deposits. Sediment-hosted deposits were reported previously (Fleming, 1852; Crookshank, 1954; Gilani, 1981; Abbas, 1985); vein deposits are newly recognized as potential targets. Because the sediment-hosted deposits had been tested and described (Gilani, 1981), our effort concentrated on the veins, mainly through geochemical reconnaissance. Iron occurrences are treated with the sedimentary rock-related commodities to which they are genetically related. This limited focus to our field efforts, plus some key geological observations of rock conditions, restricted the area in need of testing to a manageable extent. The process of selecting a worthy topic of field investigation, aimed at extending resource knowledge and manageable in the few weeks of available field time, plus support from existing chemical laboratories at the Geological Survey of Pakistan, was of itself a part of our training-by-doing operation.

It was also determined that the resource chapter would not treat the widely distributed but economically vital commodities, usually developed locally, such as sand and gravel, road metal (crushed rock for construction needs), brick clay, and common building stone. Commonly, their sources are only located close to markets, and their further development is unlikely to be influenced by contributions we might offer.

Remaining for consideration are, mainly, salt (NaCl), gypsum, cement rock (limestone), and certain clays, as well as less common occurrences of other clays, glass sand, potash salt, celestite, ocher, and barite. Some of these materials are utilized in local industries; others are not utilized, in part, because their abundance is too sparse or quality too poor.

Other commodities are mentioned for completeness rather than for their significance. Alluvial gold and jadeite have been obtained from the Indus River deposits in the Potwar Plateau area. Details on these occurrences remain unknown to us, and we suspect this signifies the deposits were economically submarginal. In any case, testing for such occurrences was not feasible, mainly because the river was accessible by vehicle in very few places.

As a result of all these considerations, we show on plate H1 primarily two kinds of data. First, the sites of known industrial commodities and those metals not further tested are shown. Second, we show the sample sites and elements in anomalous abundance from our study of vein geochemistry. Both kinds of data are briefly described in tables H1 and H2 (tables follow References Cited), keyed to the commodity distribution map (pl. H1).

Additionally, large steep faults and intrusive igneous rocks, which can offer channelways for hydrothermal fluids migrating upward, were checked in a cursory manner for mineralization. This check turned up only a few sites on faults containing visibly mineralized rock and only a few sites providing geochemical anomalous results. The chief exceptions concerned a vein along the Panjal thrust fault in the Hazara Range (fig. H2).

Thus restricted in field scope and commodity types reviewed, we had a feasible objective that could offer an opportunity to gain new insights into the resource potential of a large region, while illustrating how such an investigation might benefit by a team approach.

Project Methods

Various work methods were utilized in an effort to adapt to particular field and office situations. Initial field efforts were directed toward getting acquainted with rocks, faults, and outcrop conditions, learning to utilize old reports, and managing without the base maps. During visits to potentially mineralized sites, grab samples were taken of altered rock, veins, and alluvium, according to what was present. Typically, each sample consisted of about six or eight chips 4–8 centimeters (cm) across, or as many handfuls of alluvium, from which a surface layer, organic material, and pebbles were removed.

Many of the samples taken during the first field visit (1989) were analyzed in a laboratory of the Geological Survey of Pakistan before the second field visit (1990). Results of the first round of sampling were thus useful in sharpening our focus on what and where to collect during the second field season, namely, the quartz veins in the northernmost ranges. Field work and analytic work were completed, and an industrial commodity map was compiled during a second phase of the study.

Project Results

The rocks in much of the Potwar Plateau region are unsuitable as hosts of metallic mineral deposits. That this region was not prolifically endowed with metal accumulation has long been known; the ancient Indus Valley cities, such as Harappa, obtained their copper from western Baluchistan, probably as smelted but unrefined copper, to judge by the small accumulations of slag at that city. In essence, then, most of the study area is assessed as having a low potential for vein deposits because the rocks are too poorly indurated, which probably reflects their very shallow tectonic position and young geologic age. The absence of young intrusive rocks is also a major detrimental factor. Sedimentary ore deposits are also expected to have a low potential here because a rapid rate of deposition characterizes the rocks, thereby diluting, rather than concentrating, the deposits from any favorable process leading to sedimentary occurrences of metals.

The remainder of the study area does have rocks with sparse veins, and some of these do carry anomalous concentrations of base, precious, and indicator metals, which suggest past hydrothermal activity (pl. H1). The resource potential rating for these parts of the study area is thought to be low because of the absence of other favorable factors from geologic sources as well as from geophysical data. Results from a more systematic geologic and geochemical reconnaissance could change this rating, particularly in the oldest, deepest tectonic-level rocks of the northernmost ranges, which are not covered by any geophysical study. Consequently, the terrane of scattered veins is divided into two assessment tracts, distinguished by the degree of confidence with which the low potential rating is assigned. Basically, we conclude that, although present knowledge of the northern ranges has some favorable signs for vein-type ore deposits, they are sparse. However, too little geological, geochemical, and geophysical work has been done there to discount the possibility completely.

The industrial commodity distribution is compiled on plate H1. Although tracts of favorability are not delineated on the map, their potential for further development is reviewed below. This potential varies markedly among the commodities, being particularly good for those already in major production, such as salt, gypsum, cement rock (limestone), and certain clays. The assessment of coal is covered by Warwick and Shakoor in chapter I of this volume.

An unexpected result of this project was the realization that what was seen in the Potwar Plateau area applied also to southern Arizona and New Mexico. Both areas lie in the frontal half of an orogen. There are, of course, differences in age of deformation, as well as in the composition of the subducted plate. The Arizona-New Mexico deformation is older and took place at 40–50 million years ago (Ma). Because of this age difference, the Pakistan analog showed what the conditions of youngest cover rocks might have been like in Arizona-New Mexico during the Eocene (Drewes, 1991), with that cover subsequently eroded.

General Geologic Relations

In the Potwar Plateau area, the occurrence of anomalous concentrations of metals and industrial commodities is associated with certain geologic features—some formations, a few faults, and particularly veins and dikes—which are therefore briefly described herein. For a general review of the local structural and tectonic setting, refer to chapter A (by Warwick) of this volume and Drewes (1995).

Regional Setting

The Potwar Plateau area lies along the distal part of the southern flank of the Himalayan orogen (figs. H1, H2). This orogen developed through the collision of the Indo-Australian and Eurasian continental plates beginning at least as long ago as the Cretaceous and is still progressing (LeFort, 1975). During an early stage of convergence of these continental plates, the intervening Tethyan seaway was closed, and its deposits were deformed, massively intruded, and, along the central zone, intensely metamorphosed. As convergence continued, the orogen grew wider, extending chiefly southward but also northward. As a result of this development, the tectonic zones typical of such orogens, namely, foreland area, fold-and-thrust zone, imbricate (shingled)-thrust zone, and core zone with its suture line, formed and gradually shifted toward the orogenic foreland. Deep beneath this belt of deforming rock, the Indo-Australian plate was subducted beneath the Eurasian plate. At present, the forward or southerly propagation of the deformed zones is still in progress, and internally, the orogen is undergoing rapid uplift and erosion to ever deeper tectonic levels. The basic tectonic features are shown by Kazmi and Rana (1982).

Along its axis, the orogen has irregularities in the form of arcuate lobes and syntaxes. A major orogenic lobe occupies easternmost central Pakistan and northern India. Another such lobe, with modifications, extends through western Pakistan. Between these major lobes, the Potwar Plateau region and its southern marginal Salt Range form a minor lobe (fig. H2). Syntaxes separate this minor lobe from the adjacent major lobes. These syntaxes are complex features whose margins record a variety of strike-slip, oblique-slip, and normal faults, as well as some lateral thrust faults. Syntaxes in metamorphic terranes show considerable upward ductile flowage; the rocks of the study area are more typically deformed in a brittle style.

The terrane southeast of the Salt Range makes up part of the Indo-Gangetic foreland basin of the Himalayan orogen, whose successor depocenter axes parallel the frontal line, and the various tectonic lobes. South of the foreland basin, or locally at uplifts within it, as at the Sargodha Hills, 80–120 kilometers (km) to the southeast, bits of the Indo-Australian plate are exposed in knobs of Proterozoic metasedimentary rocks rising boldly above the flood-plain deposits (fig. H2).

Proterozoic metasedimentary rocks, which may be Tethyan basement, are also exposed in the northernmost part of the study area. Just north of the western part of the study area is the intramontane Peshawar Basin, a major tectonic sag (Yeats and Hussain, 1987). Proterozoic and Paleozoic rocks lie north of this basin, and a few tens of kilometers north of the eastern part of the study area are granitic stocks and the

Kohistan island arc complex (Yeats and Hussain, 1987; Pogue and others, 1992).

Key Geologic Features of the Potwar Plateau Area

The Potwar Plateau is a low-relief upland except where dissected by the Soan River and its tributaries (fig. H2). South of the plateau are the somewhat arcuate Salt Range, and its eastern and western extensions along the syntaxes, and the alluvial areas of the Indus and Jhelum Rivers. To the north of the plateau are, first, a zone of deformed Tertiary to Paleozoic sedimentary rocks and, then, a zone of Proterozoic metasedimentary rocks appearing in aligned moderately high mountain ranges. Each zone has a distinctive tectonic style and suite of rocks. These features are summarized with emphasis on only those rocks and structures of key interest to the resource assessment.

The Potwar Plateau is underlain mainly by Miocene to Pleistocene clastic rocks of the Rawalpindi and Siwalik Groups. (By Pakistani convention, the latter group is known simply as "the Siwaliks," a usage followed herein.) These rocks are generally so poorly indurated that they hold no fractures and thus offer few avenues of concentration for mineralizing fluids. The rocks form an open syncline (the Soan syncline, fig. A4 in chapter A of this volume), whose flanking anticlines contain oil traps at moderate depth. These rocks and structures overlie the rocks that crop out in the Salt Range and its eastern and western extensions. The northwest syncline flank is cut by shingled thrust faults having moderate amounts of displacement and involving only Neogene rocks.

The Salt Range zone is underlain by Eocambrian, Paleozoic, Mesozoic, and Paleogene rocks of a major thrust plate. The underlying northwest-dipping Main Frontal thrust fault, locally known as the Salt Range thrust fault, is spatially associated with the Salt Range Formation, a thick marl unit containing abundant salt and gypsum. Salt tectonism has strongly affected the rock sequence of this zone, particularly the lower part; salt and gypsum masses have moved from their initial stratigraphic position, probably from early times to the present, into overlying rocks, both along faults formed by regional tectonic stress and faults formed by the flowage of the salt itself and the consequent settling of overlying rocks of abundant limestone and shale and some sandstone and dolomite units. Of key interest are the salt and gypsum-bearing Eocambrian Salt Range Formation, the Lower Permian Warchha Sandstone and its local poor-quality coal seams and reported sedimentary-hosted metals, and two Jurassic units, the Chak Jabbi Limestone used as cement rock, and Datta Formation that contains glass sand and interbedded fire clay. Also of local interest are the Paleocene Hangu Formation, which has some oolitic iron ore and locally has coal seams, and the Patala Formation, which contains some clays and coal.

The subsurface rocks of the alluvial plains to the south remain largely unknown except for data from scattered oil wells. Baker and others (1988) indicated that Siwalik rocks directly overlie Paleozoic rocks just south of the Salt Range. In places to the east and west, the flood-plain deposits are underlain by the Siwaliks, typically folded and locally upended by the tectonic encroachment of the rocks above the Salt Range thrust fault. Near Mianwali, unpublished geophysical data from the Oil and Gas Development Corporation of Pakistan (OGDC, 1962, 1963) suggest the presence beneath the alluvium of a salt or gypsum stock, which implies a subsurface extension of the Eocambrian rocks and perhaps also some other units of the Salt Range.

The zone of Paleozoic to Tertiary sedimentary rocks north of the Potwar Plateau is characterized by shingled thrust faults and moderately tight abundant folds trending east-northeast (Yeats and Hussain, 1987). The southernmost and structurally lowest fault is the Main Boundary thrust fault, which dips north-northwestward; movement along this fault has placed Paleocene, Mesozoic, and Paleozoic rocks on the Miocene and younger rocks. Cement is produced from rocks of the Precambrian Shekhai Limestone and the lower Eocene Margala Hill Limestone. The Paleocene Hangu Formation and Lockhart Limestone have some coal seams, bauxite, and clays. These rocks contain calcite veins; many carry anomalous amounts of base metals; and a few also have silver, mercury, and arsenic.

The northernmost zone is underlain by Proterozoic metasedimentary rocks, namely, argillite, subgraywacke, phyllite, and, locally, phyllitic schist, which are thrust upon the Paleozoic and younger rocks of the Main Boundary thrust plate. The Panjal thrust fault separates these zones; it is commonly seen in outcrops as a reverse fault, but it is believed to flatten downdip to the north-northwest. These rocks are cut by quartz veins; those of the northwest flank of the northernmost range, the Gandghar Range, grade into aplite sheets by way of feldspar-bearing quartz veins that follow the same fracture system as the quartz veins.

Industrial Rocks and Minerals

Industrial rocks and minerals of the Potwar Plateau area are characteristically hosted by the Cambrian to Paleogene sedimentary formations and, therefore, occur in the Salt Range and in the zone of shingled thrust faults and folds. The economically important commodities are salt, gypsum, cement rock, and certain clays. Also mined from moderate-sized deposits, or on a part-time basis, are dolomite, other clays, and building stone. Still other commodities such as potash salt, celestite, barite, and alluvial jadeite were mentioned in the compilation of Ahmad (1969) but may not have had any systematic production. The distribution of these commodities is shown on plate H1, which is keyed to a summary of specific occurrences on table H1. Data on this plate and table were generated chiefly by Ahmad (1969); some new work on clays was obtained from Whitney and others (1990) and from unpublished sources.

Salt

Salt has long been mined in the Salt Range, thereby giving the mountains their name. Salt, as used in this report, means common table salt, also referred to mineralogically as halite or chemically as NaCl. Salt is widely used in industrial processes, as a preservative, and as a food additive. The earliest time of salt production is likely to have preceded the beginning of historical records, for the Indus Valley was the site of an ancient civilization, and the salt in the Salt Range was accessible at the surface. However, as salt from the surface sites was depleted, the need increased to locate deeper deposits. As a result, knowledge of its field occurrence and structural habits became important.

Salt is typically an evaporite obtained directly from the sea or indirectly from an ancient sea in the form of rock salt. Salt is commonly associated with other evaporites, such as gypsum, dolomite, limestone, and potash salt. Initially, rock salt is distributed as a bedded deposit like the associated carbonates, clays, and marls. However, because salt has a low specific gravity relative to the associated rocks and because it recrystallizes readily, it tends to flow upward in response to load or to tectonic stress. Primary bedded salt may thus be intruded as a secondary deposit in plugs. In these secondary occurrences, the bedded aspect of salt and associated rocks is disrupted and, in some plugs, is gradually obliterated, leaving a chaotic mixture of salt and gypsum pods among contorted layers of clay, marl, and carbonates. In developing such plugs, material is transferred laterally along the initial bed to the site of upward injection, thereby allowing overlying rock to collapse over depleted parts of a salt bed. This results in a network of block faults, some of which are also intruded by salt and clay.

Being as old as Eocambrian, the Salt Range Formation has probably been mobile in response to diverse stresses for a long time. The load of overlying Paleozoic rocks probably initiated flowage. Downwarping of the base of the Tethyan seaway, largely during the Mesozoic Era, likely set up new crustal stress to which salt movement responded. Later, the collision of the Indo-Australian and Eurasian continental plates generated compressive stress that resulted in the folding and thrust faulting of rocks, and some of that thrust faulting focused on the mechanically weak layer of the Salt Range Formation. The salt thus acted as a tectonic lubricant and, in turn, was chaotically injected into subordinate and mostly steep faults. Even at the present land surface, the salt and gypsum are sites of extensive slump masses, which had not been separated from intrusive salt masses on the geologic maps of the Salt Range (Gee, 1980).

In the Salt Range, the potential for finding additional bodies of salt is high, although doing so is likely to be challenging. The larger intrusive masses should be most attractive for exploration. The determination of targets that may contain large deposits is hampered, however, by the present lack of detailed mapping of extensive slump fields along the southern flank of the Salt Range. Additional mapping is needed, such as that done by the Pakistan Mineral Development Corporation (PMDC, 1986), to distinguish surficial masses of salt-bearing rock from intrusive masses. Additional detailed gravity studies, such as those conducted by Ahmad and others (1979), may be helpful in furthering subsurface exploration. Certain other geophysical tests may also be effective.

An additional area for the possible occurrence of salt or gypsum is in the plains near Mianwali (pl. H1), where a strong negative gravity anomaly suggests the presence of a plug of rock with low specific gravity beneath the alluvium. The possible depth of such a plug may be modeled through the addition of a ground gravity study to the airborne gravity study. An added attraction to the inference of a blind salt plug is the possibility of finding oil and gas traps flanking the plug.

Other sites of negative gravity anomalies occur along certain faults, such as the second large fault north of the Soan River (fig. H2). These anomalies probably indicate that faulting was facilitated by salt or gypsum intrusion along lower reaches of the fault. However, there is no evidence of either the depth, extent, or kind of salt present here, and as long as shallow bodies are available, deep mining of salt pods seems unattractive.

Gypsum

Gypsum ($CaSO_4$•$2H_2O$) and its anhydrous form, anhydrite ($CaSO_4$), are other important industrial commodities abundantly present in the Potwar Plateau area. They are widely used in the construction industry as an additive to cement and a base for the manufacture of plaster; they are also used as a soil conditioner in agriculture. Although associated with salt in many places, they are commonly more widespread than salt. In the Potwar Plateau area, they are not only found in the Salt Range Formation, but occur also in the Cambrian Khisor Formation, the Permian Sardhai Formation, and the Eocene Datta and Kuldana Formations.

Gypsum has an origin and many physical properties similar to those of salt. Large amounts of relatively pure gypsum are obtained largely from the Salt Range Formation (pl. H1); the other sources mainly satisfy local agricultural needs. The potential for developing additional gypsum resources is similar to, but probably better than, that for locating more salt. The bodies in the Salt Range Formation are likely to be podiform but may be purer than those in other formations. Major bodies are likely to occur at the larger plugs, and these may be found at major fault intersections. The development of an expanding market for gypsum is likely to be of greater concern than the finding of more of this commodity.

Cement Rock

Cement rock contains limestone or marlstone sufficiently free of silicon, iron, and magnesium and has a suitable ratio of carbonate to clay (generally 9.5:1). In the Potwar Plateau area, these conditions are met by the Chorgali Formation and the Margala Hill and Lockhart Limestones, all of Tertiary age, and by the Cretaceous Kawagarh Formation, the Jurassic Samana Suk Formation, and the Precambrian Shekhai Limestone. In places where these rocks are close to markets or to rail lines, they are quarried in large quantity for construction uses.

Because cement rock is present in many formations that are commonly extensive, the likely potential for cement rock production is excellent, and the expansion of existing sites is probably possible for a long time. Doubtless, cement rock may be found at other sites or possibly even in other formations.

Clay

Clay deposits are of several kinds of material that are used for a range of construction and industrial purposes. Most widespread, perhaps, is the clay utilized by the local brick industry in or near many large towns and all cities. Typically, these local kilns use clay from nearby soils, and so this study can do little toward supporting their continued customary development. They are not further considered.

The other clays are the focus of a separate study by Whitney and others (1990). These clays are the important fire clay and the moderately important bentonite, high-aluminum clay, laterite, bauxite, china clay, alum, and ocher. Descriptions of these commodities were given by Whitney and others (1990), but the distribution and summary of occurrences are shown on plate H1 and in table H1.

Most clay deposits occur as lenticular bodies less than a meter thick and at least a few thousand meters long. Shallow pits at most sites operate on a part-time basis, apparently serving some particular local need or industry. Projections of deposits along strike are typically easy to make; few clay deposits have the value to encourage downdip development. Accordingly, areas of gentle relief and flat-lying rocks are likely to be more productive than areas of strongly tilted rock and steep hills. Specialty clays, of course, permit development in geologically less favorable situations.

Other Commodities

Building stone is widely used where readily available, but its availability generally has not been of sufficient concern to lead to the systematic keeping of records. Typically, the stone is hand cobbed from surface occurrences or pried by simple methods from outcrops near markets. Less commonly, building stone is quarried and shaped for dimension stone or crushed for aggregate and ballast. Crushed rock sites may be adjacent to cement quarries and probably are not reported separately. Other sites of building stone, shown on plate H1, may be for dimension stone, for they appear to be of moderately indurated, yet workable sandstone, probably of a kind widely used in the more distant large cities. Sheikh and others (this volume, chap. G) discuss the resources of rock aggregate in the Islamabad area.

Sandstone, referred to as glass sand, is reported as generally present in the Datta Formation east of Mianwali. The vagueness of the site location suggests that the commodity is known or potentially present there but is not mined on an ongoing basis, perhaps because of the absence of a local market. No mention was noted in the literature of its use as an abrasive.

Celestite in calcite veinlets and potash salt near the Khewra salt occurrence are mentioned as “shows” rather than as significant deposits (Ahmad, 1969). Quartz crystal is known at one site, but commodity descriptions are not known. Sulfur is mentioned in connection with pyritiferous black shale, an association hardly likely to have commercial value (Ahmad, 1969).

Metallic Minerals

A minor first part of this review covers several kinds of sedimentary-hosted metallic minerals, probably having only low potential for development. A second part covers base- and precious-metal occurrences of probable hydrothermal association. None of these metals is being exploited; more work may be justified on testing ore, possibly for precious metals in veins.

Sedimentary-Hosted Iron Ore

Subeconomic deposits of iron ore occur at Kalabagh, about 25 km west of the study area, and at Mazari Tang (lat 33°45′ N., long 71°55′37″ E.) in the northwestern part of the study area (pl. H1). The iron ore prospect near Kalabagh has a reserve of about 292 million tons of low-grade (32 percent) hydrous iron silicate that is presently uneconomic. The Mazari Tang deposit, of unspecified tonnage, is a bedded oolitic hematite in Jurassic limestone and has an FeO content of 44.6 percent. Further details are available in Ahmad (1969) and in unpublished reports used by Ahmad.

Sedimentary-Hosted Base Metals

Copper, lead, and tin occur in the Lower Permian Warchha Sandstone and the Permian Sardhai Formation northeast of Mianwali and also north of Nilawahan Gorge (pl. H1) (Fleming, 1852; Crookshank, 1954; Gilani, 1981; Abbas, 1985; Abbas and Qureshi, 1985). Analytical results of preliminary trench samples were not encouraging, and the present review of a second site was also unattractive.

Near the village of Sanwans and 3 km east of Ghundi, both in the Mianwali area, copper and tin minerals were identified in the arkosic beds of the Warchha Sandstone and in sandy shale beds of the Sardhai Formation. The arkose is referred to in some accounts as the speckled sandstone; the flecks apparently are caused by oxidized particles of ore minerals. Some 300 samples were taken in 15 trenches in a study reported by Gilani (1981). Anomalous amounts of metals in an unspecified number of samples were reported from only two of these trenches. The report fails to mention the amount and kind of metals present in the anomalous samples. This sampling study was augmented by an ore microscopy review that indicated (1) that the tin occurs in stannite and cassiterite and as native tin and (2) that the copper occurs in chalcopyrite and malachite. The tin and copper minerals occur as thin shells around other material.

Logistical problems prevented a visit to these sites, but the same formations were examined at nearby sites and at another site (site 22f, pl. H1) along the road to the long-vanished Turta Resthouse, a landmark commonly used in reports of copper and lead in speckled sandstone. Alluvial samples taken downstream from the suspect formations and composite chip samples from the rocks themselves were taken at 11 sites. Only five of these samples had anomalous amounts of arsenic, mercury, lead, and zinc in various combinations; none contained copper, and tin was not tested for. Speckled sandstone was only faintly recognized at a few sites.

Fragmentary data suggest that, although base metals are present, concentrations are low and their distribution is erratic. The potential for occurrence of such base-metal deposits remains low, at a moderate degree of confidence. Nevertheless, it is desirable to address this problem of sedimentary-hosted base metals again with a more thorough and systematic geochemical study.

Vein-Hosted Base and Precious Metals

The combined results of reconnaissance field observations and geochemical analyses indicate a low potential for vein-type deposits of copper, lead, zinc, and silver. These data were inadequate to provide much confidence in the low potential assignment or to provide a basis for more detailed reconnaissance for sites of metal accumulation, but they do indicate that metal-bearing hydrothermal systems are present and that the reconnaissance method used can be fruitful.

Field Observations

Roadside and trailside observations on veins, faults, and igneous rocks provide useful information on alteration and mineralization of rocks in the Potwar Plateau area. The kind and number of such observations were limited by the logistical factors previously explained and by the need to devise a field plan that both utilized available knowledge and resulted in a distinct training objective. In other words, in the brief time available, we wanted to test one exploration concept or technique that could lead to a concrete result. This exploration concept actually grew as field experience was gained and as analytical results were obtained from the laboratory.

Representative and accessible steep structures, namely, faults, dikes, and veins, were initially checked for possible effects of past movement of hydrothermal fluids. Early examination over much of the study area indicated that the rocks of the several successor foreland basins are mostly so young and were so rapidly deposited that they are unindurated or very weakly indurated. According to Van Houten (1969), sedimentation rates were about 0.3 meter per 1,000 years (m/1,000 yr). As a result, the rocks do not fracture, and consequently, fluids passing through them likely would disperse rather than concentrate. Even faults in such rocks offer few advantages to passing fluids. Through this recognition, most of the Potwar Plateau central area, some of the Salt Range, and all of the Indo-Gangetic plain were eliminated from further consideration. The chief exception lay in the oldest of the basin deposits, the Murree Formation, where it was strongly incised in the Murree Hills. In the older, more indurated rocks to the northwest, the occurrence of veins provides useful signs of mineralization.

Major steeply inclined faults were checked at widely spaced intervals. Many of those of the Salt Range were related to salt tectonism and thus were deemed to be tight features that are unfavorable as conduits for fluid movement. Furthermore, these faults are likely to have developed only in the upper plate of the Salt Range thrust fault and thus would not have been practical conduits for fluids rising from great depth. Nevertheless, some of the faults of the area, such as strands of the Kalabagh fault (fig. A4 of chapter A, this volume), a major cross fault within the Salt Range near Choa Saidan Shah, an inferred structure east of the Salt Range lobe, a segment of the Soan thrust fault, and other major thrust faults of the northern part of the study area were checked at selected sites. The thrust faults in this check were steep structures, either reverse faults or reverse-faultlike leading edges or ramp zones of generally flatter features, or they were tilted after thrusting. Their effect, in any case, was that they could have provided egress to rising fluids of the sort that may carry metals. In all cases, faults were barren, except for locally, the skimpiest of iron oxide coating on fracture surfaces and, in a few cases, where veins followed segments of a fault, as was noted along the Panjal thrust fault in the Hazara Range.

Variations in the composition of the veins reflect changes in either the composition of the host rock, the tectonic level, or the proximity to the source of their hydrothermal fluids. In the limestone-rich Paleozoic, Mesozoic, and Paleogene formations, and locally, even in the limestone-poor Miocene formations, the only veins found consisted of calcite. Mostly they are a centimeter or two thick, and there is no obvious systematic orientation. Veins in Proterozoic argillite and phyllite are mainly of quartz. A few veins near the southeastern border of the zone of Proterozoic rocks were of calcite or of quartz and calcite. Veins in the northwestern flank of the northernmost range, the Gandghar Range, were of quartz and feldspar, a few centimeters thick. There, too, thin aplite sheets followed the same general fracture system in which the veins occurred. North of the study area and the Peshawar Basin, at Malakand, aplite sheets make up 5–10 percent of the rock, and nearby is a granite stock that may be a source of the aplite.

A few of the veins in the Gandghar Range carry pockets of iron oxide, possibly limonite pseudomorphs after pyrite, as well as greenish-gray unknown minerals, possibly a matte of fine crystals of chlorite or uralitized amphibole. Near some of the veins in this range, pyrite is abundant in host rocks of sheared black shale 3–10 m thick. These pyrite occurrences are associated with finely laminated algal limestone beds, which suggests that the pyritiferous zones had an organic depositional control, rather than a hydrothermal origin.

Intrusive rocks were examined wherever possible, but the available geologic maps do not record their distribution. In the Salt Range Formation near Khewra are a few dikes composed of trachyte, known as the Khewra Trap (Martin, 1956; Faruqi, 1986). The trap outcrops seen were of large blocks in the salt melange, apparently derived from dikes that once intruded the Salt Range Formation. These are medium-gray fine-grained rocks of conspicuously acicular-textured mafic minerals. In thin section, the mafic minerals appear to be amphibole altered to uralite and iron oxide minerals. Possible pyroxene and trace amounts of iron oxides are also present in the trap rock. It is proposed here that the dikes are somehow related to the Cretaceous-Paleogene Deccan traps of northwestern India. They do not show an association with mineralization.

Diabase dikes occur in and near the Cherat lime plant quarries about 30 km southeast of Peshawar. One such dike of diabase (or diorite(?)) cuts the Precambrian Shekhai Limestone. Neither dike nor host rock was mineralized.

Five dikes and sills were seen on a kilometer-long traverse across the southwest end of the Gandghar Range above the village of Bhedian. These are 1–10 m thick and light to dark greenish gray; one of the bodies had the acicular texture of the Khewra Trap. A sixth dike was seen on another traverse near Dirgi, also in the Gandghar Range. Although none of these six dikes was mineralized, the one at Dirgi was cut by quartz veinlets.

Geochemical Results

A geochemical reconnaissance was part of the vein study; the sampling method gives results of qualitative rather than quantitative significance. The intent was to determine which elements were mobile and their general geologic association. Chemical analyses indicate that most of the quartz veins and some of the calcite veins carry base metals, mercury, and silver in various combinations. The only distributional pattern noted was a concentration of samples with slight silver anomalies in the northeast corner of the study area.

Veins and alluvium were sampled. Samples were composited from 8–10 grab chips, each 1–2 cm across, taken from groups of veins, generally over roadcut or streamcut outcrops, covering 100–200 m in extent. The chips are pieces of vein, as well as altered wall rock, where present. Stream-sediment samples were also composited of 8–10 small handfuls of fine material taken at 10-m intervals across wide washes, or over 100- to 200-m segments of narrow ones. At these alluvium collection sites, the surface layer was first removed, as were pebbles, twigs, and leaves. Sites of possible contamination were avoided.

Rock chips were ground in agate mortars and sieved to –80 mesh. Alluvial samples were simply sieved to –80 mesh. All samples were then analyzed by the Geological Survey of Pakistan laboratory in Karachi for silver, arsenic, gold, cadmium, copper, mercury, lead, and zinc, using an atomic absorption method (table H2). Gold is not shown on the table because it was undetectable at 0.02 parts per million (ppm). Cadmium is not shown because it was undetected at a level of 2 ppm in a first group of samples and was a uniformly low 2–5 ppm in the second group.

In the absence of a regional body of data on normal or background values for the reported elements, judgment of background and anomalous values was made from this suite of samples plus some general experience by the first author in the southwestern United States. In the case of mercury, where analytical procedures or styles of reporting seem to have changed between the two sample groups, separate background values were estimated for each group. On table H2, anomalous values are given in boldface type. We emphasize again, these values have only limited quantitative significance and are intended to show which metals were mobile.

Geophysical Results

Airborne gravity and magnetic maps (OGDC, 1962, 1963) are available for much of the Potwar Plateau study area but do not show precisely that northern tract of greatest geologic and geochemical interest. Perhaps the most conspicuous features on these maps are strong gravity lows at scattered sites in the Salt Range. These are believed to reflect accumulations of considerable amounts of salt or gypsum at shallow depth. Such evaporate pods are, of course, known in many parts of the Salt Range. A similar very strong gravity low appears southwest of Mianwali largely just outside the area of plate H1. As already inferred, this anomaly could mark the site of a blind salt or gypsum plug, which may lie beneath the alluvium at a depth shallow enough to make the feature accessible to exploration.

Similar, but weaker, negative anomalies occur in places south of the Salt Range, as well as aligned a few kilometers north of the Soan thrust fault (Drewes, 1995). Likely, these places are also underlain by intrusive evaporites; the weaker anomalies there suggest either smaller masses, deeper masses of light rock, or a mass having less gravity contrast with adjacent rocks.

A less direct gravity and magnetic signature consists of a northwest-trending linear feature extending roughly across the central Potwar Plateau and Salt Range area. This linear feature is characterized by offsets in the patterns of gravity highs and lows and is believed to be in the lower plate of the Salt Range thrust fault, which probably cuts the Proterozoic rocks of the subducting Indo-Australian continental plate exposed along the Jhelum River lowlands. Here, then, is a subsurface fault that may have guided the upward flow of ore fluids. The upper plate high-angle faults should be tested for signs of mineralization where this inferred subsurface fault is overridden by the Salt Range rocks. Perhaps it is no coincidence that the Khewra Trap rock occurs at its Khewra locality near this proposed basement fault.

Resource Potential and Recommendations

Resource assessment principles used by the U.S. Geological Survey are applied to the Potwar Plateau area. The levels of resource potential and the levels of certainty of such assignment, given in the format of a matrix diagram, appear as appendix H1. To a large extent, the levels of resource potential reflect the kind of geologic evidence applied and the variety and strength of supporting geochemical, geophysical, and remote sensing data. As incomplete or even lacking as these supporting studies are in this case, it is necessary to apply greater emphasis on basic geology and experience.

Three major assessment tracts are identified for metallic minerals, none of which is either high or even moderate. The resource potential is unknown in the extensive flood plains of the south; essentially, no data are available from there. Geophysical coverage of the Jhelum River flood plain is of little help without some ties to known mineralized areas, particularly when the thickness of alluvial deposits and the Siwaliks is unknown.

In the remainder of the study area, the resource potential for metals in all deposit types is low. In other words, there are scattered signs that conditions may be favorable, but they make no useful patterns or association with ore-related features and are not corroborated effectively by other studies. The data from the mineralized veins are cursory; sample collections and analytical results are of interest only insofar as they indicate the possible presence of vein-type deposits of metals not likely to be of economic interest. The significance of these observations is best incorporated into the level-of-confidence factors of the assessment matrix.

Accordingly, our determination of low potential for the Salt Range, Potwar Plateau, and shingled thrust fault zone of Paleozoic and younger rocks is assigned with a high level of confidence, but that of the Proterozoic zone to the north is assigned a low level of confidence. We indicate thereby that, given more extensive geophysical and more thorough geochemical and geologic coverage, this terrane stands a chance that tracts with a higher level of potential will be uncovered.

The resource assessment of industrial rocks and minerals was not undertaken for reasons explained in the introductory section of this chapter. Coal and clays are covered in other reports. Energy resources other than coal are outside the concern of the Geological Survey of Pakistan. The general abundance of some major commodities is apparent through their occurrences in bedded rocks, and for the minor commodities there is either little potential or perhaps no demand, and thus little information is available in the literature. Many practical comments on the diverse commodities, their field setting, beneficiation requirements, and commercial uses were covered by Ahmad (1969).

This resource assessment study leads us to offer several recommendations both for improving the assessment basis and for general improvement in geologic studies and training programs. The most pressing need for a better resource assessment is for completing the geophysical coverage of the northern part of the Potwar Plateau area. Also pressing is the more systematic geochemical reconnaissance of the northern ranges plus the Murree area and, particularly, of those tracts near geophysical signatures of possible blind stocks. Geologic mapping of the three zones of the older rocks should incorporate more observations of dikes, veins, and, if any, altered ground, all features of little interest to stratigraphers.

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Tables H1 and H2 and Appendix H1

Table H1. Summary of industrial and metallic commodities from the Potwar Plateau area, northern Pakistan.

[Commodity deposit size: L, large (>1 million tons); M, moderate (1 million to 100,000 tons); S, small (<100,000 tons, includes small shows and unsubstantiated reports); U, size unreported but likely small. Do., do., ditto; dash (—), no data]

Site (shown on plate H1)	Commodity	Deposit size	Location detail[1]	Reserves (in tons or million tons (mT) where known)	Remarks
1a	Salt (NaCl)	L	Khewra	35 mT	
b	do.	L	Warchha Mandi	2.5 mT	
c	do.	L	Kalabagh	1.0 mT	Salt and gypsum intermittently present in Eocambrian Salt Range Formation.
2a	Gypsum or anhydrite.	U	Choa Saidan Shah	—	
b	do.	U	North of Lilla	—	
c	do.	U	East-northeast of Kattha Saghral	—	
d	do.	U	Northwest of Khushab	—	
e	do.	L	Daud Khel	55 mT	
3a	Limestone (cement rock).	L	Near Spin Kana village	—	Precambrian Shekhai Limestone, in tight folds.
b	do.	L?	Wah Cantonment	—	Probably large reserves.
c	do.	L	Margala Hills	—	Large reserves; Eocene limestone (probably undeveloped resources).
d	do.	U	Tarki	—	
e	do.	U	Northwest of Kulki	—	
f	do.	U	Kagha and west	—	
g	do.	U	Warchha Mandi	—	
h	do.	U	Nali and to east and northwest	—	
i	do.	L	Southeast of Daud Khel	—	Probably large reserves.
j	do.	U	Kalabagh	—	
4	Dolomite	U	16 km north of Khewra	—	Data incomplete.
5a	Iron ores	S	Mazari Tang	—	Hematite; bedded in limestone; 44.6% FeO.
b	do.	L	Kalabagh	292 mT	Hydrous silicate; Fe 32%.
6a	Fire clay	M	Choi area	—	
b	do.	U	North of Chailabdal of Kot Bahadar.	—	
c	do.	M	Wehali Cupi	125,000	Lentil 0.8 m thick; Patala Formation.
d	do.	M	Wehali	400,000	Do.
e	do.	M	Manhiala	800,000	Lentil 1.8 m thick; Patala Formation.
f	do.	U	Nail	—	
g	do.	U	Northwest of Ratuchha	—	
h	do.	L	Dalwal	3.4 mT	Lentil 0.8 m thick; Dhak Pass(?) Formation.
i	do.	U	West of Waralah	—	
j	do.	U	Karuli	—	Average 0.6 m thick.
k	do.	U	North of Karuli	—	
l	do.	S	Goli Wali	—	Average 1.2 m thick; poor quality; Datta Formation.
m	do.	U	Chattawala Nala	—	
n	do.	M	Mozehbazar	650,000	3 beds, each 1–2.8 m thick; Datta Formation.
o	do.	U	Dama	—	

Table H1. Summary of industrial and metallic commodities from the Potwar Plateau area, northern Pakistan.—Continued

Site (shown on plate H1)	Commodity	Deposit size	Location detail[1]	Reserves (in tons or million tons (mT) where known)	Remarks
p	Fire clay	U	Dama	—	
q	do.	L	Dhak Pass	1.7 mT	3 beds, each 0.6–1.3 m thick; Datta Formation.
r	do.	L	Chabil	2.5 mT	3 beds in Datta Formation.
s	do.	U	Mandoha	—	
t	do.	U	Rikhi	—	
u	do.	U	Kharwagnala	—	
v	do.	U	Sirin Nala	—	
7a	Bentonite	U	Dheri Chohan	—	
b	do.	U	Dheri Langhal	—	
c	do.	U	Akori	—	
d	do.	U	Shah Kamir	—	
e	do.	U	Dheri Maliaran	—	
f	do.	U	Pind Savika	—	
g	do.	U	Padhrar	—	
h	do.	U	East of Quadirpur	—	
i	do.	U	Southeast of Bhilomar	—	
j	do.	U	Northeast of Bhilomar	—	
k	do.	U	Chinji	—	
8a	High-aluminum clay.	U	Rattakund	—	Flint clay.
b	do.	U	Nawa	—	
c	do.	U	Sidhandi Dala Dher	—	
d	do.	U	Ratuchha	—	
e	do.	S	Uchhali	—	1.2 m thick; along contact sandstone; Eocene limestone interbedded in sandstone.
f	do.	S	Sarai	10,000	Do.
g	do.	U	Sakesar Hills	—	
9	China clay	U	West of Karuli (Rakh Simbli)	—	
10a	Laterite	U	Choi	—	
b	do.	U	South of Wehali Zerin	—	Occurs with bauxite.
c	do.	U	Northeast of Wehali Bela	—	
d	do.	U	Karuli (Rakh Simbli)	—	Occurs with fire clay.
e	do.	U	Dhok Karuli	—	
f	do.	U	Chambanwala Mohar	—	
11a	Bauxite	S	Near Spin Kana	—	
b	do.	S	Jallozai	—	Occurs along Eocene-Cretaceous unconformity.
c	do.	S	Choi	—	Two sites close together.
d	do.	M	Surg	250,000	Fe-clay along Eocene-Cretaceous unconformity.
e	do.	S	Tanewala Mager (Dherikot)	—	Pisolitic Fe-clay.
f	do.	S	Ganj Bhal (Dherikot)	—	Do.
g	do.	S	Jhalar	—	Do.
h	do.	S	Nawa	—	Do.
i	do.	S	Kawah	—	Do.

Table H1. Summary of industrial and metallic commodities from the Potwar Plateau area, northern Pakistan.—Continued

Site (shown on plate H1)	Commodity	Deposit size	Location detail[1]	Reserves (in tons or million tons (mT) where known)	Remarks
j	Bauxite	S	Mirza	—	Pisolitic Fe-clay.
k	do.	S	Pindi Trer	—	Fe-clay on Eocene-Cretaceous unconformity.
l	do.	S	Gakkar	—	Do.
m	do.	S	Hasan Abdal	—	Pisolitic Fe-clay.
n	do.	S	Kheramar	—	Do.
o	do.	M	Margala Hills	860,000	To 9 m depth; poor grade, pockets along Eocene-Cretaceous unconformity.
p	do.	U	South of Wehali Zerin	—	Occurs with laterite.
q	do.	U	Karuli (Rakh Simbli)	—	
r	do.	S	Nilawahan Gorge	—	Occurs with Fe-laterite.
s	do.	S	Nakkar	—	Do.
t	do.	S	Chambanwala Mohar (Samawali).	—	Do.
u	do.	S	Kattha–Pail	—	
v	do.	S	Arara	—	Do.
w	do.	U	Kattha Saghral	—	
x	do.	U	Kattha	—	
y	do.	U	Chambanwala Mohar? (Kathwai).	—	Do.
z	do.	S	Zaluch Creek	—	Occurs with laterite.
zz	do.	S	Daud Khel (Paikhel)	—	Do.
12	Alum	S	Kalabagh	—	Occurs in shale.
13a	Celestite	S	East of Jaba	—	Irregular veinlets.
b	do.	S	do.	—	Do.
c	do.	S	West of Jaba	—	Do.
d	do.	S	Daud Khel	—	Do.
14	Potash salt	S	Northeast of Khewra	—	Associated with impure salt and marl.
15	Ocher	S	Uchhali village	—	Yellow and red ocher.
16a	Building stone	M?	Rawalpindi area	—	Sandstone of Murree Formation, purple sandstone, Cambrian “magnesian” sandstone, and limestone from unspecified quarries.
b	do.	M?	Jutana	—	Sandstone(?).
c	do.	M?	Chammal	—	Do.
17	Quartz crystal	S	Mari and Kalabagh	—	Occurs in gypsiferous marl of Salt Range Formation.

Table H1. Summary of industrial and metallic commodities from the Potwar Plateau area, northern Pakistan.—Continued

Site (shown on plate H1)	Commodity	Deposit size	Location detail[1]	Reserves (in tons or million tons (mT) where known)	Remarks
18a	Sulfur	S	Panoba	—	
b	do.	S	East of Margala Pass	—	
c	do.	S	Luni-i-Kasi	—	From pyritiferous black shale.
19a	Barite	S	Tipra	—	$BaSO_4$ 87%; veins in Hazara Formation.
b	do.	S	Faquir Muhammad	100	$BaSO_4$ 58%–92%; with quartz veins in Eocene limestone.
20	Antimony(?)	S	Karangli Hill	—	Veins; stibnite(?) may be misidentified galena.
21a	Lead	S	Southwest of Faquir Muhammad	—	Galena in quartz-barite veins in Eocene limestone.
b	do.	S	Karangli Hill	—	Galena in "magnesian" sandstone.
c	do.	S	Khewra	—	Do.
d	do.	S	East of Musa Khel	—	Galena in Cambrian "speckled" sandstone.
22a	Copper	S	Nilawahan Gorge	—	Cuprite and malachite in "speckled" sandstone.
b	do.	S	Lufiaria	—	Do.
c	do.	S	Kharli	—	Do.
d	do.	S	Kattha-Pail	—	Do.
e	do.	S	Warchha	—	Do.
f	do.	S	Turta (site abandoned)	—	Cuprite and malachite in "speckled" sandstone; Turta Resthouse no longer shown on maps.
g	do.	S	Turta (alternate site)	—	Do.
23a	Glass sand	M?	Salt Range east of Mianwali and to northwest.	—	Datta Formation; probably a resource not site specific.
b	do.	M?	Salt Range northeast of Mianwali.	—	Do.

[1]Only selected features shown on plate H1.

Table H2. Concentrations of selected elements (in parts per million) determined by geochemical analyses of reconnaissance samples from the Potwar Plateau area, northern Pakistan.

[Elements also tested for but not found in anomalous abundances: Au, Cd. Analysts: A.A. Mahmood and Z.A. Khan (Geological Survey of Pakistan, written commun., 1989, 1990). Analytic results in bold face considered anomalous. Do., do., ditto;. <, less than]

Sample number	Field number	Geology: Host or source[1]	Geology: Rock analyzed	Element and anomaly threshold (ppm): Ag (2)	As (10)	Cu (40)	Hg (15)/0.1[2]	Pb (50)	Zn (50)	Remarks
1	89D30	Hazara Formation	Alluvium	<2	<5	29	14	23	**89**	New galvanized pipe in canyon (nala).
2	29	Limestone in Hazara Formation.	Calcite veins, specularite.	<2	<5	19	[2].09	20	20	Some autoclastic breccia.
3	28	Shekhai Limestone	Diabase or diorite	<2	<5	16	**18**	12	28	Epidotized quartz and calcite gouge.
4	27	do.	Quartz and calcite veins.	**2**	**11**	23	**85**	20	**270**	FeO stained.
5	90D36b	Murree Formation	Calcite veins	<2	<5	39	.09	20	**100**	
6	36a	Dachner Formation	Alluvium	<2	<5	21	.092	20	40	
7	34	Hazara Formation	Quartz veins	<2	<5	**42**	.06	**200**	**250**	
8	35	Fault zone	do.	<2	<5	38	**.1**	**300**	**120**	Fault between Dachner and Patala Formations.
9	89D35	Samana Suk Formation.	Calcite veins	<2	<5	11	.7	42	20	FeO stained.
10	90D37	Hazara Formation	Quartz veins	<2	<5	**113**	**.101**	**140**	**60**	Do.
11	89D31	Uch Khattak Limestone.	Calcite veins, altered pyrite.	<2	<5	30	**.88**	**460**	**160**	
12	32	Manki Formation	Calcite veins	<2	<5	**88**	**1.03**	20	**140**	Do.
13	33	Uch Khattak Limestone.	do.	<2	<5	**55**	**39**	**81**	**128**	FeO, boxwork structure.
14	90D38	Hazara Formation	Quartz veins	<2	<5	21	.092	20	40	FeO stained.
15	39	Dachner and Manki Formations.	Alluvium	<2	<5	39	.085	40	**120**	
16	89D34	Hissartang Formation	Calcite veins	<2	<5	19	**.73**	42	40	
17	25	Hazara Formation	Quartz/aplite veins	<2	5	**380**	.075	20	20	Veins sheared like host.
18	90D24	do.	Alluvium	<2	<5	**43**	.088	40	**140**	
19	19	do.	Graphitic shale	<2	**13**	**140**	.08	**60**	**180**	Quartz pods; FeO in shale, sheared.
20	20	do.	Graphitic shale, pyrite.	<2	**32**	**215**	.09	**80**	**440**	Quartz pods, FeO.
21	89D68	Samana Suk Formation.	Calcite veins	**3**	<5	7	8	26	10	Gash fractures.
22	90D22	Hazara Formation	Quartz veins	<2	<5	**185**	.081	**160**	**80**	Some host garnetiferous.
23	30	do.	Quartz/aplite veins	<2	<5	38	.065	**120**	40	
24	28	do.	Graphitic shale	<2	<5	**61**	**.125**	20	**200**	Quartz-aplite pods; altered pyrite.
25	17	Kingriali Dolomite	Alluvium	<2	<5	37	.09	40	**60**	Alluvium contains andesite, specularite, quartz.
26	18	do.	do.	<2	<5	**104**	**.1**	**320**	**700**	Site and clasts as for sample 30.
27	16	do.	do.	<2	<5	**65**	.08	20	**60**	Alluvium has some andesite; organic material.
28	3	Hazara Formation	Quartz veins	<2	<5	32	.083	40	**60**	FeO stained.

Table H2. Concentrations of selected elements (in parts per million) determined by geochemical analyses of reconnaissance samples from the Potwar Plateau area, northern Pakistan.—Continued

Sample number	Field number	Geology		Element and anomaly threshold (ppm)						Remarks
		Host or source[1]	Rock analyzed	Ag (2)	As (10)	Cu (40)	Hg (15)/0.1[2]	Pb (50)	Zn (50)	
29	5	do.	Alluvium	<2	<5	35	.077	40	**100**	
30	2	Fault zone	Calcite veins	<2	<5	18	0.094	40	40	Pyrite(?), FeO stained.
31	89D67	Hazara Formation	Quartz veins	<2	<5	16	5	41	23	FeO stained.
32	90D 7	do.	do.	<2	<5	19	.089	0	40	Unknown greenish-gray mineral.
33	8	do.	do.	<2	<5	36	.081	20	**60**	FeO stained.
34	11	Hazara Formation	Quartz veins and pyrite.	<2	<5	31	.082	**60**	40	Synclinal keel of limestone; specularite.
35	12	do.	Quartz and calcite veins.	<2	<5	**67**	**.105**	20	**80**	Sheared margin of limestone unit.
36	13	Fault zone	Calcite vein, gouge	<2	<5	15	.080	20	20	Fault between Hazara Formation and Margala Hill Limestone.
37	89D63	Hazara Formation	FeO stained slate	<2	<5	**49**	.07	40	**60**	FeO along fractures.
38	64	do.	Quartz veins	<2	<5	7	3	26	39	FeO alteration, amphibole(?).
39	65	do.	Alluvium	<2	<5	30	9	31	**124**	
40	66	do.	Quartz veins, FeO zones.	<2	<5	**137**	**40**	10	**313**	
41	62	Cretaceous limestone	Calcite veins	<2	<5	12	.09	40	20	
42	61	Cretaceous shale	do.	<2	<5	11	.088	40	40	FeO stained.
43	36	Jurassic and Cretaceous formations.	Alluvium	<2	<5	12	12	24	30	
44	40	do.	do.	<2	<5	19	**18**	18	39	
45	41	do.	do.	<2	<5	30	**19**	20	**81**	
46	42	do.	Alluvium	<2	<5	14	10	18	31	
47	59	Jurassic limestone	Calcite veins	<2	<5	8	**.77**	40	20	FeO stained.
48	58	Paleocene limestone	do.	**3**	<5	6	14	16	5	Near a major fault.
49	60	Fault zone	do.	**2**	<5	7	1	27	7	Jurassic limestone.
50	48	do.	do.	**2**	<5	6	6	14	5	Paleocene formations.
51	52	Samana Suk Formation.	do.	<2	<5	12	**.93**	40	20	Near major fault; sheared veins.
52	54	Chichali Formation	do.	**3**	<5	5	12	14	15	FeO stained.
53	47	Murree Formation	do.	**3**	<5	5	12	42	7	
54	45	do.	do.	<2	<5	34	**.96**	**60**	20	
55	43	do.	do.	**2**	<5	6	8	48	19	Epidote(?).
56	56	Siwalik Group	do.	<2	<5	10	**.93**	40	20	
57	89D26	Formation contact	do.	**3**	<5	8	8	21	9	Jurassic limestone, Paleocene limestone; FeO stained.
58	25	Lockhart Limestone	do.	**3**	<5	5	1	16	8	FeO stained.
59	23	Cambrian and Permian formations.	do.	<2	<5	5	3	18	6	
60	12	Warchha Sandstone	Alluvium	<2	<5	13	**15**	17	46	No visible copper mineral.

Table H2. Concentrations of selected elements (in parts per million) determined by geochemical analyses of reconnaissance samples from the Potwar Plateau area, northern Pakistan.—Continued

Sample number	Field number	Geology		Element and anomaly threshold (ppm)						Remarks
		Host or source[1]	Rock analyzed	Ag (2)	As (10)	Cu (40)	Hg (15)/0.1[2]	Pb (50)	Zn (50)	
61	13	Cambrian and Permian formations.	Alluvium	<2	<5	12	13	18	**55**	
62	22	Warchha Sandstone	do.	<2	<5	27	10	19	**73**	No visible copper mineral.
63	17	Patala Formation	Coaly shale	<2	<5	16	**21**	12	18	Contains pyrite.
64	18	Warchha Sandstone	Alluvium	<2	<5	25	13	16	30	Do.
65	21	Permian formations	do.	<2	<5	13	4	15	25	
66	20	Patala Formation	Coaly shale	<2	**78**	6	**61**	**2592**	**92**	Do.
67	14	Warchha Sandstone	Alluvium	<2	<5	15	**15**	19	30	No visible copper mineral, coal area.
68	15	do.	do.	<2	<5	14	13	18	27	No visible copper mineral.
69	16	do.	do.	<2	<5	11	10	17	29	Do.
70	10	do.	do.	<2	<5	13	6	20	31	Do.
71	7	do.	do.	**2**	<5	14	8	18	40	Do.
72	8	do.	do.	<2	<5	12	13	13	27	Do.
73	6	Datta Formation	Ferruginous sandstone.	<2	<5	25	10	21	**210**	

[1]Includes some formation names of informal or local usage.

[2]Samples having reported values <1 ppm Hg were probably analyzed in a different way than the others; details of methods are not available. A separate anomaly threshold of 0.1 ppm is used for these analyses.

Appendix H1. Definition of Levels of Mineral Resource Potential and Certainty of Assessment

Definitions of Mineral Resource Potential

LOW mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics define a geologic environment in which the existence of resources is unlikely. This broad category embraces areas with dispersed but insignificantly mineralized rock as well as areas with few or no indications of having been mineralized.

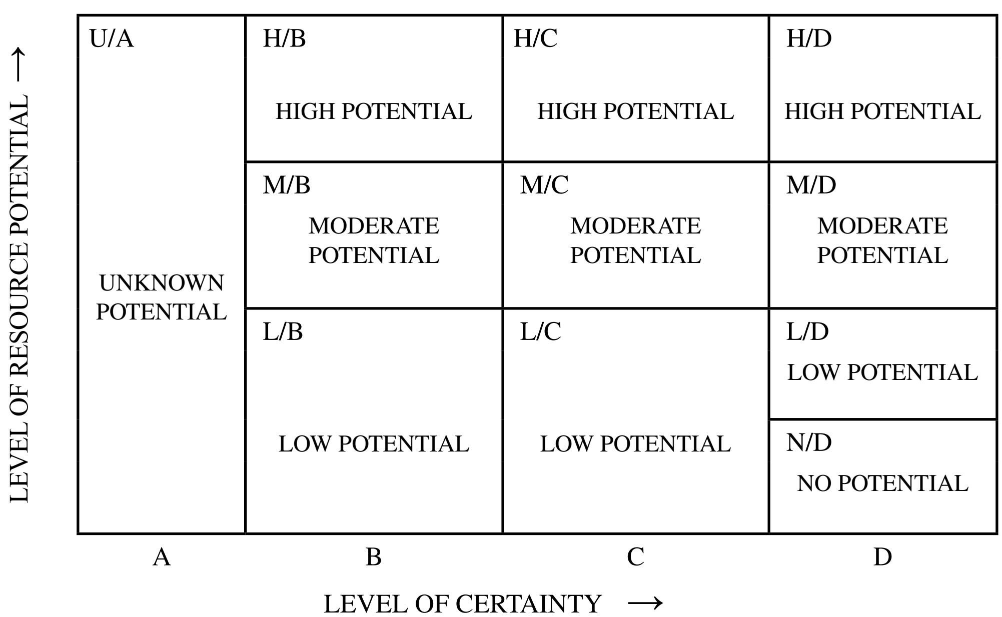
MODERATE mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a reasonable likelihood of resource accumulation, and (or) where an application of mineral-deposit models indicates favorable ground for the specified type(s) of deposits.

HIGH mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a high degree of likelihood for resource accumulation, where data support mineral-deposit models indicating presence of resources, and where evidence indicates that mineral concentration has taken place. Assignment of high resource potential to an area requires some positive knowledge that mineral-forming processes have been active in at least part of the area.

UNKNOWN mineral resource potential is assigned to areas where information is inadequate to assign low, moderate, or high levels of resource potential.

NO mineral resource potential is a category reserved for a specific type of resource in a well-defined area.

Levels of Certainty



A. Available information is not adequate for determination of the level of mineral resource potential.
B. Available information suggests the level of mineral resource potential.
C. Available information gives a good indication of the level of mineral resource potential.
D. Available information clearly defines the level of mineral resource potential.

Abstracted with minor modifications from:

Taylor, R.B., and Steven, T.A., 1983, Definition of mineral resource potential: Economic Geology, v. 78, no. 6, p. 1268–1270.

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Lithofacies and Depositional Environments of the Coal-Bearing Paleocene Patala Formation, Salt Range Coal Field, Northern Pakistan

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Chapter I of

Regional Studies of the Potwar Plateau Area, Northern Pakistan

Edited by Peter D. Warwick and Bruce R. Wardlaw

Prepared in cooperation with the
Geological Survey of Pakistan,
under the auspices of the
U.S. Agency for International Development,
U.S. Department of State, and the
Government of Pakistan

Bulletin 2078–I

U.S. Department of the Interior
U.S. Geological Survey

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Lithofacies and Depositional Environments of the Coal-Bearing Paleocene Patala Formation, Salt Range Coal Field, Northern Pakistan

By Peter D. Warwick and Tariq Shakoor

Abstract

Analyses of measured stratigraphic sections, drill-hole logs, and paleontologic and coal-quality data indicate that the coal-bearing Paleocene Patala Formation in the Salt Range of northern Pakistan originated within barrier-island and back-barrier depositional environments. Facies analysis indicates that the coal beds in the Patala Formation in the eastern part of the Salt Range coal field were deposited in mires in back-barrier environments that were landward of foreshore and nearshore marine sediments deposited unconformably on Cambrian and Permian sedimentary rocks. A north-trending, sandstone-dominated deposit in the western part of the coal field is more than 15 kilometers (km) wide and 20 meters (m) thick; it marks a low-stand shoreline of the Tethys Sea during the latter part of deposition of the Patala. Contemporaneous peat mires developed east of this paleophysiographic feature. Paleobotanic data indicate that the peat mires formed in subtropical to tropical, brackish-water environments.

Individual sandstone bodies throughout the coal field range from a few centimeters to more than 5 m in thickness and are dominated by fine to pebble-sized quartz grains. Sedimentary structures, vertical-facies profiles, and lateral lithofacies relations of rock types in the Patala Formation indicate that the sandstone bodies were deposited as foreshore, tidal-channel, and washover-fan units. Deposition of some sandstone bodies may have been influenced by local contemporaneous basement faulting.

Coal-bed thickness for the Salt Range coal field averages 0.5 m, and a preliminary estimate indicates a resource of 235 million metric tons of coal of bituminous rank. Coal-bed thickness is generally greater where the beds overlie sandstone bodies. This relation suggests that the sandstone bodies served as platforms for thick peat development. Averaged analytical results on an as-received basis indicate that coal beds yield 24.2 percent ash and contain the following (expressed as percent): 9.0 moisture, 5.3 sulfur, 33.5 fixed carbon, 33.3 volatile matter, and 16.1 oxygen. Calculated heating potential expressed as average calorific value is 4,970 kilocalories per kilogram (kcal/kg). Ash yields and sulfur contents are related to the environments of peat accumulation.

Introduction

Coal in Pakistan, although underutilized in the past, has great potential for use in electric power generation (Khan and others, 1990). In order to determine if coal deposits in Pakistan are economic, detailed geologic studies, such as characterization of coal-sample physical and chemical properties, calculations of coal resources, and analysis of depositional environments, must be conducted on all potentially exploitable deposits. Such studies will promote the full development and utilization of coal deposits in this region and may encourage exploration of other potential coal-bearing areas. Moreover, the characterization of lithofacies and the study of depositional environments of particular coal fields help to establish and predict trends in coal-bed chemical and physical characteristics. As shown by numerous studies (Galloway and Hobday, 1983; Ferm and Staub, 1984; McCabe, 1984; Fielding, 1987), the characterization of coal-bearing paleoenvironments has regional and worldwide applications for fossil-fuel resource exploration.

This report contains a review of the coal-bearing Paleocene Patala Formation of the Salt Range area of northern Pakistan (figs. I1, I2). The various rock types within the Patala are discussed along with the chemical and physical characteristics of coal and carbonaceous shale samples. The primary focus of the paper is to present an interpretation of lithofacies and depositional environments for the coal-bearing interval and a discussion on Paleocene regional paleogeography. A detailed assessment of the coal resources, defining reserve categories such as measured, indicated, and inferred, was not undertaken in this study because such estimates would be no better than the general estimates of coal resources given by Warwick and Shakoor (1988b). Future resource estimates should be calculated when and if more drilling data are available or when specific mining blocks may require evaluation.

Figure I1. Index map showing the Salt Range study area (shown in more detail in fig. I2), Makarwal coal field, and selected regional features.

Acknowledgments

This chapter is a product of a cooperative program between the Geological Survey of Pakistan (GSP) and the U.S. Geological Survey (USGS), which was sponsored by the Government of Pakistan and the U.S. Agency for International Development (USAID). Funding was provided by USAID through project 391–0478; Energy Planning and Development Project, Coal Resource Assessment Component 2a; and Participating Agency Service Agreement (PASA) 1PK–0478–P–IC–5068–00.

We are thankful to the Punjab Directorate of Industries and Mineral Development, Punjab Mineral Development Corporation, Pakistan Mine Owners Association, and Pakistan Mineral Development Corporation for providing some of the data that were used in this study. Many individual mining companies throughout the Salt Range provided coal-thickness data and access to their mines for sampling. Robert W. Hook contributed many helpful suggestions and comments to the manuscript.

Regional Geology of the Salt Range

Structural Setting

The Salt Range and Potwar Plateau (fig. I2) are part of the active foreland fold-and-thrust belt of the Himalayas of northern Pakistan (Jaumé and Lillie, 1988; Gee, 1989; Pennock and others, 1989). The Salt Range is an east-northeast-trending thrust front approximately 175 kilometers (km) long that rises abruptly from the Jhelum River plain. Most of the thrusting in the Potwar occurred during the Miocene and Pliocene (Raynolds and Johnson, 1985; Burbank and Raynolds, 1988). To the west, the Salt Range bends northward (fig. I2), where it is bound by a major north-trending, strike-slip fault (Baker and others, 1988; McDougall, 1988; McDougall and Khan, 1990; McDougall and Hussain, 1991). At the eastern end of the range, complex thrusts pass into northeast-trending anticlines (Pennock and others, 1989). To the north, the Salt Range merges with the Potwar Plateau, which is a low-relief upland except where dissected by the Soan River and its tributaries (Yeats and others, 1984).

Within the Salt Range, the structure consists of a narrow zone of intensely folded, faulted, and uplifted rocks, which contrasts with the open folds of low-structural relief of the Potwar Plateau; the sedimentary rocks south of the Salt Range thrust lack structural deformation (Yeats and others, 1984). The upthrown block of the thrust brings to the surface the Salt Range Formation along the southward-facing edge of the overthrust block, which contains evaporites of late Precambrian or Early Cambrian age (fig. I3). These evaporites underlie the Potwar Plateau and form a zone of décollement for regional thrusting (Butler and others, 1987; Jaumé and Lillie, 1988; Pennock and others, 1989).

Overlying the evaporites of the Salt Range Formation is an unusually well exposed sedimentary record of Cambrian, Permian, and younger strata (Gee, 1980, 1989; Yeats and others, 1984). Rocks of Ordovician through Carboniferous, Late Cretaceous, and Oligocene ages are absent, and major uncon-

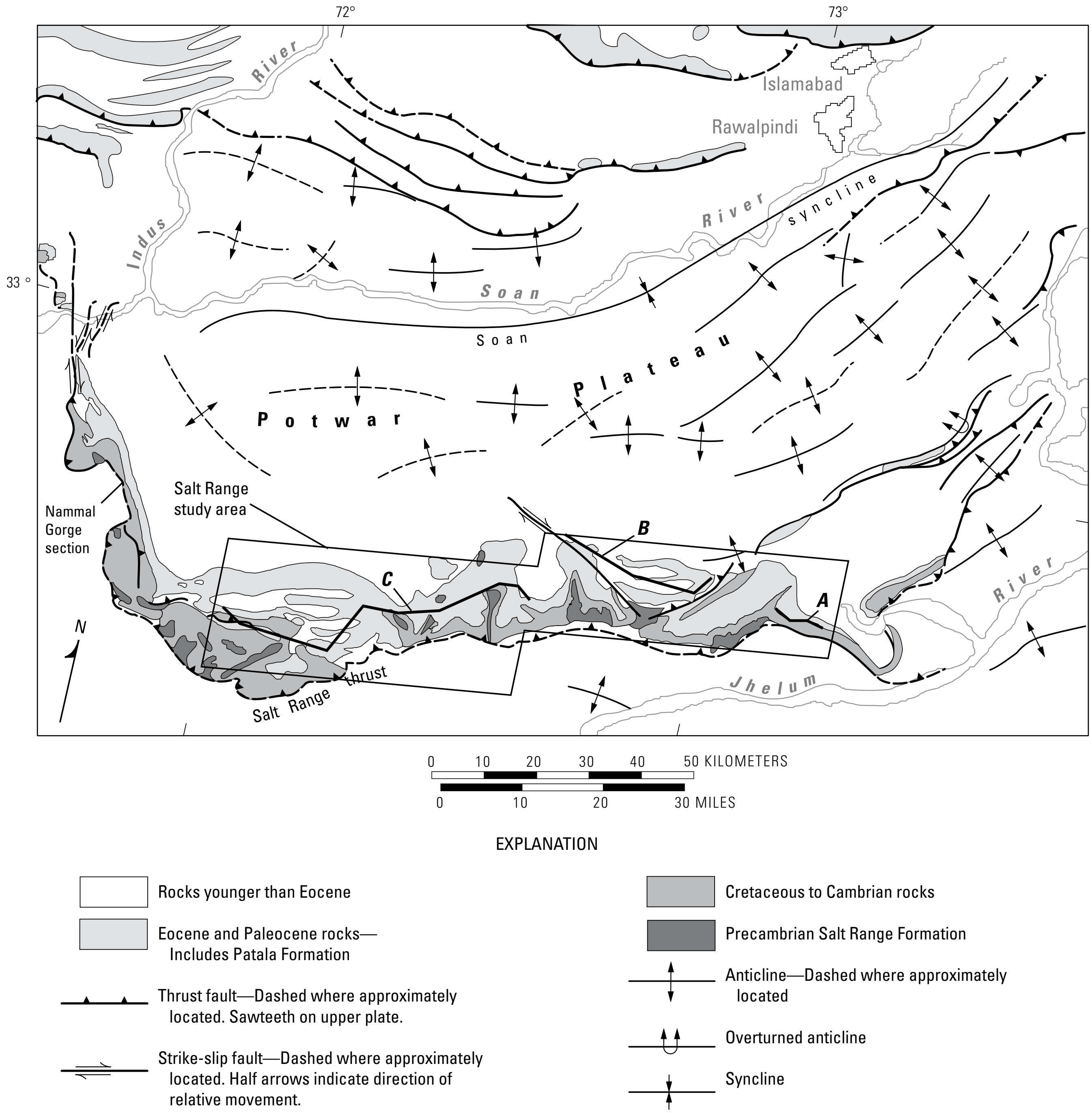

Figure I2. Index map showing the location and generalized geology of the Salt Range study area (modified from Baker and others, 1988). Heavy lines indicate the approximate location of lines of longitudinal section A on figure I8, B on figure I10, and C on figure I11; also see map A, plate I1.

formities exist in the area (Shah, 1980) (fig. I3). North of the Salt Range thrust, this sedimentary sequence dips steeply to the north and is preserved in the subsurface of the Potwar Plateau (Leathers, 1987; Baker and others, 1988). Drilling immediately south of the Salt Range has shown that Cambrian to Eocene rocks are absent (Baker and others, 1988); therefore, the coal-bearing Patala Formation is not present south of the Salt Range thrust.

Stratigraphy

In the eastern part of the Salt Range, Paleocene coal-bearing rocks unconformably overlie Cambrian and Lower Permian rocks (fig. I3). The Cambrian rocks (Baghanwala Formation) consist of beds of pale-red to moderate-reddish-brown siltstone interbedded with mudstone and fine- to medium-grained sandstone (Ghauri, 1979; Khan and Khan, 1979). The

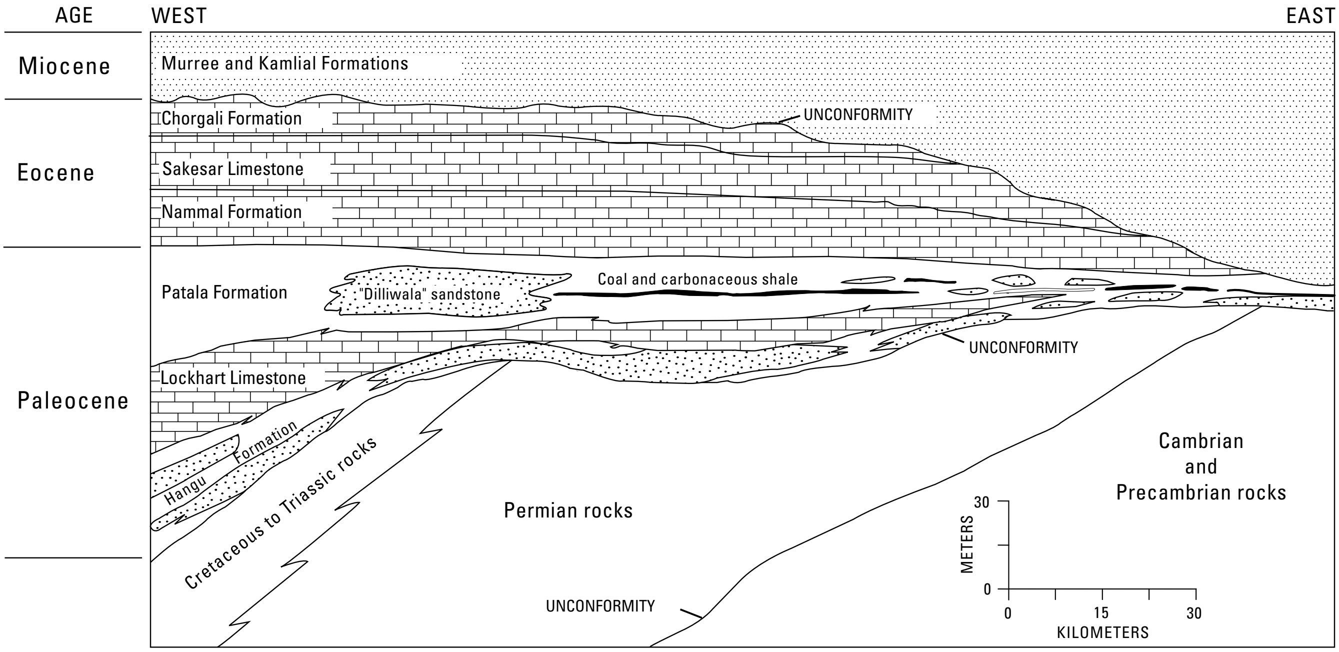

Figure I3. Generalized east-west longitudinal section of Tertiary formations in the Salt Range study area. Stratigraphic control is based on figures I8–I12 (modified from Warwick and Shakoor, 1988b). Stipple patterns, sandstone; brick pattern, limestone; no pattern, undifferentiated rock types. Vertical exaggeration is × 500.

Lower Permian rocks (Tobra Formation and Warchha Sandstone) consist of interbedded mudstone, siltstone, sandstone, and conglomerate that were deposited during the glaciation of Gondwana (Wynne, 1881; Medlicott, 1886; Middlemiss, 1892; Reed and others, 1930; Reed, 1942; Schindewolf, 1964; Teichert, 1967; Ghauri, 1977; Law and Hussain, 1989).

In the eastern and central parts of the Salt Range, the coal-bearing Patala Formation overlies and is associated closely with the Hangu Formation and Lockhart Limestone (fig. I3). The Hangu Formation (0–90 meters (m) thick) consists of light-gray, burrowed, slightly calcareous beds of fine- to medium-grained sandstone, which are usually flat or ripple bedded and interbedded with siltstone, dark-gray mudstone, and minor amounts of carbonaceous shale (fig. I4*A*). The Lockhart Limestone (5–70 m thick) consists of dusky-yellow, nodular, skeletal wackestone to packstone (fig. I4*B*). In the eastern part of the Salt Range, the Lockhart pinches out toward the east (fig. I3).

In the eastern area where the Lockhart is absent, the lower part of the Patala and Hangu are indistinguishable; the resulting unit has mostly Patala characteristics. Therefore, in this chapter, the use of the Hangu Formation is restricted; where the Patala and Hangu are indistinguishable, the rocks are called Patala.

The Patala Formation (5–90 m thick) consists of interbedded claystone, siltstone, mudstone, sandstone, marl, limestone, carbonaceous shale, and coal. The formation conformably overlies the Lockhart and is conformably overlain by thick (>100 m) beds of limestone of Eocene age that consist of the (1) Nammal Formation (shaly, marly, nodular, skeletal mudstone to wackestone), (2) Sakesar Limestone (nodular to massive bedded, cherty, skeletal wackestone to packstone), and (3) Chorgali Formation (interbedded marl and skeletal mudstone to wackestone) (Shah, 1980; Jurgan and others, 1988; Jurgan and Abbas, 1991; Wardlaw and others, this volume, chap. F). The Eocene limestones are unconformably overlain by the Miocene Murree and Kamlial Formations, which consist of beds of greenish-gray and brown, massive, coarse-grained to pebbly sandstone alternating with red and brown clay (Gee, 1980) (fig. I3).

Biostratigraphic and Paleoenvironmental Studies

Some recent biostratigraphic investigations of the Paleocene coal-bearing rocks of the Salt Range are by Köthe (1988), E.M. Brouwers and S.F. Fatmi (1991, written commun.), Afzal and Daniels (1991), Bybell and Self-Trail (this volume, chap. B), Edwards (this volume, chap. C), Frederiksen and others (this volume, chap. D), Gibson (this volume, chap. E), and Wardlaw and others (this volume, chap. F). These reports suggest that the age of the Patala Formation ranges from Paleocene to early Eocene. Nearly all samples collected from 15 locations in the Patala Formation contain the brackish-water palm pollen genus *Spinizonocolpites* as well as dinoflagellate cysts, which led Frederiksen and others (this volume, chap. D) and Edwards (this volume, chap. C) to suggest that the depositional context was near marine and that the paleoclimate was subtropical to tropical. Gibson (this volume, chap. E) studied three limestone and marl samples from a central Salt Range core that were taken 20 m above and 15 m below the

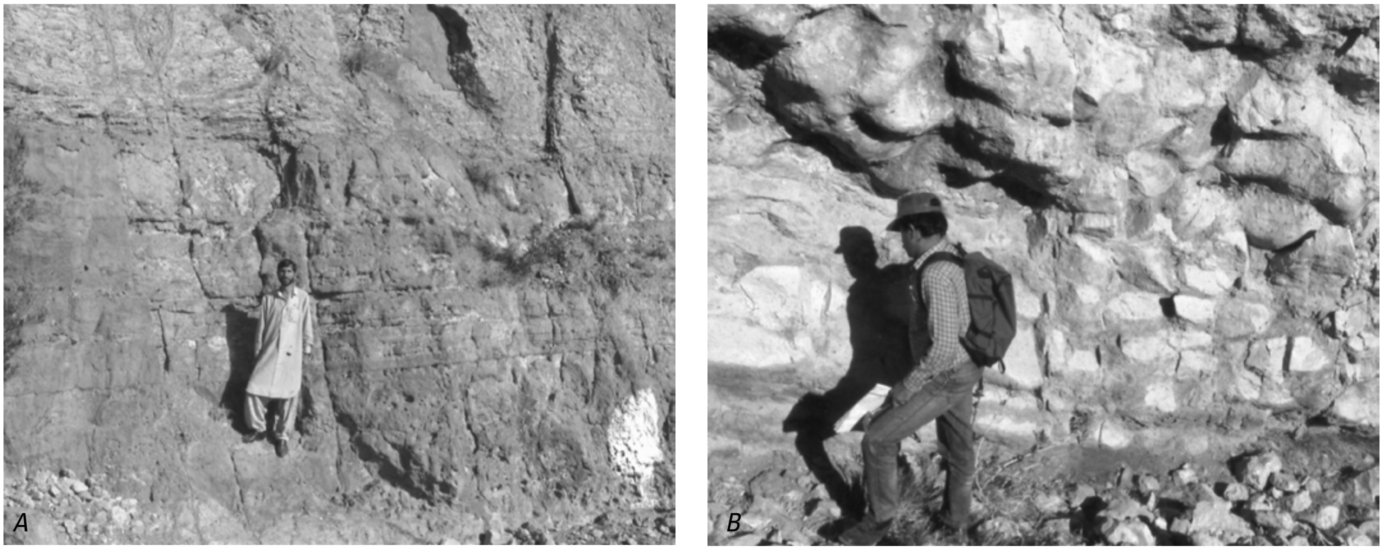

Figure I4. Representative exposures in the western part of the study area of the Hangu Formation (*A*) and the Lockhart Limestone (*B*). The Hangu Formation generally consists of flat-bedded clastic rocks, and the Lockhart Limestone is made up of nodular carbonate rocks.

coal-bearing zone and suggested that the depositional environment for the samples was in shallow to very shallow inner neritic areas at less than 30 m water depth. Afzal and Daniels (1991) studied planktonic and benthic foraminifers from the Patala and Nammal Formations of the western Salt Range and suggested that the rocks were deposited in open-marine, outer-shelf depositional conditions. Shah (1980) was the first to describe Patala barrier deposits in the central part of the Salt Range and informally named them the "Dilliwala" sandstone. Wells (1984), Alam and others (1987), Warwick and Shakoor (1988b), Mashhadi and others (1990), and Warwick and others (1990b) briefly described the depositional environments for the Patala coal-bearing deposits as having been deposited landward (toward the east) of a large barrier-island system near the western end of what is now the Salt Range.

Coal Field Studies

Most coal and carbonaceous shale deposits in the Salt Range are contained within the Paleocene Patala Formation; limited occurrences are in the Lower Permian Tobra Formation (Gee, 1938; Bhatti, 1967; Shah, 1980; Alam and others, 1987). Although the Paleocene Hangu Formation in the Salt Range contains a few carbonaceous beds, minable coal beds (generally >0.5 m thick) in the Hangu are present in the Makarwal area of the Surghar Range (Danilchik and Shah, 1987; Warwick and others, 1995), about 40 km west of the western end of the Salt Range (fig. I1).

Warwick and Shakoor (1988b) presented a review of the stratigraphy of the Patala Formation in the Salt Range coal field and a collection of measured sections and borehole data. They made a preliminary estimate of 235 million metric tons of original coal resources for the Paleocene coal deposits of the Salt Range coal field. Warwick and Hussain (1990) reviewed the stratigraphy, coal characteristics, and resources of northern Pakistan coal fields. They reported that the Salt Range coal field produces about 0.45 million metric tons of coal per year. Chemical and physical characteristics for 60 samples of Salt Range coal and carbonaceous shale were reported by Warwick and others (1990a, b). The apparent rank of the coal was found to be high-volatile C bituminous, and averaged selected analytical results of tests on coal samples are shown in table I1. Warwick and Javed (1990) compared Salt Range coal-quality data with data from other Pakistan coal fields and found that Salt Range coals are similar to other Pakistan bituminous coals.

Methods

This study is based on field work conducted from 1987 through 1989. Stratigraphic sections in Paleocene and associated rocks were measured (maps A–C, pl. I1) along the main Salt Range escarpment and into canyons cut into the escarpment. These sections, along with previously unpublished drill-hole data, were compiled by Warwick and Shakoor (1988b). Additional data were available from Alam and others (1987) and Mashhadi and others (1990) that present the results of a recent GSP coal-exploratory drilling program in the Salt Range. Selected stratigraphic sections and drill-hole logs from these sources and from unpublished GSP data were used to construct longitudinal sections (lines of section A, B, and C, on fig. I2 and on map A, pl. I1) to show the lateral and vertical variation of lithofacies in the lower Tertiary units along the east-northeast-trending Salt Range front. A "best fit" method was employed on each longitudinal section, using the coal-bearing zone as datum.

Table I1. Averaged selected analytical results of tests on coal samples from the Patala Formation listed by area within the Salt Range coal field, northern Pakistan.

[Western area is west of long 72°30′ E.; central area is between longs 72°30′ E. and 73° E.; eastern area is east of long 73° E. *N*, number of samples; avg., average; s.d., standard deviation. All values as received or whole-coal basis except thickness. Data from Warwick and others (1990b)]

	Western coal field			Central coal field			Eastern coal field			Total coal field		
	N	**avg.**	**s.d.**	***N***	**avg.**	**s.d.**	***N***	**avg.**	**s.d.**	***N***	**avg.**	**s.d.**
Thickness (in meters)												
Coal-bed thickness	18	0.42	0.22	13	0.6	0.3	6	0.43	0.15	37	0.49	0.25
Proximate analysis (in percent)												
Moisture	19	9.11	2.93	17	9.15	1.43	8	8.23	2.8	44	8.97	2.4
Ash yield	19	21.8	8.72	17	22.61	8.79	8	33.42	9.68	44	24.23	9.76
Volatile matter	19	34.62	4.7	17	33.75	4.46	8	29.26	3.68	44	33.31	4.77
Fixed carbon	19	34.47	4.95	17	34.48	4.29	8	29.09	5.25	44	33.5	5.1
Ultimate analysis (in percent)												
Carbon	19	50.37	7.45	17	50.07	6.35	8	41.15	7.51	44	48.58	7.74
Hydrogen	19	4.96	.54	17	4.92	.58	8	4.39	.59	44	4.84	.59
Nitrogen	19	.98	.16	17	.86	.13	8	.63	.14	44	.87	.19
Total sulfur	19	6.42	2.88	17	4.09	1.35	8	5.35	2.55	44	5.32	2.52
Pyritic sulfur	19	5.41	2.59	17	2.91	1.43	8	3.42	2.82	44	4.08	2.50
Organic sulfur	19	.86	.86	17	1.04	.44	8	1.76	.91	44	1.1	.61
Sulfate sulfur	19	.14	.07	17	.13	.13	8	.17	.12	44	.14	.1
Oxygen	19	15.44	3.04	17	17.44	2.59	8	15.05	3.75	44	16.14	3.12
Heat of combustion (in Btu/lb)												
Calorific value	19	9,355	1,385	17	9,151	1,225	8	7,521	1,407	44	8,943	1,467
Major element (in percent)												
Al	3	1.04	.24	6	2.57	1.64	2	4.3	3.11	11	2.47	1.9
Ca	3	.19	.05	6	.18	.05	2	.18	.04	11	.18	.04
Fe	3	4.83	2.37	6	2.3	1.11	2	3.4	.28	11	3.19	1.74
K	3	.06	.03	6	.14	.13	2	.23	.18	11	.13	.12
Mg	3	.06	.02	6	.08	.05	2	.07	.05	11	.07	.04
Na	3	.03	.02	6	.05	.02	2	.06	.03	11	.05	.02
Si	3	1.83	.45	6	7.08	7.31	2	13.0	2.83	11	6.73	6.53
Ti	3	.15	.01	6	.33	.19	2	.78	.45	11	.36	.3
Minor element (in parts per million)												
Ag	3	.11	.07	6	.09	.07	2	.08	.02	11	.09	.06
As	19	18.2	17.14	12	9.56	6.19	4	15.97	15.28	35	14.31	14.31
B	3	100.33	29.5	6	121.17	45.51	2	110.0	0.	11	113.45	36.05
Ba	3	18.23	14.42	6	22.12	14.19	2	38.5	36.06	11	24.04	18.07
Be	3	4.9	1.21	6	4.0	1.92	2	1.9	.56	11	3.86	1.81
Br	3	1.57	.81	6	6.88	4.17	2	5.6	1.98	11	5.2	3.86
Cd	3	.13	.05	6	.13	.07	2	.08	.01	11	.12	.06
Ce	19	38.99	34.11	12	21.41	14.67	4	34.55	23.83	35	32.45	28.34
Cl	3	100.0	0.	6	103.33	8.16	2	100.0	0.	11	101.81	6.03
Co	19	6.58	5.86	12	6.61	4.87	4	7.32	8.51	35	6.68	5.68
Cr	19	37.26	27.67	12	31.88	22.23	4	47.72	25.96	35	36.61	25.44
Cs	19	.54	.51	12	.42	.35	4	.69	.6	35	.52	.46
Cu	3	12.27	7.80	6	15.05	6.38	2	15.0	5.66	11	14.28	6.12
Eu	19	.90	.62	12	.56	.38	4	.71	.48	35	.76	.54
F	3	33.33	11.55	6	26.67	12.11	2	20.0	0.	11	27.27	11.04
Ga	1	10.0	0.	6	11.58	5.89	2	13.9	17.11	9	11.92	7.73
Ge	3	15.33	8.5	6	14.77	9.11	2	3.05	.49	11	12.79	8.9
Hf	19	2.53	2.04	12	2.7	1.98	4	5.2	2.03	35	2.89	2.13
Hg	3	.14	.01	6	.02	.02	2	.03	.03	11	.02	.02
La	19	20.06	17.38	12	12.07	8.93	4	19.3	12.75	35	17.23	14.64

Table I1. Averaged selected analytical results of tests on coal samples from the Patala Formation listed by area within the Salt Range coal field, northern Pakistan.—Continued

	Western coal field			Central coal field			Eastern coal field			Total coal field		
	N	avg.	s.d.	*N*	avg.	s.d.	*N*	avg.	s.d.	*N*	avg.	s.d.
Minor element (in parts per million)—Continued												
Li	3	11.53	6.71	6	47.17	31.02	2	66.0	62.22	11	40.87	35.85
Lu	19	.31	.16	12	.24	.15	4	.28	.16	35	.28	.15
Mn	3	23.0	9.54	6	33.0	19.22	2	31.5	6.36	11	30.00	15.09
Mo	1	2.4	0.	6	8.05	2.4	2	13.7	10.32	9	8.68	5.33
Nb	3	5.0	1.9	6	11.47	9.64	2	29.5	6.36	11	12.98	11.24
Nd	3	16.0	4.36	6	16.03	5.27	2	26.0	18.38	11	17.83	8.23
Ni	3	13.57	6.83	6	22.47	13.83	2	26.0	7.07	11	20.68	11.52
P	3	131.03	215.62	6	177.62	140.04	2	103.0	9.9	11	151.34	141.84
Pb	3	11.5	6.95	6	14.67	7.17	2	13.8	5.94	11	13.64	6.4
Pr	3	11.53	7.99	6	4.18	5.35	2	2.9	.28	11	5.95	6.34
Rb	19	41.82	15.18	12	31.21	21.03	4	22.7	14.83	35	35.99	18.23
Sb	19	.35	.18	12	.31	.09	4	.65	.3	35	.37	.2
Sc	19	7.42	5.87	12	5.87	4.08	4	7.15	4.43	35	6.85	5.09
Se	19	9.28	2.78	12	11.77	3.48	4	21.0	6.73	35	11.48	5.04
Sm	19	4.52	3.35	12	2.76	1.87	4	3.77	2.56	35	3.83	2.89
Sn	1	3.5	0.	6	4.6	2.03	2	6.05	4.88	9	4.8	2.48
Sr	3	186.67	60.28	6	142.17	103.85	2	131.0	55.15	11	152.27	83.24
Ta	3	.4	.08	6	.93	.52	2	1.95	.92	11	.71	.71
Tb	19	.64	.37	12	.44	.30	4	.51	.33	35	.55	.34
Th	19	5.89	3.93	12	7.12	3.13	4	12.85	6.58	35	7.11	4.46
U	3	1.89	1.07	6	2.6	1.4	2	9.4	6.5	11	3.64	3.69
V	3	33.0	16.09	6	46.5	24.94	2	76.0	33.94	11	48.18	26.53
W	3	.53	.06	6	1.36	.5	2	2.0	.99	11	1.25	.71
Y	3	16.33	6.11	6	15.62	4.13	2	19.0	4.24	11	16.43	4.42
Yb	19	2.31	1.21	12	1.57	.99	4	2.06	1.12	35	2.02	1.15
Zn	3	67.33	37.81	6	70.83	85.92	2	61.0	43.84	11	68.09	64.68
Zr	3	33.0	2.0	6	579.0	1,235.46	2	315.0	106.07	11	382.0	908.31

Lithofacies of the Patala Formation

The Patala Formation can be divided into several lithofacies, which in decreasing order of abundance are claystone, siltstone, mudstone, sandstone, marl, limestone, carbonaceous shale, and coal. A mudstonelike lithofacies, described by Whitney and others (1990) as a paleosol, is common near the base of the Paleocene sequence in the Salt Range. Outcrop and subsurface information provides local lithofacies characterization of the rocks that are described below. The physical characteristics and distribution of these lithofacies are depicted in figures I5–I12.

Claystone, Siltstone, Mudstone, Marl, and Limestone

The claystone, siltstone, mudstone, marl, and limestone lithofacies make up most of the Patala Formation. The claystone lithofacies is usually dark gray to greenish black and is generally less than 3 m thick. The claystone contains pyrite, either as small disseminated crystals or clusters up to several centimeters in diameter, and burrows, which are commonly filled by pyrite. The claystone lithofacies may be interbedded with light- to dark-gray siltstone or with sandstone streaks and layers that range from a few centimeters to 1 m in thickness. Claystone lithofacies is gradational, and siltstone and sandstone deposits have thin (a few centimeters thick) claystone interbeds that drape over bedforms preserved on bedding surfaces. The claystone lithofacies associated with coal and carbonaceous beds in the middle part of the formation is usually carbonaceous and rooted. The siltstone lithofacies is flat or ripple bedded, calcareous in places, and may be rooted and burrowed. Individual siltstone beds are usually less than 3 m thick. Sandstone and siltstone interbeds are common and grade laterally into larger sandstone bodies (discussed below). Intervals that are usually less than 10 m thick, where the claystone and siltstone lithofacies are intermixed, are referred to as mudstone lithofacies. In the upper and lower parts of the

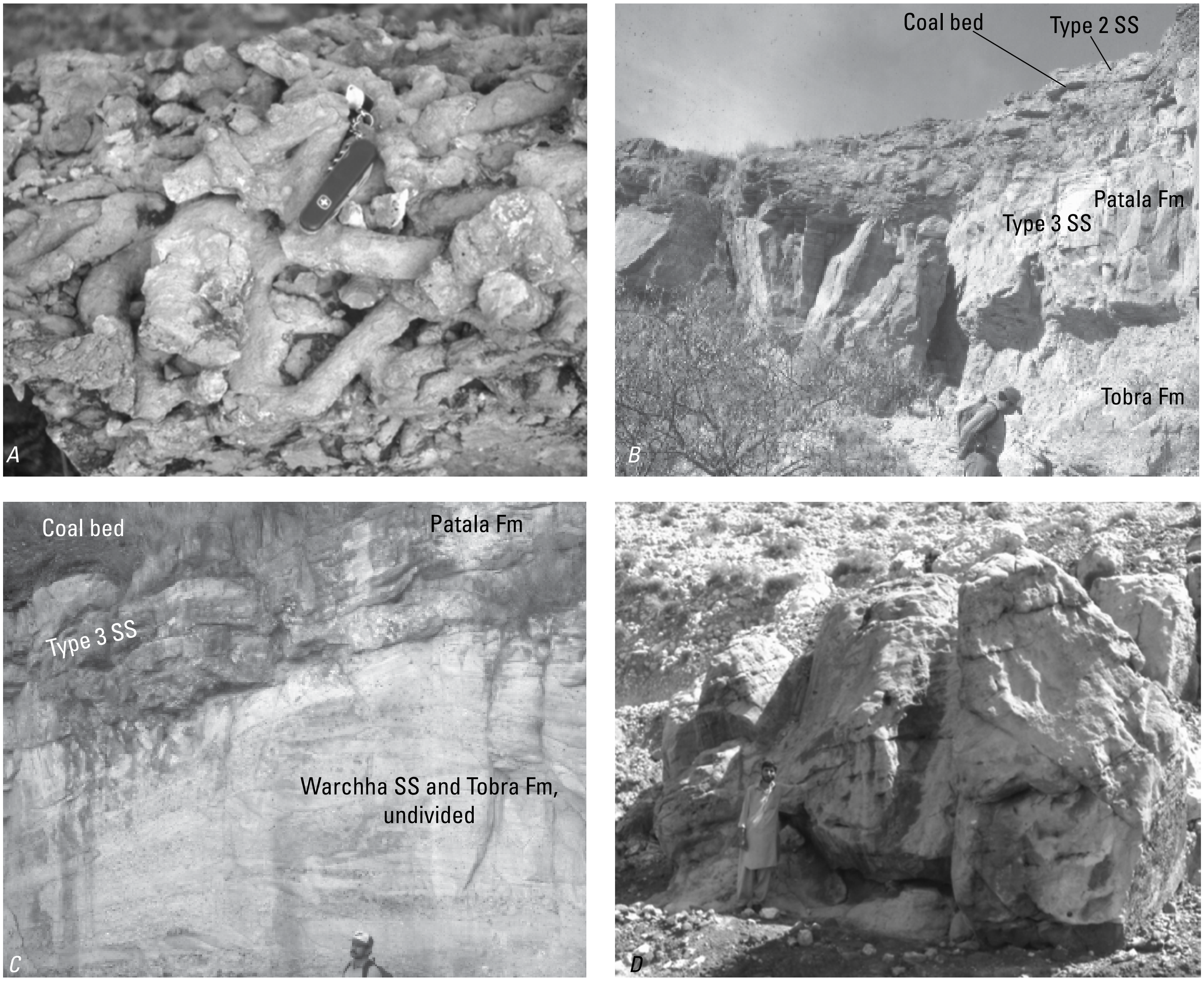

Figure I5. Representative exposures of sandstone types and structures in the Patala Formation. Fm, Formation; SS, sandstone. *A*, Burrows in a type 2 sandstone probably made by thalassinideanlike shrimp. Note the Y-shaped bifurcating tube below the knife that is common in burrows made by shrimp. Knife is 9 cm long. *B*, Exposure in the eastern part of the Salt Range coal field. The Patala Formation unconformably overlies diamictite of the Permian Tobra Formation and consists of type 2 and 3 sandstones separated by a thin (5-cm-thick) coal bed. *C*, Exposure in the eastern part of the Salt Range coal field. The Patala Formation unconformably overlies conglomeratic sandstone of the Permian Tobra Formation and Warchha Sandstone; the lower part of the Patala Formation consists of type 3 sandstone overlain by a coal bed. *D*, Exposure in the western part of the Salt Range coal field of a type 3, quartz-rich, sandstone barrier deposit.

formation, the claystone and siltstone lithofacies contain foraminifers and are interbedded with marl and limestone lithofacies to form units up to 2 m thick.

The marl lithofacies is usually olive gray and, along with the light-gray limestone lithofacies, contains foraminifers and oyster shells. The marl lithofacies consists of poorly cemented calcareous mudstone and skeletal debris and is gradational with the limestone lithofacies, where together they form beds usually less than 1 m thick. The limestone facies ranges from a well-cemented calcareous mudstone to a fossiliferous wackestone. The limestone and marl lithofacies are glauconitic and pyritic.

The claystone, siltstone, limestone, and marl lithofacies of the upper and lower parts of the Patala Formation are interpreted to have been deposited in neritic, low-energy environments because of the lack of rooting and abundance of foraminifers. This interpretation is supported by foraminiferal assemblages studied by Gibson (this volume, chap. E). The claystone and siltstone lithofacies in the coal-bearing middle part of the Patala Formation probably were deposited in near-marine paludal, possibly tidally influenced environments. These environments are inferred because of the proximity of the lithofacies to marine deposits above and below them, the presence of brackish-water pollen taxa, common clay drapes overlying bedding bedforms, rooting, and the close association of the lithofacies with coal and carbonaceous shale lithofacies.

Sandstone

The sandstone lithofacies within the Patala Formation generally occurs in three forms:

1. Type 1 consists of flat- to ripple-bedded, fine-grained sandstone beds a few centimeters thick that occur in intervals dominated by claystone and siltstone lithofacies; these sandstones can be interlayered with carbonaceous shale or impure coal and can be rooted. Individual beds can be traced laterally for as much as 20 m.

2. Type 2 sandstone lithofacies consists of continuous tabular bodies as much as 2 m thick that are traceable laterally for up to 100 m. These sandstones are fine to medium grained, wavy bedded, ripple laminated, or cross stratified, and have small (<0.25 m thick) tabular- and trough-crossbed sets. The basal contact is usually sharp, and the upper contact is gradational with the overlying sediments. Burrows are common and generally are filled with mud or pyrite. Most burrows (fig. I5*A*) are similar to those made by thalassinidean shrimp (compare with those described by Bromley and Frey (1974)). Type 1 and type 2 sandstone lithofacies usually occur together in mudstone-dominated intervals. Type 1 grades laterally into type 2.

3. Type 3 sandstone lithofacies forms continuous bodies that are laterally traceable for several kilometers and may exceed 5 m in thickness (figs. I5*B–D*). Grain sizes in type 3 sandstones range from medium to pebbles, and all type 3 sandstones are quartzose. These sandstone bodies usually display a fining-upward grain size. The upper contact of type 3 sandstone bodies is gradational. Sedimentary structures consist of planar beds, ripple lamination, and trough to broad low-angle, and tabular cross stratification. Trough and tabular cross-stratified bed sets as much as 0.5 m thick and 2 m wide occur within internal scour features that are laterally continuous across outcrops. The upper parts of type 3 sandstone bodies commonly have thin claystone interbeds or claystone drapes that overlie ripple lamination at reactivation surfaces. Individual type 3 sandstone bodies are stacked locally and form composite bodies dominated by type 3 sandstone up to 20 m in thickness. These thick bodies contain several fining-upward sequences that are usually separated by burrowed siltstone and type 2 sandstone lithofacies.

The vertical change in lithofacies and sedimentary structures of the sandstones in the Patala Formation indicate that the sandstones were shoreface sandstones, probably deposited in a barrier-island system. These interpretations are supported by the presence of brackish-to-marine fossils and the abundance of quartzose sandstones; these characteristics are typical of most barrier deposits (Moslow, 1984).

The bodies dominated by type 3 sandstone are characterized by (1) a scoured base and multiple internal channel scours, (2) a vertical decrease in scale of bimodal trough, tabular, and ripple cross stratification at reactivation surfaces, and (3) a general fining upward in grain size, all of which are typical of barrier deposits (Barwis and Hayes, 1979; Galloway and Hobday, 1983; Moslow, 1984). The low-angle cross-stratification sets commonly preserved in the bodies dominated by type 3 sandstone probably represent beach-foreshore deposits. The abundant trough-and-tabular crossbedding found in these bodies was probably produced within the intertidal zone. Such scour features could have been produced by tidal channels. The upper- and lower-shoreface deposits were probably removed by the scour associated with the movement of the shoreface. The upper parts of these bodies are commonly rooted, indicating shallow-water or subaerial environments of deposition; however, no dune deposits have been observed. Similar barrier-type sandstone bodies have been described by Hobday and Horne (1977) and Horne and others (1979) in the Appalachian coal fields of the eastern United States, and by Roehler (1988) in the Rock Springs coal field of the western United States.

Type 1 and type 2 sandstones probably were deposited in a variety of intertidal environments that were generally away from the high-energy shoreface environments in which the type 3 sandstones were deposited. Type 2 sandstone lithofacies containing small sets of tabular cross stratification, found between and above type 3 sandstone bodies, and within mudstone-dominated intervals, probably represents tidal-delta or small tidal-creek deposits. These type 2 sandstones commonly contain burrows like those made by thalassinidean shrimp such as are found in Pleistocene shallow-marine and estuarine-salt marsh sediments in eastern North Carolina (Curran and Frey, 1977). Type 1 and 2 sandstone lithofacies not associated with type 3 sandstone lithofacies probably represent distal washover deposits that were deposited in protected back-barrier environments such as back-barrier mires. Back-barrier and washover deposits directly overlie the barrier deposits in both the eastern and western parts of the Salt Range coal field. This vertical profile of lithofacies is typical of regressive-shoreline sequences (Galloway and Hobday, 1983; Moslow, 1984).

Carbonaceous Shale and Coal

In the eastern and central parts of the Salt Range, coal and carbonaceous shale lithofacies generally occur within a 5-m-thick zone in the middle part of the Patala Formation, usually within a single bed less than 1 m thick that can be split by dark-gray claystone or thin (<0.25 m thick) bands of quartzose type 1 sandstone. These lithofacies are discontinuous, commonly overlie quartzose type 3 sandstone bodies, and merge laterally with sandstone, claystone, and siltstone

Figure I6. Exposure of the upper part of a carbonaceous shale bed showing numerous flattened burrows filled with mudstone. Such features are common in Salt Range coal and carbonaceous shale beds of the Patala Formation. Hammer head is 19 cm long.

lithofacies. Such organic-matter-rich intervals are restricted to the middle part of the Patala Formation.

Coal beds in the Patala Formation are gradational laterally and vertically with carbonaceous shale. Megascopically, the coal beds are generally thinly banded (bands <3 centimeters (cm) thick) and characterized by bright bands isolated in a matrix dominated by dull, resinous organic material. The number of bright bands decreases as the coal grades into carbonaceous shale. Thin (<1 cm thick) fusain bands are present but not common. Nodules of pyrite as much as 5 cm in diameter are commonly dispersed throughout the coal; these usually occur as replacements of burrow infillings and are more common in the upper parts of the coal beds (fig. I6). Thin (<0.5 cm thick) gypsum veins are common and tend to occur along the cleat of the coal bed. Ghaznavi (1988) has described the petrology of three Salt Range coal samples as consisting of 79.1 percent vitrinite, 11.2 percent inertinite, and 9.7 percent liptinite.

Warwick and others (1990b) reported that thicknesses of coal and carbonaceous shale beds from 37 sample locations averaged 0.49 m (table I1). Results of proximate and ultimate analyses, reported on an as-received basis, indicate that coal beds have the following average characteristics: 24.23 percent ash yield, 5.32 percent total sulfur content, 4.08 percent pyritic sulfur content, and 8,943 British thermal units per pound (Btu/lb) (4,972 kilocalories per kilogram (kcal/kg)) calorific value. Concentrations of Ti, at 0.36 percent; Zr, at 382 parts per million (ppm); and Se, at 11.48 ppm (table I1) are high in comparison with averages for these elements in coals of similar rank (Stach and others, 1982; Ward, 1984; R.B. Finkelman, written commun., 1989). In general, the thickest coal beds have the lowest total sulfur content and are in the central area of the coal field (table I1). These variations in coal-bed character are probably related to the depositional environments of the peats.

The close association of the coal and carbonaceous shale lithofacies with the sandstone and finer grained lithofacies indicates that the coal and carbonaceous shale of the Patala Formation were probably deposited in back-barrier environments. This interpretation has been suggested by various authors (Wells, 1984; Alam and others, 1987; Mashhadi and others, 1990; Warwick and others, 1990b) and is supported by the presence of brackish-water pollen taxa and generally high sulfur contents in the coal beds. The Salt Range coal and carbonaceous lithofacies probably formed in mires of back-barrier/lagoonal areas that were protected from coastline-related sediment influx by barriers composed of bodies dominated by type 3 sandstone.

Paleosol

Within the lower 5 m of the Paleocene rocks of the Hangu and Patala Formations of the Salt Range are white, massive claystones and hematite-rich mudstonelike rocks. The claystones are up to 10 m thick and are interbedded with the hematite-rich mudstones (Ashraf and others, 1972; Abbas and Hassan, 1985; Hassan, 1985; Whitney and others, 1990). The hematite-rich mudstones are pale red to reddish brown, generally less than 3 m thick (fig. I7*A*) and usually contain root traces and light-gray to dark-reddish-brown glaebules (spherical masses) as much as 3 cm in diameter (fig. I7*B*). Textures for the mudstonelike rock range from angular and subangular-blocky to granular (using the classification of soil peds by Soil Survey Staff (1975) and Birkeland (1984) and modifications by Retallack (1988)). These claystones and mudstones may be overlain by a carbonaceous shale or coal beds, and type 3 sandstone, and are usually underlain by oxidized Cambrian or Permian rocks of the coal field area. However, more than one hematite-rich mudstone bed may occur anywhere within the lower 5 m of the Paleocene rocks. Analyses of claystone and mudstone samples collected by Whitney and others (1990) indicate that the claystone consists primarily of boehmite, gibbsite, and kaolinite, and the mudstonelike rock generally consists of hematite, goethite, lepidocrocite, and a variety of Fe oxides and oxyhydroxides.

Whitney and others (1990) interpreted the massive claystones as bauxites and the hematite-rich mudstonelike material as laterites. These bauxite and laterite deposits probably represent the B horizon of paleosols that formed on C horizon paleosurfaces of exposed Cambrian and Permian rocks or pretransgressive Paleocene rocks. Where not removed by transgressive upper-shoreface processes, the organic-matter-rich carbonaceous shales and coal beds that overlie the bauxites and laterites represent the A horizon of the paleosol. Bauxite is thought to form in regions with high, nonseasonal rainfall; under rain forests; on quartz-poor, base-rich, parent materials, and at nearly neutral pH (Goudie, 1973; Retallack, 1989). Although the mode of formation of laterite is controversial, it may form in regions characterized by high rainfall, marked dry seasons, and warm temperatures that are in the subtropical to tropical range (McFarlane, 1976; Retallack, 1989). The presence of both later-

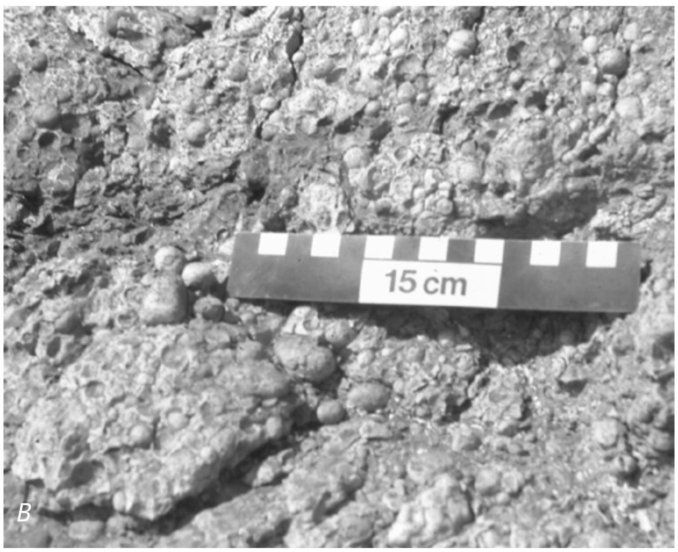

Figure I7. Characteristics of the hematite-rich mudstonelike rocks (laterite/paleosol) near the base of Paleocene rocks in the Salt Range. *A*, Hematite-rich laterite/paleosol overlain by fine-grained lithofacies of the Patala Formation in the eastern part of the Salt Range coal field. Fm, Formation. *B*, B horizon glaebules found in some laterites in the Salt Range.

ite and bauxite deposits associated with the Paleocene unconformity of the Salt Range indicates tropical to subtropical conditions. A tropical to subtropical climate is to be expected because of the equatorial position of the Indian subcontinent during Late Cretaceous and Paleocene time (Molnar and Tapponnier, 1975).

Lateral and Vertical Distribution of Lithofacies of the Patala Formation

The lateral and vertical distributions of the lithofacies in the Patala Formation record an initial transgressive phase, followed by a regressive phase and a final transgressive phase of the Paleocene Tethys Sea. For the purposes of this discussion, the coal field may be divided into three geographic areas that are characterized by different depositional environments. These areas (fig. I2) are eastern (east of long 73°00′ E.), central (between longs 72°30′ E. and 73°00′ E.), and western (west of long 72°30′ E.). Whereas the northern limit of the coal field is generally defined by the outcrop of the overlying Miocene Murree/Kamlial Formation (Gee, 1980), the southern limit is defined by the outcrop of the Patala Formation (fig. I2 and pl. I1).

Eastern Area of the Salt Range Coal Field

The lateral and vertical distribution of lithofacies in the Patala and adjacent formations in the eastern area of the Salt Range is depicted on an east-west longitudinal section (fig. I8). Outcrop observations indicate that conglomerates of the Lower Permian Tobra Formation and sandstones of the Warchha Sandstone fill channel scours that are incised into the underlying Cambrian Baghanwala Formation: erosional relief can be as much as 30 m (fig. I8, section S–13). The lower part of the Patala in the eastern area of the Salt Range is dominated by a quartzose, type 3 sandstone lithofacies that is commonly in contact with Permian sandstone and conglomerates (figs. I5*B*–*C*, I8, I9). Differentiation between the Permian and Tertiary sandstones can be difficult; although the Tertiary sandstone appears to be more quartz rich in hand sample, this observation requires petrographic confirmation.

Bauxite and laterite deposits are common near the base of the Paleocene section in the eastern area of the coal field. At places, the weathered parent-rock C horizon is preserved below the Paleocene unconformity, but the A horizon and bauxite and laterite of the B horizon were subsequently replaced by bodies dominated by type 3 sandstone.

Within the eastern area, the major sandstone deposits in the Patala Formation occur as stacked type 2 and type 3 sandstone bodies that are as much as 15 m thick (fig. I9). Type 3 sandstone bodies have a sharp base that overlies either the Tobra Formation or the Baghanwala Formation (fig. I9) or the fine-grained lithofacies of the Patala Formation (section S–6 in fig. I8). In several areas, thick cumulative sandstone deposits are dominated by type 3 sandstone bodies that are elongate in a northerly direction and have increased sandstone thicknesses toward their axes (map B, pl. I1). The most extensive of these ranges from 6 to 12 m in total thickness and is more than 3 km wide where total sandstone thickness exceeds 9 m (between longs 73°05′ E. and 73°10′ E., map B on pl. I1).

Examples of the type 1 and 2 sandstone lithofacies can be found in well-exposed sections within the eastern area of the Salt Range coal field. In the eastern area, a 7.5-m-thick body dominated by type 3 sandstone contains multiple channel scours (fig. I9). The lower 2 m has trough crossbeds as much as 2.15 m wide and 0.6 m thick. Quartz pebbles are common at the bases of all scours. The middle 4 m of this body contains alternating beds (<1.0 m thick) of (1) trough- and tabular-crossbedded sandstone, (2) rippled and burrowed type 2 sandstone, and (3) claystone and siltstone lithofacies. The upper 2.5 m of the body contains iron-stained, broad, low-angle crossbedding. Paleocurrent determinations from trough and tabular crossbeds indicate a general bimodal paleocurrent distribution. This body is laterally continuous for several kilometers and at one location (section S–3 of Warwick and Shakoor (1988b)), a 3-m-wide, 1-m-thick channel fill within the upper part of a body dominated by type 3 sandstone consists of burrowed siltstone with plant debris. A thin (0.25-m-thick) carbonaceous shale bed makes up the upper part of the channel fill.

Bodies dominated by type 3 sandstone are commonly overlain by coal and carbonaceous shale lithofacies (figs. I5*B*,*C*), which, in turn, are overlain by claystone and siltstone lithofacies interbedded with type 1 sandstones and thin (<2 m thick), laterally continuous (up to 50 m) type 2 sandstone bodies that usually contain flat and rippled bedding and burrows. Total sandstone content decreases upward in the Patala Formation. Claystone in the upper part of the formation grades into marl interbedded with limestone beds of the overlying Nammal Formation (fig. I9).

The cumulative sandstone bodies of the eastern Salt Range probably represent the deposits of a barrier system. This interpretation is supported by (1) an abundance of bimodal, trough and tabular, and low-angle cross stratification in type 3 sandstones; (2) the discontinuous, elongate shape of the cumulative-sandstone deposits; (3) the close association with brackish-marine rocks; (4) the presence of quartzose sandstones; and (5) the similarities between Salt Range sandstone body shapes and sedimentary structures and other

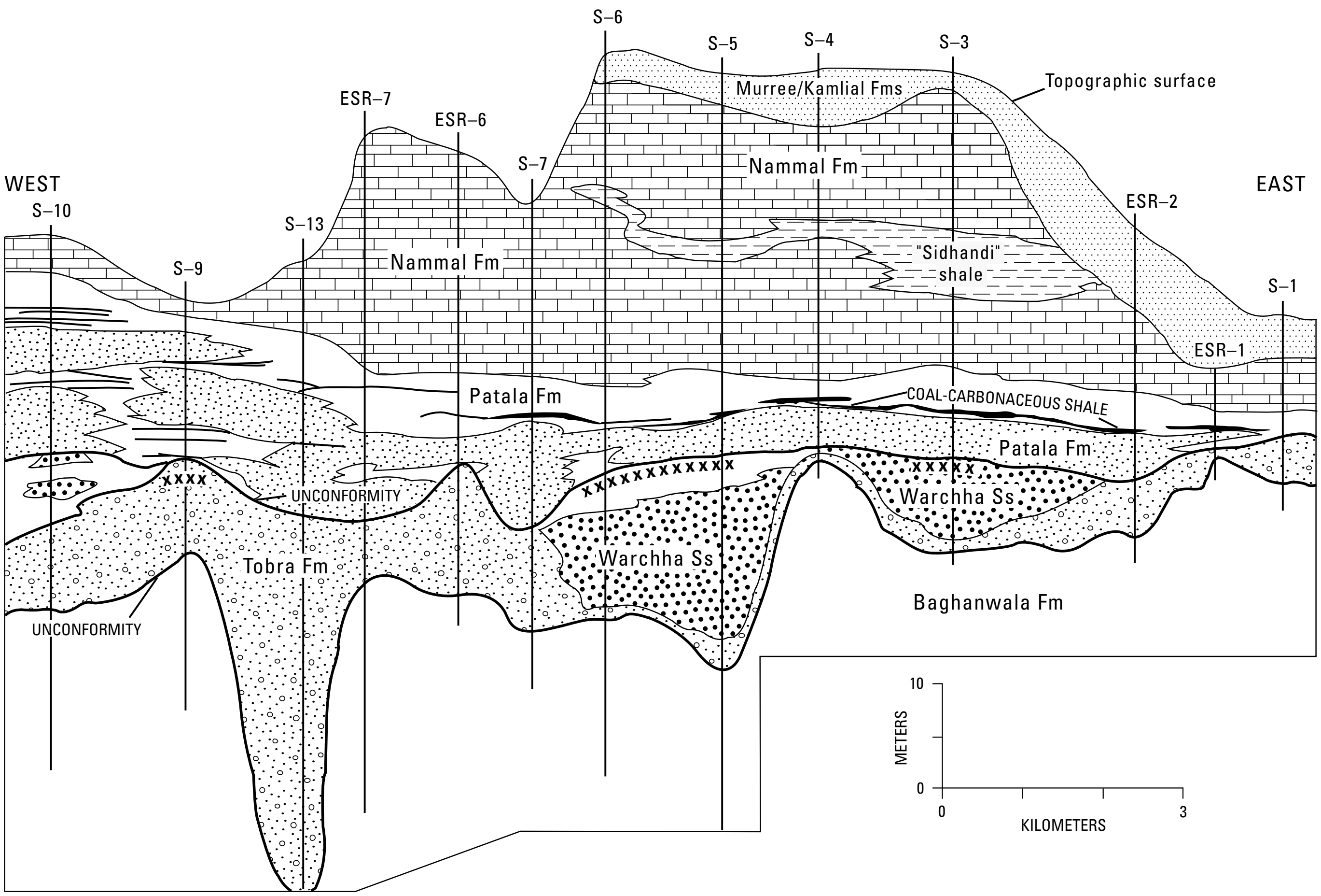

Figure I8. Detailed east-west longitudinal section of the coal-bearing and associated rocks in the eastern part of the Salt Range coal field. Approximate location of the line of section is shown as section A on figure I2 and on map A, plate I1. Names refer to stratigraphic units discussed in the text. The section numbers used in this study refer to those used in Warwick and Shakoor (1988b), who gave detailed locations, references, and lithologic descriptions for each section or drill hole. Datum for the cross section is the coal-bearing zone. Key marker beds in each section or drill hole were used for correlation. Fm(s), Formation(s); Ss, Sandstone; three stipple patterns, sandstone in the Murree and Kamlial Formations, Patala Formation, and Warchha Sandstone; brick pattern, limestone; no pattern, mixed siltstone, mudstone, and marl; stipple pattern with circles, conglomerate and diamictite; XXXX, weathered paleosurface. Vertical exaggeration is × 150.

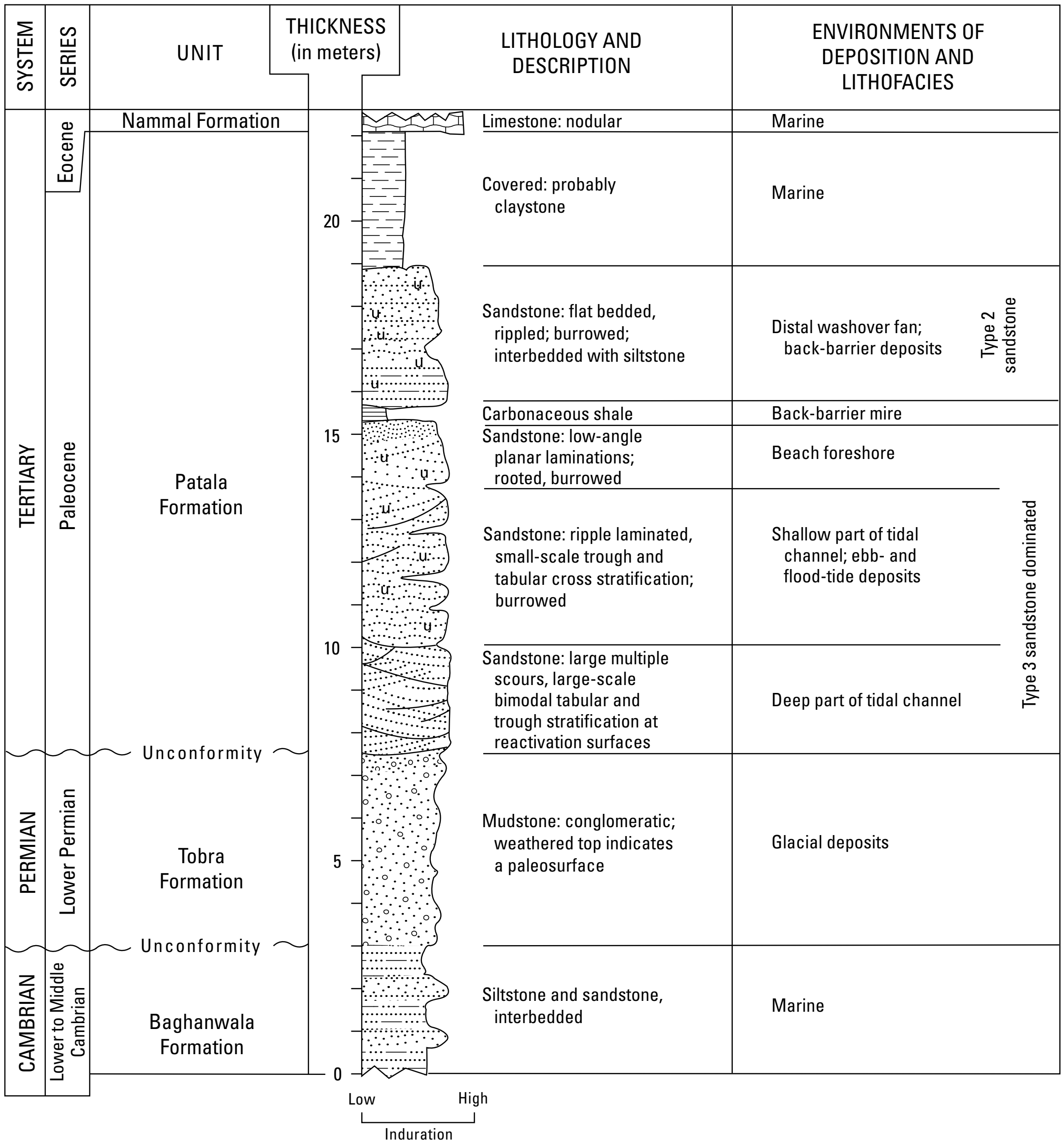

Figure I9. Detailed stratigraphic section of the coal-bearing and associated rocks in the eastern part of the Salt Range coal field. Location of section is near S–6 and S–7 (fig. I8), at lat 32°44′03″ N., long 73°11′45″ E. (map A, pl. I1); detailed description is given as section O–2 of Warwick and Shakoor (1988b).

barrier-island deposits (Galloway and Hobday, 1983; Moslow, 1984; Staub, 1985). The internal sedimentary structures within each body dominated by type 3 sandstone and the relative elongation of these bodies parallel to the thinning of the Patala Formation (maps A and B, pl. I1) indicate that the bodies probably formed along a shoreline of numerous tidal channels whose deposits, along with beach-foreshore sandstones, dominate the preserved barrier sequence.

The thickness of the Patala Formation in the eastern area of the Salt Range is less than in other areas of the coal field, and the variation in thickness in the east appears to be related, in part, to the occurrence of sandstone (maps A and B, pl. I1), which, presumably, is less compactable than finer grained rocks. Some thickness variation of the Patala also may be related to the paleotopography of the surface upon which the Tertiary sediments were deposited. If sand accumulated in paleovalleys, the thickest parts of the Patala Formation may correspond to these areas. Sections S–13, ESR–7, and S–7 (fig. I8) illustrate this relation.

In the eastern area of the Salt Range the thickest coal and carbonaceous shale beds (as much as 2.13 m) generally form discontinuous, elongate, northerly trending beds that are roughly 2–3 km long and 1 km wide (map C, pl. I1). The beds grade laterally into interbedded thin (<0.25 m) coal and carbonaceous shale beds or into dark-gray claystone. The areas of thick coal tend to overlie or occupy areas of slightly lateral to thick deposits dominated by type 3 sandstone. This relation suggests that the underlying sandstone, which would not be as compactable as adjacent finer grained sediments, served as a platform for plant growth and peat accumulation on a subsiding coastal plain. In the easternmost area of the coal field (map C, pl. I1), anomalously thick coal beds (as much as 2.13 m) were described by LaTouche (1894). Areas of thick coal such as these occur as narrow (<250 m wide), elongate bodies (map C, pl. I1) and, generally, have been completely mined out. Such thick coal may represent peat accumulation within abandoned channels. This interpretation is supported by the elongate shape of the coal bodies and outcrop observations of the upper parts of channel fill sequences that consist of organic material (section S–3, Warwick and Shakoor (1988b)).

Coal samples collected from the eastern area of the coal field produced greater ash yields than samples collected from other areas of the field (table I1). These increased ash yields in an easterly or landward direction probably indicate that eastern areas of peat accumulation were more prone to an influx of sediment, which may have been derived from exposed uplands toward the east. Frequent type 1 sandstone partings in the coal beds in this area suggest periodic washover sedimentation. Landward increases in organic sulfur and selenium content (table I1) indicate that organic sulfur and selenium were enriched in these more landward, possibly fresher water environments. The increase of average organic sulfur content eastward (table I1) may indicate that freshwater environments of peat accumulation were inundated subsequently by sulfide-rich marine waters. Similar depositional environments have been proposed for increases in organic sulfur content in Appalachian coal beds (Davies and Raymond, 1983).

The upper part of the Patala Formation in the eastern Salt Range contains a foraminifer-rich claystone lithofacies and is gradational to a generally nodular to shaly limestone of the Nammal Formation, which suggests that the upper part of the Patala was probably deposited in neritic environments.

Central Area of the Salt Range Coal Field

Within the central area of the Salt Range coal field, quartzose type 2 and 3 sandstone bodies become less common in a westerly direction (fig. I10). Type 1 sandstones are commonly observed in the coal-bearing interval in the eastern part of the central area. As in the eastern area of the field, areas of thick bodies dominated by type 3 sandstone are discontinuous and elongate in a northerly direction in the eastern part of the central coal field (map B, pl. I1). The thickest (>21 m) cumulative sandstone in the central area of the coal field is about 20 km west of the thick cumulative sandstones of the eastern area of the field. This distance may represent the spacing between the position of the earlier easternmost shoreline and the regressive shoreline that followed in the central area of the field.

A general lack of major sandstone bodies in the western part of the central coal field indicates a later westward shift of the shoreline. The areas with little sandstone content (between longs 72°30′ E. and 72°55′ E., map B on pl. I1) probably represent back-barrier environments. These areas were protected from coarse clastic influx associated with shoreline processes that apparently deposited the large complex dominated by type 3 sandstone (map B, pl. I1) west of long 72°30′ E. (described below).

Coal and carbonaceous shale deposits in the western part of the central coal field were probably deposited in back-barrier mires. Areas lateral to coal and carbonaceous shale deposits probably received clastic sediments that inhibited peat accumulation. The sediments may have been tidally transported. Environments of deposition in the more eastern part of the central area were similar to those in the eastern area of the field, where peat accumulated on platforms dominated by type 3 sandstone (maps B and C, pl. I1). The thicker coal beds occur proximal to areas of the thickest cumulative type 1, 2, and 3 sandstone deposits. Similarly shaped coal bodies and associated rocks have been described by Horne and others (1979) from Appalachian back-barrier environments.

Coal samples collected from the central area of the Salt Range coal field have a lower average total-sulfur yield than samples collected from other areas of the field (table I1). Lower organic- and pyritic-sulfur yields account for the major decrease in total sulfur in the central area of the field. Decreases in organic-sulfur yield (as a percentage of total sulfur) westward may indicate more marine-dominated environments of peat deposition in the western part of the study area. Casagrande and others (1977), likewise, found that as a percentage of total sulfur, organic-sulfur yields from Florida Everglades marine-peat samples were less than those from Okefenokee freshwater-peat samples. Pyritic sulfur, however, is greater in the western and eastern areas of the Salt Range coal field (table I1). Although the causes for the reduction of pyritic-sulfur content in the coals of the central area of the field are not clear, the differences may be related to the depositional origin of the overlying rocks. Because marine roof rocks are known to have contributed to the pyritic-sulfur content of coals in central and eastern North America (Williams and Keith, 1963; Gluskoter and Simon, 1968), pyritic-sulfur yields in the western area of the Salt Range coal field similarly may be related to an increased marine influence. Marine conditions for roof-rock deposition and increased pyritic-sulfur content also may be reflected by an abundance of pyrite-filled burrows observed commonly in the upper part of coal beds in the western area of the field.

The underlying Lockhart Limestone may have influenced the thickness of the Patala Formation in the central area of the coal field. The Lockhart Limestone, which is represented by a thin (<1 m thick) carbonate-rich zone in the eastern part of the central coal field, increases to more than 10 m in thickness in the western part of the same region (fig. I10). The thickness of the Patala Formation (map A, pl. I1) becomes more uniform toward the west in association with decreased net sandstone content and because the formation was not deposited on pre-Paleocene topography. An anomalous, westerly trending, thin area of the Patala between longs 72°45′ E. and 73°00′ E. (map A, pl. I1), however, may

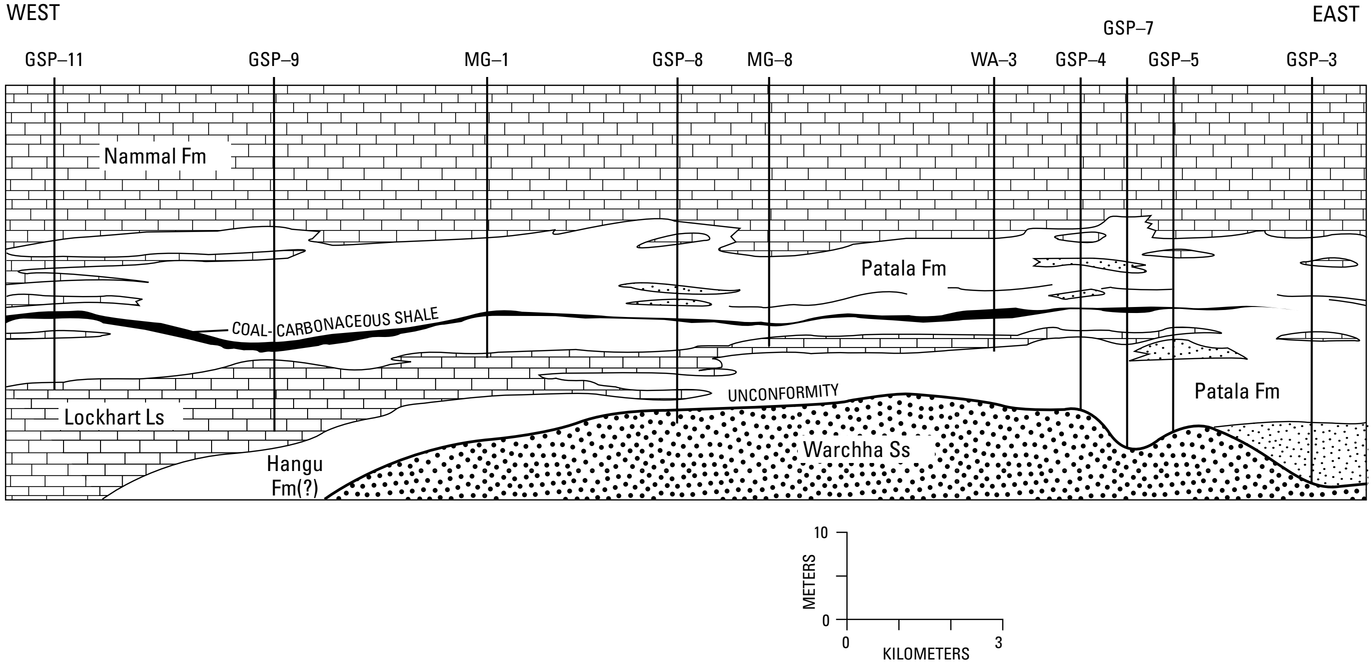

Figure I10. Detailed east-west longitudinal section of the coal-bearing and associated rocks in the central part of the Salt Range coal field. Approximate location of the line of section is shown as section B on figure I2 and map A, plate I1. The drill-hole numbers used in this study refer to those used by Warwick and Shakoor (1988b) and Alam and others (1988), who gave detailed locations, references, and lithologic descriptions for each section or drill hole. The upper part of the drill holes through the Eocene limestone is not shown. Datum for the cross section is the coal-bearing zone. Key marker beds in each section or drill hole were used for correlation. Names refer to stratigraphic units discussed in the text. Fm, Formation; Ls, Limestone; Ss, sandstone; two stipple patterns, sandstone in the Patala Formation and Warchha Sandstone; brick pattern, limestone; no pattern, siltstone, mudstone, and marl. Vertical exaggeration is × 170.

indicate that thickness variations in the Lockhart influenced the thickness of the overlying Patala. These relations can be seen on the cross section and isolith and isopach maps (fig. I10; maps A and B, pl. I1). The causes for thickness variations within the Lockhart are not clear but may be related to offshore sandstone bodies within the Lockhart. Petrographic studies of the Lockhart from this area by B.R. Wardlaw (oral commun., 1992) have shown that the Lockhart in this area has an increased sandstone content in comparison with other areas toward the west. On the basis of stratigraphic relations, the Lockhart is proposed to have been deposited simultaneously with the deposition of the lower part of the coal-bearing sediments of the eastern area of the field. The upper part of the Patala in the central coal field is similar to that of the eastern area and probably represents neritic depositional environments.

Western Area of the Salt Range Coal Field

The most significant feature of the western area of the Salt Range coal field is a large (as much as 20 m thick and 15 km wide), north-trending complex dominated by type 3 sandstone that separates the eastern coal-bearing and the western barren parts of the Patala Formation (figs. I11, I12; maps B and C on pl. I1). This sandstone complex, informally called the “Dilliwala” sandstone by Shah (1980), is traceable in outcrop throughout the central part of the western area (map B, pl. I1). The complex is interpreted here as a maximum regressive, or low-stand, position of the Paleocene Tethys shoreline in the Salt Range. West of the complex, the Patala Formation is dominated by fine-grained lithofacies that were deposited in shallow, open-marine environments (Gibson, this volume, chap. E).

Sandstone lithofacies in the western Salt Range have characteristics similar to sandstone lithofacies found in the eastern area of the Salt Range coal field. In a typical section for the western area (fig. I12), bodies dominated by type 3 sandstone contain stacked type 3 sandstone bodies with both trough and tabular crossbeds. Each sandstone body is usually bound by a laterally persistent basal scour. Low-angle crossbedding is common throughout the sandstone section (fig. I12), instead of occurring only at the top of the sandstone body, as in the eastern examples (fig. I9). The bodies are usually overlain by rooted siltstone and carbonaceous shale lithofacies.

The discontinuous nature of these bodies in the central and eastern areas of the coal field is not apparent in the large cumulative-sandstone deposits of the western area of the field. Rather, the cumulative-sandstone deposits in the west are continuous laterally for up to 20 km and may represent a microtidal-shoreline depositional system. Microtidal barriers typically are more continuous laterally than mesotidal barriers (Hayes, 1975; Barwis and Hayes, 1979). Additionally, the bodies dominated by type 3 sandstone of the western area contain low-angle cross stratification throughout, which may indicate that foreshore processes were more dominant in the west than tidal-channel processes were in the central and eastern areas of the field.

Coal and carbonaceous shale lithofacies proximal to the "Dilliwala" sandstone complex dominated by type 3 sandstone are commonly split by type 1 and 2 sandstones. In the eastern part of the western area, coal and carbonaceous shale beds contain fewer rock partings and are more laterally continuous (fig. I11). These trends indicate that barrier-washover sedimentation may have been more common in the back-barrier mires proximal to the "Dilliwala" complex.

The development of the thick, widespread "Dilliwala" sandstone complex in the western area of the coal field may have been structurally influenced. Baker (1988) discussed the influences of basement offsets (as much as 1 km) on ramping and thrusting in the Salt Range area. Studies of airborne-magnetic and gravity data from the Potwar area led H.D. Drewes (written commun., 1991) and H.R. Blank (oral commun., 1992) to suggest that a northwest-trending basement fault occurs under the western part of the Potwar Plateau. This fault is in close proximity to the present position of the "Dilliwala" sandstone complex and areas where Gee (1980, 1989) and Fatmi and Haydri (1986) observed that several Paleozoic formations vary in thickness, pinch out, and reappear. If the pre-regional thrust position of the western Salt Range was proximal to this or other basement faults, the facies and thickness variations observed in the western Salt Range could have been related to deposition that was contemporaneous with movement along the basement fault. One of the mechanisms of barrier-island formation is that of offshore sandstone buildup in areas of shoaling (Reinson, 1979). A shoaling area may have developed over an uplifted part of the basement during the Paleocene, which may have been responsible for the buildup of the "Dilliwala" sandstone complex and the variation of thicknesses of the Hangu Formation, Lockhart Limestone, and Patala Formation observed in the western area (fig. I11). Similar structural controls on sedimentation and barrier-island formation have been demonstrated in the Appalachian region of the eastern United States (Staub, 1985).

The Nammal Gorge section of the western Salt Range is depicted at the western end of the cross section shown on figure I11. Gibson (this volume, chap. E) reported that foraminiferal assemblages from five samples of claystone, marl, and limestone collected from the Patala Formation at this location represent a shallow, inner neritic depositional environment in the lower part of the Patala, and a middle to outer neritic marine depositional environment in the upper part of the Patala. These depositional environments are similar to those proposed by

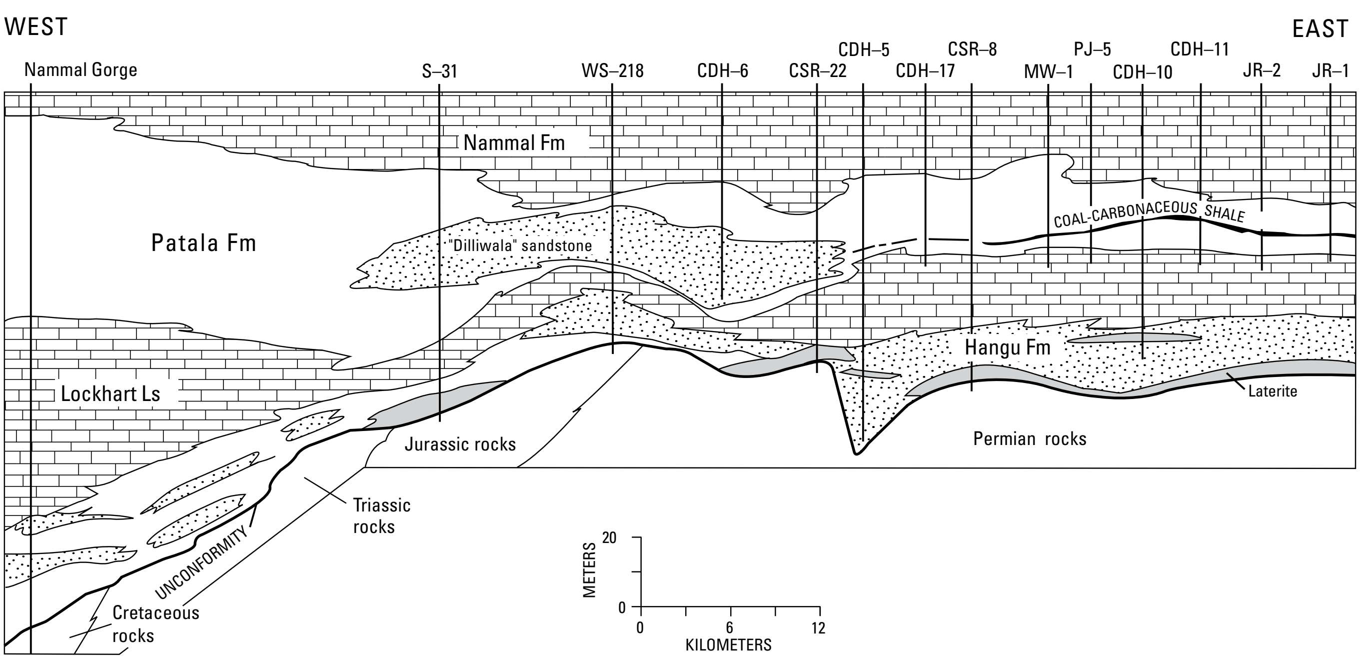

Figure I11. Detailed east-west longitudinal section of the coal-bearing and associated rocks in the western part of the Salt Range coal field. Approximate location of the line of section is shown as section C on figure I2 and on map A, plate I1. Nammal Gorge section is from unpublished GSP data (location not shown on map A, pl. I1). The section numbers used in this study refer to those used by Warwick and Shakoor (1988b), who gave detailed locations, references, and lithologic descriptions for each section or drill hole. The upper part of the drill holes through the Eocene limestone is not shown. Datum for the cross section is the coal-bearing zone. Key marker beds in each section or drill hole were used for correlation. Names refer to stratigraphic units discussed in the text. Fm, Formation; Ls, Limestone; stipple pattern, sandstone; brick pattern, limestone; shaded areas, laterite; no pattern, siltstone, shale, marl, and limestone. Vertical exaggeration is × 165.

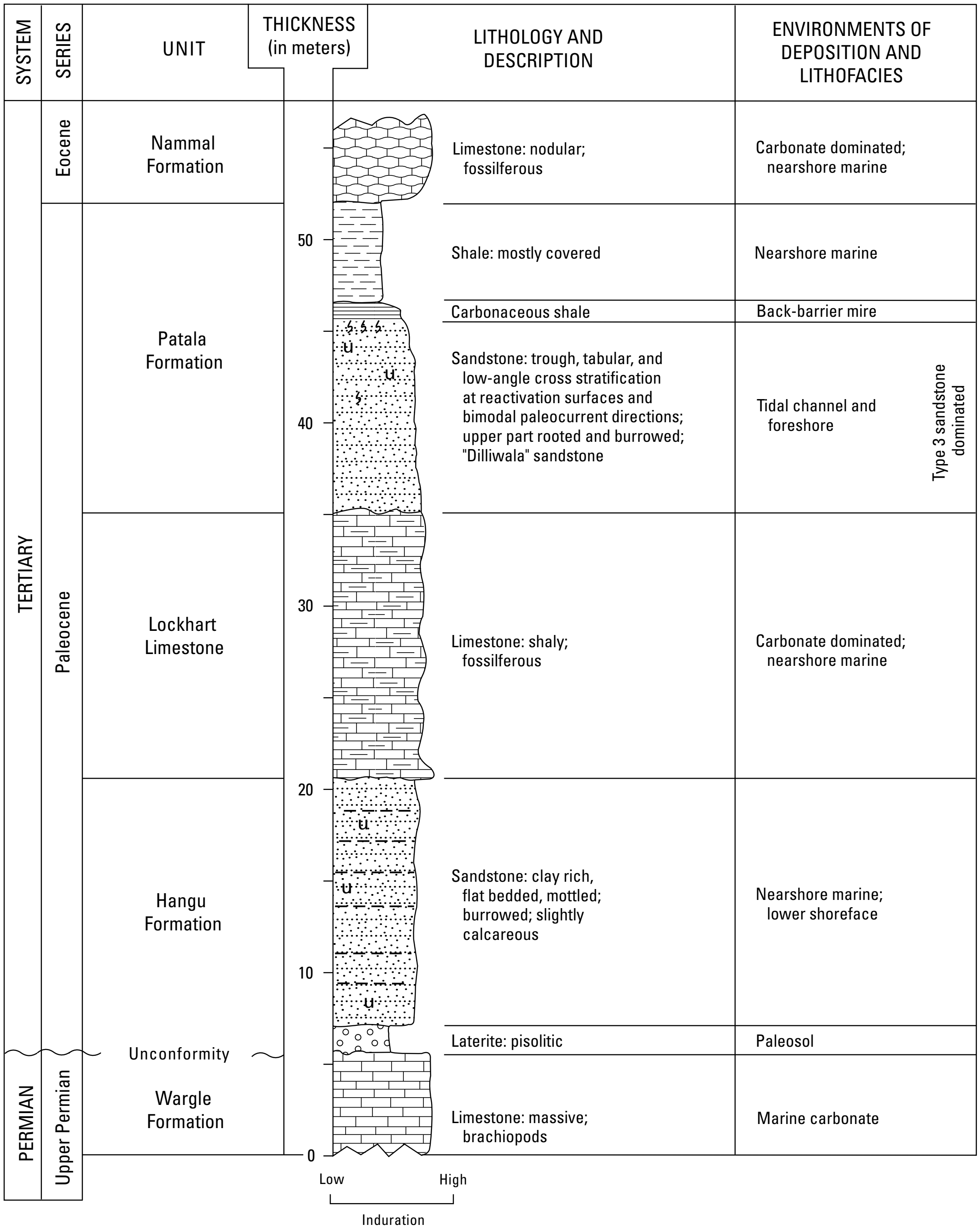

Figure I12. Detailed stratigraphic section S–29 of the coal-bearing and associated rocks in the western part of the Salt Range coal field. Location of section is near CSR–22 (fig. I11), at lat 32°31′55″ N., long 72°23′35″ E. (map A, pl. I1); detailed description was given by Warwick and Shakoor (1988b).

Afzal and Daniels (1991). These interpretations suggest that the Patala Formation in the Nammal Gorge area represents deposits of more open-marine conditions than those found in the time-correlative eastern coal-bearing parts of the sequence. This evidence suggests further that the barrier complex in the western area of the coal field separates deposits of the back-barrier peat-forming environments from deposits of the more open-marine environments exposed at Nammal Gorge.

Summary and Discussion

The distribution of rock types and their internal sedimentary features indicate that the Patala Formation in the Salt Range was deposited in shallow-marine, barrier, and back-barrier coastal environments (fig. I13). In the eastern area of the Salt Range, thick lithofacies dominated by type

3 sandstone represent barrier deposits that were made along a shoreline trending roughly north to northeast. The barrier deposits make up discontinuous elongate bodies that are characterized by tidal-channel and foreshore deposits and probably represent the remains of a mesotidal shoreline. Small, discontinuous peat mires formed along a presumably narrow coastal plain that was bound on the east by a source area of exposed Paleozoic rocks. Fluvially transported detrital input into the eastern area of the coal field appears to have been minimal and restricted to fine-grained clastic sediments.

The Paleocene sediments of the eastern area of the coal field were deposited during a transgressive and subsequent regressive phase of relative sea-level change (fig. I13). Upon subsidence of a Paleozoic bedrock platform, Paleocene sediments covered paleosols developed on Cambrian, Permian, and lower Paleocene rocks. Paleocene shoreline processes locally reworked Permian glacial sediments, which may have been a source for some of the basal sandstones in the Tertiary Hangu and Patala Formations. The Hangu Formation in the Salt Range coal field probably represents transgressive shallow siliciclastic-shelf and near-marine deposits. The Lockhart Limestone, which overlies the Hangu in the Salt Range, was deposited west of the shoreline (fig. I13*A*). Following a relative drop in sea level, the shoreline shifted rapidly some 50 km to the west. The peat-forming mires expanded westward and developed on the abandoned beach and tidal-channel deposits of the eastern area of the field and eventually spread to the central and western areas of the field (fig. I13*B*). This broad area of peat accumulation was protected from marine incursion by the northerly trending barrier complex in the western area of the coal field. Peat accumulation behind the barrier was not continuous laterally but was flanked by sediment-rich areas that may have been deposited in intertidal areas. Peats proximal to the western barrier deposits were subject to frequent washover sedimentation, as shown by type 1 and 2 sandstone partings in the coal beds of

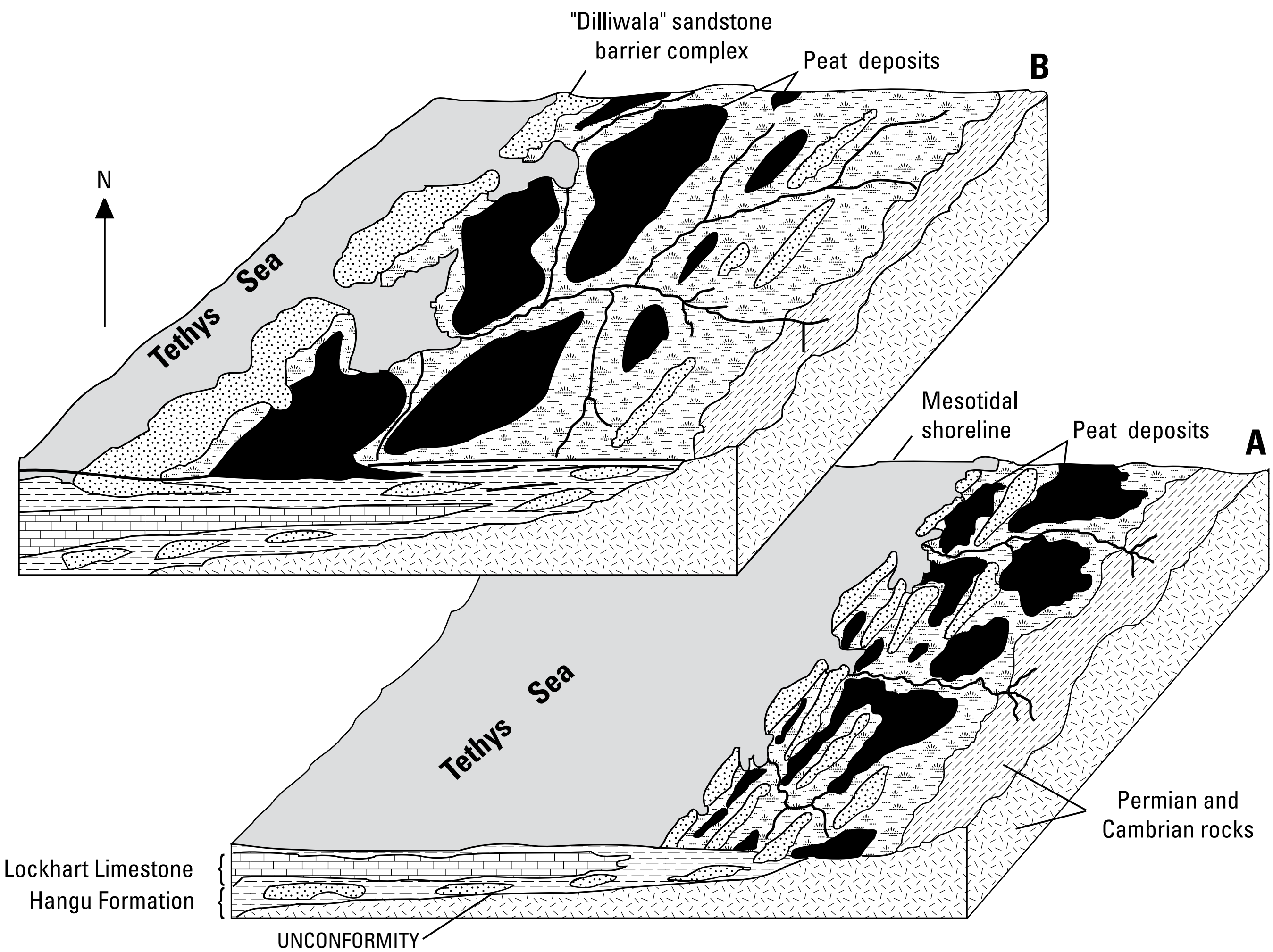

Figure I13. Block diagrams showing depositional environments of the Paleocene coal-bearing sediments in the Salt Range coal field. *A*, Arrangement of depositional environments during the Paleocene maximum transgression of the Tethys Sea that resulted in the formation of a mesotidal shoreline, small laterally discontinuous peat deposits, and the deposition of the Lockhart Limestone. *B*, Subsequent Paleocene regression of the Tethys Sea resulted in the deposition of the "Dilliwala" sandstone barrier complex and back-barrier peats.

that area. Peat accumulation in all parts of the coal field favored areas with a sand substrate.

Coal and carbonaceous shale deposits in the central and western area of the field generally are more continuous laterally and are of better quality than those deposited in the eastern area of the field (Warwick and others, 1990b). Thus, the relative lowstand in sea level was an optimum time for peat accumulation.

The thick buildup of deposits dominated by type 3 sandstone in the western Salt Range indicates that a relatively static shoreline may have been controlled by a paleotopographic high that was created by uplifted blocks of pre-Tertiary and basement rocks. This high appears to have influenced sedimentation since the early Paleozoic. The barrier and back-barrier environments were eventually inundated by the transgression of the Eocene Tethys Sea as shown by deep-water marine claystones in the upper part of the Patala at Nammal Gorge and the more than 100 m of carbonate rocks in the overlying Nammal Formation and Sakesar Limestone.

The regional trend of the Paleocene shoreline on the leading edge of the Indian subcontinent is difficult to establish. Wells (1984), Yeats and Hussain (1987), and Warwick and Wardlaw (1992) suggested that an elongate depositional basin extended from the Potwar into the adjacent Kohat area and further south during Paleocene and Eocene time (fig. I14). The basin probably formed along the collision zone between the Pakistan-India plate and a microplate prior to the collision of the former with Asia. The microplate may have been part of what is now Afghanistan (Boulin, 1981; Scotese and others, 1988). The near-marine environments described above probably formed on the eastern margin of this basin. Similar depositional environments, presumably on the northern margin of this basin, have been found in the Kotli area (approximately 100 km northeast of the Salt Range (Wells and Gingerich, 1987)) and in the Kala Chitta and Attock-Cherat Ranges (approximately 100 km northwest of the Salt Range; described by Meissner and others (1974), Wells (1984), and Yeats and Hussain (1987)). The somewhat confining nature of this basin may have increased tidal ranges within the basin and contributed to the formation of a mesotidal shoreline in the eastern area of the Salt Range.

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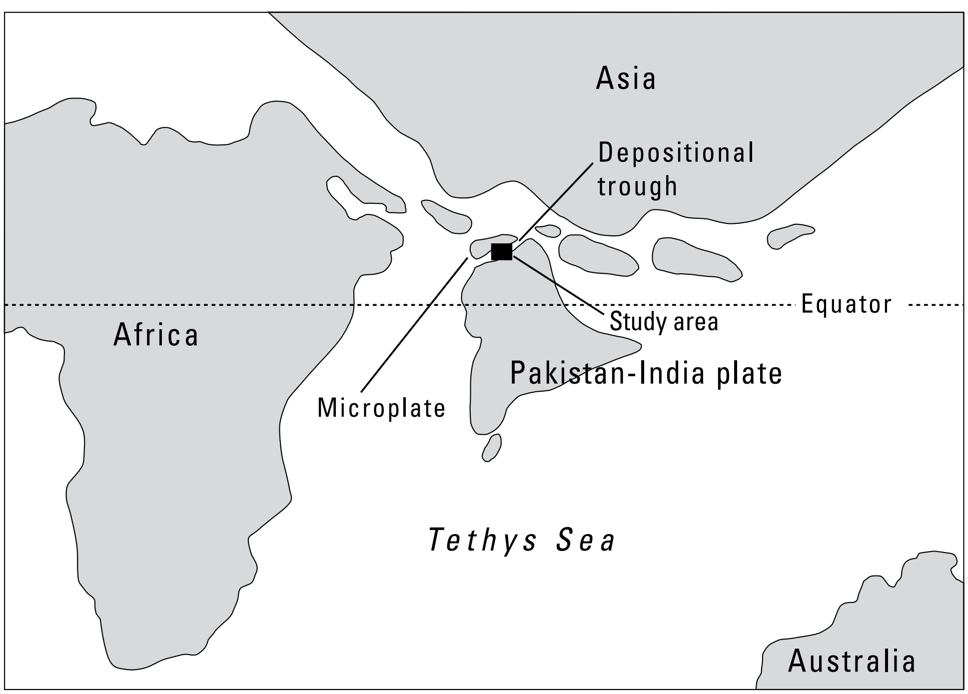

Figure I14. Late Paleocene continental configuration of the Pakistan-India plate and a microplate showing a Paleocene–Eocene depositional trough (modified from Scotese and others, 1988).

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