

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

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Chapter I of  
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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 paleogeographic 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 11.** Index map showing the Salt Range study area (shown in more detail in fig. 12), Makarwal coal field, and selected regional features.

## Acknowledgments

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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

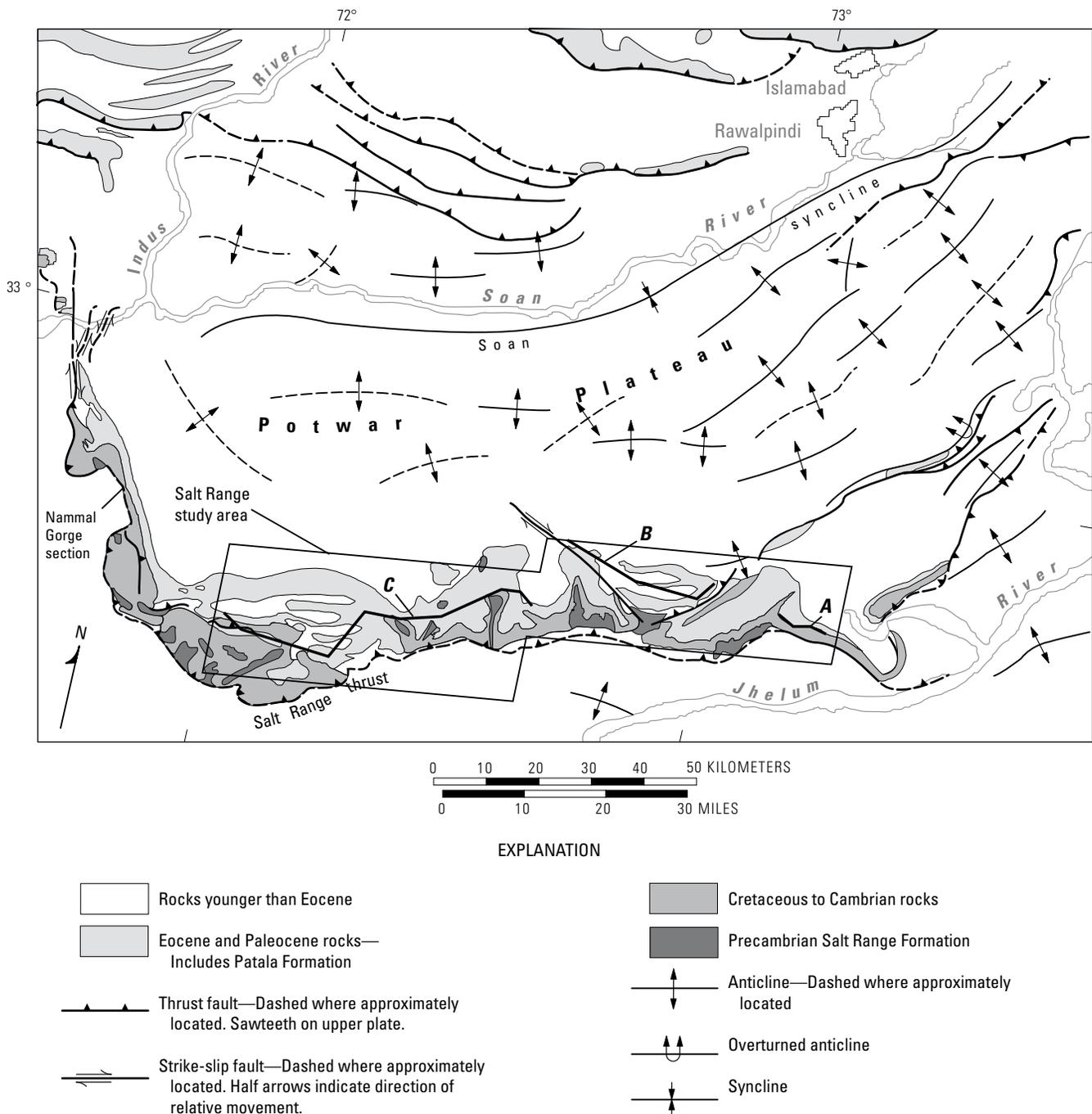
### Structural Setting

The Salt Range and Potwar Plateau (fig. 12) 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. 12), 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. 13). 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-

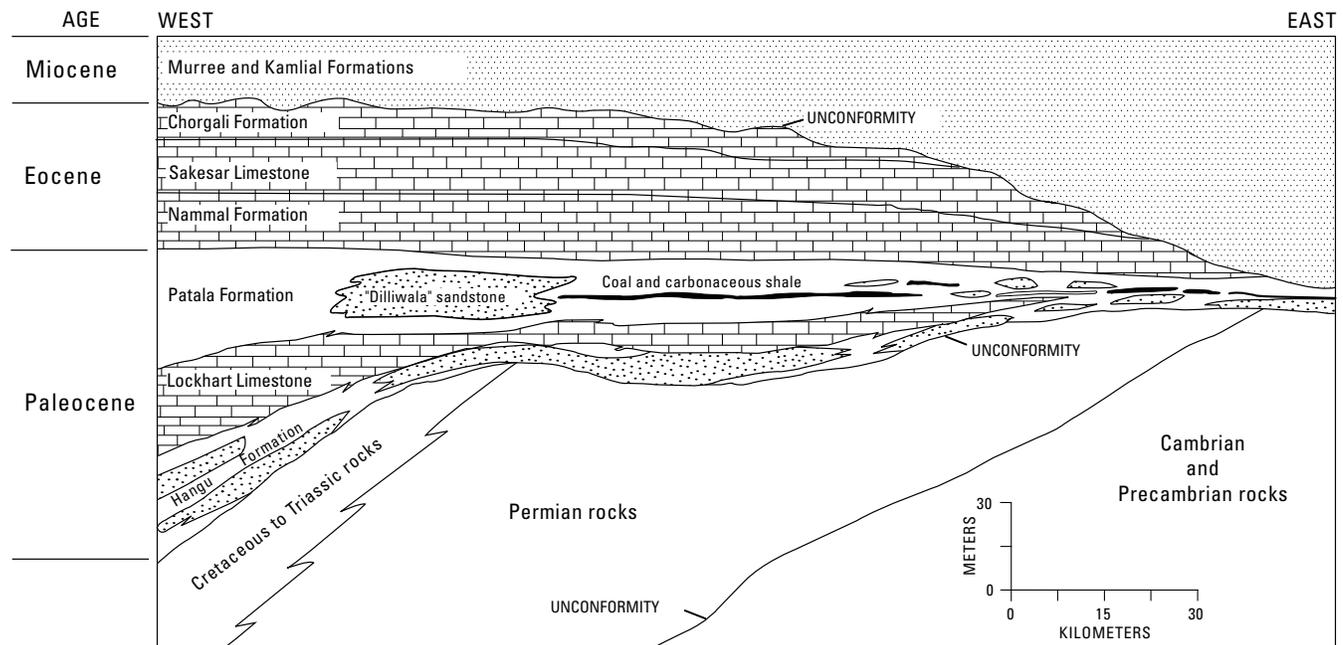


**Figure 12.** Index map showing the location and generalized geology of the Salt Range study area (modified from Baker and others, 1988). Heavy lines indicate the approximate location of lines of longitudinal section A on figure 18, B on figure 110, and C on figure 111; also see map A, plate 11.

formities exist in the area (Shah, 1980) (fig. 13). 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. 13). 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 13.** Generalized east-west longitudinal section of Tertiary formations in the Salt Range study area. Stratigraphic control is based on figures 18–112 (modified from Warwick and Shakoor, 1988b). Stipple patterns, sandstone; brick pattern, limestone; no pattern, undifferentiated rock types. Vertical exaggeration is  $\times 500$ .

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. 13). 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. 14A). The Lockhart Limestone (5–70 m thick) consists of dusky-yellow, nodular, skeletal wackestone to packstone (fig. 14B). In the eastern part of the Salt Range, the Lockhart pinches out toward the east (fig. 13).

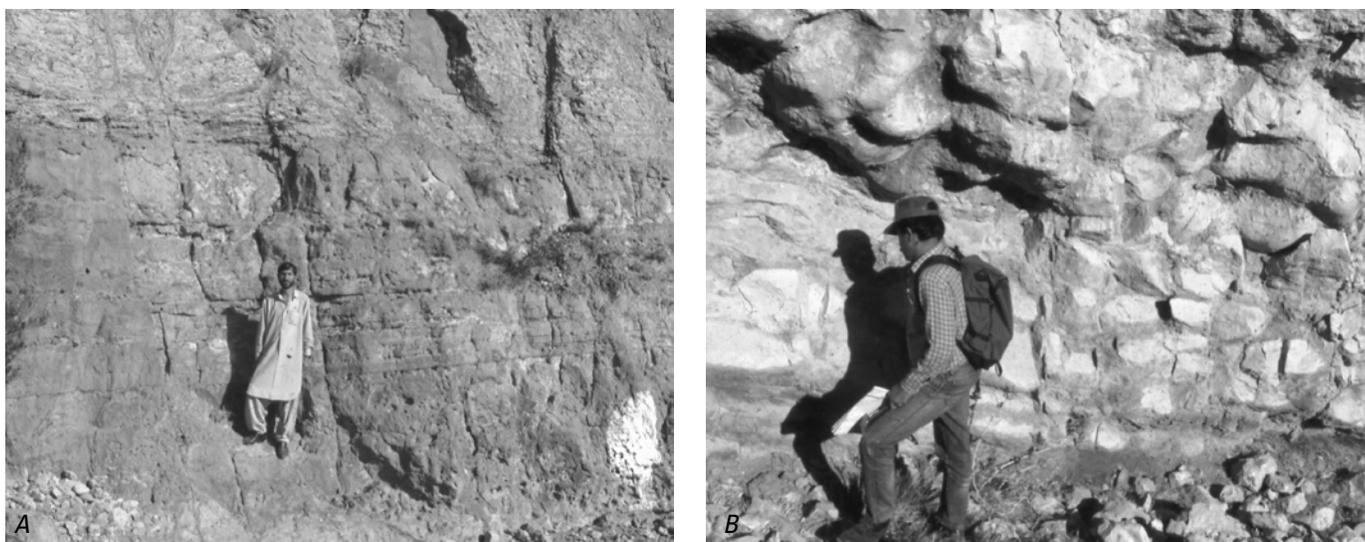
In the eastern area where the Lockhart is absent, the lower part of the Patala and Hangu are indistinguishable; the resulting unit has mostly Patala characteristics. Therefore, in this chapter, the use of the Hangu Formation is restricted; where the Patala and Hangu are indistinguishable, the rocks are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

sive 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 Kamliar 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. 13).

## 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 14.** 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 “Dilliwalla” 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 II. 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 11.** 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 11.** 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		
	<i>N</i>	avg.	s.d.	<i>N</i>	avg.	s.d.	<i>N</i>	avg.	s.d.	<i>N</i>	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

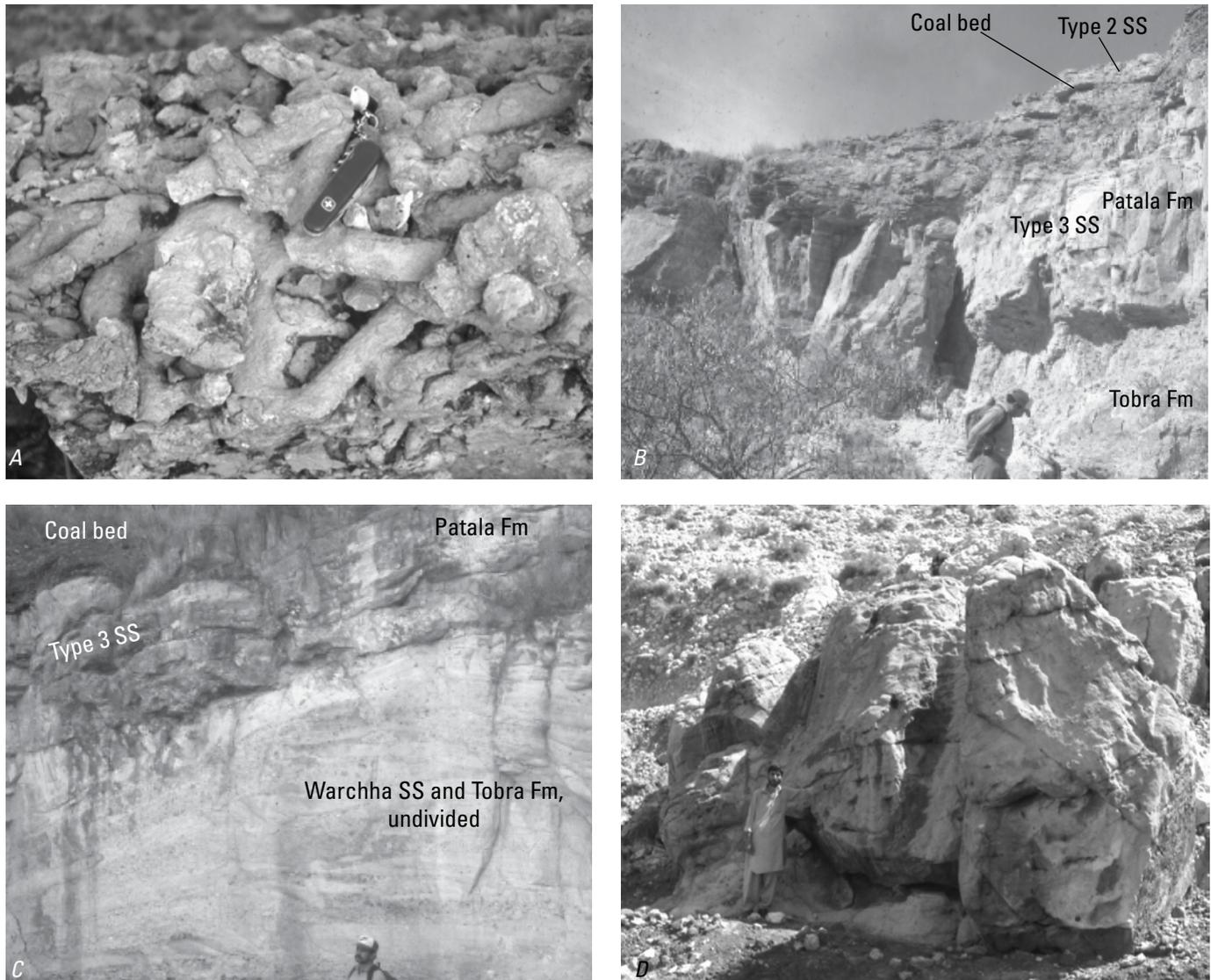
## Lithofacies of the Patala Formation

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 clay-

stone 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 15.** 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 thalassinidean-like 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. I5A) 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. I5B–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 abun-

dance 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 16.** 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. I7A) and usually contain root traces and light-gray to dark-reddish-brown glaebules (spherical masses) as much as 3 cm in diameter (fig. I7B). Textures for the mudstonelike rock range from angular and subangular-blocky to granular (using the classification of soil pedes 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 17.** 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. I5B-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).

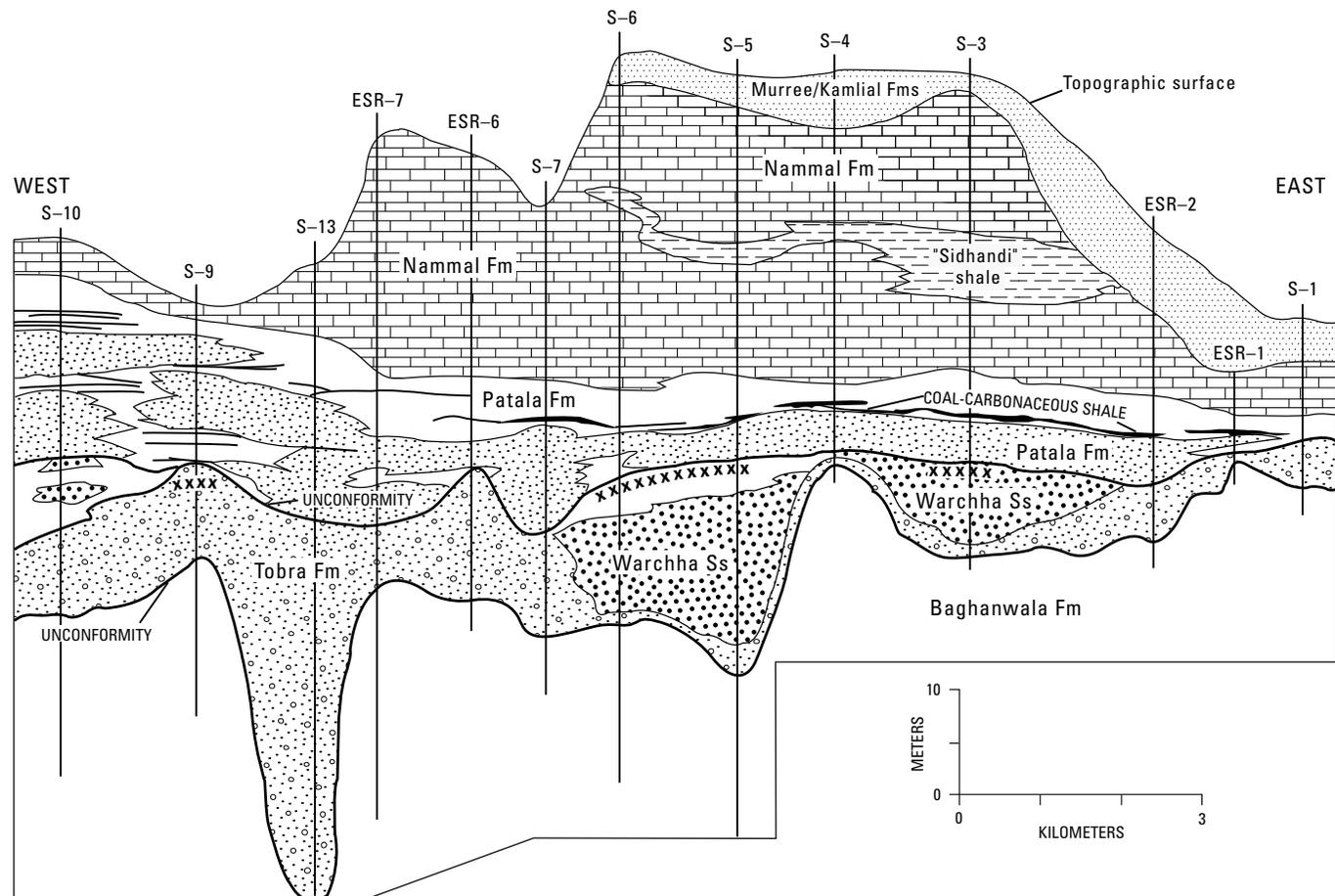
Examples of the type 1 and 2 sandstone lithofacies can be found in well-exposed sections within the eastern area of the Salt Range coal field. In the eastern area, a 7.5-m-thick body dominated by type 3 sandstone contains multiple channel scours (fig. I9). The lower 2 m has trough crossbeds as much

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.

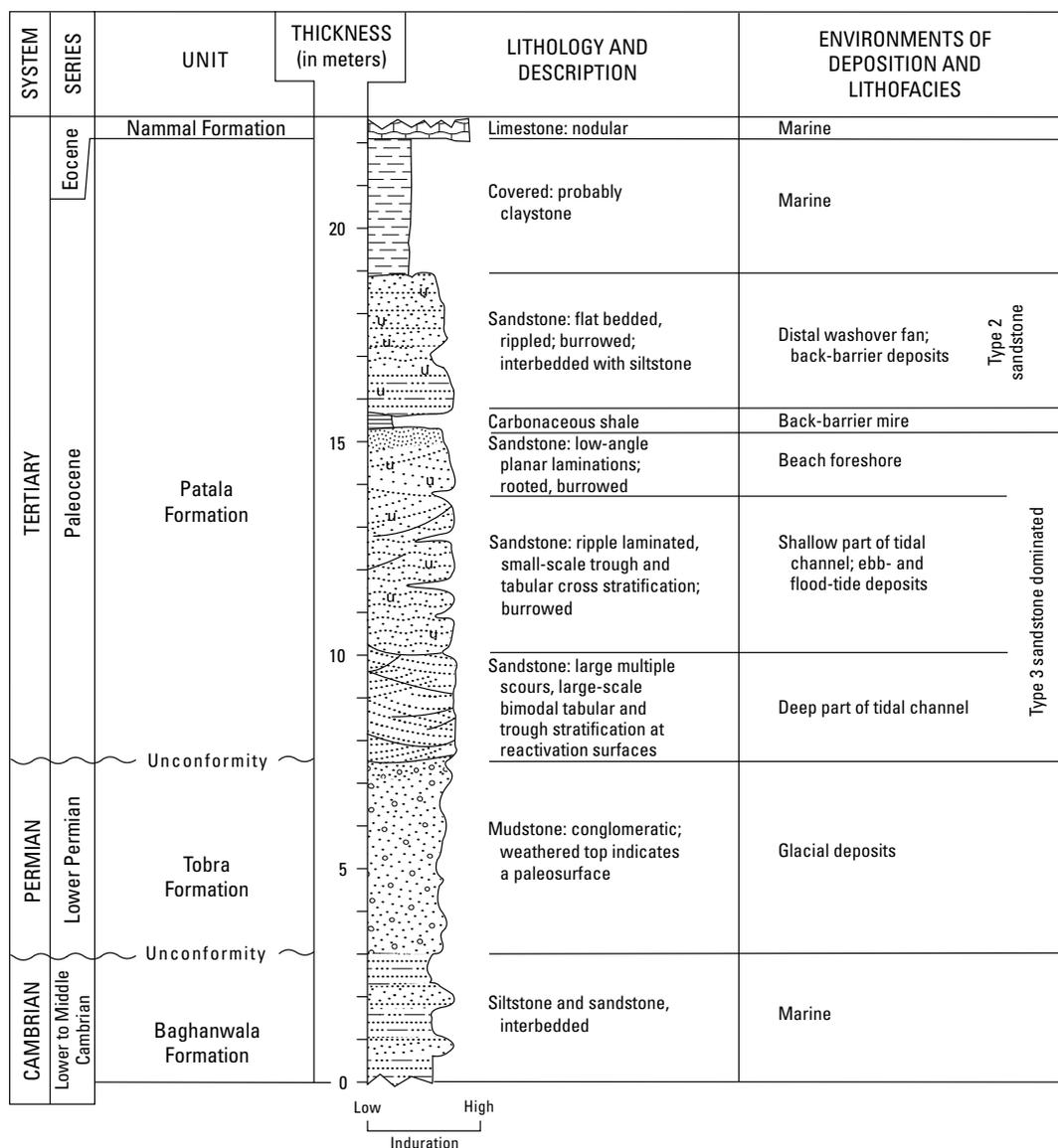
15B,C), which, in turn, are overlain by claystone and siltstone lithofacies interbedded with type 1 sandstones and thin (<2 m thick), laterally continuous (up to 50 m) type 2 sandstone bodies that usually contain flat and rippled bedding and burrows. Total sandstone content decreases upward in the Patala Formation. Claystone in the upper part of the formation grades into marl interbedded with limestone beds of the overlying Nammal Formation (fig. 19).

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 18.** 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  $\times 150$ .



**Figure 19.** 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. 18), at lat 32°44'03" N., long 73°11'45" E. (map A, pl. 11); detailed description is given as section 0-2 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. 11) 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. 11), 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. 18) 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. 11). 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 wash-over 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.

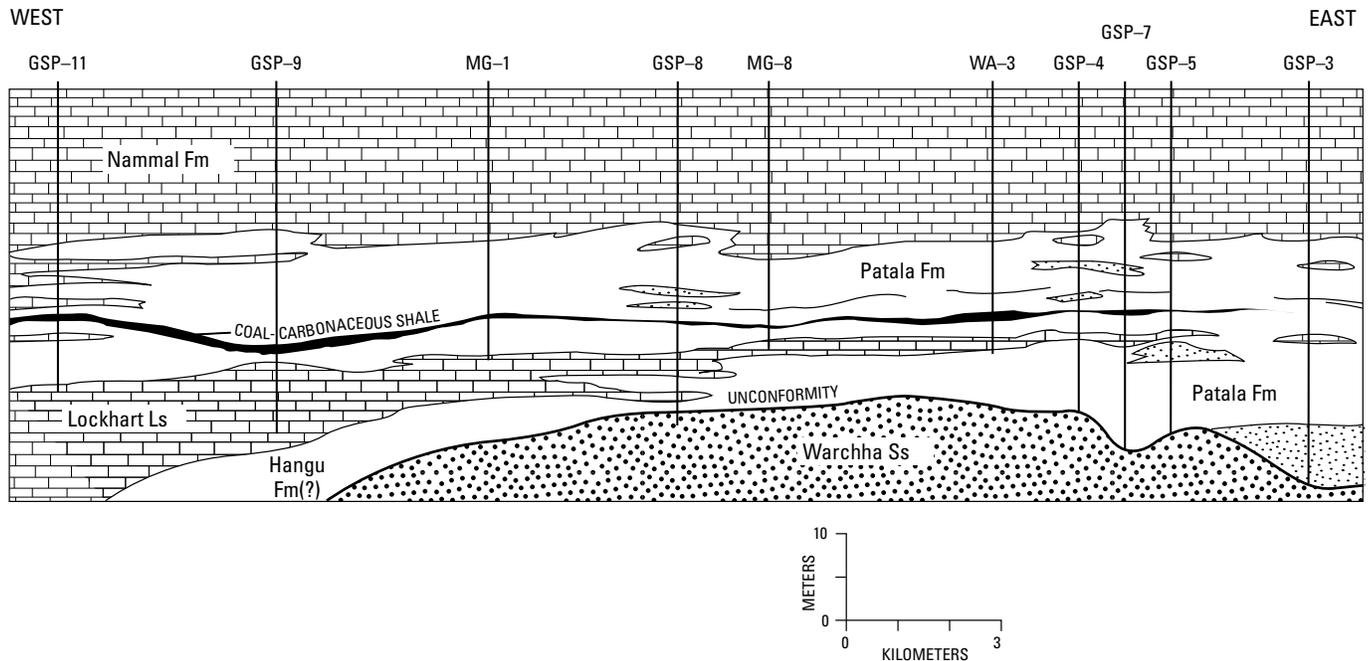
A general lack of major sandstone bodies in the western part of the central coal field indicates a later westward shift of the shoreline. The areas with little sandstone content (between

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 10.** 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  $\times 170$ .

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

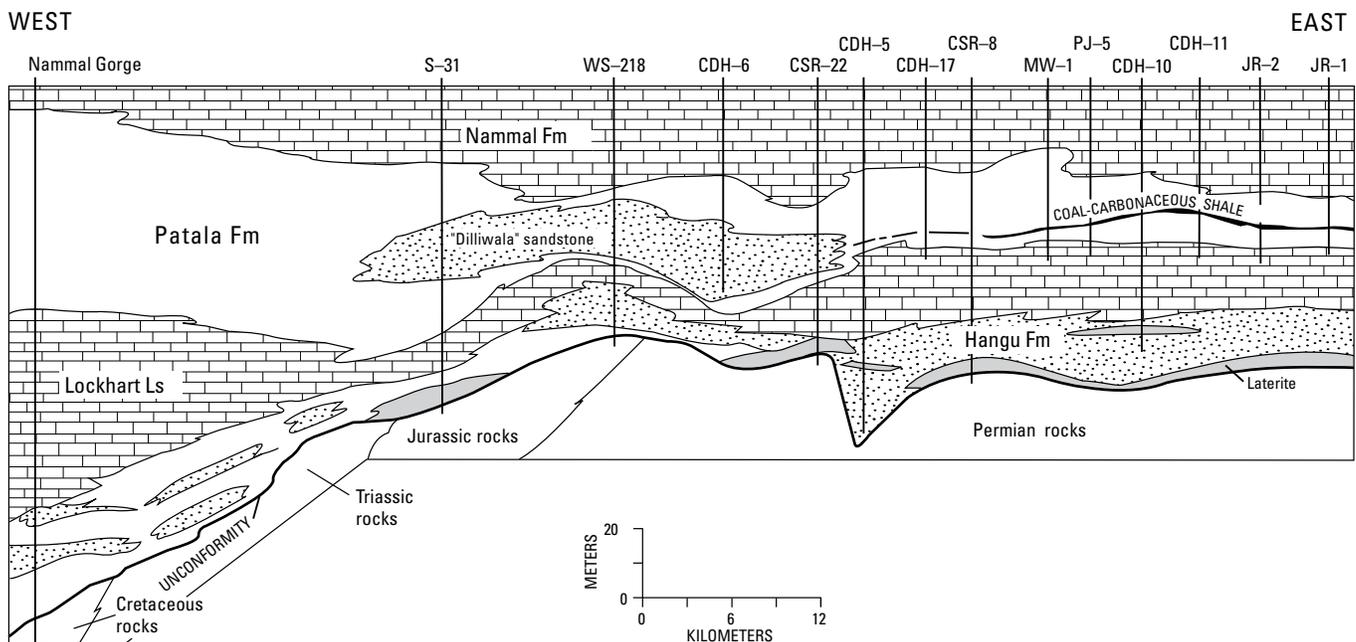
typically are more continuous laterally than mesotidal barriers (Hayes, 1975; Barwis and Hayes, 1979). Additionally, the bodies dominated by type 3 sandstone of the western area contain low-angle cross stratification throughout, which may indicate that foreshore processes were more dominant in the west 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

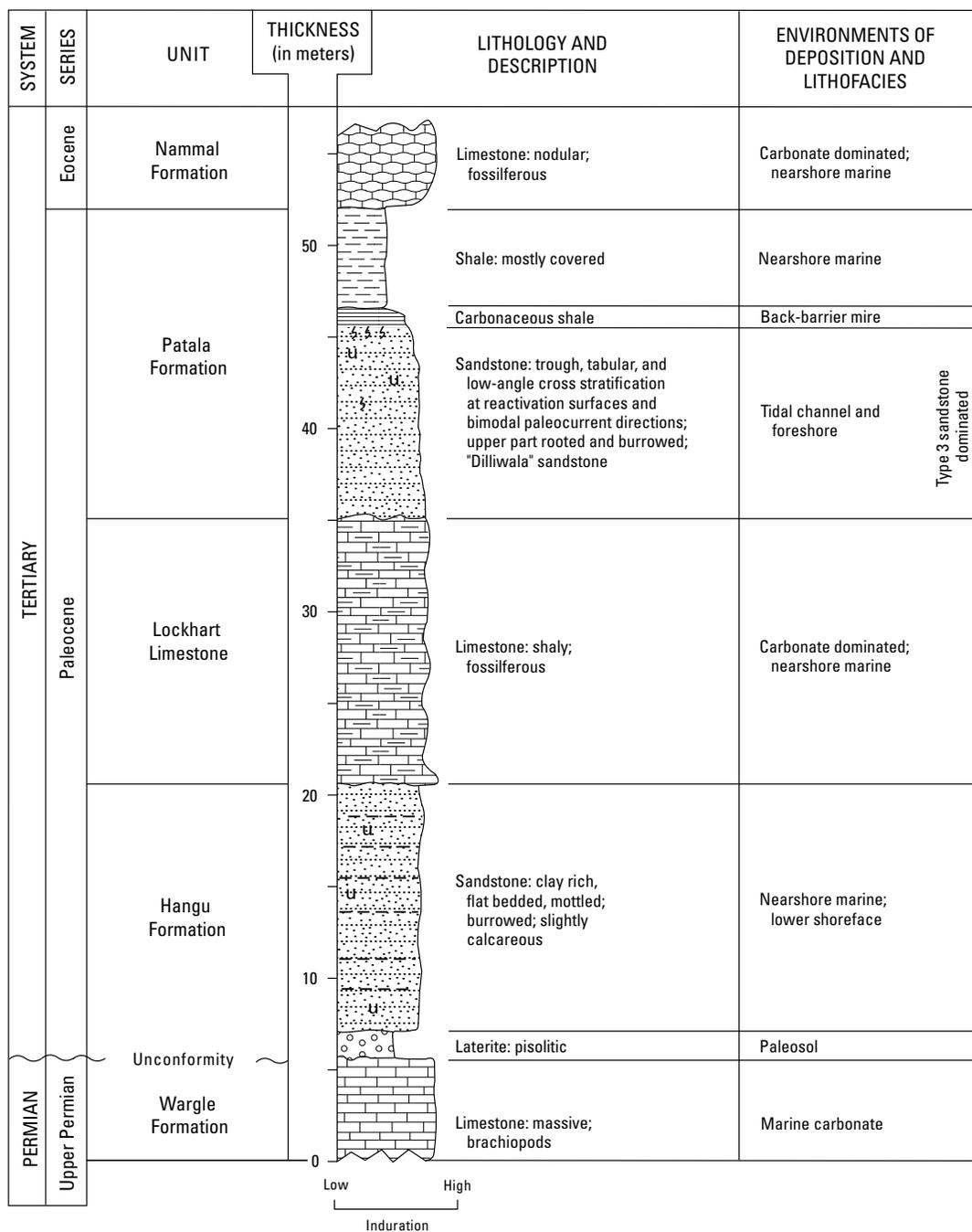
Fatmi and Haydri (1986) observed that several Paleozoic formations vary in thickness, pinch out, and reappear. If the pre-regional thrust position of the western Salt Range was proximal to this or other basement faults, the facies and thickness variations observed in the western Salt Range could have 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  $\times 165$ .



**Figure 112.** 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.

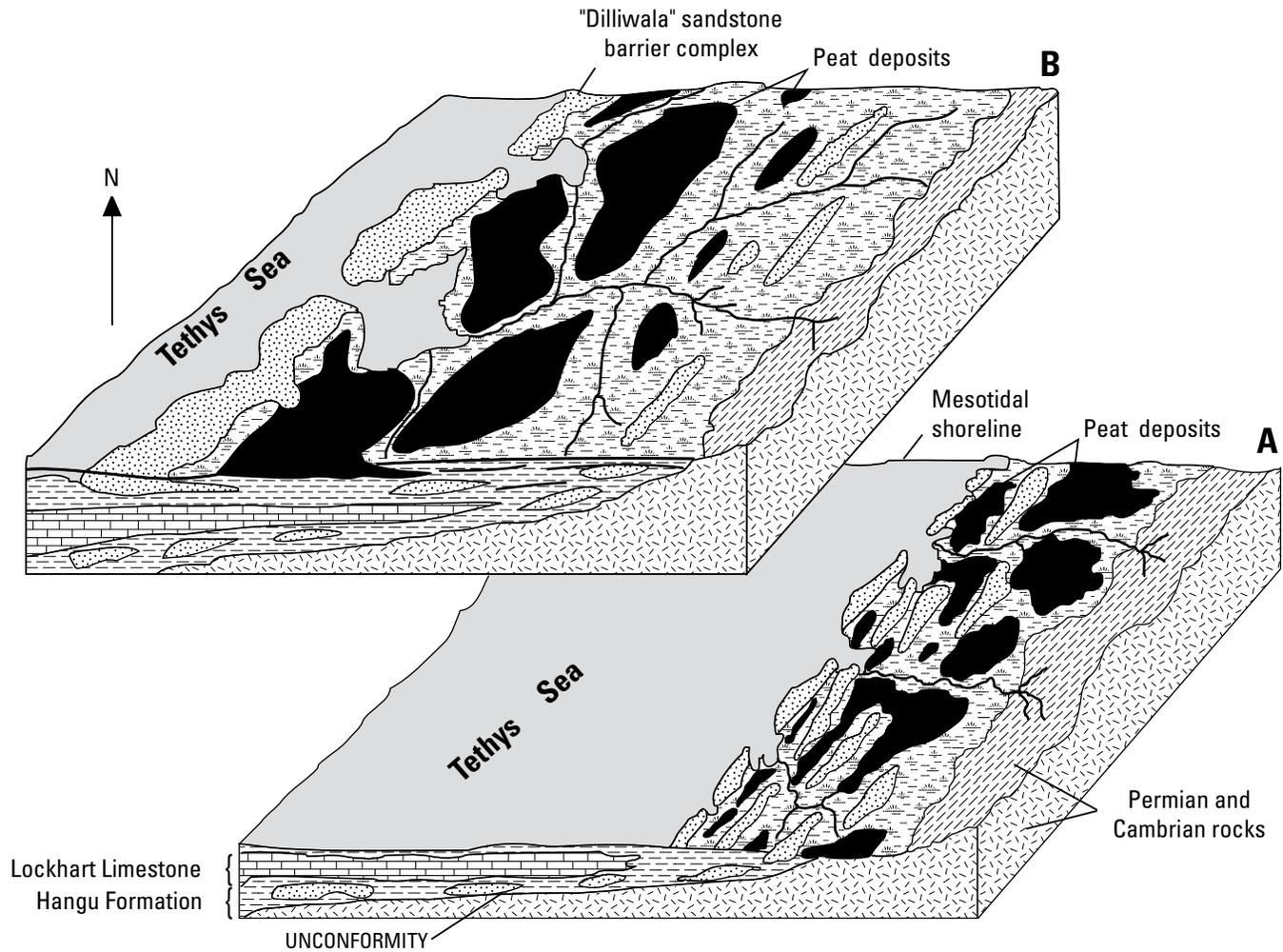
## Summary and Discussion

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. I13A). 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. I13B). 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.

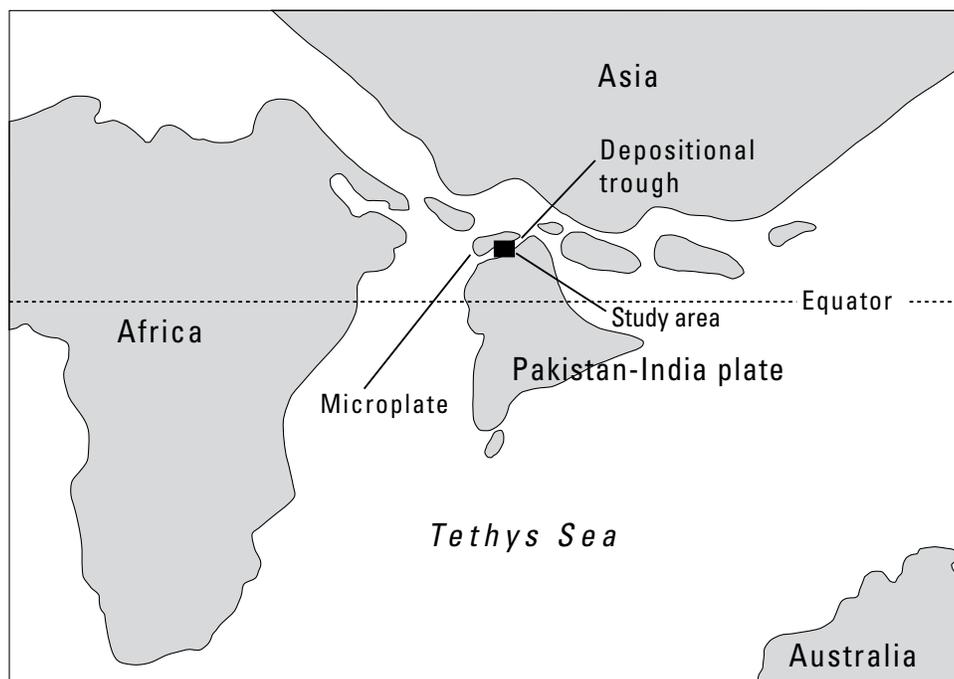
The thick buildup of deposits dominated by type 3 sandstone in the western Salt Range indicates that a relatively static shoreline may have been controlled by a paleotopographic high that was created by uplifted blocks of pre-Tertiary and basement rocks. This high appears to have influenced sedimentation 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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