The Pintail Coal Bed and Barrier Bar G— A Model for Coal of Barrier Bar-Lagoon Origin, Upper Cretaceous Almond Formation, Rock Springs Coal Field, Wyoming

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1398

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By HENRY W. ROEHLER

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Description of a paralic coal-forming depositional environment from studies of outcrops on the southeast flank of the Rock Springs uplift

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THE PINTAIL COAL BED AND BARRIER BAR G— A MODEL FOR COAL OF BARRIER BAR-LAGOON ORIGIN, UPPER CRETACEOUS ALMOND FORMATION, ROCK SPRINGS COAL FIELD, WYOMING

By HENRY W. ROEHLER

ABSTRACT

Barrier bar G and the overlying Pintail coal bed are in the upper part of the Almond Formation; they were deposited near the head of a shallow marine embayment that was located along the western shores of the Late Cretaceous (early Maestrichtian) epeiric sea. The barrier is composed of a lens of dominantly fine grained, quartzose sandstone more than 60 miles long and about 4 miles wide that separates gray marine shale to the east from continental rocks containing coal to the west. Eighteen miles of outcrops of the Almond Formation in the study area on the southeast flank of the Rock Springs uplift expose a long cross-sectional profile of the barrier and its lagoon and marine equivalents.

Barrier bar G was deposited along a mesotidal coastline that had numerous tidal inlets, large flood-tidal deltas, and small ebb-tidal deltas. Lithofacies of the barrier sandstone include lower, middle, and upper shoreface, dune, tidal channel, and washover sequences that are easily identified by their sedimentary structures and fossils.

The Pintail coal bed was deposited in a lagoon, landward of barrier bar G. As the barrier prograded, the back-barrier flat was progressively covered by swamp deposits that include the seaward wedge-out of the coal bed. The coal bed is massive and locally more than 6 feet thick. It contains splits and partings of carbonaceous shale. The splits and partings are interpreted to be deposits of tidal inlet and tidal creek origin that suggest direct relationships exist between water salinity, plant habitats, and lithologies. Analytical data indicate that the Pintail coal bed was deposited in a freshwater, forest swamp habitat that contained thick-stalked, woody vegetation, including trees and shrubs. Similar data show that the carbonaceous shale was deposited in a tidally influenced, brackish-water, reed swamp (salt marsh) habitat that contained herbaceous, thin-stalked, aquatic, grasslike vegetation, without appreciable peat accumulation.

The Pintail coal bed is a low-sulfur (<1 percent) bituminous coal with heating values that range between 11,780 and 12,240 British thermal units per pound on an as-received basis. Total in-place resources of the bed within the study area are estimated to be 77 million short tons. Underground methods appear to be the most favorable manner for recovering the Pintail coal along with other overlying and underlying coal beds from a single mine containing several mine levels.

A barrier-lagoon, coal-forming model has been developed from the depositional history of barrier bar G and the Pintail coal bed. The model demonstrates that the barrier and its lagoon evolved through saltwater to brackish-water to freshwater stages, with the times of maximum peat accumulation occurring in the freshwater stage.

INTRODUCTION

The investigation is part of the ongoing research by the U.S. Geological Survey into the occurrence, quality, and quantity of the coal deposits of the United States. The research provides economic and engineering data for coal leasing and sale, safe mine design, profitable mine operation, and adequate reclamation of lands disturbed by mining.

The paper presents the results of a study of the origin, areal distribution, composition, and genetic relations of the Pintail coal bed, barrier bar G, and associated rocks in a small segment of the Rock Springs coal field in Wyoming. A model was developed for a bayhead barrier bar-lagoon coal-forming depositional environment from the paleogeography, sedimentology, and paleontology of the upper part of the Almond Formation during part of the Late Cretaceous. The methodology used can be applied to studies of coal beds of similar origin in other parts of the Rock Springs coal field and in other coal fields in the western United States.

The author has borrowed freely from the geologic literature in writing the paper, but the conclusions reached are exclusively his and are based mostly on field observations. Peat beds associated with barrier bar sands in Holocene deposits are useful in interpreting the overall depositional setting for the Pintail coal bed and barrier bar G, but the author does not believe that good analogs of the Upper Cretaceous deposits investigated in this study are present anywhere in the world today.

LOCATION AND ACCESSIBILITY OF THE STUDY AREA

The Pintail coal bed, barrier bar G, and associated rocks were studied along a belt of northeast-trending outcrops within the Almond Formation on the southeast flank of the Rock Springs uplift in southwest Wyoming. The outcrops are about 18 mi long, and are located in T. 15–17 N., R. 101–102 W., 21–28 mi southeast of Rock Springs, Wyo. (fig. 1).

The northern part of the study area is accessible by an improved gravel road that trends east from a junction with Wyoming Highway 430, 19 mi southeast of Rock Springs, Wyo. The southern part of the study area is accessible by an unimproved road that crosses Highway 430 in a northeast direction 31 mi southeast of Rock Springs and follows a valley formed along the outcrops of the Lewis Shale, the stratigraphic unit which overlies the Almond Formation. The accessibility of local outcrops is generally limited to foot travel or to four-wheel-drive vehicles on abandoned seismograph roads or on trails used seasonally by hunters and sheep ranchers.

PHYSIOGRAPHY

The desert terrain of the study area is predominantly barren northeast-trending sandstone ridges that are separated by soil- and sage-covered shale valleys. Annual precipitation is less than 8 in. (Root and others, 1973). The area is uninhabited except for a few people at the Mud Springs Ranch on Wyoming Highway 430, 30 mi southeast of Rock Springs. Altitudes of outcrops of barrier bar G and adjacent rocks vary between 7,000 and 7,300 ft above sea level, but nearby escarpments may rise a few hundred feet higher. The rocks are well exposed, except for a few dry, alluvium-filled drainages that cross the line of outcrops. Sand dunes, soil, and vegetation cover outcrops locally.

FIELD METHODS

The Pintail coal bed, barrier bar G, and other coal beds and stratigraphic units discussed in the paper were named by the author during field investigations between 1974 and 1979. The units are shown on geologic maps of the Camel Rock, Cooper Ridge NE, and Mud Springs Ranch 7½-minute topographic quadrangles (Roehler, 1977b, 1978a, 1979a). Resources of the Pintail coal bed are listed in U.S. Geological Survey Professional Papers 1065-B and 1065-C (Roehler, 1979b, 1979c). An abbreviated version of the present investigation was included in a 1979 field trip guidebook for Cretaceous rocks of the Rock Springs uplift (Roehler, 1979d).

The outcrops in the study area offer an excellent opportunity for the geological investigation of a well-exposed, ancient barrier sandstone and an associated coal bed. Outcrops of the barrier and coal trend about N. 25° E. at an angle of about 30 degrees to the N. 5° W. strike of the ancient barrier strandline. Hence, a long, oblique, cross-sectional profile is visible through the barrier and its marine and lagoon equivalents along the 18 mi of outcrops studied. During the investigation, 104 stratigraphic sections were measured along these outcrops with Jacob's staff and Abney level (fig. 2). Fourteen additional sections were measured at 10 localites (localities A to J, fig. 3) to provide supplementary details concerning lithofacies and primary sedimentary structures. The entire length of the outcrops was walked while measuring the sections, which allowed continuous observation and recording of details of thickness and facies changes.

Twenty-seven samples of sandstone from outcrops were collected for petrographic study; four samples of coal were collected for palynomorph identifications; three samples of coal and carbonaceous shale were collected for maceral, as well as proximate and ultimate, analyses. The Pintail coal bed was trenched 94 times with pick and shovel to reveal the thickness and characteristics of freshly exposed coal, and the composition of splits, partings, seat rock, and roof rock. Four widely spaced holes were drilled by the U.S. Geological Survey in 1977 as part of a coal-resource assessment program. No cores were taken in the drill holes, but geophysical logs were run and these provide limited data concerning the thickness of the barrier sandstone and coal bed for distances downdip from outcrops.

ROCK SPRINGS COAL FIELD

The Rock Springs coal field is roughly 72 mi long (north-south) and 60 mi wide (east-west). It includes all the Rock Springs anticlinal uplift and parts of the adjacent Green River, Great Divide, and Washakie basins in southwestern Wyoming, in the area immediately north of the common boundary of Wyoming, Utah, and Colorado.

Coal has been mined continuously in the Rock Springs coal field since 1867, when the Union Pacific Railroad was constructed across southern Wyoming. Since 1867, nearly 35,000 acres of the coal field have been worked through more than 65 openings. Total production from the field as of 1980 was estimated by the author to be

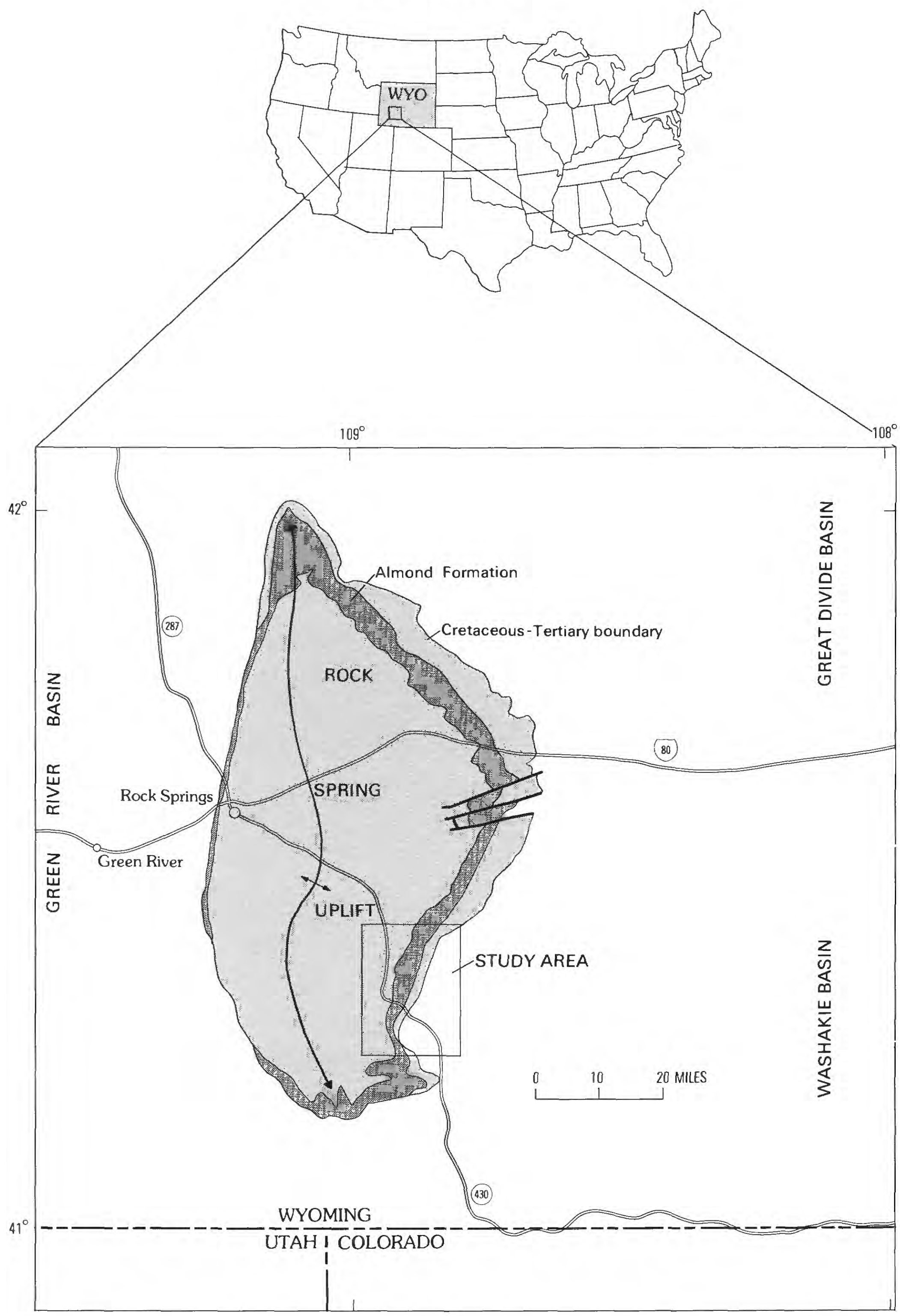


FIGURE 1.—Index map showing the location of the study area in the Rock Springs uplift, Wyoming.

about 250 million short tons. These figures represent about 3 percent of the geographical area and less than 1.5 percent of the total resources of the field.

The Rock Springs coal field contains nearly 6,000 ft of coal-bearing rocks, if the thicknesses of the Rock Springs, Almond, and Lance Formations of Cretaceous

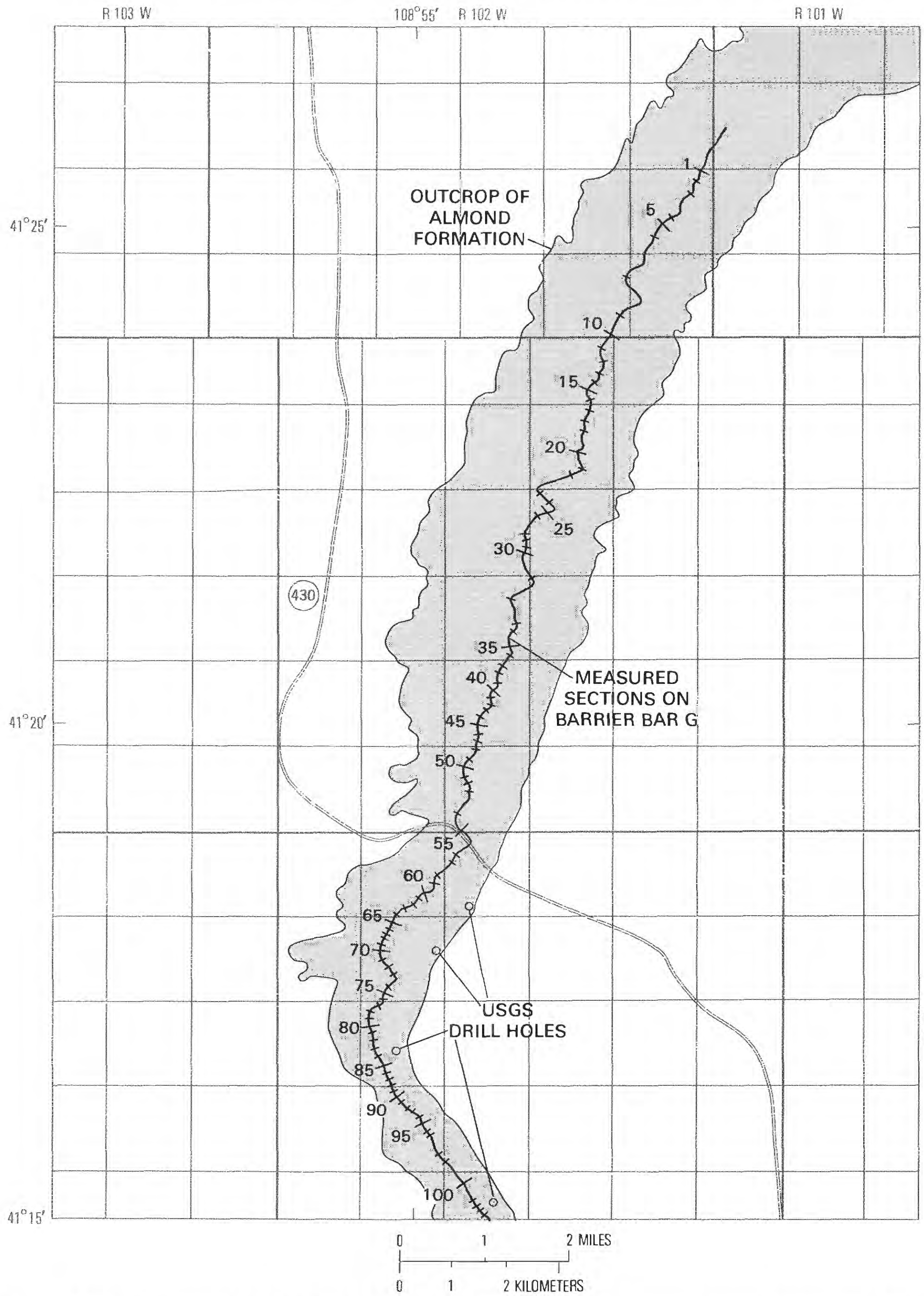


FIGURE 2.—Geologic map of the Almond Formation (shaded) in the study area showing the location of outcrops of barrier bar G (heavy line), measured sections (104) across barrier bar G and the Pintail coal bed, and U.S. Geological Survey drill holes.

age, and the Fort Union and Wasatch Formations of Tertiary age, are combined. The five formations contain more than 150 minable beds of low-sulfur (<1 percent) sub-bituminous to bituminous (9,000 to 13,000 Btu/lb) coal within seven distinctly different coal-forming depositional environments identified by the author in

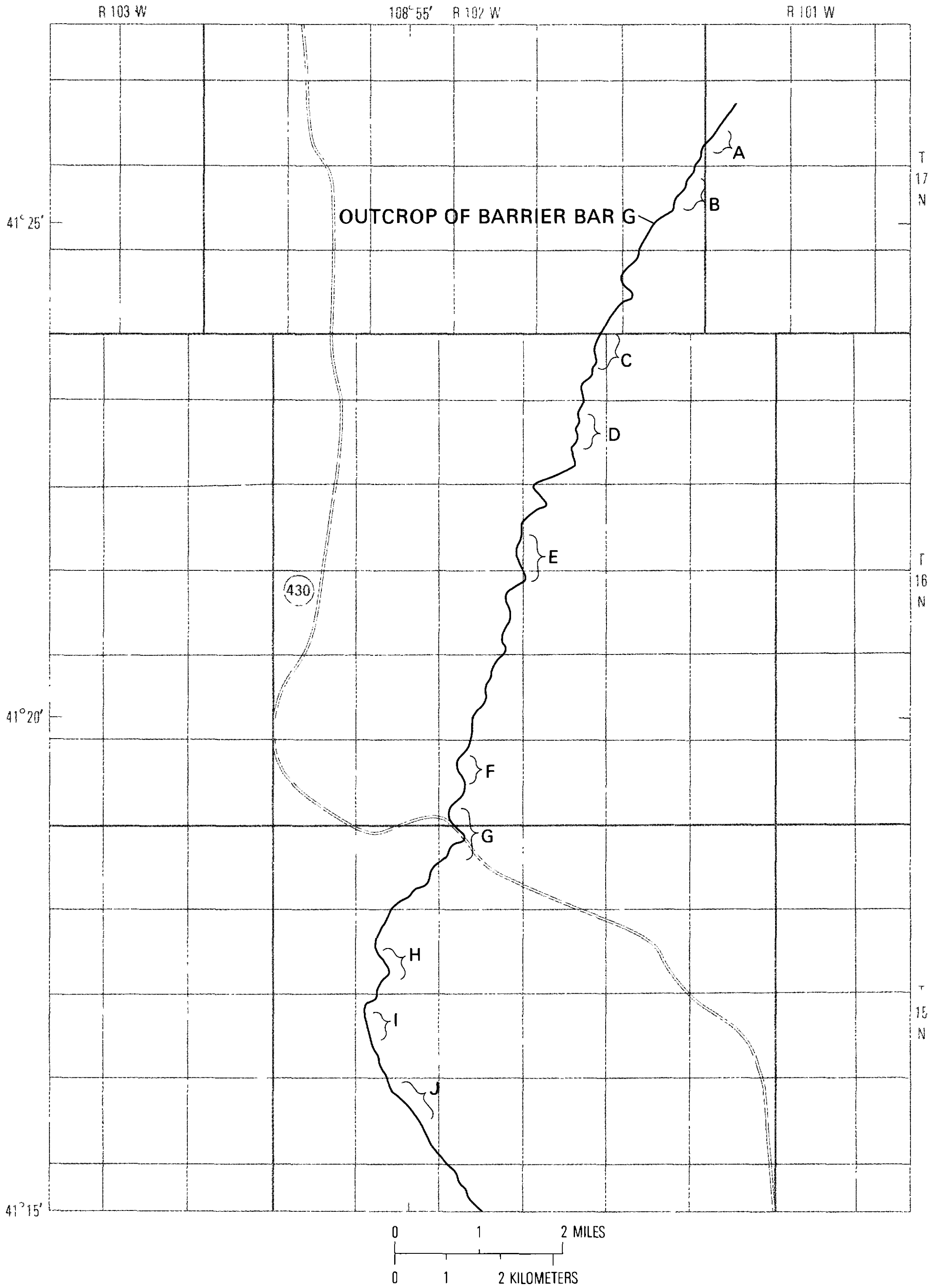


FIGURE 3.—Map of the study area showing localities A to J for which depositional environments and lithofacies of barrier bar G, the Pintail coal bed, and associated rocks are described in detail. The stratigraphic positions of the localities are shown by large dots in cross section in figure 13.

the field. They are alluvial plain, coastal plain, strand plain, delta plain, and barrier-lagoon in Cretaceous rocks (fig. 4), and intermontane fluvial-paludal and paludal-lacustrine in Tertiary rocks. This paper examines one coal bed and the underlying rocks of barrier-lagoon origin.

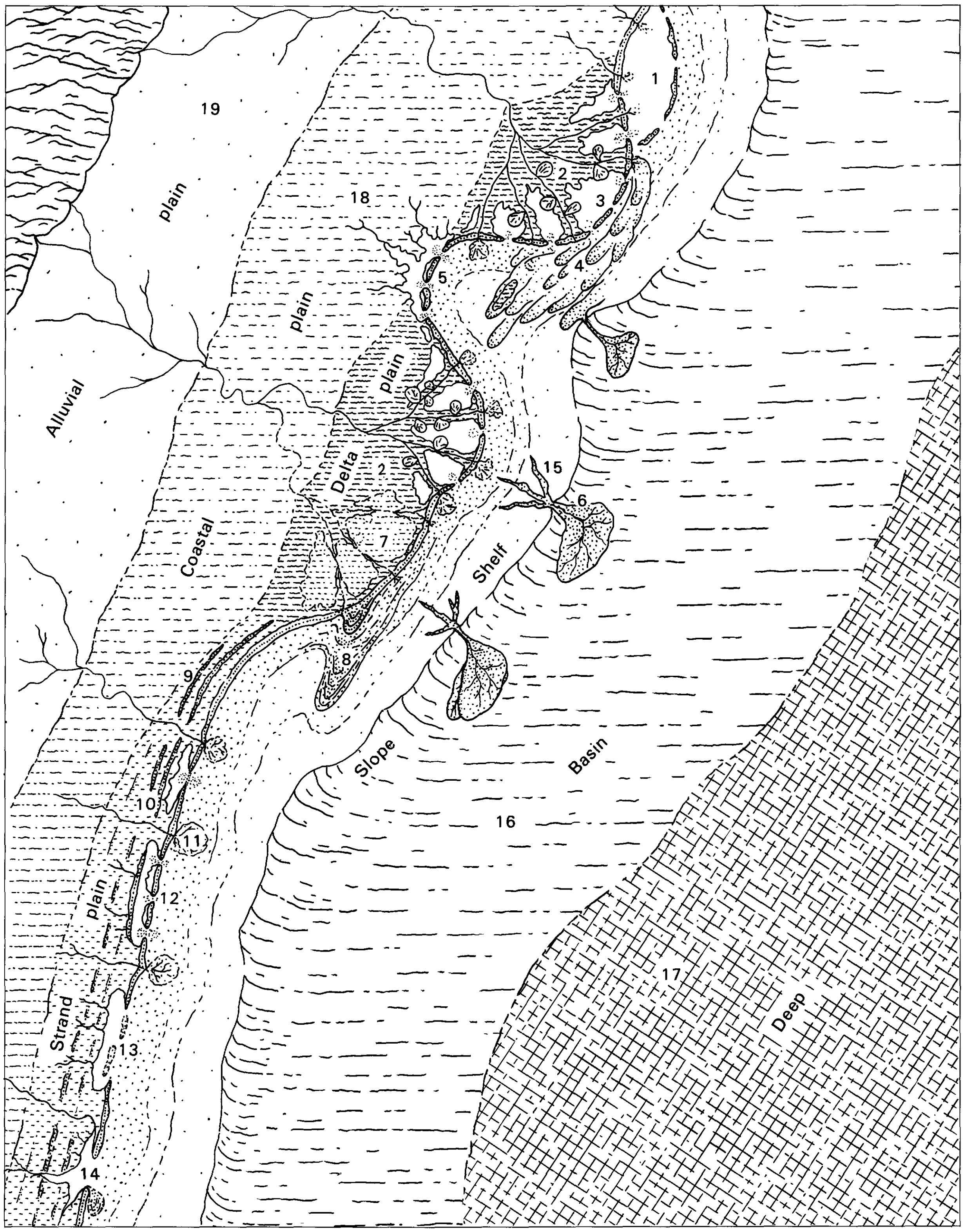


FIGURE 4 (above and facing page).—Physiographic map showing hypothetical relationships of depositional environments associated with marine coastlines in the western interior of the United States in the Late Cretaceous.

EXPLANATION

Map No.	Morphologic Feature	Example
1	Transgressive sandstone	Upper part of Almond Formation—barrier bar AA—NW ¼ NE ¼ sec. 22, T. 16 N., R. 102 W. (Wyo.)
2	Arcuate delta	Lower part of Rock Springs Formation—sec. 20, T. 19 N., R. 104 W. and secs. 21, 28, T. 20 N., R. 102 W. (Wyo.)
3	Delta front barrier islands and interdistributary bays	Lower part of Rock Springs Formation—N ½ SE ¼ sec. 24, T. 19 N., R. 102 W. (Wyo.)
4	Longshore-offshore bars	Dad Sandstone Member of the Lewis Shale—T. 16 N., R. 91 W. (Wyo.)
5	Barrier plain—depositional envoirnment of barrier bar G	Upper part of Almond Formation—T. 15-16 N., R. 102 W. (Wyo.)
6	Submarine fan	Lower part of Blair Formation—Highway I-80 roadcut—SW ¼ NE ¼ sec. 32, T. 20 N., R. 102 W. (Wyo.)
7	Abondoned delta lobe	Lower part of Rock Springs Formation—sec. 20, T. 19 N., R. 104 W. (Wyo.)
8	Delta front accretionary bar	Lower part of Rock Springs Formation—S ½ sec. 23, T. 12 N., R. 107 W. (Wyo.)
9	Strand plain ridge and swale	Upper part of Rock Springs Formation—NC sec. 15, T. 3 N., R. 21 E. (Utah)
10	Strand plain with bay	McCourt Sandstone Tongue of Rock Springs Formation—S ½ sec. 19, T. 12 N., R. 107 W. (Wyo.)
11	Distributary mouth bar	Rock Springs Formation—E ½ NE ¼ SE ¼ sec. 12, T. 18 N., R. 102 W. (Wyo.)
12	Strand plain barrier island	McCourt Sandstone Tongue of Rock Springs Formation—S ½ secs. 20, 21 and 22, T. 12 N., R. 107 W. (Wyo.)
13	Strand plain bay mouth bar	Sego Sandstone—Cottonwood Canyon—T. 19 S., R. 23-24 E. (Utah)
14	Sound with accretionary bar	Fox Hills-Lance Formations—NE ¼ and S ½ sec. 21, T. 19 N., R. 100 W. (Wyo.)
15	Shelf channel	Middle part of Blair Formation—SW ¼ SE ¼ sec. 36, T. 17 N., R. 103 W. (Wyo.)
16	Offshore marine	Baxter Shale—sec. 19, T. 18 N., R. 103 W. (Wyo.)
17	Deep marine	Niobrara Limestone—Eastern Wyoming; Eastern Colorado
18	Coastal plain	Lower part of Almond Formation—SE ¼ SE ¼ sec. 29, T. 16 N., R. 102 W. (Wyo.)
19	Alluvial plain	Ericson Sandstone—NW ¼ NE ¼ sec. 20, T. 16 N., R. 102 W. (Wyo.)

STRATIGRAPHY OF THE ALMOND FORMATION IN SOUTHWEST WYOMING AND ADJACENT AREAS

NOMENCLATURE, LITHOLOGY, AND THICKNESS

The name "Almond coal group" was originally used by Schultz (1920) for 700–950 ft of white and brown sandstone, shale, clay, and coal that crop out at the top of the Mesaverde Formation near the Almond Stage Station at Point of Rocks, Wyo. Hale (1950) later elevated the Mesaverde Formation in the Rock Springs uplift to a group, and then he subdivided the group in descending order into four formations: (1) the Almond Formation composed of 400–800 ft of gray and brown sandstone, siltstone, shale, and coal; (2) the Ericson Formation composed of 900–1,200 ft of gray sandstone; (3) the Rock Springs Formation composed of 1,200–1,800 ft of gray and brown sandstone, shale, siltstone, and coal; and (4) the Blair Formation composed of 1,200–1,700 ft of gray shale and siltstone. The Almond Formation conformably overlies the Ericson Formation, most commonly named the Ericson Sandstone; their contact is gradational. The Almond Formation normally intertongues with and is overlain by the Lewis Shale. The relations of the Almond to overlying and underlying Cretaceous formations across the study area are shown on a generalized regional northwest-southeast cross section (fig. 5).

Chronostratigraphic and lithostratigraphic equivalents of the Almond Formation are present in the upper part of the Williams Fork Formation in northern Colorado (Izett and others, 1971), the Meeteetse Formation in central Wyoming (Gill and Cobban, 1973), and the Adaville Formation in western Wyoming (Smith, 1965).

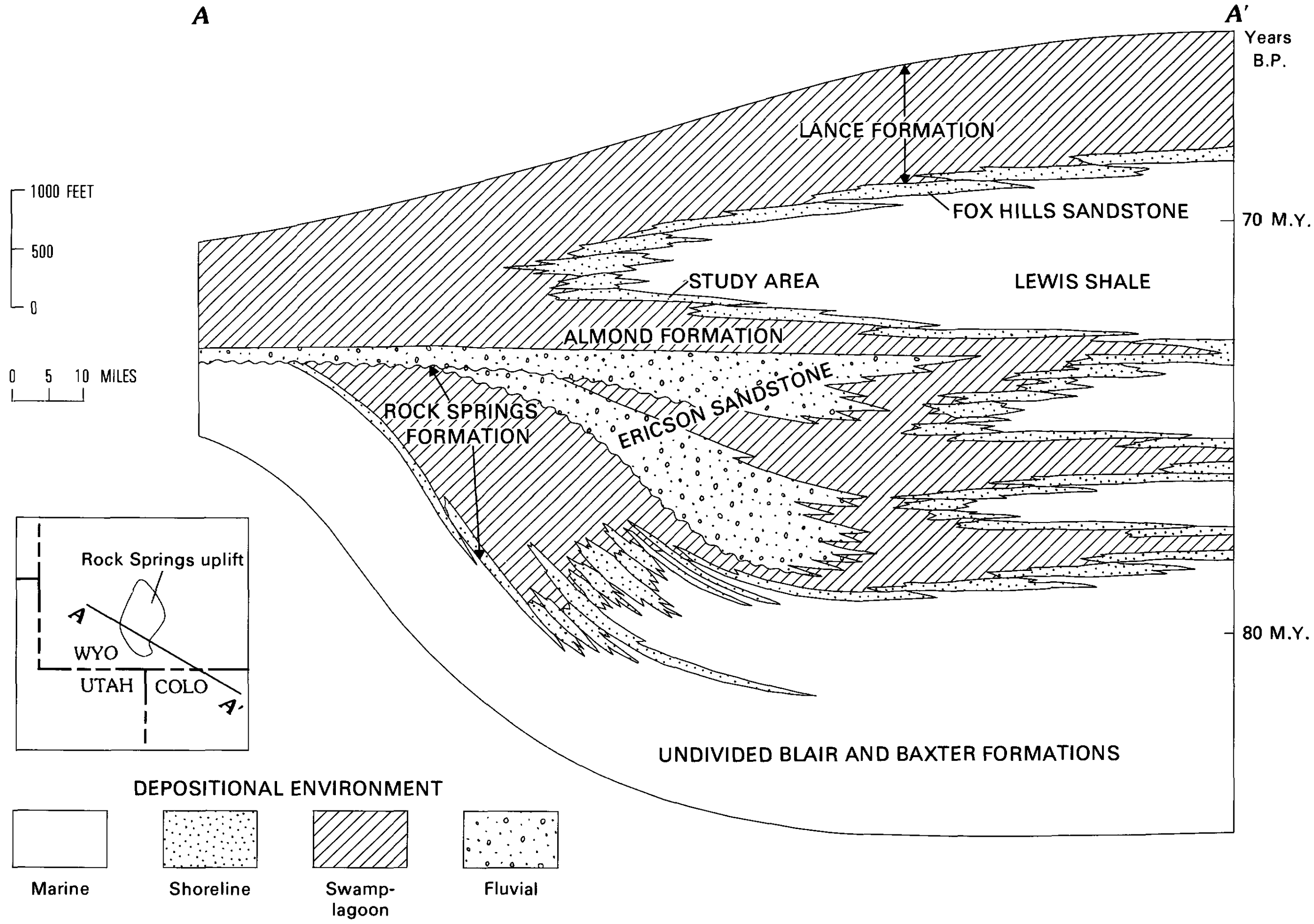


FIGURE 5.—Generalized northwest-southeast cross section *A-A'* of Upper Cretaceous formations in southwest Wyoming and northwest Colorado, showing their age (in millions of years), thickness, stratigraphic relations, and basic depositional environments.

OUTCROPS OF THE ALMOND FORMATION IN THE ROCK SPRINGS UPLIFT

The Almond Formation is exposed as a band of outcrops from 1 to 3 mi wide that nearly encircles the Rock Springs uplift. The formation has a maximum thickness of nearly 800 ft along parts of the east flank of the uplift, where it is conformably overlain by the Lewis Shale; it thins and is missing in places along the west flank because of Laramide erosion across the crest of the uplift in late Late Cretaceous time (Roehler, 1961). The formation is unconformably overlain in most places on the west flank by the Paleocene Fort Union Formation. The Pintail coal bed has been identified in outcrops on both the east and west flanks, but barrier bar G is restricted to the east flank. The locations of outcrops of the Almond Formation in the study area are shown in figure 1.

PALEOCLIMATE AND PALEOGEOGRAPHY

The Almond Formation was deposited in a subtropical to warm-temperate climate (Kaufman, 1977, p. 91) along the western shores of the epeiric sea (fig. 6) that extended from northern Alaska and Canada southward to the Gulf of Mexico across central North America during the Late Cretaceous (Gill and Cobban, 1966). The epeiric sea was thousands of miles long and hundreds of miles wide. The depositional basin of the epeiric sea was asymmetric and the zone of maximum subsidence and sediment accumulation was along the western margin of the seaway (King, 1959). When barrier bar G and the Pintail coal bed were deposited, the western shores of the sea were slowly transgressing westward across what is now the southern part of the State of Wyoming and had reached the area of the east flank of the Rock Springs uplift, as shown on a paleogeographic map (fig. 7). At this time the shoreline consisted of a chain of barrier islands that trended north-south across the east flank of the uplift. The barrier islands were situated at the head of an embayment in an interdeltaic area between the Red Desert delta (Asquith, 1970) to the north and an unnamed delta west of Craig in northwestern Colorado. The embayment is commonly called the Rock Springs embayment by petroleum geologists working in the area.

Moderately high tides that affected the origin and development of barrier bar G (discussed later) probably resulted from a focusing of tidal currents as they flowed westward and became constricted toward the head of the Rock Springs embayment. The sands that accumulated along the shores of barrier bar G were constantly reworked by waves and drifted southward as the result of pronounced longshore currents.

PALEONTOLOGY AND AGE

Few age-diagnostic megafossils from the Almond Formation have been collected in the Rock Springs uplift area. J. R. Gill (USGS Locality D6870) found the ammonite index fossil *Baculites baculus* near the top of the Almond Formation about 20 mi north of the study area in NE¼ sec. 10, T. 20 N., R. 101 W., at a collecting site about 0.5 mi south of the Jim Bridger Powerplant. The specimen was collected from a stratigraphic interval about 300 ft above barrier bar G and the Pintail coal bed. Gill and others (1970) reported the presence of the ammonite index fossil *Baculites eliasi* in the basal part of the Lewis Shale northwest of Rawlins, Wyo., in rocks that are stratigraphic equivalents of the middle part of the Almond Formation, barrier bar G, and the Pintail coal bed in the Rock Springs uplift. The overall paleontological relations suggest that the upper part of the Almond Formation is 70–72 million years old and earliest Maestrichtian in age (Gill and others, 1970, p. 6).

Fossil collections from the Almond Formation in the Rock Springs uplift area include a large assemblage of freshwater, brackish-water and saltwater mollusks, and a few vertebrates and ammonites. The fauna listed below were collected by J. R. Gill and the author at U.S. Geological Survey Localities D6401, D6402, D6404, D6411, D6413, D6416, D6869, D6870, D6871, D9185, D9186, D9187, D9190, D9191, D9193, D9398, D9399, D9400, D9401, and D9402. (Data concerning the location of collection sites, and the identification and paleoecology of the taxa, are available at the Branch of Paleontology and Stratigraphy, U.S. Geological Survey, P. O. Box 25046, Denver, Colorado 80225.)

Mollusks:

Nerita n. sp.	*Modiolus* cf. *M. meekii*
Oreohelix sp.	*Crenella* sp.
Holospira cf. *H. dyeri*	*Pholadomya* sp.
Anomia gryphorhynchus	*Astarte* sp.
Anomia micronema	*Dentalium pauperculum*
Leptesthes sp.	*Micrabacia americana*
Ethmocardium n. sp.	*Lucina* sp.
Crassostrea subtrigonalis	*Tellina* sp.
Crassostrea wyomingensis	*Corbicula cytheriformis*
Veloritina occidentalis	*Tulotomops* sp.
Veloritina cleburni	*Nuculana* sp.
Glycymeris wyomingensis	*Pecten* (*Chlamys*) sp.
Glycymeris holmesiana	*Euspira obliquata*
Pachymelania wyomingensis	
Rhombopsis n. sp.	
Banis cf. *B siniformis*	*Cryptorhytis* n. sp.
Buccinidae n. genus and sp.	*Pyropsis* cf. *P. bairdi*
Melampus n. sp.	*Oligotycha concinna*
Corbula perundata	*Cylichna* sp.
Terebrimya sp.	*Dimorphoptychia* cf. *D. rutherfordi*
Teredina sp. (tubes only)	*Anguispira* cf. *A. russeli*
Cymbophora holmesi	*Dircella* cf. *D. insculpta*
Protodonax sp.	*Ancilla* n. sp.
Inoceramus balchii	*Eoacteon* cf. *E. linteus*
Perrisonota sp.	*Haminea* sp.

Vertebrates:

Shark teeth
Dinosaur bones
Turtle bones
Fish bones and scales

Ammonites:

Hoploscaphites quadrangularis
Baculites baculus
Sphenodiscus sp.

EVIDENCE FOR BARRIER DEPOSITION BASED ON PREVIOUS INVESTIGATIONS

The author believes that the sandstones in the upper part of the Almond Formation are of barrier origin, and this agrees with the interpretations of other geologists who have worked in these rocks during the past 20 years. The sandstone morphology fits the critera for barrier islands that were described by Bernard and others (1962, p. 185), and their sedimentary characteristics agree with those used by Davies and others (1971) in constructing a model for ancient barrier environments.

A marine shoreline origin for the upper part of the Almond Formation was first recognized by Hale (1950, p. 54), who stated that the sandstones in that part of

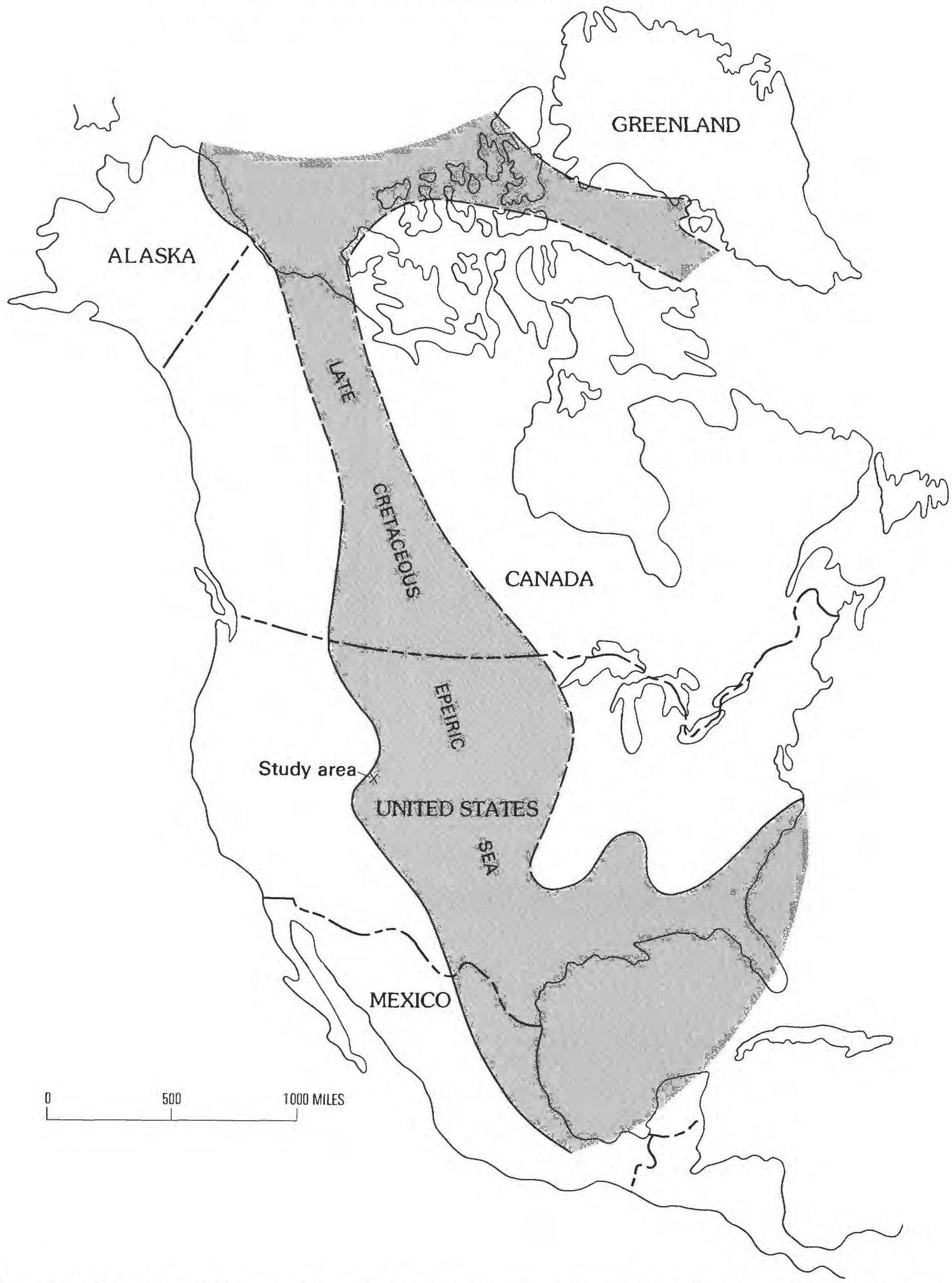


FIGURE 6.—Map of North America showing the location of the study area on the western shore of the Late Cretaceous epeiric sea. From Gill and Cobban (1966).

the section "pass imperceptibly into marine shales." In 1960 Weimer speculated that the upper part of the Almond Formation was deposited as barrier islands. A few years later, Jacka (1965) described primary sedimentary structures and lithofacies that demonstrated that Almond sandstones were unmistakably of barrier origin. Investigations by Flores in the Almond Formation (1978) included a cursory sedimentologic examination of barrier bar F, a sandstone unit that overlies and is similar in most respects to barrier bar G in the study area.

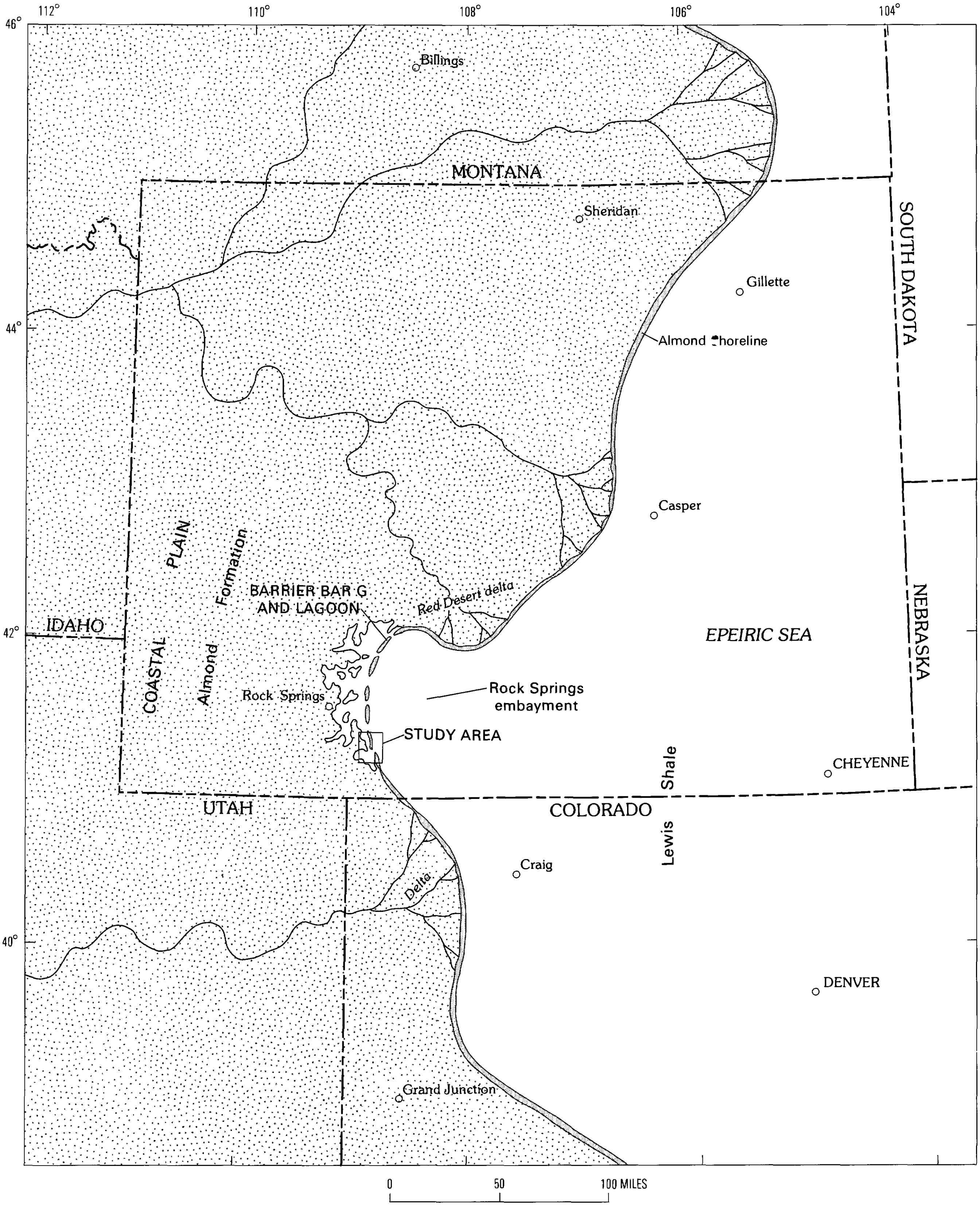


FIGURE 7.—Paleogeographic map of part of the western shoreline of the Late Cretaceous epeiric sea showing the location of barrier bar G and the Pintail coal bed.

CAUSES FOR BARRIER FORMATION

Barriers commonly form along coasts where there are low-angle seaward slopes and abundant, renewable supplies of sediments that are reworked by waves and longshore currents (Busch, 1974; Hayes and Kana, 1976; Hayes, 1979). Tidal influence is sometimes necessary to sustain inlets, open-water bays, and lagoons. Three theories of barrier origin were proposed by Hoyt (1967): (1) evolution from offshore submerged bars, which emerge and develop into barrier islands by lowering of sea level; (2) longshore sediment transported from a spit, headland, or other coastal projection that eventually entraps part of a coastline behind it to form a lagoon; and (3) beach ridges that develop into islands by submergence and the flooding of landward areas.

The barrier bars in the Almond Formation probably formed by processes that combine the first two theories of Hoyt. Their origin and location in the Rock Springs coal field is specifically attributed to the formation of the Rock Springs embayment, which resulted from a major marine transgression and the submergence of a coastal plain, and to the southward longshore drift of sediments from the Red Desert delta to the north, which tended to cut off the head of the Rock Springs embayment to form a barrier chain. The superpositioning of four other barrier systems in the Almond Formation above barrier bar G in the study area may have resulted from slow but continuous coastal subsidence and contemporaneous minor marine transgression, and from the differential compaction of coastal sediments. The sands that composed the barrier shorelines were essentially noncompactible, whereas the adjacent soft, finer-textured marine and lagoonal sediments, mostly muds, were highly compactible. In this depositional setting, abandoned lenses of barrier sandstone remained as submerged moundlike ridges that provided the locus for renewed barrier bar sedimentation. In the vicinity of the mounds, waves began to drag the bottom, the wave energy was dissipated, and a submarine bar began to grow vertically, similar to a process described by Johnson (1919). The barren sand banks that subsequently emerged evolved first into isolated, vegetated barrier islands, and then into a barrier coastline attached to the mainland. The self-perpetuating superpositioning (allocyclism) of barrier sandstones in the upper part of the Almond Formation was terminated by an external event—a eustatic rise of sea level—that resulted in a major marine transgression accompanied by deep coastal submergence, deposition of marine muds, complete abandonment of former shorelines, and subsequent formation of shorelines 20–25 mi west of the study area.

PALEOENVIRONMENTS

The stratigraphic position of barrier bar G and its relation to other barrier bars and other depositional environments in the Rock Springs uplift are shown on a generalized restored stratigraphic cross section (fig. 8). Figure 8 was constructed from eight measured sections and adapted from a more detailed cross section (Roehler, 1978b).

The Almond Formation in the Rock Springs uplift was divided by Jacka (1965) into two parts: an upper part consisting of marsh, mudflat, lagoonal-bay, barrier beach, surf zone, infra-surf zone, and marine facies; and a lower part consisting of alluvial facies. The author (Roehler, 1977a) has expanded Jacka's two-part division into three parts—upper, middle, and lower—that more clearly define and separate the key lithologic, geographic, and paleontologic units of the formation. The upper part (100–400 ft thick) is light-gray, very fine grained to medium-grained sandstone and interbedded gray shale, gray and brown carbonaceous shale, and coal, that was deposited in shallow marine, barrier bar, and lagoonal environments. The middle part (125–250 ft thick) is dark-gray and brown carbonaceous shale, coal, and some thin interbedded gray shale and gray, fine-grained, crossbedded sandstone, that was deposited in a lagoonal environment. The lower part (100–600 ft thick) is mostly interbedded gray, very fine grained to medium-grained, crossbedded sandstone, dark-gray and brown carbonaceous shale, and sparse, very thin beds of coal, that was deposited in a swampy coastal plain environment. Fossils collected from the upper, middle, and lower parts of the formation consist of saltwater, brackish-water and freshwater fauna and flora, respectively. The upper part contains marine mollusks, shark teeth, ammonites, and numerous trace fossils such as burrows, borings, tracks, and trails. The middle part has abundant oysters and other brackish-water mollusks. The lower part contains sparse vertebrate remains that include dinosaur, turtle, crocodile, and fish bones.

One of the sections measured in the study area, section Q (fig. 9), shows that barrier bar G is located at the base of a sequence of sandstones that were first mapped as stratigraphic marker beds AA, A, D, F, and G (Roehler, 1978a) and later identified as barrier bars (Roehler, 1979c). Barrier E is present at the north edge

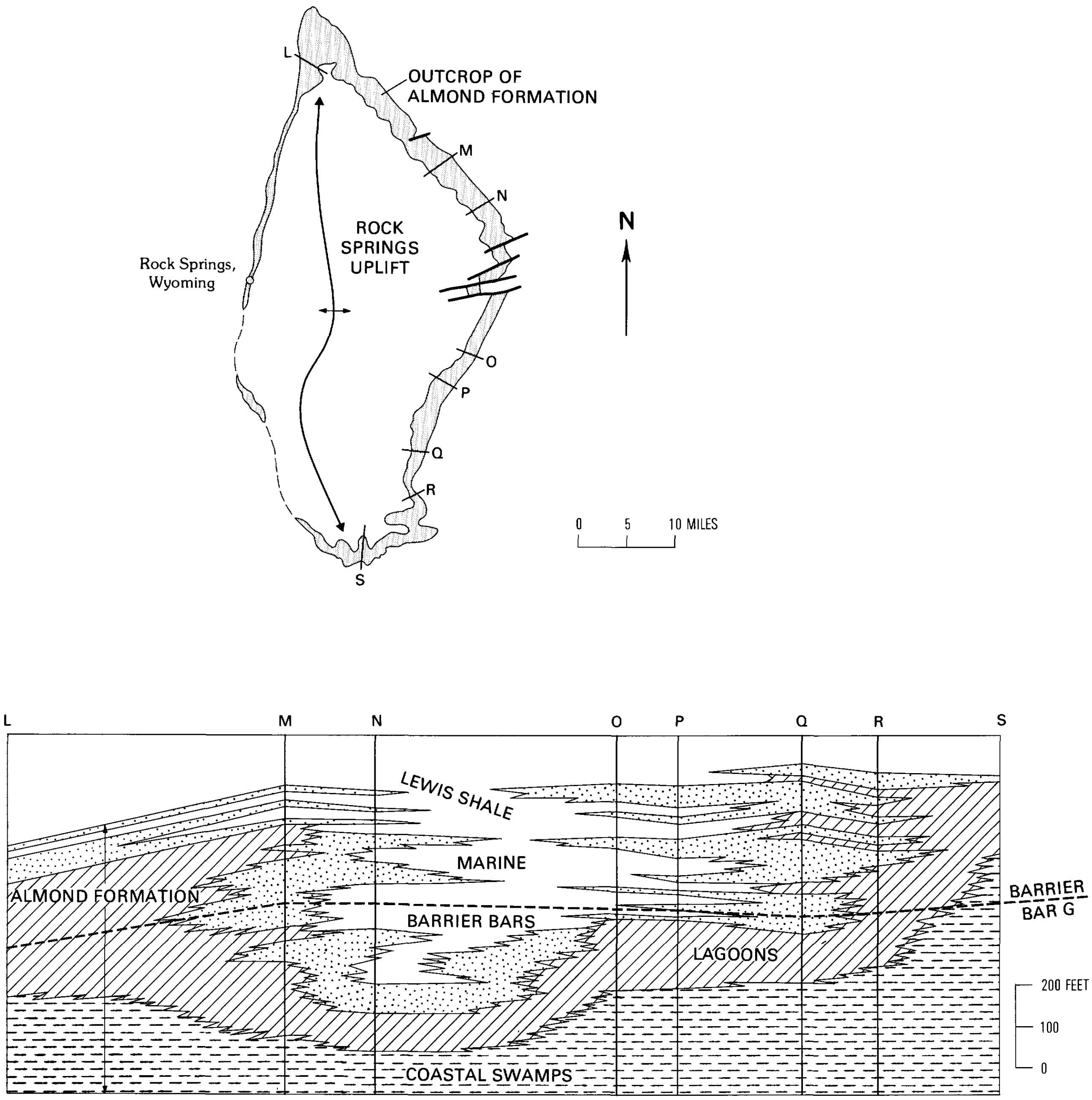


FIGURE 8.—Location map and cross section of measured sections L to S showing depositional environments of the Almond Formation on the east flank of the Rock Springs uplift.

of the study area, but is missing in section Q. Three of the barriers, A, F and G, are visible on an aerial photograph (fig. 10), taken about 1.0 mi north of section Q. The lagoonal section that underlies barrier bar G on fig. 9 is the landward expression of barrier bars that do not crop out in the Rock Springs uplift, but are present in subsurface rocks east of the uplift in the Washakie basin. The section labeled swamp at the base of the Almond Formation in figure 9 is part of a broad coastal plain that was present before the advance of the Late Cretaceous epeiric sea westward across the Rock Springs uplift area.

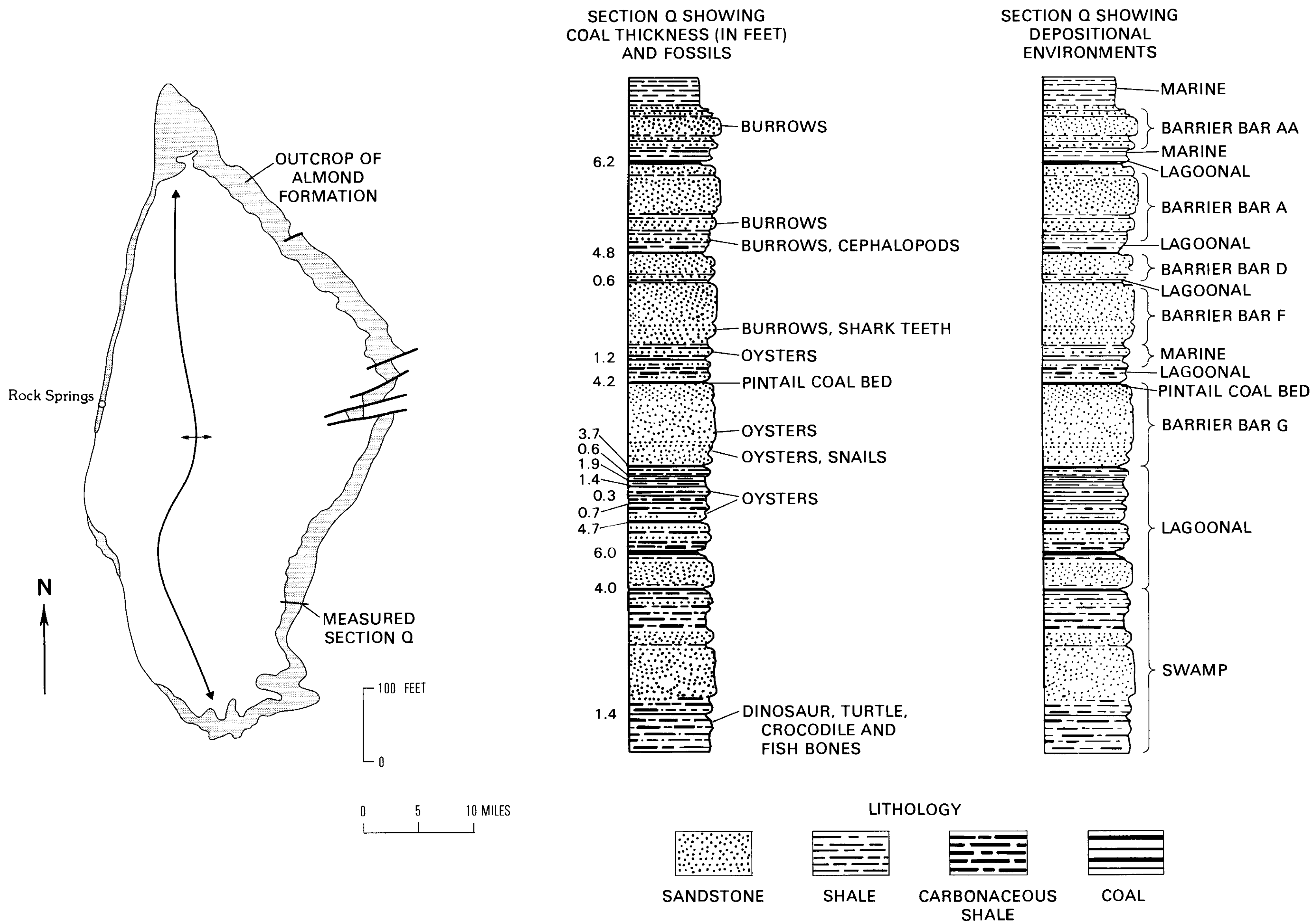


FIGURE 9.—Fossils, coal thicknesses, and depositional environments at section Q in the Almond Formation in sec. 33, T. 16 N., R. 102 W. The relation of section Q to other rocks in the Almond Formation on the east flank of the Rock Springs uplift is shown in figure 8.

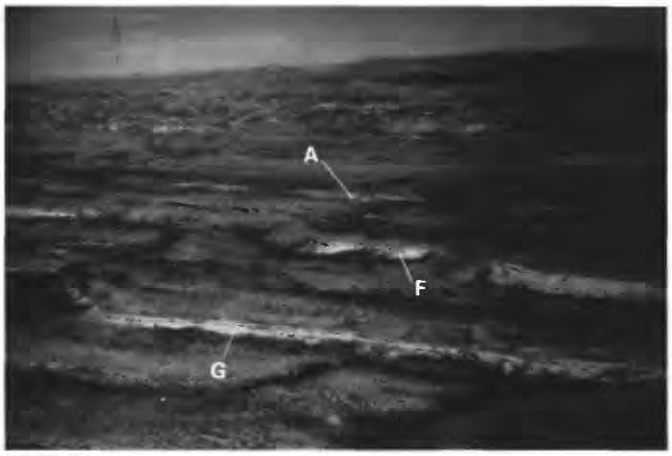


FIGURE 10.—Oblique aerial view of barrier bar G and overlying barrier bars A and F. View is to the northeast from about 500 feet above ground level in NE¼ sec. 28, T. 16 N., R. 102 W. Width of photograph is approximately 3.5 mi.

BARRIER-LAGOON DEFINITION AND CLASSIFICATION

TERMINOLOGY USED IN THE PAPER

The American Geological Institute Glossary of Geology (Bates and Jackson, 1980) defines a barrier island as a long, low, narrow wave-built sandy island that is sufficiently above high tide and parallel to the shore, and that commonly has dunes, vegetated zones, and swampy terranes extending lagoonward from the beach. A barrier chain is defined as a series of barrier islands, barrier spits, and barrier beaches extending along a coast for a considerable distance. The glossary states that the term "barrier bar," although synonymous with "barrier island," is not acceptable because a bar is ordinarily depicted as a submerged ridge. The terms "barrier island" and "barrier bar" are nonetheless used interchangeably in this report because: (1) barrier bar G during its formation evolved from a bar to an island to a coastal beach; and (2) the terms as applied in this paper refer to a linear shoreline sandstone composing a barrier coastline, and not to specific morphological features, such as beaches, bars, or islands along that coastline. Barriers are characteristically unstable because they are mostly unconsolidated sand of relatively uniform composition and texture that is continuously reworked by winds, tides, longshore currents, and storms. As a result of this reworking, tidal inlets and bays migrate laterally along the length of the barrier chains, constantly changing the shape and geographic location of the inlets and islands that make up the chains. Geologists studying ancient barriers find that the geometries of specific morphological features are difficult to delineate from studies of outcrops, and they are nearly impossible to delineate in subsurface rocks unless drill holes are closely spaced. On the other hand, the sandstone lens composing the overall barrier chain is easily identified and correlated, and it is this linear unit to which the terms bar and island are here applied.

The glossary defines a coastal lagoon as a shallow stretch of seawater, such as a sound, channel, bay, or saltwater lake, near or communicating with the sea and partly or completely separated from it by a low, narrow elongate strip of land, such as a reef, barrier island, sand bank, or spit. The term lagoon in this paper is applied to the areas of incursion of saltwater or brackish water between a barrier island chain and a coastal plain.

SUMMARY OF BARRIER MORPHOLOGY AND NOMENCLATURE

The physiography of coastal areas is strongly affected by tides. According to Hayes (1979) coastal types for medium wave energy (Height=2–5 ft) are as follows:

Class	*Tidal Range*	*Example*
Microtidal	0–3 ft	Gulf of St. Lawrence
Low-mesotidal	3–6 ft	New Jersey
High-mesotidal	6–12 ft	Plum Island, Mass.
Low-macrotidal	12–16 ft	German Bight
Macrotidal	16 ft	Bristol Bay, Alaska

Barrier bars will form along coasts affected by microtides and mesotides, but the extreme hydrologic energy of macrotides prevents barrier formation. Hayes and Kana (1976) describe the morphological differences between microtidal and mesotidal barriers as follows:

Barrier type	Length	Shape	Washover features	Tidal inlets	Flood-tidal deltas	Ebb-tidal deltas
Microtidal	Long (18–62 mi)	Elongate; hot dog	Abundant washover terraces and washover fans	Infrequent	Large, commonly coupled with washovers	Small to absent
Mesotidal	Stunted (2–12 mi)	Drum-stick	Minor beach ridges or washover terraces; washover fans are rare	Many	Moderate size to absent	Large with strong wave-refraction effects

A mesotidal system is suggested for barrier bar G by comparing the microtidal-mesotidal differences with the data shown on plate 1. The islands of barrier bar G are 5–7 mi long; the islands are roughly drumstick-shaped; washover fans are present, but not common; tidal inlets are numerous; flood-tidal deltas are large—as wide as several miles; and ebb-tidal deltas are moderately large to small. The estimated tidal range of barrier bar G is between 4.5 and 8 ft.

The morphologic nomenclature of modern mesotidal barrier islands, tidal inlets, and tidal deltas is described on a planimetric sketch (fig. 11). Nearly all the features identified in figure 11 are recognizable in the barrier sequences in the Almond Formation; the features specifically associated with barrier bar G are discussed at length later in the paper.

The morphologic terms applied to barrier islands and associated rocks in the Almond Formation, which include barrier bar G, are identified and illustrated on a schematic cross section (fig. 12). The sands that were deposited by waves and currents along the shores and in nearshore areas of the seaward parts of the barriers comprise the berm, forebeach, upper shoreface (surf), middle shoreface, and lower shoreface lithofacies. The lower shoreface sands graded seaward into shallow marine shales. The overall shoreface sequence coarsened upward, and it coarsened laterally from a seaward to landward direction. Dune sands were deposited by wind in subaerial parts of the barriers, above the level of high tides. Sands were deposited by tidal currents in ebb-tidal deltas, in flood-tidal deltas, and on tidal flats. Washover fans resulted from severe storms that washed sand from seaward parts of the barriers onto the back-barrier flats and into the lagoons. Lenticular sand bodies, such as fluvial channel deposits and tidal channel deposits, were present in parts of the lagoons. The sediments of lagoonal origin were mostly bay-fill muds, paludal-carbonaceous mud and peat, and oyster reefs composed of sand and shell material. Landward of the lagoons were coastal swamps.

Barriers normally expand, or grow, by continuous accretion of sediments in seaward directions (progradation), in landward directions (retrogradation), or in lateral directions parallel to the shoreline. Barriers prograde because the sediment supply exceeds the rate of subsidence of the marine shoreline (Busch, 1974). Why the superposed barriers in the study area (that is, barriers AA, A, D, E, and F, fig. 9) developed separately and not as a single, thick, long-lived, retrograding and prograding barrier sandstone system is a subject for speculation. A logical explanation is that differential subsidence along the marine shorelines caused fluvial avulsion that resulted in sediment starvation and barrier abandonment.

Peats that form in association with prograding barrier systems, such as barrier bar G, frequently become economically important deposits of coal. On the other hand, peats associated with retrograding barrier systems probably have little economic importance. The sands that compose retrograding barriers are derived from beach and shoreface parts of the barrier, usually during storms. These sands are constantly reworked and washed landward over emergent parts of the barrier into the lagoon, eroding and contaminating peat deposits that may be present in the lagoon. The retrograding process is probably too rapid for the formation of large, stable lagoons and for the origin and preservation of thick peat deposits. The upper part of barrier bar AA in the study area is a retrograding sandstone sequence; it is not overlain by coal (see fig. 9). Retrograding sandstones in Upper Cretaceous rocks in the western United States are seldom more than a few feet thick; they are usually poorly sorted, iron stained, bioturbated, and commonly contain chert pebbles, clay clasts, shark teeth, and shell material.

DESCRIPTION OF BARRIER BAR G AND ITS LAGOON

GENERAL CHARACTERISTICS

The sandstone unit called barrier bar G in this report is a segment of a north-trending marine shoreline. The sandstone is lenticular in cross section, is more than 60 mi long, has a maximum vertical thickness of 95 ft, and is about 3.5 mi wide. It separates an interval of marine rocks (which contain marine fossils) to the east, from continental rocks (which contain freshwater and brackish-water fossils) to the west. The marine rocks are mostly gray shale. The continental rocks are mostly gray mudstone, lenticular sandstone, carbonaceous shale, and coal. The continental rocks are partly laterally equivalent to and partly lap eastward (seaward) onto the barrier sandstone. The evidence indicates that the continental rocks are of lagoon origin, but only the seaward parts of the lagoon are represented within the area studied.

The barrier sandstone coarsens upward and landward; it is composed dominantly of gray, very fine grained to medium-grained, angular to subangular, clear to milky quartz grains with minor amounts of other variously colored rock fragments. The sandstone is readily divisible into tidal channel, tidal inlet, tidal delta, dune, washover fan, and shoreface lithofacies. The paleogeography, paleontology, and sedimentology provide overwhelming evidence that the sandstone studied is of barrier origin.

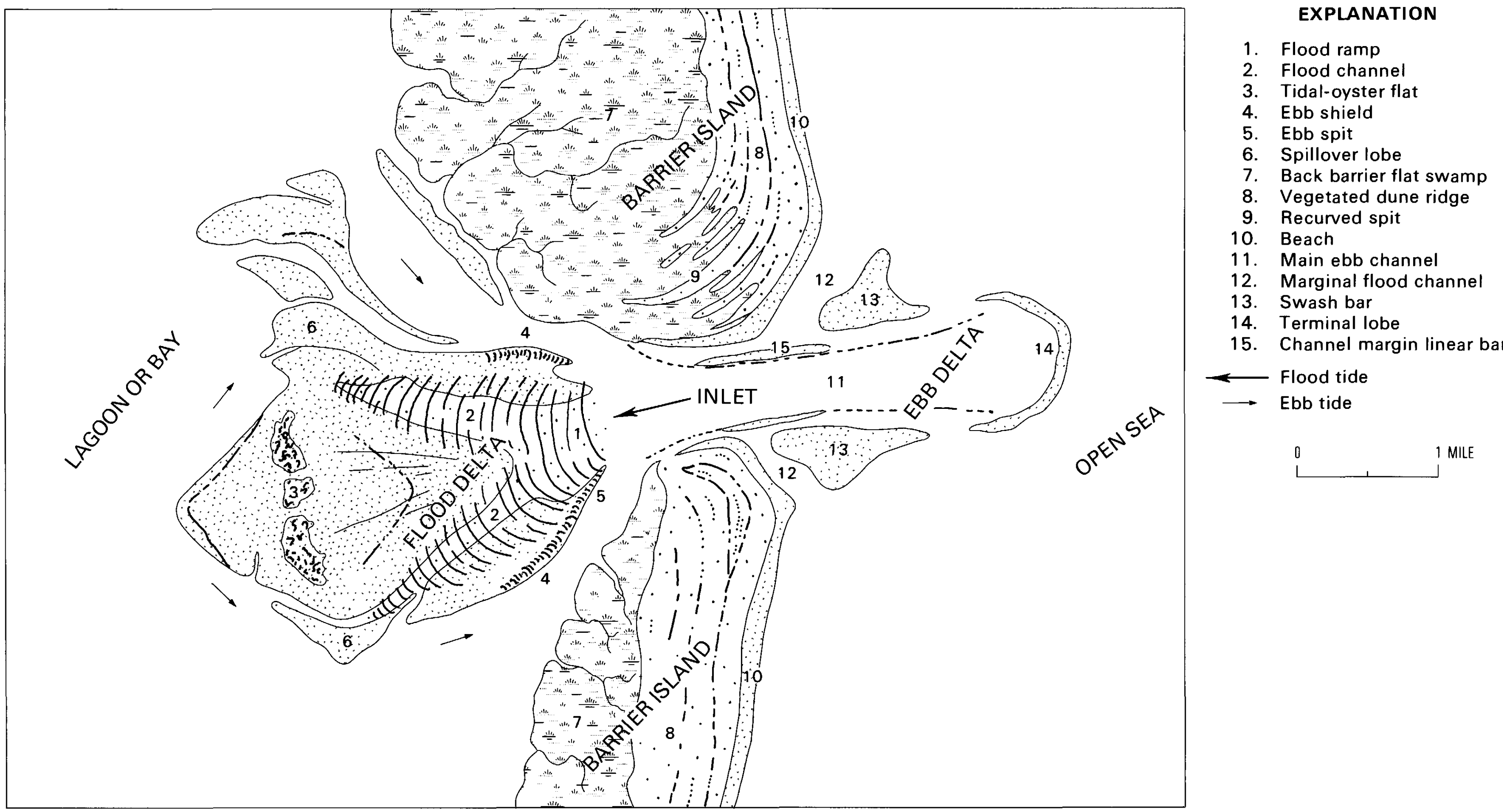


FIGURE 11.—Nomenclature of mesotidal barrier islands, tidal inlets, and tidal deltas. (From photographs and sketches by Hayes and Kana, 1976.)

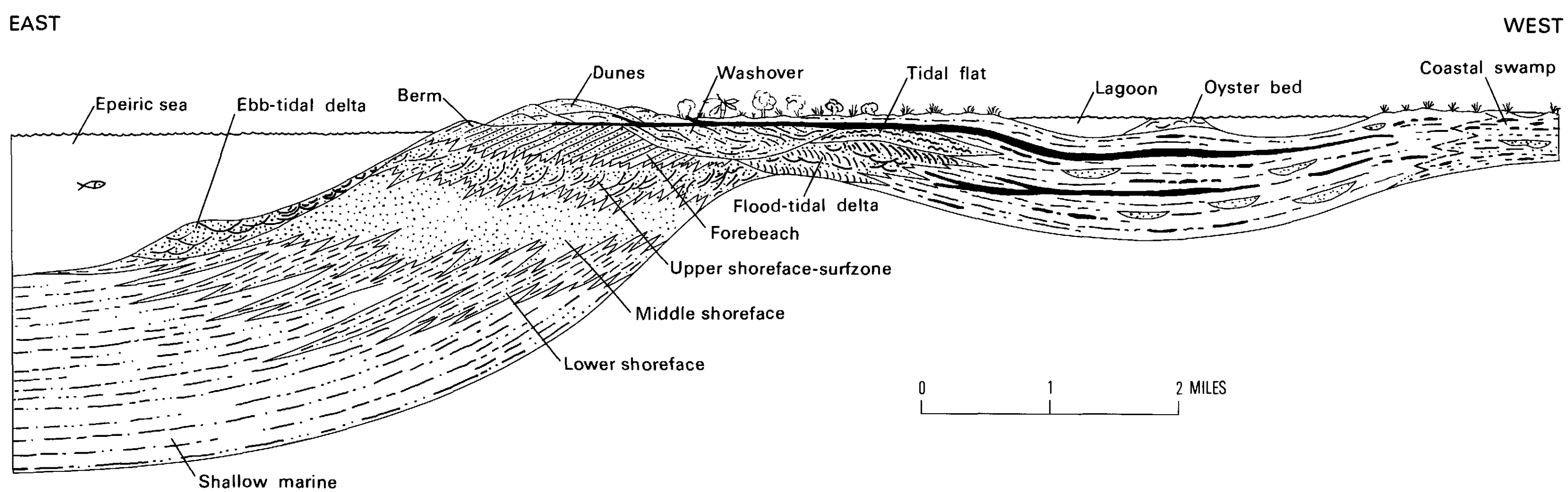


FIGURE 12.—Cross section showing the morphology and lithofacies terminology of barrier islands and associated rocks in the Almond Formation.

CROSS SECTIONS CONSTRUCTED FROM MEASURED SECTIONS

Measured sections were used to construct two cross sections (plate 1) that correlate stratigraphic units and identify depositional environments and lithofacies, respectively. The measured sections illustrated in the columns on plate 1*A* use two remarkably persistent oyster beds as data lines to correlate stratigraphic units. The uppermost of these beds is called the oyster marker bed (OMB), and is present from less than 10 to more than 80 ft above the Pintail coal bed in sections 40 to 104. A second persistent oyster bed is called the oyster ridge marker (ORM), and is situated at a lower stratigraphic position; it is in contact with or overlies the Pintail coal bed by as much as 38 ft in sections 7 to 35. Plate 1*B* interprets the depositional environments and identifies specific lithofacies from the lithologies and sedimentary structures that are illustrated in the measured sections on plate 1*A*. The pronounced distortion of bedding planes above and below the Pintail coal bed on plate 1*B* results partly from the lenticular shape, thickness differences, and differential compaction of the various lithologic units, and partly from the fact that the base of the Pintail coal bed was used as a datum plane when constructing the cross section. For convenience, a simplified page-size reduction of plate 1*B* is included in the text as figure 13.

Marine deposits in the open-water parts of the Late Cretaceous epeiric sea, seaward of barrier bar G, are shown along the left margin of plates 1*A* and 1*B*, near section 1. At section 1, barrier bar G is composed of less than 10 ft of lower shoreface (LSF) sandstone and siltstone within thick nearshore marine shale (MS). The barrier sandstone thickens southwestward (landward) from left to right across plates 1*A* and 1*B*, through mostly ebb-tidal delta (ED), dune (DU), forebeach (FB), surf (SU), middle shoreface (MSF), and tidal channel (TC) sandstone lithofacies, between sections 2 and 55. The barrier reaches its optimum thickness in section 47, where it is composed of mostly forebeach (FB) and middle shoreface (MSF) sandstone lithofacies. Between sections 53 and 57 a tidal inlet (TI) is present that marks the boundary between barrier bar G and a flood-tidal delta (FD) situated in the lagoon landward of the barrier. Sections 58–104 are composed of flood-tidal delta (FD), tidal flat (TF), bay-fill (BF), oyster bed (OB), salt marsh (SW), tidal channel (TC), coal (PS), and washover fan (WO) lithofacies of lagoonal origin that are lateral landward equivalents of barrier bar G. Barrier bar G is overlain in most of the sections by peat swamps (PS) that formed the Pintail coal bed and by adjacent salt marsh (SW) lithofacies. The oyster ridge marker (ORM), its lateral bay-fill (BF) equivalents, and the overlying beds, including the Waxwing coal bed and the oyster marker bed (OMB), are probably not related to barrier bar G, but are part of an overlying barrier sequence, which is not shown. Barrier bar G is nearly everywhere underlain by nearshore-marine shale (MS), which is slightly carbonaceous in places. Most or all of the Finch coal bed, sections 64–99, was deposited in a lagoon that predates barrier bar G.

EVIDENCE FOR BARRIER BAR G PROGRADATION

Repetitive vertical successions of lithofacies in barrier bar G and in associated rocks in the study area indicate that the barrier prograded during its depositional history. For example, the vertical successions between sections 10 and 55 on plates 1*A* and 1*B* can be consistently numbered from bottom to top (marine to nonmarine) as follows:

6. Lagoon-fill material composed of mud, oyster beds, and tidal channel sand.
5. Lagoon and back-barrier flat carbonaceous mud and peat.
4. Dune, washover, tidal channel, and forebeach sand.
3. Upper shoreface surf zone sand.
2. Middle shoreface sand.
1. Marine mud.

If Walther's Law (Walther, 1893–94) is applied, which by paraphrasing states that a vertical lithofacies can be used to predict the lateral distribution of the same lithofacies, then the vertical succession numbered 1–6 is simply a reflection of a horizontal succession. Therefore, barrier bar G is the result of progradation. Obviously, if the barrier had retrograded, the number sequence would be reversed (1 at the top; 6 at the bottom).

COLOR CHANGES IN SHOREFACE SANDSTONES

The color change of very light gray or white in dune and upper shoreface sandstones to tan and brown in middle and lower shoreface sandstones is abrupt and striking in most places in barrier bar G in the study area. Several possibilities exist to explain these and similar color changes in sandstones along the western shorelines of the Late Cretaceous epeiric sea (fig. 6): (1) the presence of hematite and other iron minerals in the middle and lower shoreface sandstone that are present in only minor amounts or are missing in the upper shoreface and dune sandstone (the presence and absence of these minerals could have resulted from a mechanical segregation of light and heavy mineral sand grains by

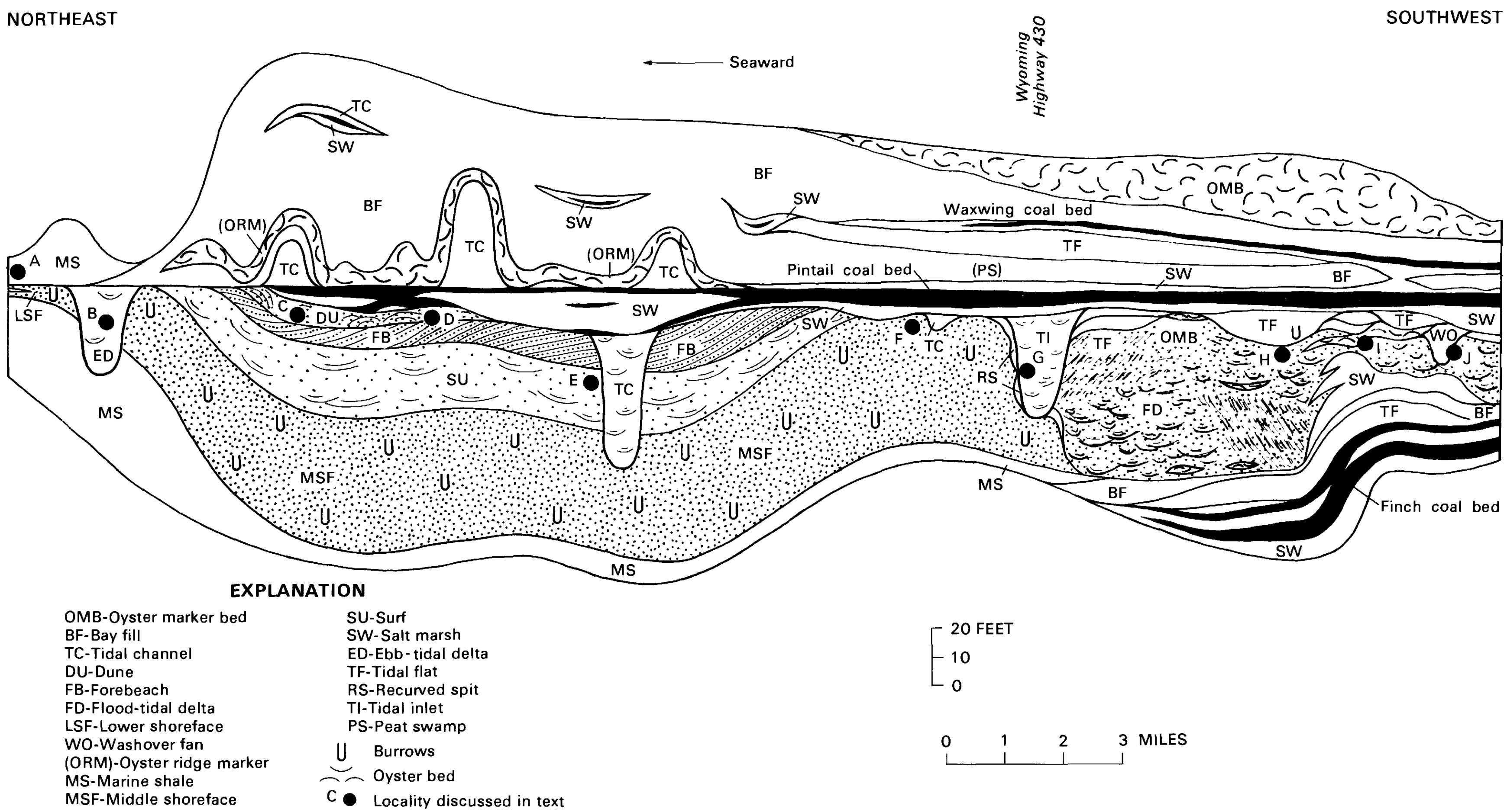


FIGURE 13.—Restored cross section along barrier-coal outcrops in the Almond Formation illustrating depositional environments and lithofacies.

waves and wind before the lithification of the sands); (2) sun bleaching of exposed beach sands prior to lithification; (3) organic leaching of dune and upper shoreface sandstones by acid ground waters associated with overlying coal beds either during or after lithification; and (4) detrital dolomite or biotite that is present only in the middle and lower shoreface. No. 1 most easily explains the color change in barrier bar G.

LITHOFACIES AT SELECTED LOCALITIES

Ten localities, lettered A to J (plate 1), were selected for detailed examination because the rocks are well exposed and reflect the principal barrier-lagoon lithofacies in the study area. Each of the localities is described and illustrated by columnar sections and photographs. The stratigraphic positions of sandstones that were sampled for petrographic analysis at the localities are identified at the left margins of the columnar sections by a letter and number (for instance D3 is locality D, sample number 3). The same system of letters and numbers is used to identify horizons sampled for coal and microfossil studies.

LOCALITY A—LOWER SHOREFACE

Barrier bar G at locality A is composed of 1- and 1.5-ft-thick benches of lower shoreface sandstone that is interbedded with 3.7 ft of gray, soft shale of nearshore marine origin (figs. 14 and 15). The sandstones are very fine grained, silty, hematitic, and weather brown and tan. The bedding in the upper bench consists of even, parallel laminae that suggest quiet-water deposition. The lower bench is massive and bioturbated, and contains abundant trace fossils of *Ophiomorpha* sp., a long, rough-textured crustacean burrow ½–1 in. in diameter. Barrier E is present at the top of the columnar section in figure 14; it wedges out in outcrops about 2 mi to the south.

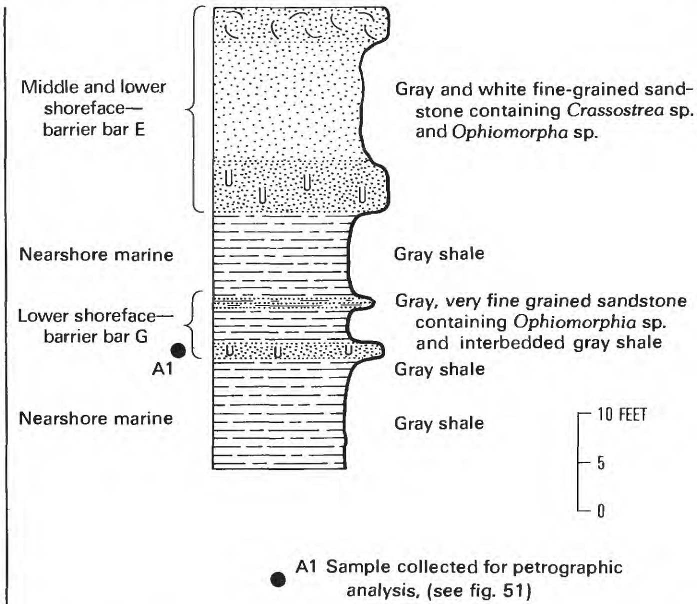


FIGURE 14.—Columnar section of part of the Almond Formation at locality A, NW¼SW¼ sec. 15, T. 17 N., R. 101 W. Depositional environments and lithofacies are identified to the left of the column and lithologies are described to the right of the column.

FIGURE 15.—Lower shoreface sandstone (LSF) of barrier bar G at locality A in NW¼SW¼ sec. 19, T. 17 N., R. 101 W. The lower shoreface sandstone is interbedded with and underlain by nearshore marine shale (MS).

LOCALITY B—EBB TIDAL DELTA

Exposures of barrier bar G at locality B consist of brown and tan sandstone capping a south-trending ridge. The sandstone is mostly gray, very fine grained to fine grained and poorly sorted. It contains a few small, rounded hematite concretions, and sparse, thin lenses of small, gray, clay pebbles with some interbedded gray shale in the lower part. The structures in the sandstone consist of small-scale, narrow, elongate, steeply dipping trough crossbeds; convolute bedding is present locally (fig. 16). The long axes of the troughs and the dips of bed laminae indicate an east to northeast sediment transport direction, as shown in a rose diagram (fig. 17). At the place where the section was measured the sandstone is only 18.5 ft thick, but in exposures 500 ft to the north it is more than 40 ft thick. Where the section thickens, there are abundant gray-clay pebble lenses and some disseminated plant debris.

The paleogeographic location within thick nearshore marine shale, the irregular thickening, and the sedimentary structures of the sandstone at locality B suggest

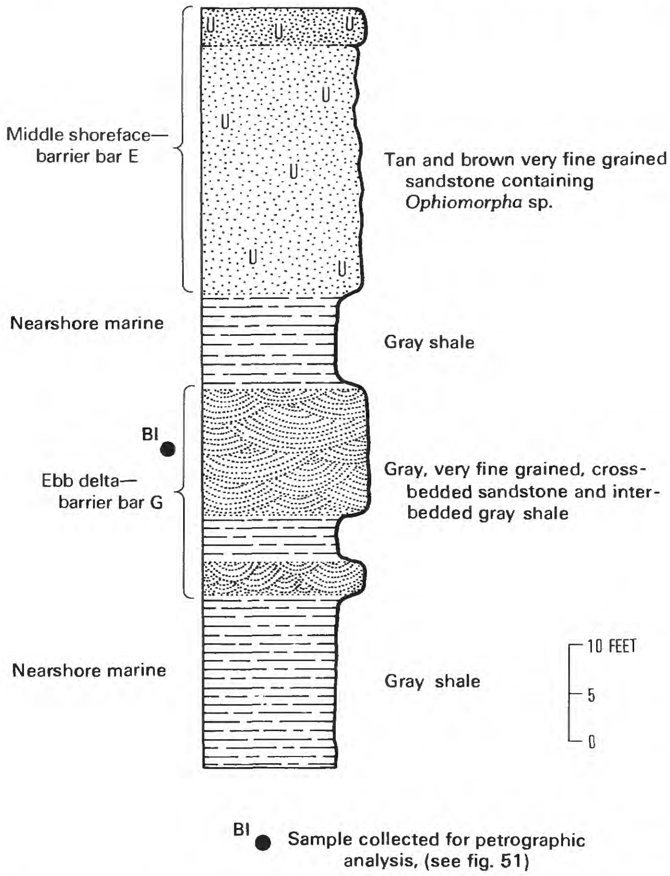


FIGURE 16.—Columnar section of part of the Almond Formation at locality B located in C NW¼ sec. 25, T. 17 N., R. 102 W. Depositional environments and lithofacies are identified to the left of the column and lithologies are described to the right of the column.

that it was deposited as part of an ebb-tidal delta, possibly the terminal lobe (fig. 11, no. 14). An ebb-tidal delta hypothesis for the origin of this sandstone is supported by the close association and bedding characteristics of two other laterally equivalent sandstones that crop out south and southwest of locality B. The first sandstone, about 6 ft thick, crops out in a small area of a dry wash about 1,500 ft south of locality B (fig. 18). It consists of white sandstone containing very low-angle, hummocky crossbeds as much as 0.1 ft thick that dip uniformly from S. 63° E. to N. 75° W. in seaward directions. The sandstone is probably part of a channel margin linear bar (fig. 11, no. 15). A second sandstone outcrop forms an isolated knob that caps a ridge about 2,500 ft southwest of locality B (fig. 19). This 37-ft-thick sandstone is light gray and fine grained. It consists of small-scale, low-angle, planar crossbeds, 0.7–1.0 ft thick, that have multidirectional dips (see rose diagram, fig. 20). The variability in the directions of dip suggests that this sandstone was deposited as a swash bar near a tidal inlet (fig. 11, no. 13), where there was a complex intermingling of longshore and tidal currents.

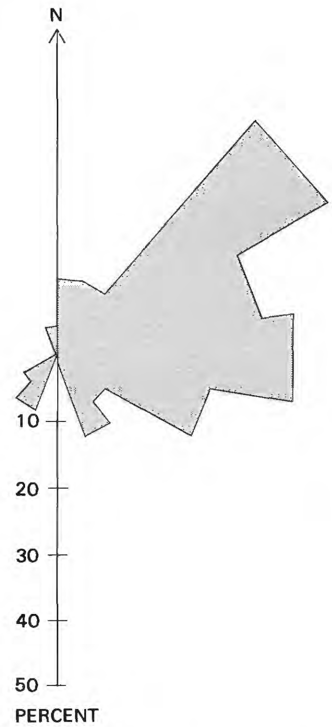


FIGURE 17.—Rose diagram showing sediment transport directions of sandstone beds in an ebb-tidal channel at locality B; 50 measurements.

FIGURE 18.—White sandstone (arrow) believed to have been deposited as a channel margin linear bar. Outcrop is in NW¼SE¼ sec. 25, T. 17 N., R. 102 W.

LOCALITY C—DUNES AND UPPER SHOREFACE

A measured section at locality C (fig. 21) is accessible by a straight road that trends west-southwest from near the southeast corner of sec. 36, T. 17 N., R. 102 W. This road was originally bulldozed for a seismograph

FIGURE 19.—Sandstone interpreted as part of a swash bar near a tidal inlet of barrier bar G. Outcrop is in NE¼SW¼ sec. 25, T. 17 N., R. 102 W.

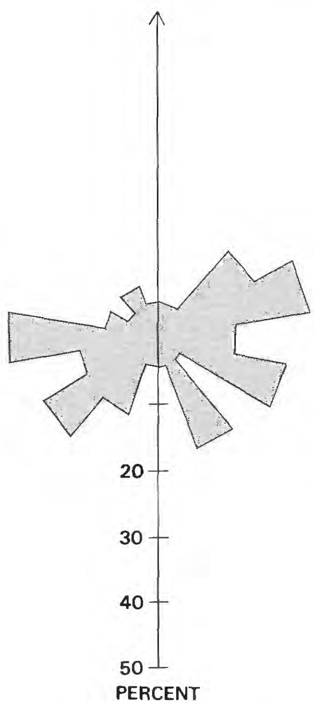


FIGURE 20.—Rose diagram showing sediment transport directions of sandstone beds in a swash bar at locality B; 50 measurements.

line during oil and gas explorations, but it has been subsequently used and improved by ranchers and hunters.

The barrier crops out as a prominent, white, ledge-forming escarpment at locality C and for several miles south of the locality as shown in figure 22. Dune and upper shoreface (forebeach and surf) sandstone lithofacies are well exposed. A thick middle shoreface sandstone is also present, but it is largely covered by soil and vegetation on a long dip slope that rises topographically (westward) from the upper parts of the barrier that are shown in figure 22.

The dune lithofacies is composed of light-gray, fine- to medium-grained sandstone that has landward-dipping, low-angle, small-scale, parallel crossbeds. The dune sandstone is 8 ft thick and is welded to the underlying forebeach sandstone (fig. 23). The top of the dune sandstone was eroded and weathered prior to the deposition of the overlying Pintail coal bed; the upper 1 ft of the sandstone has abundant root casts and is dark gray because of organic staining (fig. 24). Underlying the dune sandstone are 5 ft of light-gray, fine- to medium-grained forebeach sandstone in even, parallel beds 0.2–0.4 ft thick. The surf zone that underlies the forebeach is composed of 25 ft of light-gray, fine- to medium-grained sandstone in small-scale, low-angle, trough crossbeds and some small-scale, high-angle, planar crossbeds.

The Pintail coal bed at locality C consists of 3.2 ft of clean, bright coal; the bed wedges out and is missing in sections that were measured north of locality C. The tidal channel that overlies the Pintail coal bed in figure 21 is a local lens of fining-upward brown sandstone with small-scale, trough crossbeds. The channel is poorly exposed and is not visible in the photograph (fig. 20). The oyster ridge marker (ORM) crops out as a small brown ledge about 20 ft above the Pintail coal bed. The oyster ridge marker is composed of 5 ft of fine- to medium-grained brown sandstone with no distinct bedding; it contains weathered and partly transported oyster shell fragments.

LOCALITY D—DUNES AND UPPER AND MIDDLE SHOREFACE

Locality D is in a remote part of the study area. An abandoned, west-trending seismograph road provides access by four-wheel drive vehicles across the southwest part of sec. 11 and the southeast part of sec. 10, T. 16 N., R. 102 W. The road branches near the center of sec. 11 from a well-used, north-trending road situated on the Lewis Shale. In the southcenter of the NW¼SE¼ sec. 10, T. 16 N., R. 102 W., the west-trending seismograph road enters an area of active sand dunes and becomes impassable. Locality D is located about 0.5 mi north of the sand dunes and is accessible only on foot.

The outcrops of barrier bar G at locality D are 82 ft thick (fig. 25). The dune sandstones at the top of the barrier are light-gray, very fine grained to medium grained and are about 4 ft thick. The bedding is mostly small-scale, low-angle, planar, and trough crossbeds.

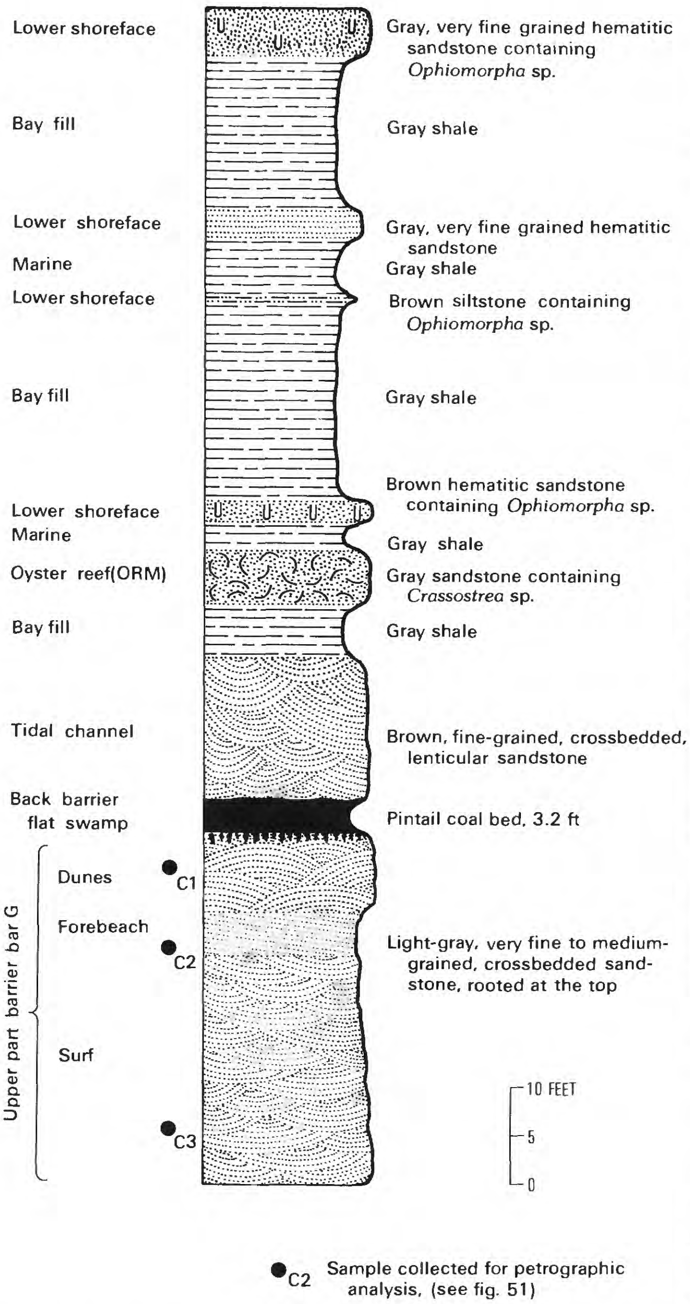


FIGURE 21.—Columnar section of part of the Almond Formation at locality C in NE¼NE¼ sec. 3, T. 16 N., R. 102 W. Depositional environments and lithofacies are identified to the left of the column and lithologies are described to the right of the column.

FIGURE 22.—Outcrops of barrier sandstone at locality C in NE¼NE¼ sec. 3, T. 16 N., R. 102 W. DU, dune sandstone; FB, forebeach sandstone; SU, surf sandstone. View is southward.

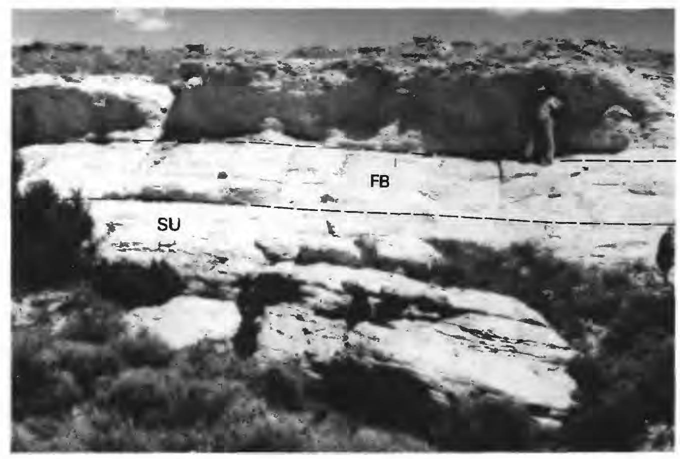


FIGURE 23.—Barrier bar G at locality C in NE¼NE¼ sec. 3, T. 16 N., R. 102 W., showing dune (DU), forebeach (FB), and surf (SU) sandstone lithofacies. Scale is indicated by person standing in the upper right part of the photograph.

The forebeach lithofacies consists of 18 ft of light-gray, very fine grained to medium-grained sandstone in parallel to subparallel beds. The surf zone is 15 ft thick and is composed of light-gray, very fine grained to medium-grained sandstone in small-scale, low-angle, trough crossbeds and some small-scale, fairly high-angle, planar crossbeds. The basal 43 ft of the barrier are composed of tan and brown, very fine grained to fine-grained, middle shoreface sandstone. The middle shoreface sandstone is bioturbated and contains abundant *Ophiomorpha* sp. (fig. 26); the upper part has two thin dark-brown hematitic layers that are resistant to weathering and cap dip slopes.

A cross-sectional profile of a beach is preserved at the top of the barrier sequence along the north side of a dry wash that trends east-west and crosses the outcrops at locality D. The dune sandstone (part of the foredune ridge) at the top of the barrier can be seen to grade laterally into a berm sandstone across a swale that is interpreted as the back shore or back beach. This relationship is visible in figure 27, where a person is standing in the swale; the dunes cap the outcrops upslope to

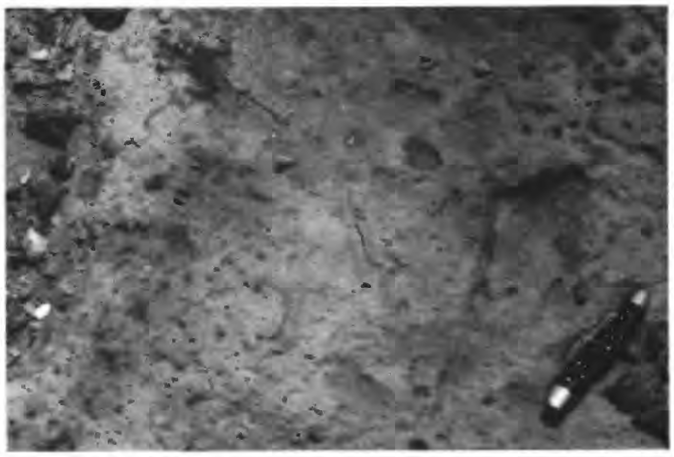


FIGURE 24.—Root casts and organic staining on the upper surface of dune sandstone in barrier bar G at locality C in NE¼NE¼ sec. 3, T. 16 N., R. 102 W.

the left, and the berm forms a low rise about 30 ft to the right. Remnants of planar crossbedding in the berm include foreset laminae, an avalanche crest, and tabular-like bedding that suggests laminar flow from a marineward direction up the forebeach (right to left). The eroded remnants of a ridge-and-runnel system are present as a small mound with low relief on the top of the outcrops of the forebeach 140 ft to the right (seaward) of the crest of the berm. The ridge-and-runnel system has planar crossbedding with distinct foresets that dip westward (landward) at 20°–35°, in a direction normal to the strike of the strandline. The position of the ridge-and-runnel system suggests that the beach had a broad swash zone and a low angle of slope.

The Pintail coal bed at locality D is 5.5 ft thick, but is split into a lower coal bench 2.2 ft thick and an upper coal bench 3.2 ft thick by a 3.1 ft of carbonaceous shale. The lower coal bench rests directly upon rooted barrier sandstone. The upper coal bench is overlain by a brackish-water unit, the oyster ridge marker bed (ORM). The stratigraphic relations of the Pintail coal bed and adjacent rocks are shown in figure 28, a photograph taken of outcrops above the swale mentioned in the preceding paragraph.

LOCALITY E—UPPER AND MIDDLE SHOREFACE AND TIDAL CHANNEL

The locality is adjacent to a Mountain Fuel Supply Company natural gas pipeline that trends westward for about 13 mi from Brady field to where it crosses the barrier-coal outcrops in the study area in sec. 16, T. 16 N., R. 102 W. It is accessible by a road that parallels the pipeline.

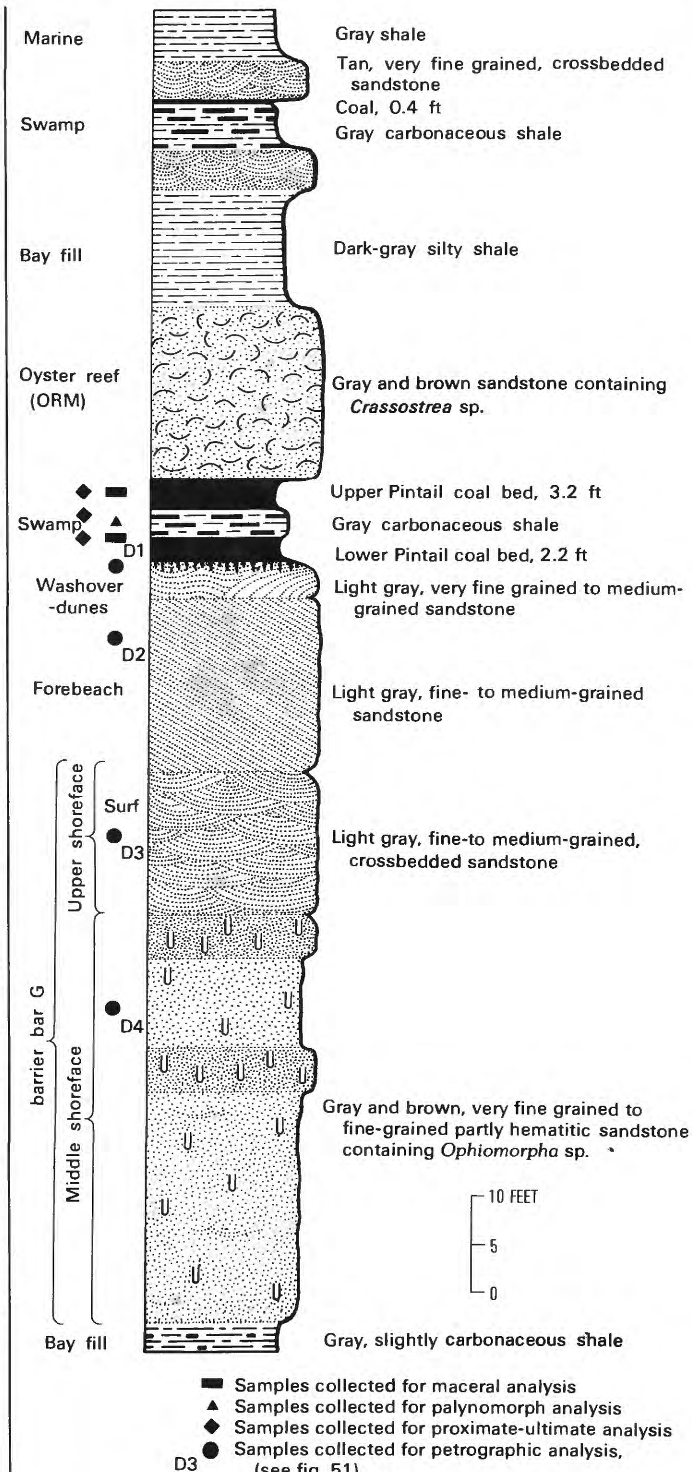


FIGURE 25.—Columnar section of part of the Almond Formation at locality D in NE¼ sec. 10, T. 16 N., R. 102 W. Depositional environments and lithofacies are identified to the left of the column and lithologies are described to the right of the column.

Barrier bar G has a thickness of 70 ft and is composed of forebeach, upper shoreface (surf) and middle shoreface

FIGURE 26.—Hematite replaced *Ophiomorpha* sp. in middle shoreface sandstone of barrier bar G at locality D in NE¼ sec. 10, T. 16 N., R. 102 W.

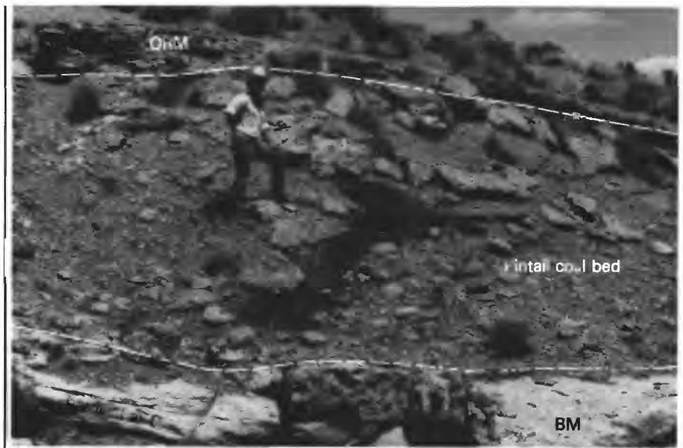


FIGURE 28.—The Pintail coal bed exposed in a trench dug at locality D in NE¼ sec. 10, T. 16 N., R. 102 W. The oyster ridge marker (ORM) overlies the coal bed and the barrier sandstone underlies the coal bed.

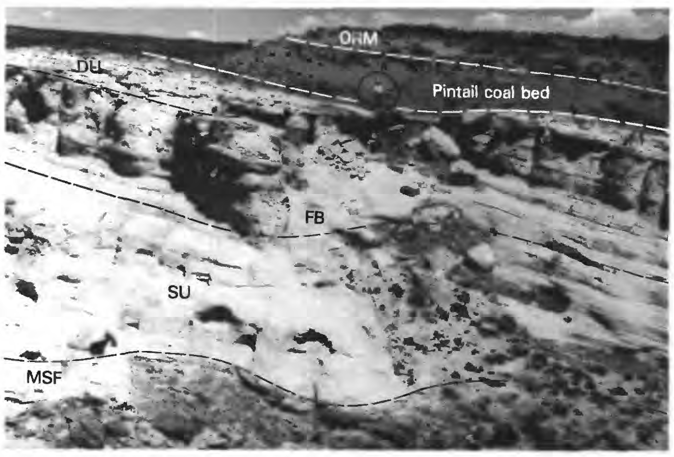


FIGURE 27.—Barrier bar G at locality D in NE¼ sec. 10, T. 16 N., R. 102 W., showing the oyster ridge marker (ORM), the Pintail coal bed, and dune (DU), berm (BM), forebeach (FB), surf (SU), and middle shoreface (MSF) sandstone lithofacies. Scale is indicated by a person (circled) standing in the swale between the dune-washover and berm sandstones. View is northward parallel to the facies strike of the barrier; the sea was to the right.

sandstone in the northern part of the locality. The sedimentary structures of these sandstones are similar to those described previously. The upper 57 ft of the upper and middle shoreface barrier sandstones is replaced southward across the locality by rocks deposited in a tidal channel, as shown in figure 29. The tidal channel is filled with small, lenticular lenses of fining-upward, tan, small-scale, low-angle, trough crossbedded, very fine grained to medium-grained sandstone that is interbedded with thin beds of gray shale and siltstone (fig. 30). The directions of the dips of the bedding in the channel sandstones indicate that the sediment transport direction was eastward (seaward) (fig. 31). The unidirectional eastward transport indicates that the channel did not act as a conduit for flood tides. The south margin of the channel is covered by Quaternary sand dunes, soil, and vegetation for several hundred feet south of locality E, but on aerial photographs the channel appears to have an overall width of about 2,100 ft.

The Pintail bed is split into three thin, widely separated coals, each of which is less than 1.5 ft thick at locality E; southward for a short distance along outcrops, the two lower coal beds wedge out and are missing. The oyster ridge marker bed here is 5–8 ft thick. Many of the *Crassostrea* sp. shell fragments within the marker bed are water-worn, pitted, and crisscrossed by numerous borings. The borings are sinuous, less than 0.04 in. wide, and probably are caused by the sponge, *Clinona* sp. (W. A. Cobban, oral commun., 1979).

LOCALITY F—TIDAL CHANNEL AND MIDDLE SHOREFACE

The locality is about 0.5 mi north of Wyoming Highway 430 and is accessible by an unimproved road that branches northward from the highway in SW¼ sec. 33, T. 16 N., R. 102 W., 0.5 mi east of the Mud Springs Ranch.

The upper 10–15 ft of barrier bar G is covered by soil and vegetation at locality F. The exposed part consists of 12 ft of tan and brown, very fine grained to fine-grained, bioturbated, middle shoreface sandstone containing abundant *Ophiomorpha* sp. (fig. 32). The barrier sandstone is abnormally thin at the locality, and a considerable part of it here may have been eroded prior to the deposition of overlying beds.

Overlying barrier bar G at locality F is about 10 ft of white, lenticular tidal channel sandstone (fig. 33). This

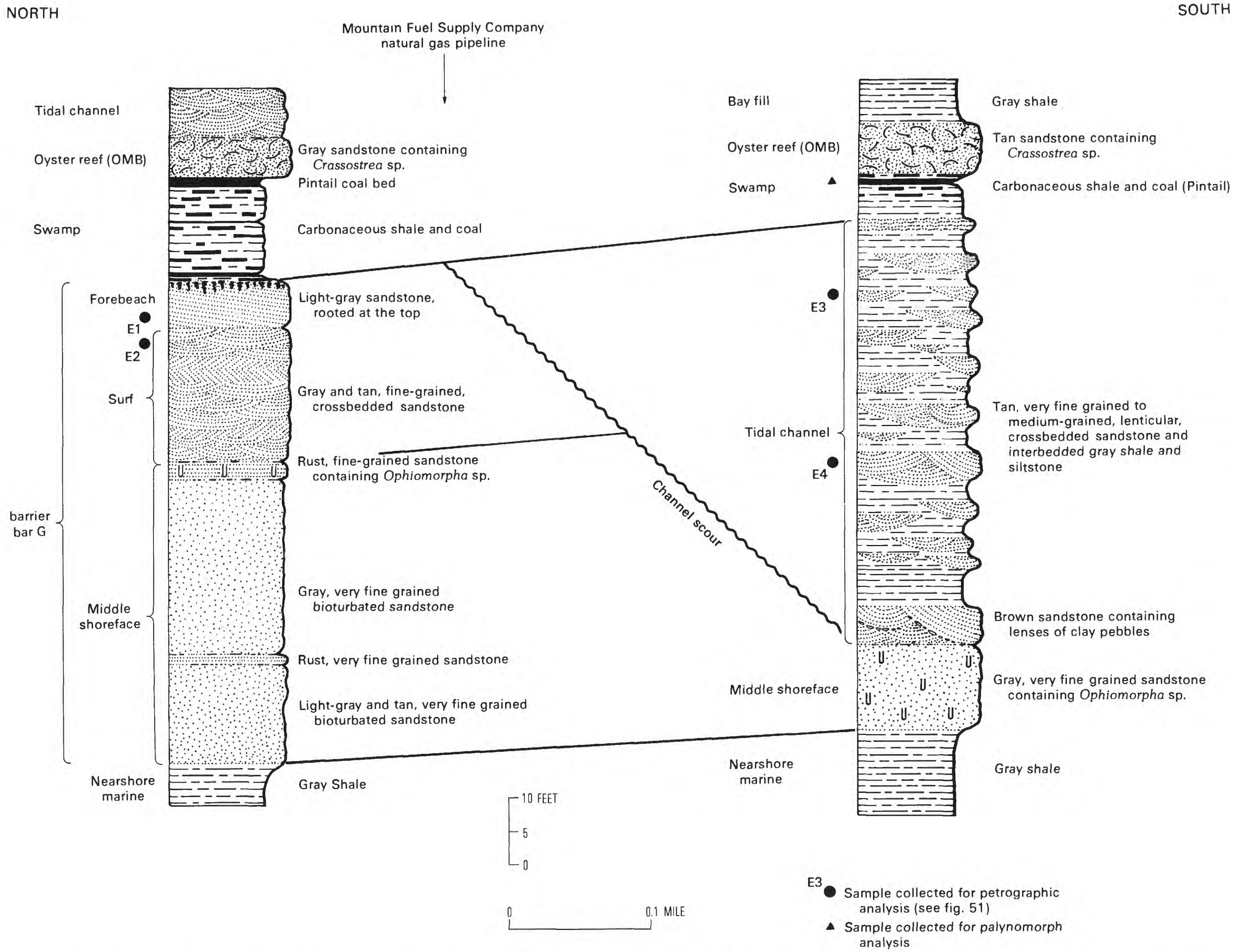


FIGURE 29.—Columnar sections of part of the Almond Formation at locality E in SE¼ sec. 16, T. 16 N., R. 102 W. Depositional environments and lithofacies are identified to the left of the columns and lithologies are described to the right of the columns.

FIGURE 30.—Thin, lenticular sandstone interbedded with siltstone and shale in a tidal channel sequence in barrier bar G in the southern part of locality E in SE¼ sec. 16, T. 16 N., R. 102 W. Scale is indicated by a person standing near the center of the photograph.

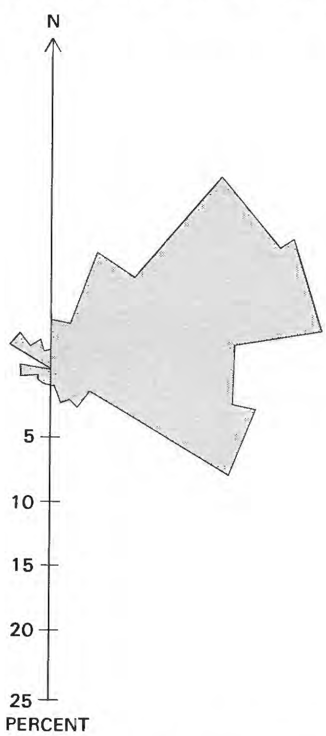


FIGURE 31.—Rose diagram showing sediment transport directions of sandstone beds in a tidal channel at locality E; 100 measurements.

fining-upward, very fine grained to medium-grained sandstone is poorly sorted and has small-scale trough crossbeds. It is much lighter colored, coarser, and cleaner than most of the lagoonal sandstones studied, which suggests that it was derived from reworked dune and beach sands from the upper part of the barrier

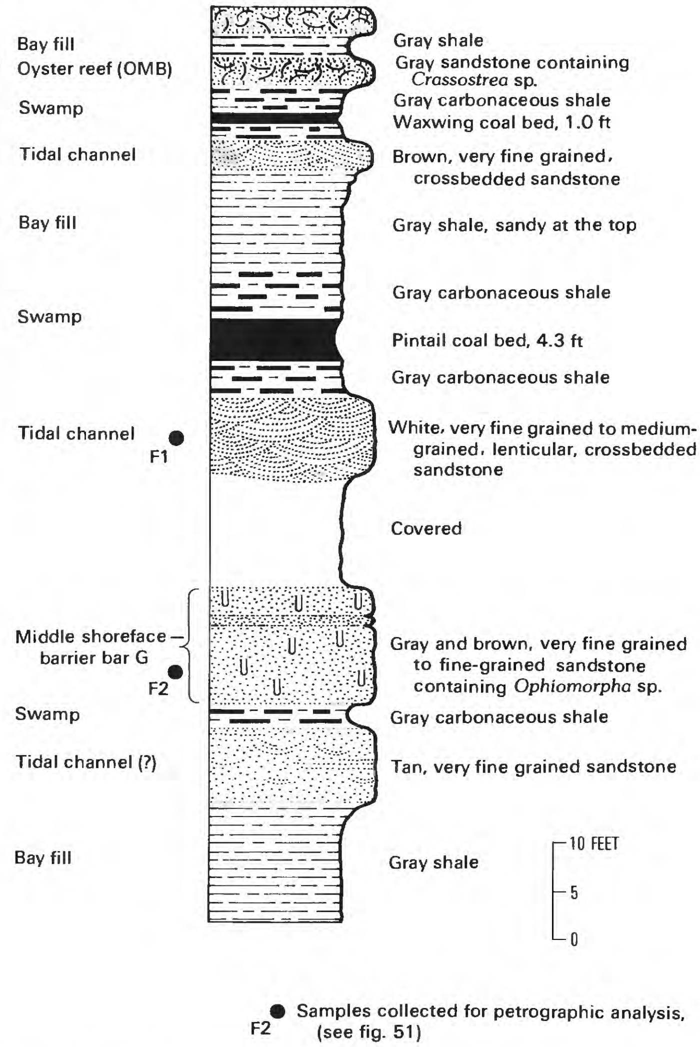


FIGURE 32.—Columnar section of part of the Almond Formation at locality F in S½NW¼ sec. 33, T. 16 N., R. 102 W. Depositional environments and lithofacies are identified to the left of the column and lithologies are described to the right of the column.

located to the east. The sands were probably transported by meteoric and tidal waters in a small stream that flowed landward (westward) off the back-barrier flat through a swampy area at the seaward edge of the lagoon.

The Pintail coal bed is composed of 4.3 ft of clean, bright coal in a trench that was dug above the tidal channel at the locality. Twenty-one feet above the top of the Pintail coal bed is a 1-ft-thick bed of coal that was named the Waxwing coal bed by the author (Roehler, 1978a). The Waxwing coal bed is lenticular and is missing in outcrops north of locality F, but it persists for more than 6 miles to the south of the locality as a bed having a persistent thickness between 1 and 2 ft.

The oyster marker bed (OMB) that overlies the Waxwing coal bed at locality F has an appearance and

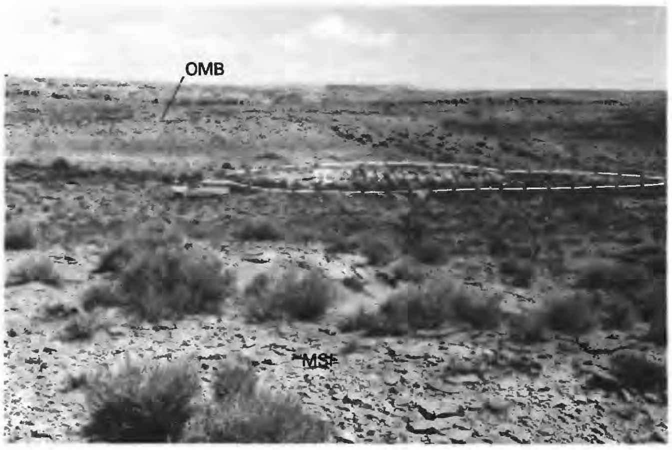


FIGURE 33.—Tidal channel (TC) situated above a middle shoreface sandstone lithofacies (MSF) of barrier bar G at locality F in S½NW¼ sec. 33, T. 16 N., R. 102 W. The oyster marker bed (OMB) forms a small ridge overlying the tidal channel. The Pintail coal bed overlies the tidal channel here.

composition similar to the oyster ridge marker (ORM) at localities C, D, and E. However, the two marker beds are clearly at different stratigraphic positions, as shown on plate 1, and, as explained later in a discussion of the geologic history of barrier bar G, they have different origins.

LOCALITY G—RECURVED SPIT, TIDAL INLET, AND FLOOD-TIDAL DELTA

Locality G straddles Wyoming Highway 430 in SW¼ sec. 33, T. 16 N., R. 102 W. and NW¼ sec. 4, T. 15 N., R. 102 W., 0.7 mi east of the Mud Springs Ranch. The barrier outcrops 200 ft north of the highway (section 3, fig. 34) consist of middle shoreface, surf, and recurved spit sandstone. Only the upper 10 ft of the middle shoreface sandstone is exposed there; it consists of tan, bioturbated, fine- to medium-grained sandstone with scattered *Ophiomorpha* sp. The overlying surf sandstone is about 6 ft thick and is composed of white, fine- to medium-grained sandstone in small-scale, trough crossbeds. The recurved spit at the top of the barrier sandstone sequence is 10 ft thick and is composed of white, fine- to medium-grained sandstone in thin, even, parallel beds that dip southward (into an adjacent tidal inlet) and contain a few, scattered *Ophiomorpha* sp. Southward along the barrier outcrops, but still north of Highway 430 (sections 4 and 5, fig. 34 and fig. 35), the surf and recurved spit sandstones are replaced by a tidal inlet that cuts through the barrier sandstones. The inlet has a scoured base and is filled with tan and gray, very fine grained to medium-grained sandstone that contains coal fragments and clay pebbles in large-scale, low-angle, trough crossbeds. The crossbeds dip mostly in northwest and southeast directions (fig. 36), which correspond to the transport directions for the sediments that moved landward through the inlet on flood tides and seaward through the inlet on ebb tides, respectively. Mineralized wood in the lower parts of the inlet sandstone sometimes contains *Teredo* tubes, the burrows of a small pelecypod, commonly called a ship worm. The inlet sandstone thins south of Highway 430 across the locality, as shown in figure 34.

Quaternary alluvium fills the valley of Salt Wells Creek and covers outcrops for several hundred feet south of Highway 430 at locality G. Near the south edge of the locality the barrier section is again well exposed (section 6, fig. 34). There, the tidal inlet has thinned to 6 ft of tan, crossbedded sandstone; it is underlain by 10 ft of tan, very fine grained to medium-grained, tabular, crossbedded sandstone, that comprises the northern edge of a large flood-tidal delta. The flood-tidal delta was deposited mostly by migrating megaripples (fig. 37) in a sandstone sequence that has distinctly northwest (landward) sediment transport directions (fig. 38). The direction of dip of the bedding indicates a strong northwest flow of tidal currents across part of a flood ramp and through a flood channel. The geographic relations of the flood ramp and flood channel lithofacies are illustrated in figure 11, nos. 1 and 2. Below the flood-tidal delta sandstone are 8 ft of light-gray, even, parallel, thin-bedded sandstone that is tentatively designated a recurved spit. Normal surf and middle shoreface sandstone units are present at the base of the section.

The Pintail coal bed at locality G is composed of 3.6–4.2 ft of clean coal, except for outcrops immediately north of Highway 430, where it is burned to red powdery ash and clinkers. A tidal-channel sandstone of lagoonal origin and the oyster marker bed overlie the Pintail coal bed and are easily identified in the outcrops at the locality illustrated in figure 35.

LOCALITY H—TIDAL FLAT AND FLOOD-TIDAL DELTA

Flood-tidal delta equivalents of barrier bar G at locality H are composed of 36 ft of tan, very fine grained to medium-grained sandstone (fig. 39). The sandstone here comprises a segment of the southern part of the flood-tidal delta that was described at locality G. The flood-tidal delta sandstone at locality H has large-scale, planar crossbeds with mostly steeply southwest-dipping foreset laminae (fig. 40). These beds were deposited by southwest-migrating sand waves along the southern part of the flood ramp (fig. 41). The flood-tidal delta is overlain by 13 ft of tan and gray, very fine grained, irregularly lenticular, rippled sandstone in beds as thick

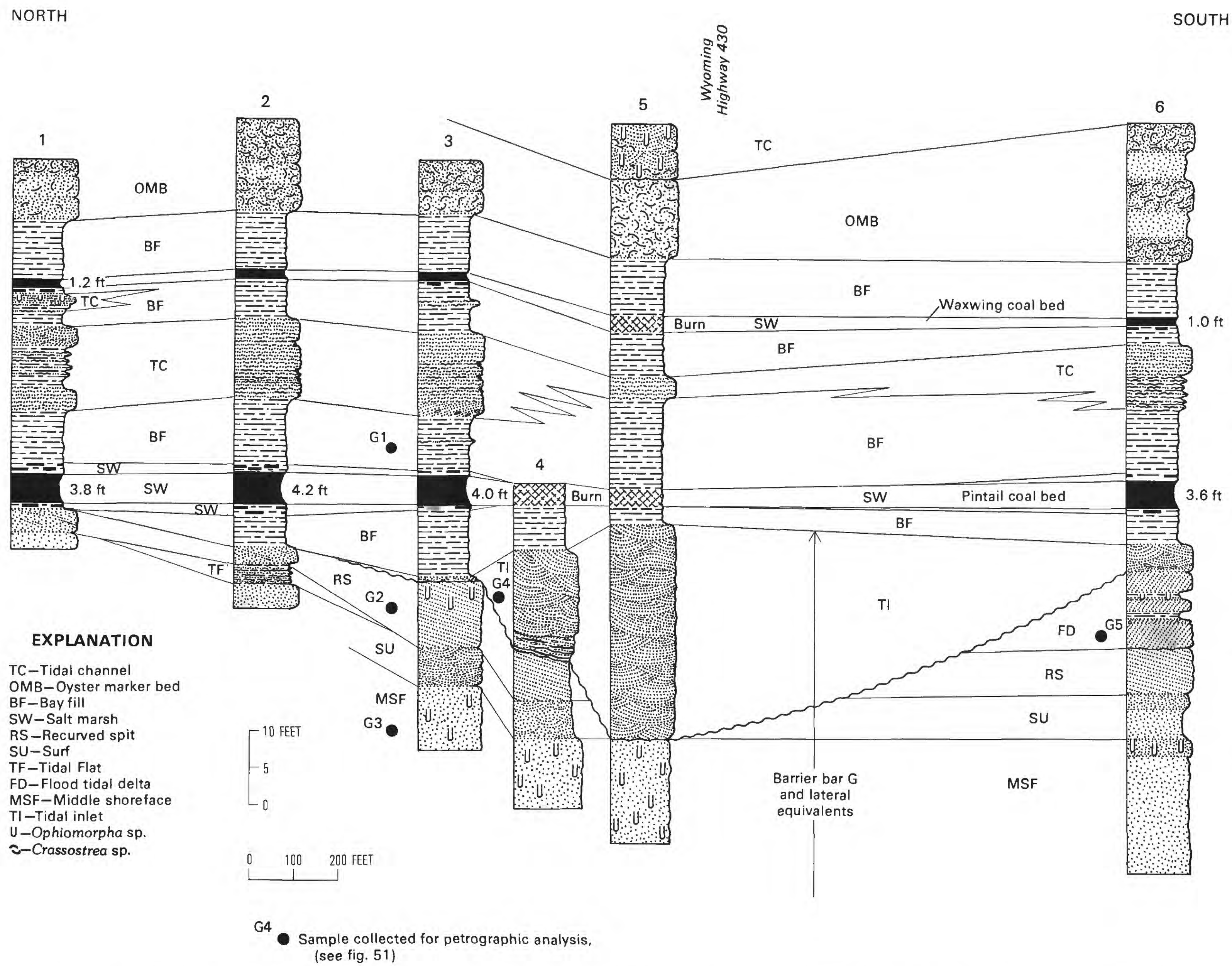


FIGURE 34.—Columnar sections of part of the Almond Formation at locality G in SW¼ sec. 33, T. 16 N., R. 102 W and NW sec. 4, T. 15 N., R. 102 W. Lithologies are identified on plate 1.

FIGURE 35.—Barrier bar G on the north side of Highway 430 in SW¼ sec. 33, T. 16 N., R. 102 W., showing the oyster marker bed (OMB), tidal channel (TC), tidal inlet (TI), recurved spit (RS), surf (SU), and middle shoreface (MSF) sandstone lithofacies. Person (circled) in the left center of photograph provides scale.

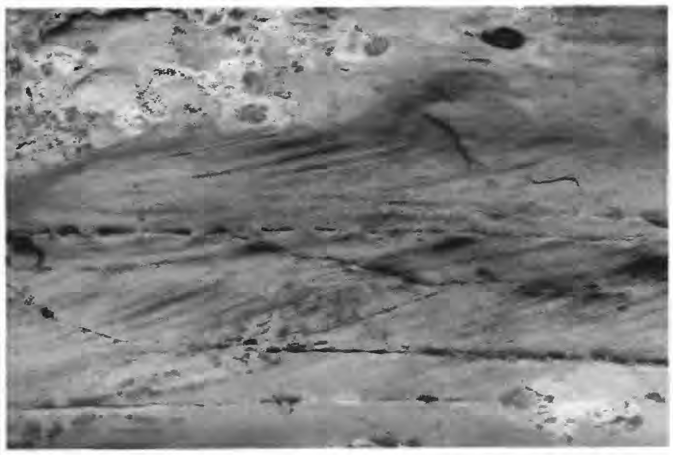


FIGURE 37.—Parallel sets of northwest-dipping (landward) laminae that are part of a flood ramp or flood channel in a flood-tidal delta sandstone lithofacies at locality G in SW¼NW¼ sec. 4, T. 15 N.,R. 102 W. Camera lens cap is used for scale.

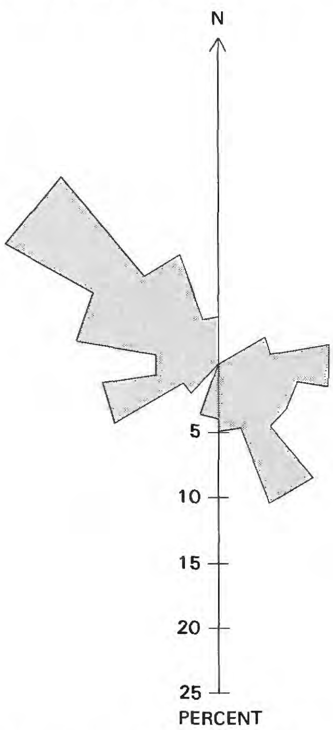


FIGURE 36.—Rose diagram showing sediment transport directions of sandstone beds in a tidal inlet at locality G; 100 measurements.

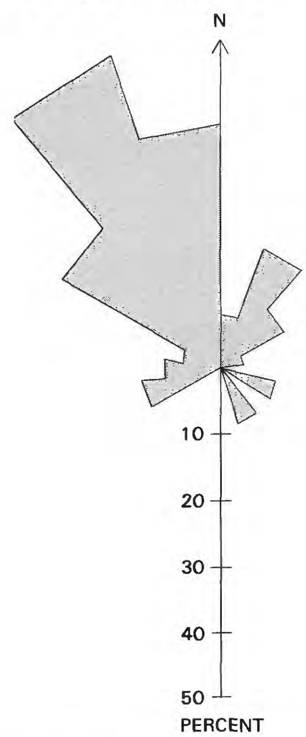


FIGURE 38.—Rose diagram showing sediment transport directions of sandstone beds in a flood-tidal delta at locality G; 50 measurements.

as a few inches that are interbedded with thin, gray, sandy shale. These rocks are of tidal-flat origin (figs. 42 and 43). The tidal flat (see fig. 11, no. 3) has numerous trace-fossil burrows tentatively identified by the author as *Skolithos* (fig. 44) and *Diplocraterion* (fig. 45). The *Skolithos* burrows resemble the burrows of the Holocene fiddler crab, *Uca* sp., that have been observed on tidal flats along the coast of South Carolina. Shells of *Crassostrea* sp. are present in a 2-ft-thick sandstone at the base of the tidal flat sequence in measured sections about 200 ft north of the locality (sections 71 and 72, plate 1), and these shells are believed to be located in an oyster flat resting on the landward part of the flood delta (fig. 11, no. 3).

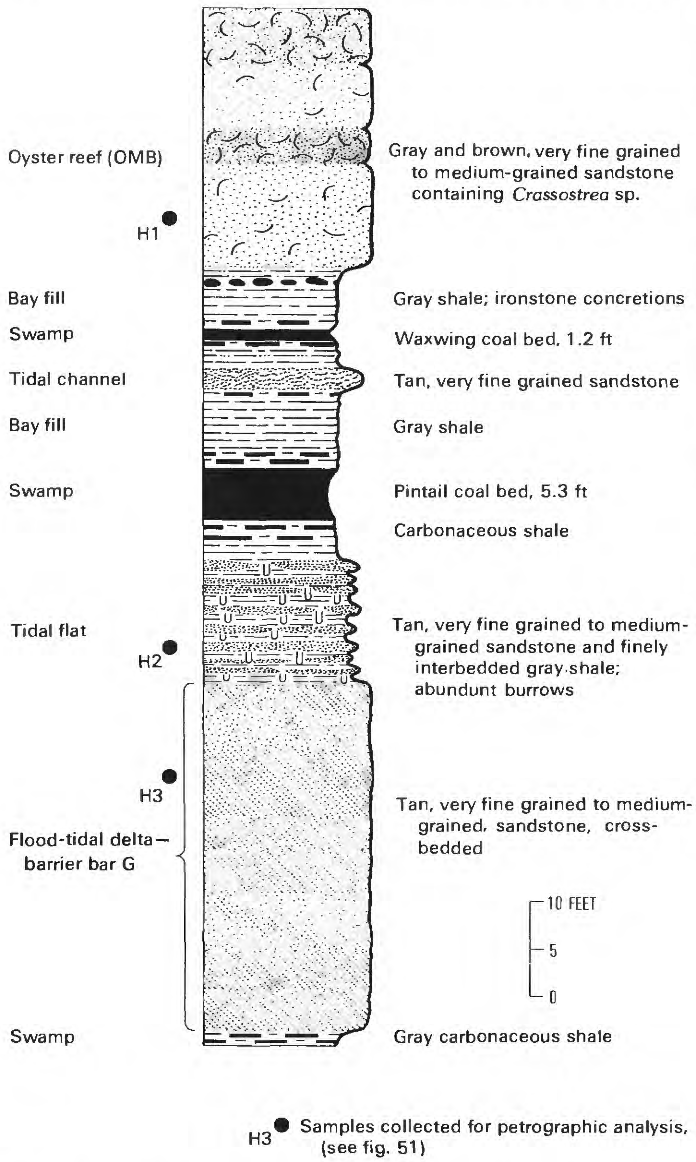


FIGURE 39.—Columnar section of part of the Almond Formation at locality H in NE¼SW¼ sec. 8, T. 15 N., R. 102 W. Depositional environments are identified to the left of the column and lithologies are described to the right of the column.

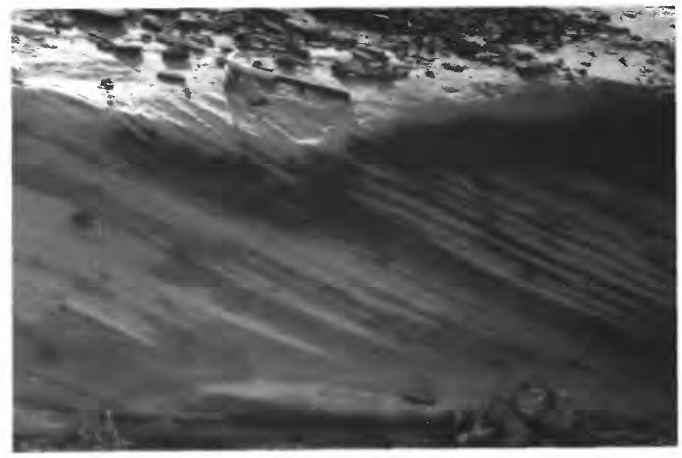


FIGURE 40.—Sand wave in a flood-tidal delta (FD) of barrier bar G at locality H in NE¼SW¼ sec. 8, T. 16 N., R. 102 W. The foreset laminae dip strongly to the southwest. Handle of the pickmattock used for scale is 17 in. long.

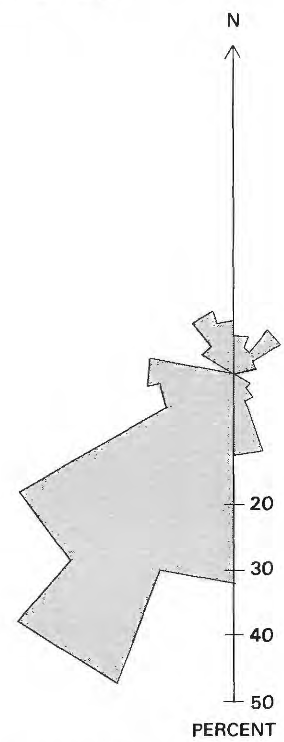


FIGURE 41.—Rose diagram showing sediment transport directions of sandstone beds in the southern part of a flood-tidal delta at locality H; 100 measurements.

The Pintail coal bed is 5.3 ft thick at locality H. The oyster marker bed is 24 ft thick and has dark-brown layers that contain shell concentrations and interbedded tan layers that contain only scattered shells, all in sandstone matrices. Parts of the oyster marker bed have low-angle foreset laminae with southerly dip components, which suggests a southward accretion direction for the oyster bed. *Crassostrea* valves in the bed are locally large and well preserved (fig. 46).

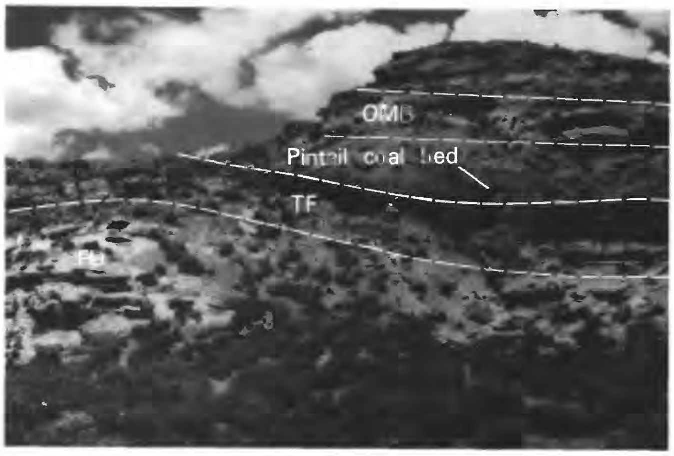


FIGURE 42.—Locality H in NE¼SE¼ sec. 8, T. 15 N., R. 102 W., showing the stratigraphic positions of the oyster marker bed (OMB), the Pintail coal bed, a tidal flat sequence (TF), and a flood-tidal delta sequence (FD).

FIGURE 43.—Tidal flat sequence of thin interbedded sandstone and shale at locality H in NE¼SW¼ sec. 8, T. 15 N., R. 102 W.

FIGURE 44.—*Skolithos*? burrows in a tidal flat sequence at locality H in NE¼SW¼ sec. 8, T. 15 N., R. 102 W. Photograph shows vertical orientation. Knife at top of photograph is about 0.3 ft long.

FIGURE 45.—*Diplocraterion*? burrow in tidal flat sequence at locality H in NE¼SW¼ sec. 8, T. 15 N., R. 102 W. Photograph shows vertical orientation.

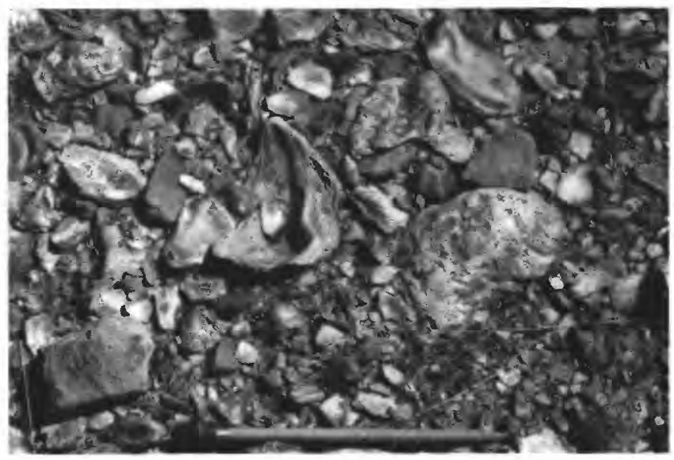


FIGURE 46.—*Crassostrea* sp. in the oyster marker bed (OMB) at locality H in NE¼SW¼ sec. 8, T. 15 N., R. 102 W. Pencil is about 0.5 ft long.

LOCALITY I—FLOOD-TIDAL DELTA AND LAGOON

The lateral equivalents of barrier bar G at locality I consist of 7 ft of white, crossbedded sandstone that was deposited at the southern edge of the flood-tidal delta discussed at localities G and H. The flood-tidal delta sandstone here is thinner and is rapidly wedging out southward in outcrops into lagoonal rocks that are composed mostly of gray shale, siltstone, carbonaceous shale, and coal (figs. 47 and 48). Overlying the flood-tidal delta sandstone are thin beds of shale and sandstone that contain *Crassostrea* sp.; these are part of an oyster flat (fig. 11, no. 3). Between the oyster flat and the overlying Pintail coal bed are 4.7 ft of thin-bedded, gray, current-rippled, extensively burrowed sandstone, siltstone, and thin, interbedded gray shale that correlate to the tidal flat sequence containing the *Skolithos* burrows at locality H.

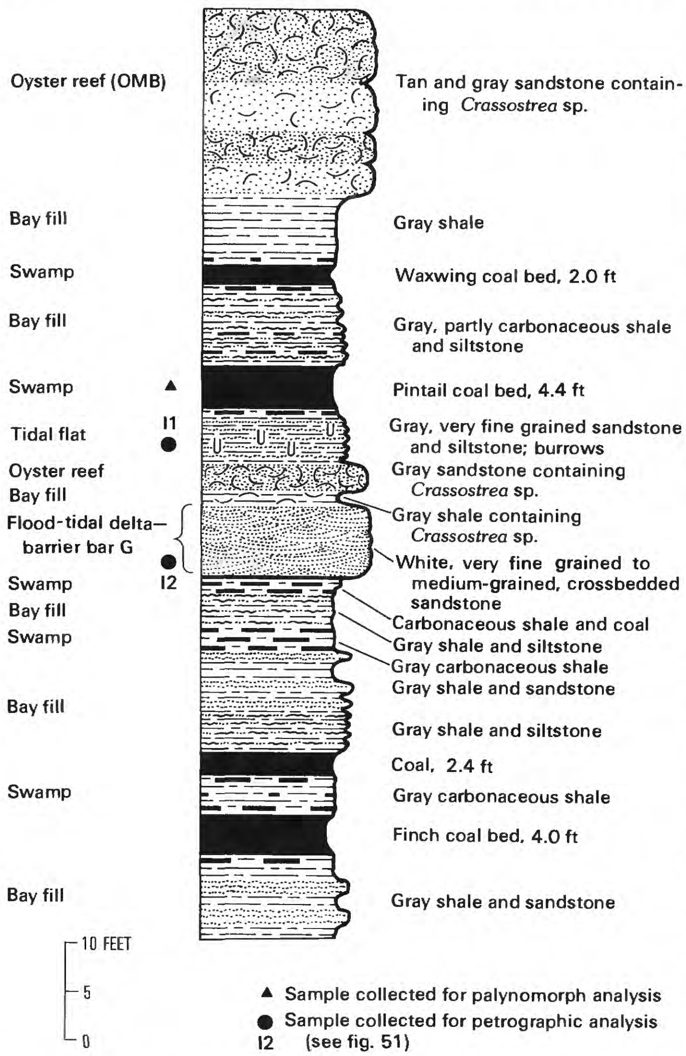


FIGURE 47.—Columnar section of part of the Almond Formation at locality I in SW¼NW¼ sec. 17, T. 15 N., R. 102 W. Depositional environments are identified to the left of the column and lithologies are described to the right of the column.

The Pintail coal bed at the locality is composed of 4.4 ft of clean, bright coal. Overlying the Pintail coal bed are 18 ft of bay-fill and swamp deposits composed of shale and siltstone with 2.0 ft of coal, the Waxwing coal bed, near the middle. The oyster marker bed is 19 ft thick and contains layered shell concentrations.

LOCALITY J—WASHOVER FAN AND LAGOON

The lateral equivalents of barrier bar G at locality J, near the southern boundary of the study area, are mostly gray, parallel, tabular, very fine grained to medium-grained sandstone beds with landward-dipping laminae and some small-scale, trough crossbeds that

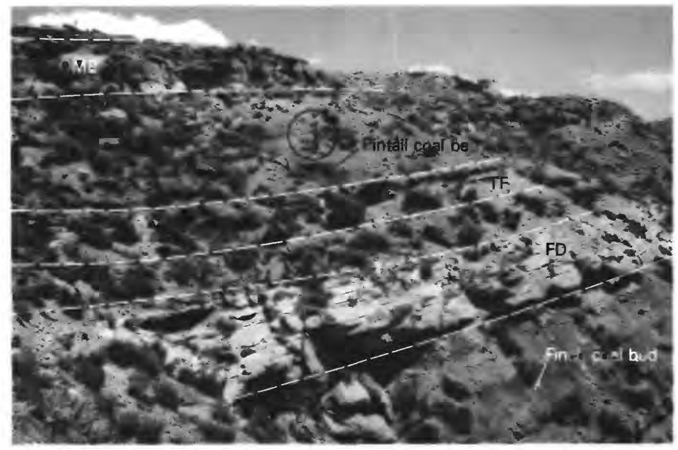


FIGURE 48.—Locality I showing the oyster marker bed (OMB), the Pintail coal bed, a tidal flat sequence (TF), a flood-tidal delta sequence (FD), and the Finch coal bed. Person (circled) is about 5.5 ft tall.

are part of a large washover fan of probable storm origin. The washover fan is exposed along a line of outcrops that cross the northeast part of sec. 20, T. 15 N., R. 102 W, but it is covered south of there in the southeast part of sec. 20 (south of section 7, figure 49). The intertonguing relations of the washover fan and adjacent lagoonal rocks to the north are illustrated in sections 1, 2, and 3, in figure 49. Thin, tabular beds that compose part of the washover fan are shown in figure 50. The section underlying the fan is mostly gray sandstone, siltstone, shale, carbonaceous shale, and coal that are bay-fill and swamp deposits of lagoonal origin.

The Pintail coal bed is present above the washover fan at locality J, where it consists of 3.1–4.3 ft of clean coal. A swamp sequence composed mostly of carbonaceous shale separates the Pintail coal bed from the overlying Waxwing coal bed. Overlying the Waxwing coal bed is a bay-fill sequence of mostly soft, dark-gray shale capped by the ledge-forming oyster marker bed.

SANDSTONE PETROLOGY

The sandstone lithofacies of barrier bar G and its lateral equivalents are composed 65–85 percent of clear to milky quartz grains; 15–35 percent of varicolored rock fragments, mica, feldspar, and brown, tan, or white cement; and 1–2 percent of heavy mineral grains. Photomicrographs of the various sandstone lithofacies from localities A to J are shown in figure 51. The sand grains are angular to subangular and the longest dimension ranges from less than 1/16 mm to more than 1/4 mm; the mean grain diameter commonly is 1/8–1/4 mm (fig. 52). The sandstones are predominantly

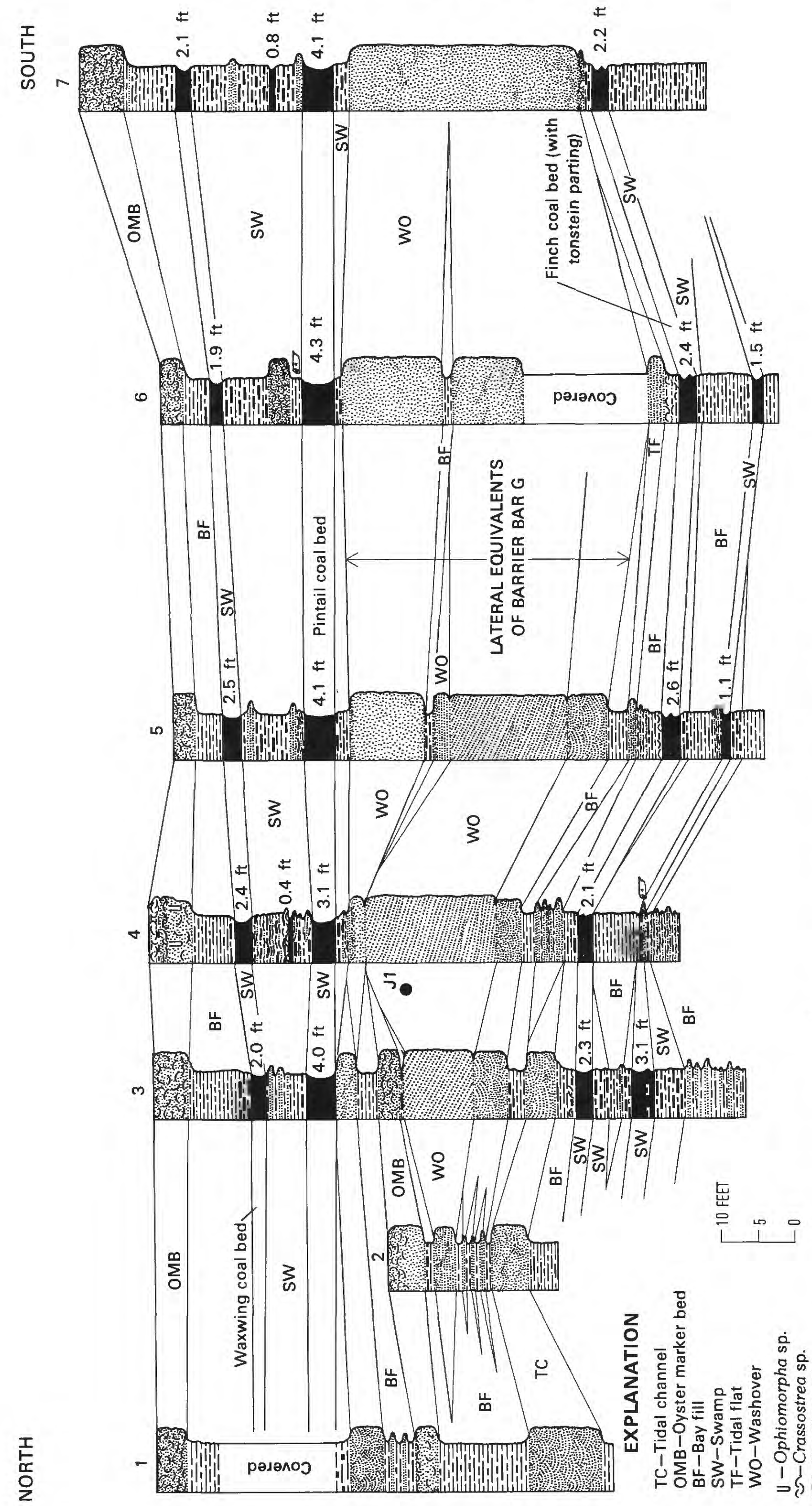


FIGURE 49.—Columnar sections (1, 3, 4, 5, 6, 7) of the Almond Formation at locality J in E½ sec. 20, T. 15 N., R. 102 W. Lithologies are identified on plate 1.

FIGURE 50.—Parallel, tabular-bedded sandstone composing part of a washover fan at locality J. By removing the dip component related to postdepositional deformations, it is obvious that these eastward-dipping sandstones originally dipped gently westward. The Jacob's staff used for scale is 5.0 ft long.

fine grained, and barrier bar G can be characterized as a fine-grained barrier system. The coarsest sand grains are predictably found in dune, forebeach, tidal-inlet, and flood-delta lithofacies, because of the high energy level of the environments; the sand grains become progressively finer textured seaward from the forebeach to the middle shoreface to the lower shoreface. The grains are poorly to moderately well sorted. The surf, forebeach, berm, and dune sandstones are nearly always cleaner and better sorted than other lithofacies.

Three kinds of interstitial cement have been observed visually in outcrop sandstone samples. Sand grains in the middle shoreface are cemented by hematite and an unidentified white clay, which is probably illite. The upper shoreface and dune sandstones are also cemented by white clay. The tidal-channel, flood-tidal delta, and tidal-flat sandstones are cemented by an undetermined tan carbonate, which is probably calcite.

The heavy mineral grains are 90–95 percent nonopaque. The nonopaque fraction is generally composed of 10–25 percent garnet, 25–50 percent zircon, 5–15 percent rutile, and 25–45 percent tourmaline. The heavy minerals indicate plutonic source beds.

DEPOSITIONAL HISTORY AND PALEOGEOGRAPHY

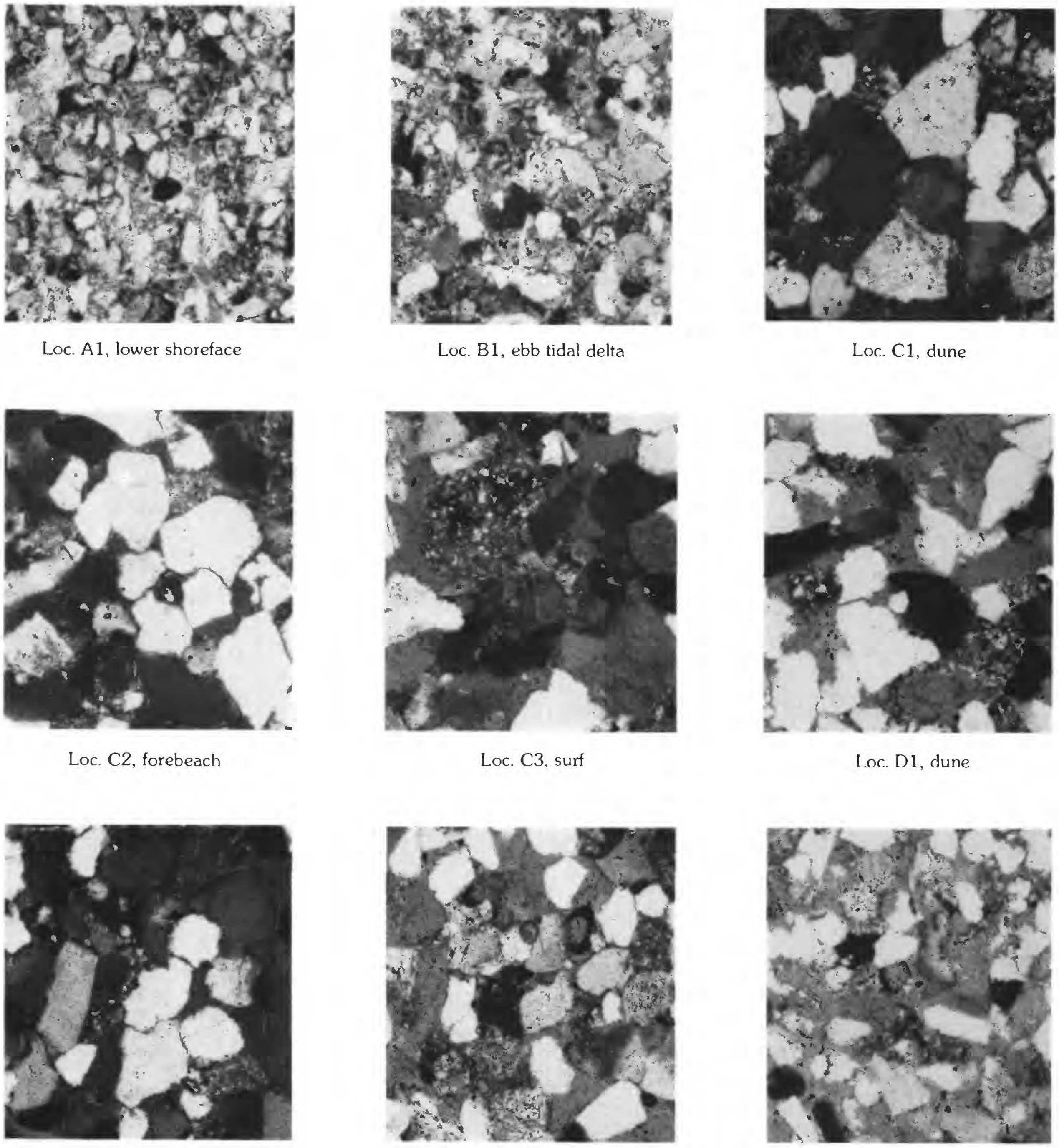
Barrier bar G evolved through stages of youth, maturity, and old age before the barrier system was abandoned and later partly destroyed by marine transgression and erosion. Five stages of evolution are portrayed on paleogeographic maps (figs. 53 to 57). The stratigraphic positions of the five stages are indicated on plate 1. The paleogeographic maps are diagrammatic reconstructions that depict the locations of the depositional environments and lithofacies that were identified in measured sections along the line of barrier outcrops; the author has used artistic license to depict hypothetical conditions away from the outcrops—conditions that are, nonetheless, consistent with those of Holocene barriers.

A close relationship of the Pintail coal bed and barrier bar G is demonstrated from the fact that the coal and barrier sandstone are either in contact or are situated within a few feet of each other across the area studied. The relationship is not coincidental. The prograding barrier sandstone provided a stable platform for peat accumulation and a reservoir of freshwater for utilization by plants growing upon the barrier. Conversely, the fibrous peat mat that formed the Pintail coal bed provided a blanket of extremely tough, resilient material that shielded the underlying soft barrier sand from fluvial and marine erosion prior to burial and diagenesis.

YOUTH

The earliest period of deposition of barrier bar G is not well understood because it is poorly preserved in the rock record. The barrier appears to have originated as a chain of narrow, barren, or sparsely vegetated sand banks, or sand islands, situated 1.0 to 2.0 mi offshore, whose sedimentation was controlled by southward longshore currents (fig. 53). The subaerial parts of the islands were probably formed by linear dune ridges (DU). Back-barrier flats were small or missing. A forebeach (FB) sand deposit was present on the seaward side of the barrier and shallow marine parts included surf (SU), middle shoreface (MSF), and lower shoreface (LSF) sands. Mud (MS) was deposited in deeper marine waters for unknown distances offshore.

Early in the barrier history a lagoon (LA) evolved from a saltwater arm of the sea into a narrow, brackish, open-water estuary or bay. The resulting lagoon was thus situated between small, barren, barrier islands to the east and a freshwater coastal plain to the west. The lagoon contained numerous linear sand bars and oyster reefs (OB). Landward of the lagoon were broad areas of tidal creeks and salt marshes (SW). Tidal inlets (TI) through the barriers were located opposite the mouths of major drainages entering the lagoon from the west. This relationship suggests that the barrier itself formed by the submergence of a beach ridge during marine transgression.



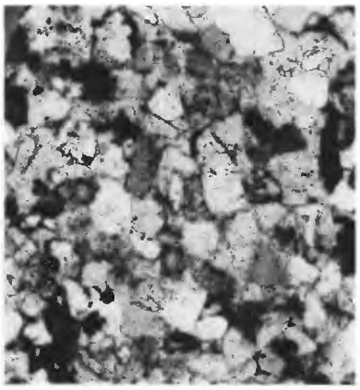
Loc. A1, lower shoreface — Loc. B1, ebb tidal delta — Loc. C1, dune

Loc. C2, forebeach — Loc. C3, surf — Loc. D1, dune

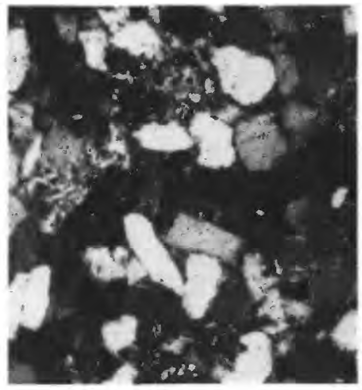
Loc. D1A, berm — Loc. D2, forebeach — Loc. D3, surf

FIGURE 51 (above and following pages).—Photomicrographs of sandstones composing barrier bar G and its lateral equivalents. Sample collection sites are indicated on columnar sections in figures that accompany descriptions of localities A to J. Magnification × 50; under slightly polarized light to enhance grain images.

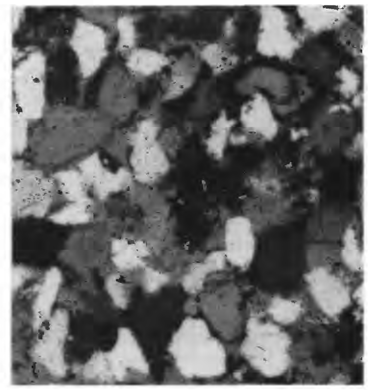
Sparse vegetation along the shores of the lagoon was adapted to saltwater and brackish water. The vegetation probably included emergent hydrophytes similar to the cordgrass, *Spartina*, and the mangrove, *Rhizophora*, genera that are common in similar Holocene environments. Sediments deposited at the margins of the lagoon were mostly carbonaceous muds, whereas dark-gray noncarbonaceous muds were deposited in subtidal open-water parts of the lagoon. The chemistry of the lagoon substrate probably is alkaline and aerobic



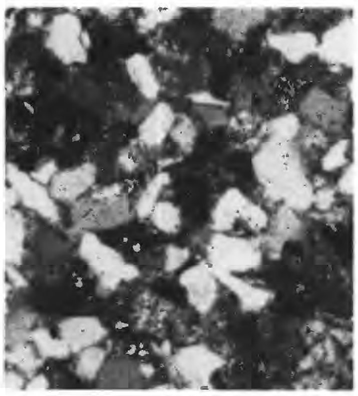
Loc. D4, middle shoreface



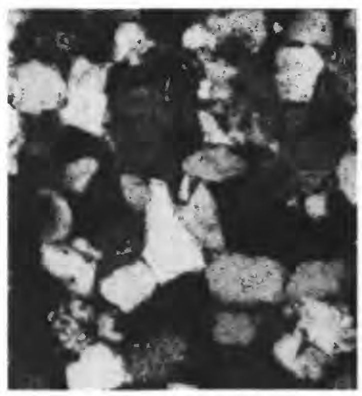
Loc. E1, forebeach



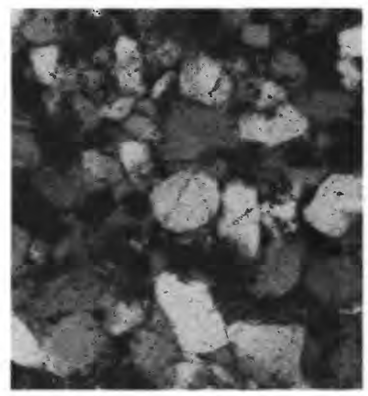
Loc. E2, surf



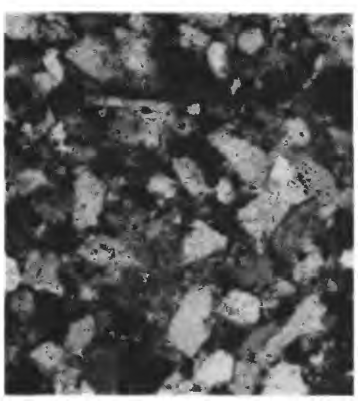
Loc. E3, upper tidal channel



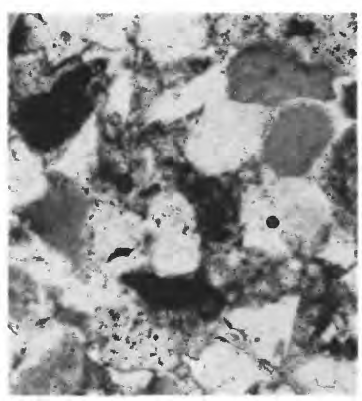
Loc. E4, lower tidal channel



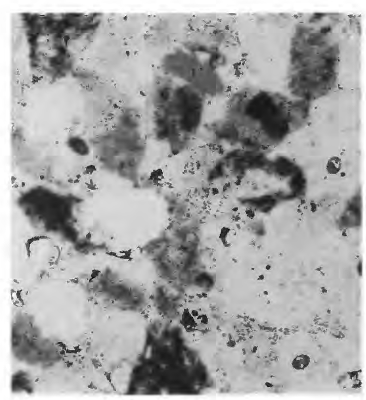
Loc. F1, tidal channel



Loc. F2, middle shoreface



Loc. G1, tidal flat

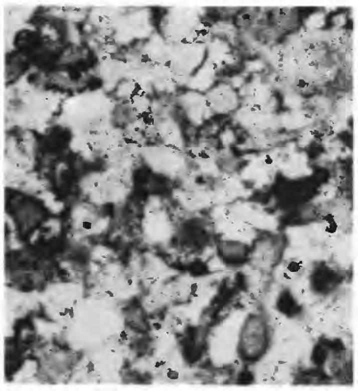


Loc. G2, recurved spit

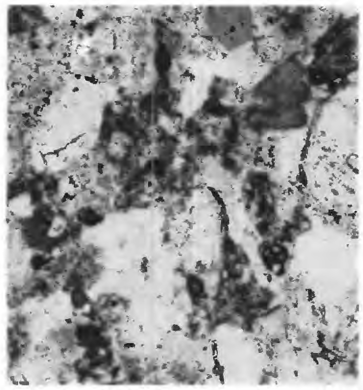
nearly everywhere, and therefore was not conducive to the formation and preservation of peat.

MATURITY

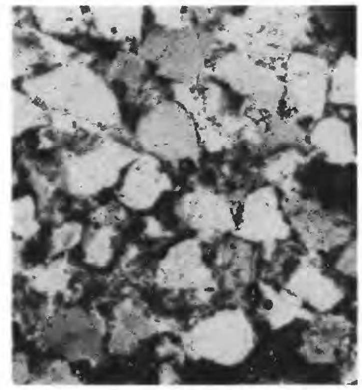
The barrier reached its optimum size and shape during the stage of maturity (fig. 54). During this period of development it consisted of a distinct chain of drumstick-shaped islands, the ends of which were terminated by recurved spits at tidal inlets. The barrier had well developed foredune ridges (DU) and freshwater peat swamps situated across back-barrier flats (PS). The influence of tides upon sedimentation is evident by the presence of flood-tidal deltas (FD), ebb-tidal deltas (ED), tidal inlets (TI), and tidal channels (TC). Oyster beds (OB) were present on parts of the flood-tidal deltas. The presence of a large washover fan (WO) suggests that the barrier was



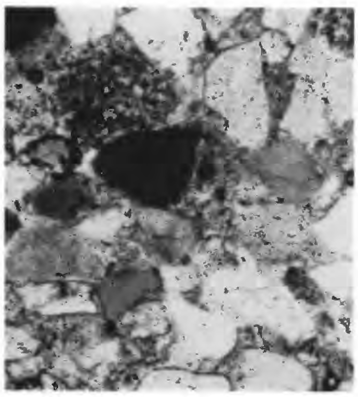
Loc. G3, middle shoreface



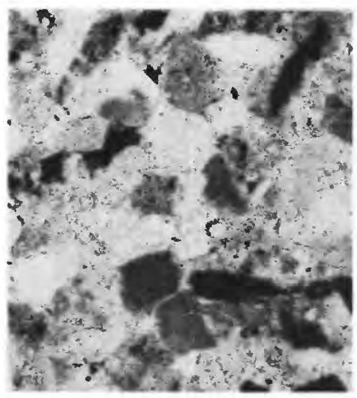
Loc. G4, tidal inlet



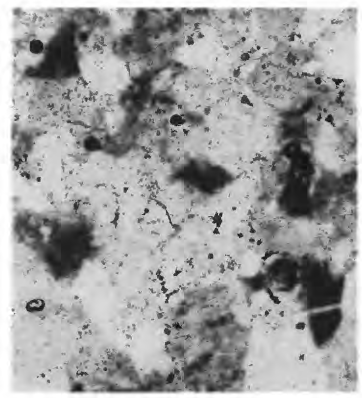
Loc. G5, flood tidal delta



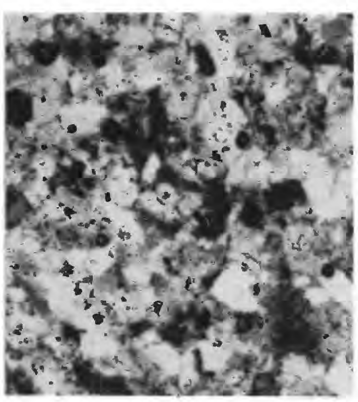
Loc. H1, oyster marker bed



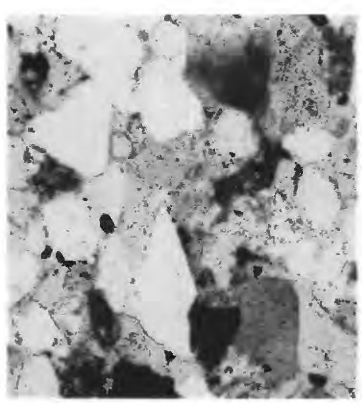
Loc. H2, tidal flat



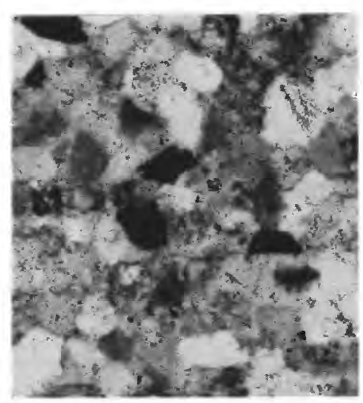
Loc. H3, flood tidal delta



Loc. I1, tidal flat



Loc. I2, flood delta



Loc. J1, washover fan

occasionally subjected to severe hurricane-type storms. Forebeach (FB), surf (SU), middle shoreface (MSF), and lower shoreface (LSF) sand lithofacies actively prograded seaward, and marine mud (MS) was deposited offshore.

The geographic location and geometry of the large flood-tidal delta in the northwest part of T. 15 N., R. 102 W. is readily discernible in sandstone outcrops. Sand waves on the flood ramp in sec. 4, T. 15 N., R. 102 W. (locality G, fig. 37) have foreset laminae that dip northwest. Similar northwest dips are present southward for several hundred feet across outcrops of the flood-tidal delta in sec. 5, T. 15 N., R. 102 W., but at a point in the northwest part of sec. 8, T. 15 N., R. 102 W., the northwest dips in the foresets abruptly change direction to the southwest. The southwest dips persist from there southward across the west part of sec. 8, T. 15 N., R. 102 W. (fig. 40). The change in dip directions

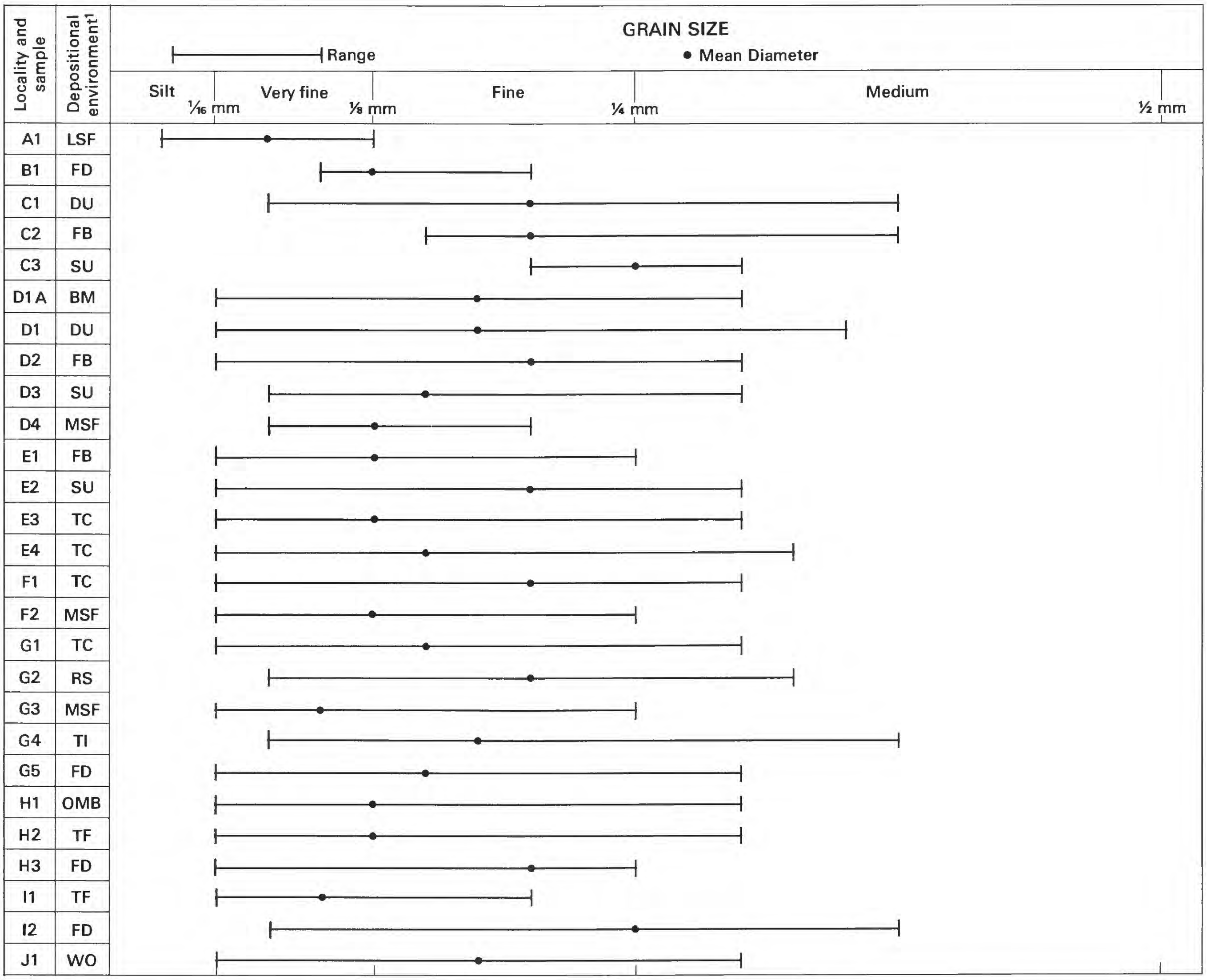


FIGURE 52.—Grain sizes of selected sandstone samples from outcrops of barrier bar G and its lateral equivalents. Abbreviations for depositional environments are explained on plate 1.

is construed as reflecting a planimetric axis, which confirms that the flood-tidal currents fanned outward into the lagoon after leaving the tidal inlet (fig. 11). Further evidence concerning the size and shape of the flood-tidal delta is provided by the location of tidal flats and oyster flats in shallow, brackish-water, lagoonward parts of the flood-tidal delta at localities H and K, discussed previously.

As a result of barrier progradation the lagoon (LA) behind the barrier began to expand in a seaward direction. The expansion was primarily over the back-barrier flat, where it was accompanied by the weathering and erosion of the exposed upper parts of the underlying barrier sand. Saltwater-saturated sands in the upper, older parts of the barrier were flushed by freshwaters of meteoric origin, and dense concentrations of shrubs and trees appeared. Large freshwater rivers entered the lagoon from the coastal plain to the west, which introduced freshwater vegetation and initiated peat (PS) deposition in areas that were partly interspersed with or rested upon older brackish-water bay-fill and salt marsh (SW) deposits. The bay-fill and salt marsh sediments were composed of gray, silty mud and gray and brown carbonaceous mud, respectively.

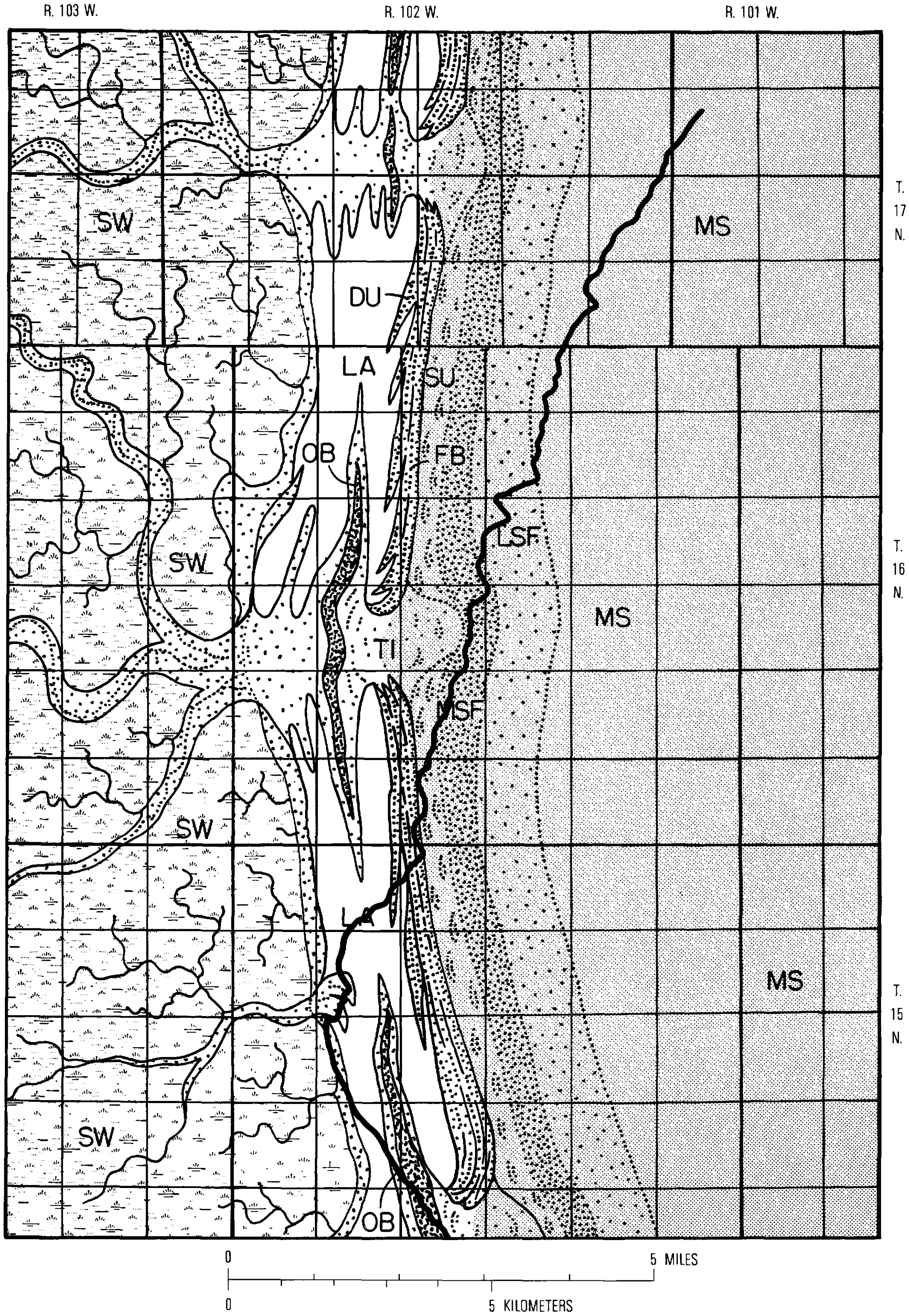


FIGURE 53.—Paleogeographic map of barrier bar G and its lagoon in the stage of youth. SW, Tidal creeks and salt marshes; LA, lagoon; OB, oyster reef; FB, forebeach; TI, tidal inlet; DU, dune ridges; SU, surf; MSF, middle shoreface; LSF, lower shoreface; MS, offshore mud. Heavy line shows the geographic location of outcrops of the barrier in the studied area.

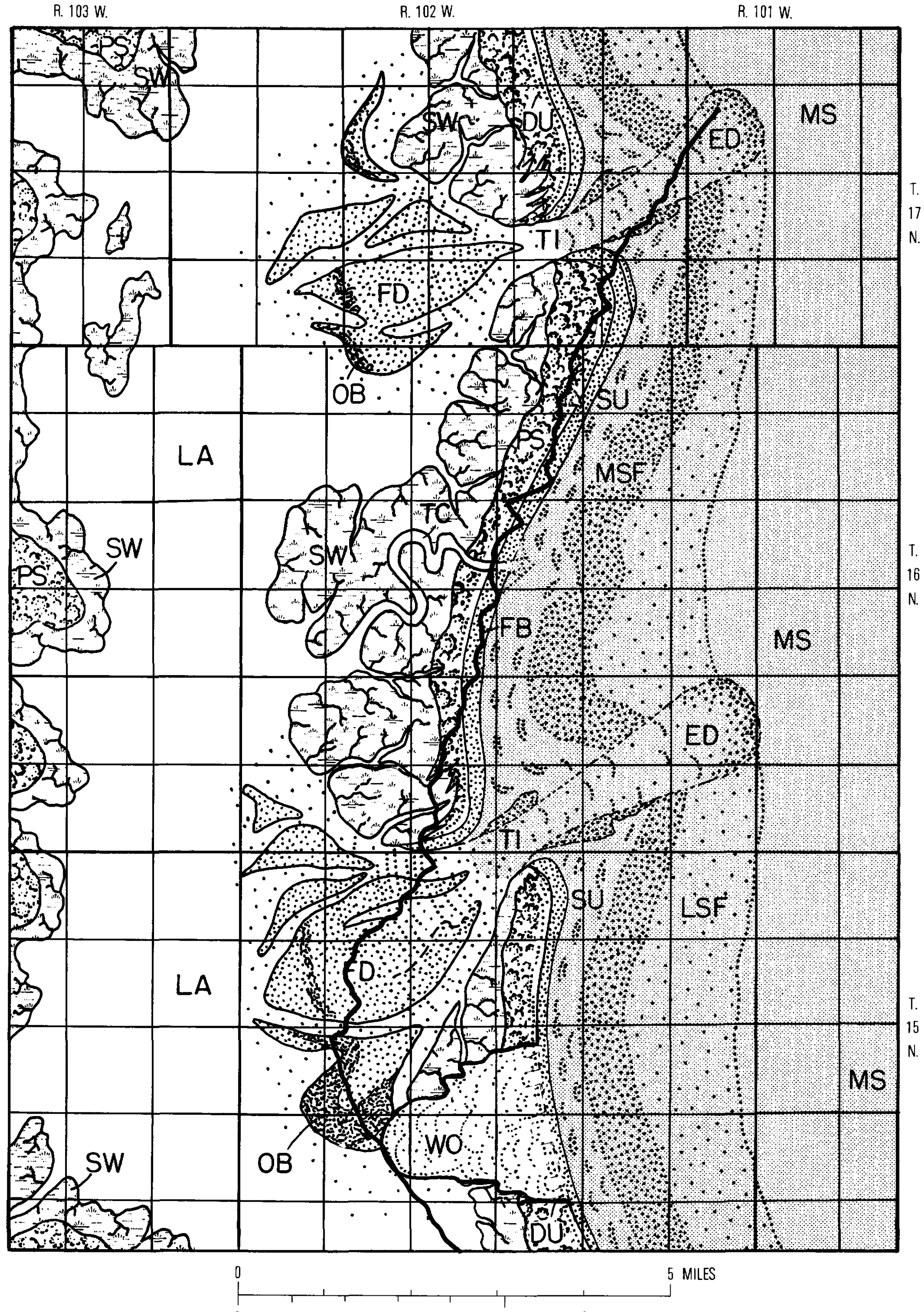


FIGURE 54.—Paleogeographic map of barrier bar G and its lagoon in the stage of maturity. PS, Peat swamp; SW, tidal creeks and salt marshes; LA, lagoon; WO, washover; FD, flood tidal delta; ED, ebb tidal delta; TI, tidal inlet; OB, oyster reef; DU, dune ridges; FB, forebeach; SU, surf; MSF, middle shoreface; LSF, lower shoreface; MS, offshore mud. Heavy line shows the geographic location of outcrops of the barrier in the studied area.

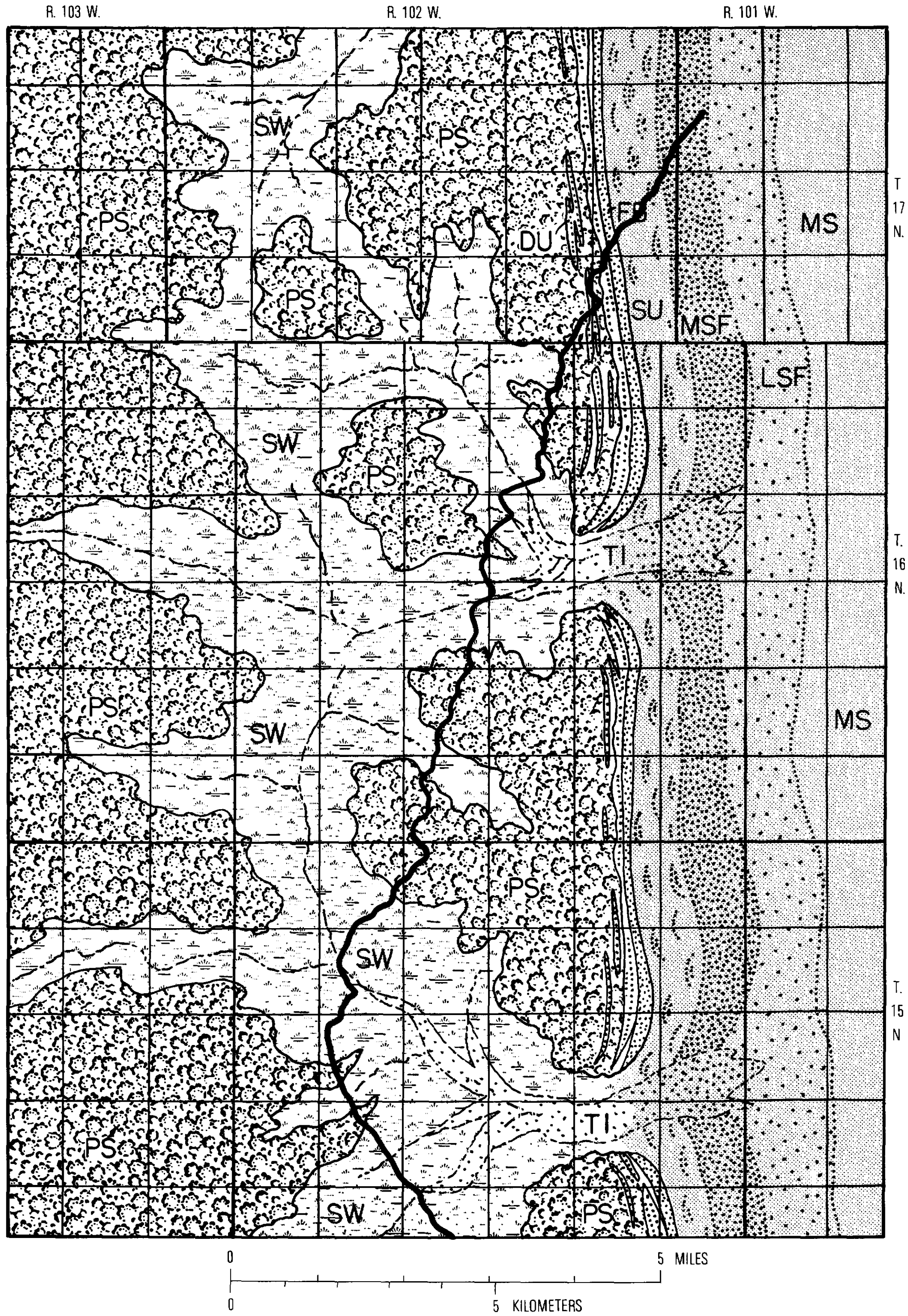


FIGURE 55.—Paleogeographic map of barrier bar G and its lagoon in the stage of old age. PS, Peat swamp; SW, tidal creeks and salt marshes; DU, dune ridges; FB, forebeach; SU, surf; MSF, middle shoreface; LSF, lower shoreface; MS, offshore mud. Heavy line shows the geographic location of outcrops of the barrier in the studied area.

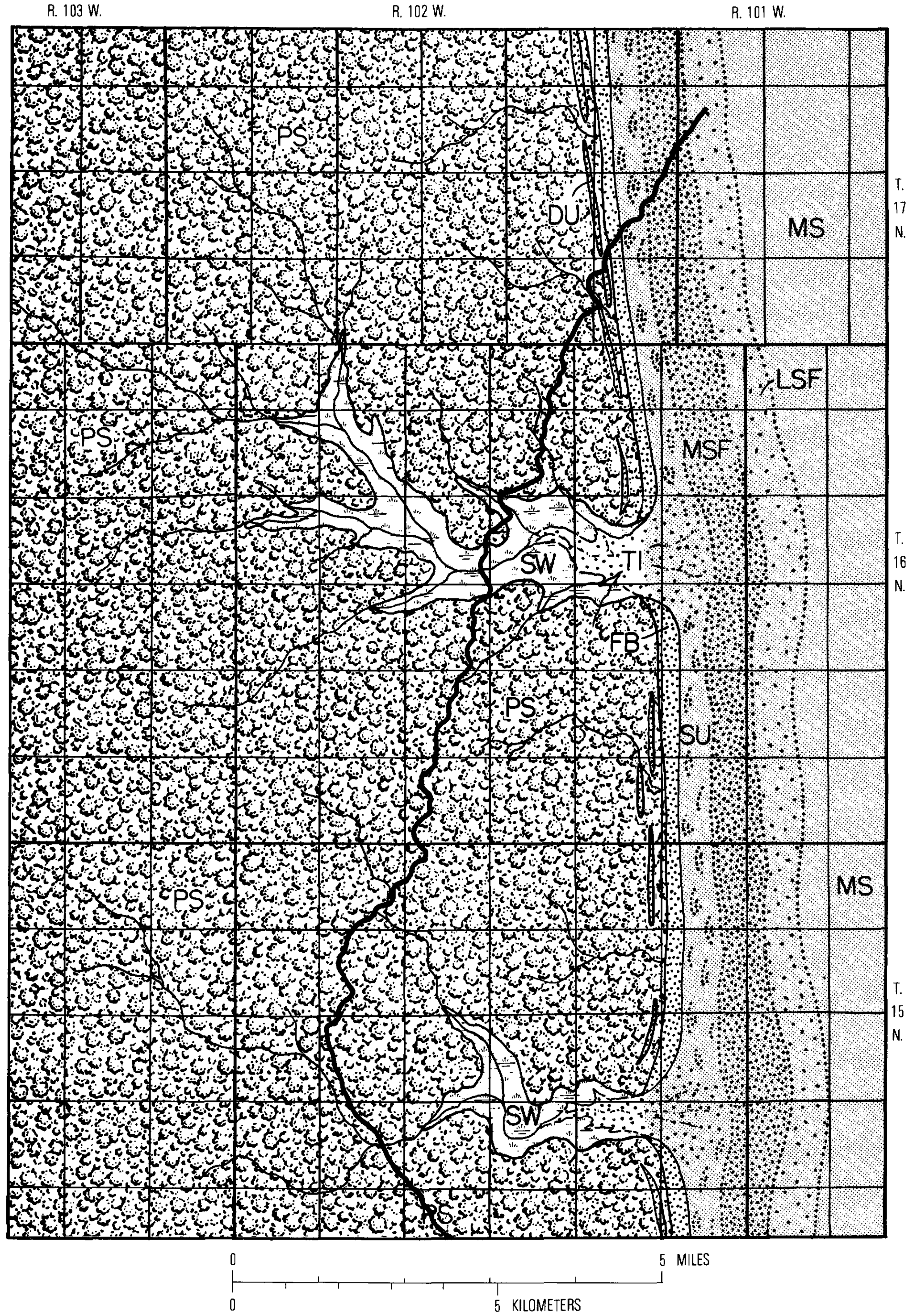


FIGURE 56.—Paleogeographic map of barrier bar G and its lagoon at the time the barrier was abandoned. PS, Peat swamp; TI, tidal inlet; SW, tidal creeks and salt marshes; DU, dune ridges; SU, surf; MSF, middle shoreface; LSF, lower shoreface; MS, offshore mud. Heavy line shows the geographic location of outcrops of the barrier in the area studied.

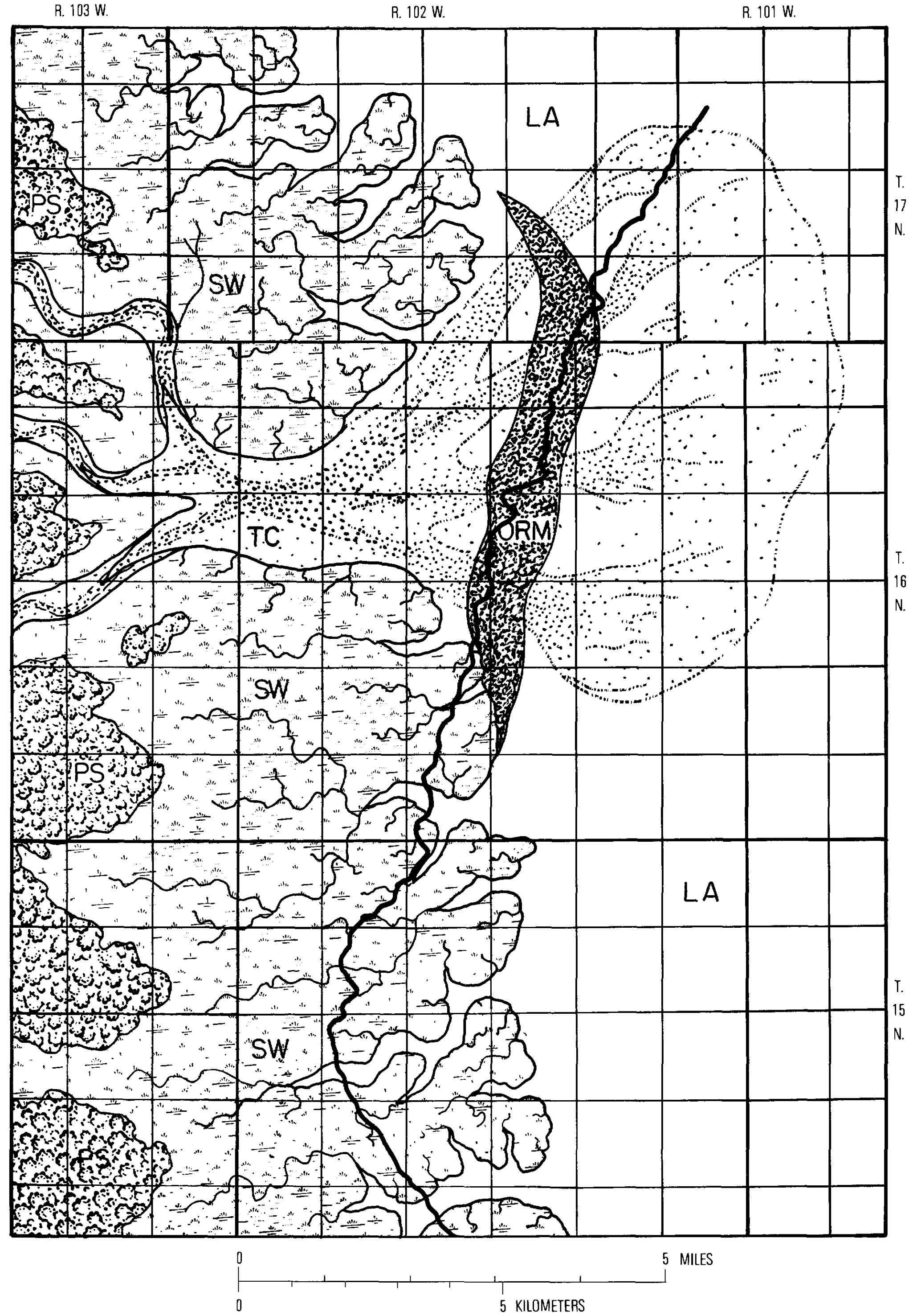


FIGURE 57.—Paleogeographic map of the study area following marine transgression over barrier bar G. PS, Peat swamp; SW, tidal creeks and salt marshes; LA, lagoon; ORM, oyster reef; TC, tidal channel; The heavy line shows the geographic location of outcrops of the barrier.

OLD AGE

The lagoon behind barrier bar G began to fill in, and the barrier system ceased to exist as a well-defined island chain. It acquired many of the physiographical characteristics of a strand plain or foreland, as is apparent by the disappearance of bay-fill muds (BF) that were replaced by salt marsh deposits (SW) in the rocks directly underlying the Pintail coal bed (see fig. 55 and plate 1). The barrier sands continued to prograde seaward by uninterrupted deposition of forebeach (FB), surf (SU), middle shoreface (MSF), and lower shoreface (LSF) facies; marine mud (MS) deposition continued offshore.

The lagoon continued to expand seaward over the back-barrier flat. Former open-water areas of the lagoon were replaced by tidal channels and salt marshes (SW). The waters freshened and islands and platforms of thick vegetation were introduced where lenticular peat deposits (PS) formed. Freshwater swamps covered parts of the dune field (DU) and all of the back-barrier flat, and they formed point-like projections landward from the back-barrier flats into brackish-water salt marshes (SW) in the lagoon. Inlets (TI) were maintained by tides, but flood- and ebb-tidal deltas were much reduced in size or were absent.

ABANDONMENT

The author speculates that the rate of progradation of the barrier sandstone slowed, then ceased, and the shoreline began to subside. Figure 56 depicts the study area at the approximate time that shoreline submergence and marine transgression started following barrier abandonment. At that time the shoreline was nearly straight. The shoreline was located nearly 3 mi east of where the deposition of barrier bar G began, and few vestiges of barrier-lagoon physiography remained. The barrier was reduced to a sandy beach with remnants of a dune field behind it. The shoreline continued to be washed by tides, and salt marshes (SW) were present in small areas inland from tidal inlets (TI). Almost all the former lagoonal area inland from the dune fields (DU) was occupied by freshwater peat swamps (PS), which subsequently formed a blanket coal deposit (the upper part of the Pintail coal bed). Surf (SU), middle shoreface (MSF), and lower shoreface (LSF) sand facies were present but were much attenuated seaward of the forebeach (FB); marine mud (MS) deposition continued unabated offshore.

MARINE TRANSGRESSION

Barrier bar G was partly destroyed by marine erosion that accompanied minor transgression of the epeiric sea, probably only a few miles westward across the top of the abandoned barrier system. A minor marine transgression is suggested by the fact that only a thin interval of marine shale separates barrier bar G from the overlying superposed barrier bar F. The record of the marine transgression is obscure, but the shorelines at that time consisted of tidal channels and salt marshes; no transgressive beach sandstones have been identified.

As the coastline submerged, the freshwater peat swamps (PS) overlying barrier bar G were first replaced by brackish-water salt marshes and then by a large open-water lagoon (LA) behind a new barrier complex. The evidence for this interpretation is based on the presence of tidal channels (TC), oyster beds (ORM), and carbonaceous shale (SW) that rest directly upon the Pintail coal bed, and by the fact that all these lithologies are in turn overlain by gray, bay-fill (BF) mudstone or shale (plate 1).

The erosion that accompanied the marine transgression obliterated nearly all the topographic expression of barrier bar G. Some of the irregular thinning of the Pintail coal bed in sections 10 to 32 (plate 1) probably resulted from this erosion. The erosion surface is not readily apparent in outcrops of barrier bar G, but similar marine erosion is visible where it has removed large segments of barrier bar D in the study area in the W½ sec. 22, T. 16 N., R. 102 W. (Roehler, 1979c). Channellike depressions in barrier bar D that are filled with marine shale are as much as 30 ft deep.

The oyster marker bed (ORM) that immediately overlies tidal channel sandstones in sections 11, 21, 22, and 31 (plate 1) originated by the draping of oyster beds across a small delta system where salt and fresh waters mixed, as depicted in figure 57.

PALEOECOLOGY

The peat beds from which the Pintail coal bed formed are of lagoonal origin and were deposited under freshwater conditions. Peat deposition under saltwater or brackish-water conditions did not take place for the following reasons: (1) the water salinity restricted the growth of many types of plants; (2) the oxidation of alkaline substrates; and (3) the extensive degradation of organic matter by micro-organisms. This implies that most of the peat accumulated during the late stages of barrier-lagoon development when the lagoon had largely filled in and had become a large freshwater swamp.

CLASSIFICATION OF PLANT HABITATS

Marshes, swamps and bogs have been classified under the general term "wetlands" by the U.S. Fish and Wildlife Service (Cowardin and others, 1979) and the U.S. Army Corps of Engineers Institute for Water Resources (Reppert and others, 1979). The wetland classification explains the distinguishing characteristics of basic wet environments, such as marine, estuarine, riverine, lacustrine, and palustrine, and it works well in modern-day ecosystems, where sediments and living organisms can be observed in three dimensions. The classification system is difficult to use by geologists studying ancient rocks and fossils in two dimensions along outcrops that divide the eroded and covered parts of formations. For this reason, a more geologically oriented classification system of "forest swamp" and "reed swamp", which was applied by Stach and others (1982), is used in this paper. The terms "forest swamp" and "reed swamp" correspond to tree swamp and salt marsh, respectively.

The forest swamp habitat consisted of freshwater, poorly drained swamps and bogs dominated by profuse, thick-stalked, woody vegetation that included trees and shrubs and produced extensive peat accumulations. The characteristic resulting lithology was coal. The reed swamp habitat consisted of brackish-water vegetation that was intermittently or permanently water-covered, and that was dominated by sparse, herbaceous, thin-stalked, grasslike, salt-tolerant vegetation, and no appreciable peat accumulations. The characteristic resulting lithology was carbonaceous shale.

The forest swamp and reed swamp habitats envisioned by the author for barrier bar G and its lagoon are illustrated diagrammatically in figure 58. The surface of the barrier was the site of peat accumulations in a forest swamp habitat under freshwater conditions. The lower, buried parts of the barrier sandstone were probably saturated by salt water, as are modern barrier islands along the coast of South Carolina and Georgia, but the upper parts contained freshwater. The interface of freshwater and saltwater within the sandstone was maintained by the density differences of the two waters and by the continuous recharge of freshwater of meteoric origin. The lagoon behind the barrier had areas of both forest swamp and reed swamp habitats. Areas adjacent to tidal inlets and tidal creeks were occupied by brackish-water vegetation as a result of the influx of seawater during periods of high tides. Between areas of tidal influence were islands and platforms of freshwater occupied by forest swamp vegetation.

EVIDENCE OF REED SWAMP AND FOREST SWAMP HABITATS

Fossil-wood (limb and trunk) fragments characteristic of the forest swamp habitat are present at a number of places along the outcrops of the Pintail coal bed, usually in the upper 1–2 ft of the bed (fig. 59). Most of the wood has been identified as coniferous, possibly pinaceous, and shows little evidence of growth rings (R. A. Scott, oral commun., 1979). The lack of growth rings probably indicates that the Late Cretaceous climate at the time of the coal formation was warm and wet and had little seasonal variation. The carbonaceous shale splits and partings in the Pintail coal bed generally do not contain fossil wood, but they do contain abundant impressions of unidentified aquatic, herbaceous, ribbonlike plants that characterize the reed swamp habitat.

Palynomorphs in the Pintail coal bed and in carbonaceous shale associated with the coal bed are presently

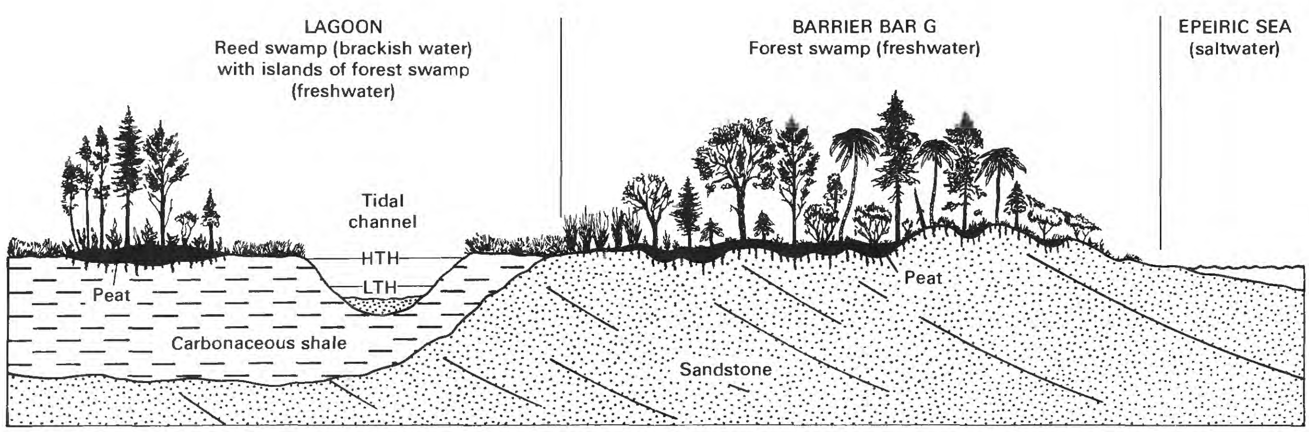


FIGURE 58.—Cross section showing hypothetical forest swamp and reed swamp habitats envisioned for barrier bar G and its lagoon. LTH, low tide height; HTH, high tide height. Not to scale

FIGURE 59.—Fossil tree stump at the top of the Pintail coal bed at locality I in SW¼NW¼ sec. 17, T. 15 N., R. 102 W. The stump has crumbled into blocks below the jackknife (0.3 ft long).

being studied by Farley Fleming at the University of Colorado. Preliminary results of his investigations indicate that the relative abundance of certain categories of palynomorphs varies widely in the coal and shale samples. The percentages of palynomorphs in six categories are shown in figure 60 (Farley Fleming, written commun., 1981). Although the data will require substantiation by the study of many more coal and shale samples, the coal assemblage appears to be composed largely of angiosperm pollen, whereas the carbonaceous shale assemblage is composed largely of spores and algal cysts. The differing distribution of these categories indicates that there is a direct relationship between the palynomorphs and the lithology, which suggests the existence of distinct habitats. Some of the most common palynomorphs identified by Fleming are illustrated in figure 61.

The Pintail coal bed was sampled for maceral analysis at locality D (fig. 24). The bed at locality D consists of a lower coal bench, 2.2 ft thick, a middle carbonaceous shale parting, 3.1 ft thick, and an upper coal bench, 3.2 ft thick. Significant maceral matter was obtained from both coal benches, but the carbonaceous shale parting is brown and oxidized and contains very little relict carbonaceous material that could be observed microscopically in maceral terms. The macerals from the upper and lower coal benches, figures 62 and 63, were identified by R. W. Stanton (written commun., 1981). Stanton concluded that the coal benches contain significant amounts of macerals derived from woody material, whereas the carbonaceous shale visually contained negligible woody material (less than 1 percent). The woody material was mostly derived from large trees, a fact that suggests it originated in a forest swamp habitat. The only significant difference in the maceral

SAMPLE LITHOLOGY AND LOCALITY		PALYNOMORPH CATEGORY, IN PERCENT					
		Monolete spores	Trilete spores	Algal cysts ?	*Schizosporis parvus*	Gymnosperm pollen	Angiosperm pollen
Pintail coal bed	Loc. D (fig. 24)	18	15	7	0	14	46
	Loc. E (fig. 28)	12	28	5	1	16	38
	Loc. I (fig. 42)	17	17	2	0	17	47
Carbonaceous shale parting	Loc. D (fig. 24)	23	20	28	10	16	3

FIGURE 60.—Percentages of six palynomorph categories in the Pintail coal bed and in a carbonaceous shale parting in the coal (Farley Fleming, written commun., 1981).

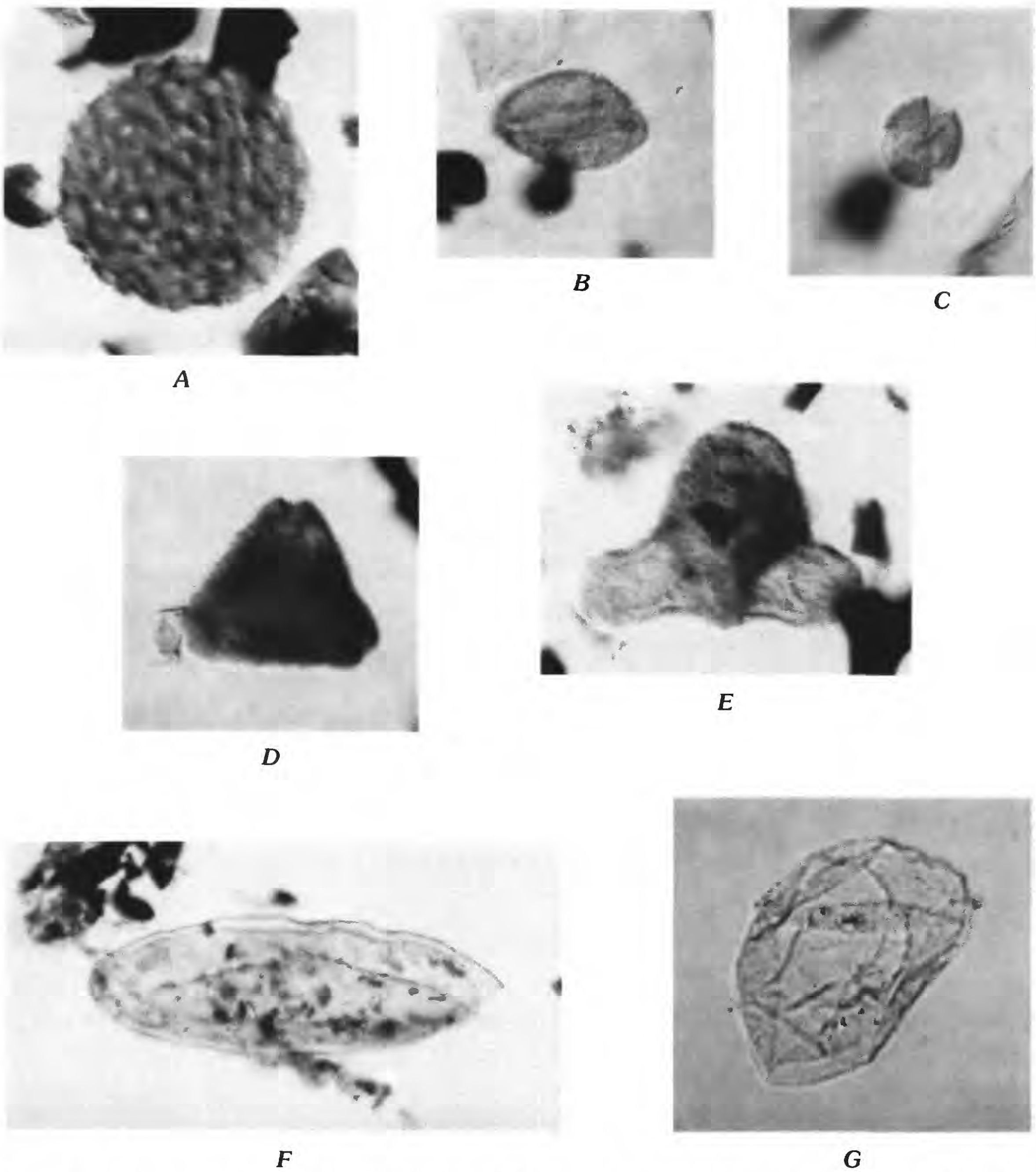


FIGURE 61.—Palynomorphs from the Pintail coal bed at locality E (*A, B, C, D, E*) and from a carbonaceous shale parting in the coal at locality E (*E, G*). *A, Erdtmanipollis pachysandroides*; *B, Liliacidites* sp.; *C, Tricolpites* sp.; *D, Proteacidites* cf, *P. thalmanni*; *E, Aquilapollenites quadrilobus*; *F, Schizosporis parvus*; *G*, Algal cyst? × 1,000.

composition of the two coal benches is that the coal in the upper bench shows a greater degree of diagenetic degradation and evidence of more oxidation (higher inertinite content).

The most revealing evidence for the presence of reed swamp (noncoal-forming) swamp and forest swamp (coal-forming) habitats is the thickness and location of carbonaceous shale splits and partings in the Pintail coal bed. As mentioned previously, the peat in the lower half of the coal bed accumulated during the stages of maturity and old age in lenses on freshwater islands and platforms that formed in the lagoon on and between areas of brackish water where carbonaceous mud was deposited (figs. 54 and 55). The splits and partings in

		Pintail coal bed	
		Lower Bench (2.2 ft)	Upper Bench (3.2 ft)
	Telecollinite	83	71
	Gelocollinite	1	2
	Corpocollinite	1	5
	Telinite	Trace	Trace
Total	Vitrinite	85	78
	Sporinite	1	1
	Resinite	2	1
	Cutinite	Not detected	Trace
Total	Exinite	3	2
	Inertodetrinite	3	9
	Fusinite	1	1
	Semifusinite	8	10
	Macrinite	Trace	Not detected
Total	Inertinite	12	20

FIGURE 62.—Maceral analyses (in percent) of samples of the Pintail coal bed at locality D. For location of sampled intervals see figure 25.

the lower half of the coal bed are thus directly related to water salinity and indirectly to the geographic positions of tidal creeks and tidal inlets. During the abandonment stage (fig. 56), freshwater peat nearly blanketed the lagoon and back-barrier flat as a feature of a discrete forest swamp, and these beds formed the laterally persistent, massive bench of coal that is present in the upper half of the Pintail bed.

The thick carbonaceous shale split in the Pintail coal bed in measured sections 19–34 (plate 1), adjacent to locality E in the west-central part of T. 16 N., R. 102 W., exemplifies the reed swamp-forest swamp habitats. Figure 64 is a block diagram of the area that interprets the location of the habitats from an elevated, oblique angle looking east across locality E during the stage of old age (compare with fig. 55). In figure 64 note that reed swamp habitats occupied low topographic areas in juxtaposition to tidal creeks and tidal inlets. The substrate in these areas was composed of the remains of brackish-water, herbaceous plants that were deposited as carbonaceous mud (SW). At slightly higher topographic elevations, possibly as little as 3–6 ft, were islands and platforms of freshwater-woody vegetation representing the forest swamp habitat (PS). The substrate there was primarily peat, the precursor of the Pintail coal bed.

HOLOCENE ANALOG

The coal-forming depositional environment of the Pintail coal bed is somewhat analogous to Quaternary peat accumulations in the Snuggedy Swamp in South Carolina. Snuggedy Swamp was investigated by Staub and Cohen (1977), who believed that it began as a lagoon composed of salt marshes and open-water bays behind a Pleistocene barrier island. In time, freshwater vegetation encroached upon the salt marshes and formed islands of peat in areas between tidal creeks. The peat islands eventually enlarged and coalesced to form a blanket of peat that covered most of the swamp and lapped onto the barrier island. The freshwater-peat deposits in Snuggedy Swamp are as much as 15 ft thick. The salt marsh deposits in the swamp are mainly clays, silts, and sands, but with a few thin (less than 12 in thick) discontinuous peats of probable brackish-water origin.

The Snuggedy Swamp is dissimilar to the Pintail coal bed in several important ways. The swamp is located several miles inland from active barrier-lagoon sedimentation. The quality of the peat deposited in Snuggedy Swamp is only low enough in ash within the central parts of the swamp to yield a medium-high ash coal following the effects of coalification. Some of the thickest peat deposits occupy former inlets of the Pleistocene barrier island.

COAL COMPOSITION AND RANK

PROXIMATE ANALYSES OF CORE SAMPLES

Analyses of core samples from holes drilled in the study area in 1982 by the U.S. Department of Energy, Laramie Energy Technical Center, indicate that the Pintail coal bed is High Volatile C Bituminous in rank and has heating values that range between 11,780 and 12,240 Btu/lb on a moist, mineral-matter-free basin as determined by the Parr Formula (ASTM Standard D–388–77).

As received, proximate analyses of core samples from the Pintail coal bed are shown in figure 65. The U.S. Department of Energy MSR–10C hole was drilled in the NE¼SE¼ sec. 28, T. 16 N., R. 102 W. The Pintail coal bed was cored at depths between 163 and 179 ft. The hole is situated near measured section 43 (plate 1). Core hole MSR–14C was drilled in the SE¼SE¼ sec. 8, T. 15 N., R. 102 W. and cored the Pintail coal bed at depths between 351 and 372 ft. The hole is located near measured section 61 (plate 1). As shown, the analyses of the coal from the two holes are remarkably similar, although they are 2½ miles apart.

ULTIMATE ANALYSES OF CORE SAMPLES

Ultimate analyses of coal samples from U.S. Department of Energy core holes and from outcrops in the area studied indicate that the Pintail coal bed consistently

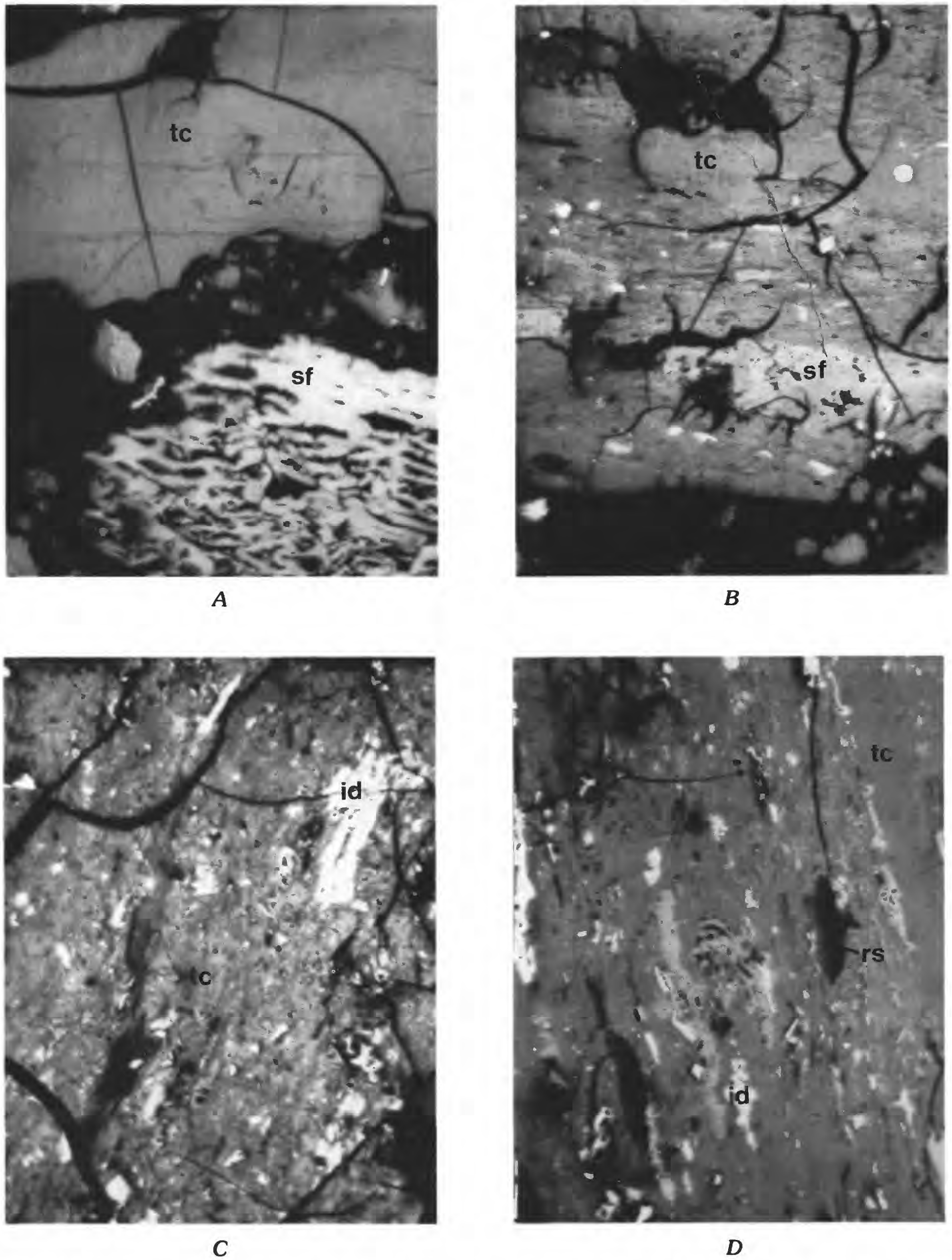


FIGURE 63.—Coal macerals in the Pintail coal bed (lower bench, *A*, *B*; upper bench, *C*, *D*) at locality D. tc, telecollinite; rs, resinite; id, inerto-detrinite; sf, semifusinite. For location of sampled intervals see figure 25. × 350.

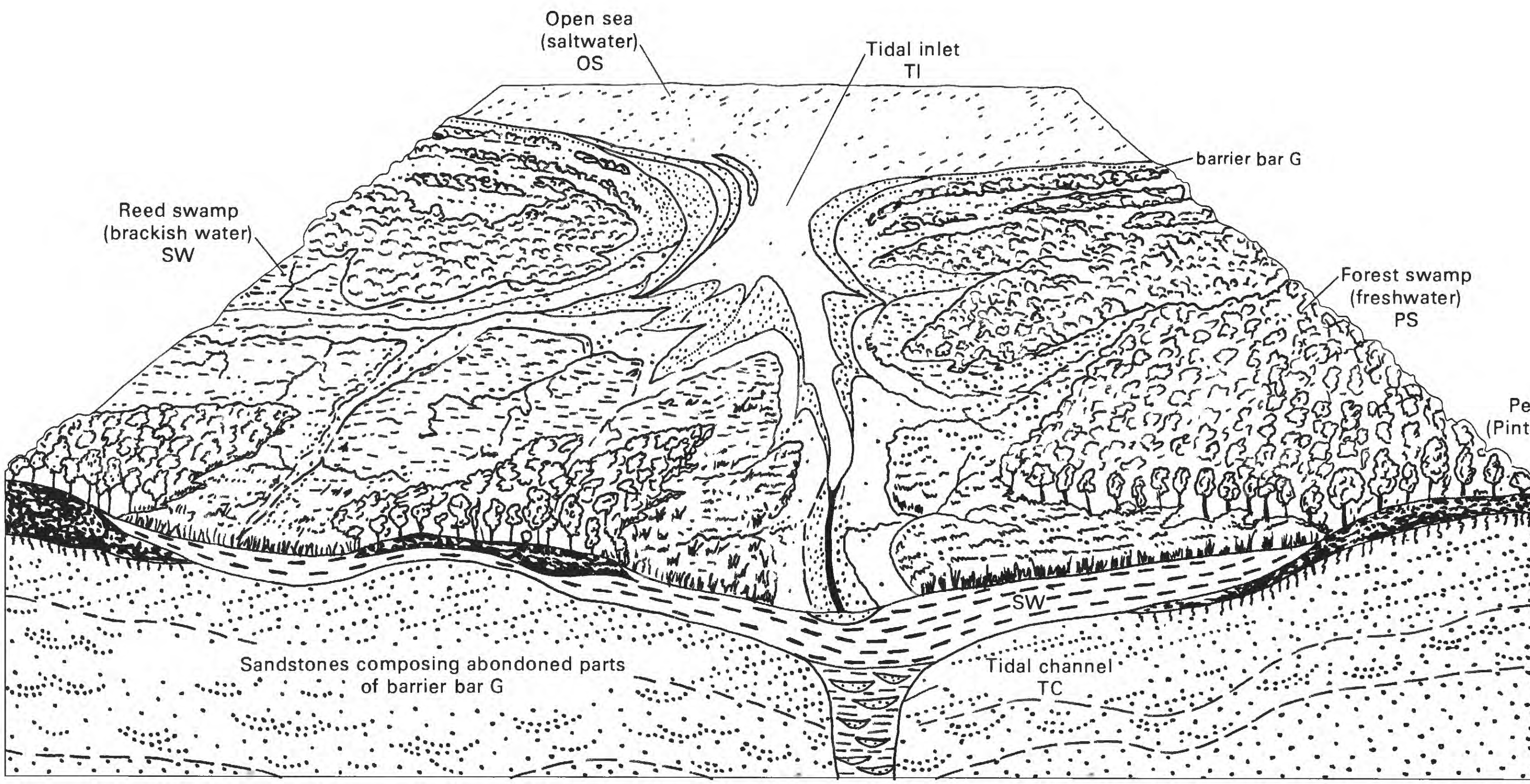


FIGURE 64.—Diagrammatic reconstruction of part of barrier bar G showing the location of reed swamp and forest swamp habitats. The block diagram is an oblique aerial view from sec. 18, T. 16 N., R. 102 W. eastward toward the tidal inlet located in sec. 13, T. 16 N., R. 102 W. The tidal channel in the center-foreground is at locality E (see plate 1).

PROXIMATE ANALYSIS (PERCENT)	U.S. Department of Energy hole: MSR-10C; NE¼ sec. 28, T. 16 N., R. 102 W.	MSR-14C; SE¼ sec. 8, T. 15 N., R. 102 W.
Moisture	13.0	10.9
Ash	4.9	6.4
Volatile matter	31.9	31.4
Fixed carbon	50.2	51.3
Heating value (Btu/1b)	11,140.0	11,380.0

FIGURE 65.—Proximate analyses, in percent (as-received), of core samples of the Pintail coal bed from core holes MSR-10C and MSR-14C. Data from McClurg and others (1983).

contains less than 1 percent sulfur. These analyses, in figure 66, reveal that hydrogen ranges between 5 and 6 percent and nitrogen between 0.8 and 1.1 percent. The amount of carbon is variable and appears to reflect changes in coal composition that take place between fresh, unweathered coal samples and weathered coal. The analyses of outcrop samples show a decrease of carbon by nearly 50 percent and an increase of oxygen by nearly 50 percent, when they are compared with the analyses of the core samples (fig. 66).

WEATHERING OF OUTCROP COAL SAMPLES

The amount of surface weathering of coal beds in the Rock Springs coal field was studied by Schultz (1910). Schultz collected samples from several mines at various distances from entry ways and then calculated the amount of overburden at the sample sites. His work indicates that the heating value of the coal was reduced by at least 35 percent by the affects of weathering along outcrops.

The upper and lower benches of the Pintail coal bed and its carbonaceous shale split were sampled in a trench that was dug in outcrops at locality D in NE¼ sec. 10, T. 16 N., R. 102 W. The three samples were submitted to Geochemical Testing, Somerset, Pa., for proximate analysis. Surface weathering makes the analytical results unreliable, but they are nevertheless listed in figure 67. The analyses indicate that the coal has very low heating value (4,427 and 5,519 Btu/lb). Using the Parr formula, the lower coal bench on a moist, mineral-matter-free basis has a heating value of 6,440 Btu/lb and is classified lignite A; the upper bench has a heating value of 4,880 Btu/lb and is classified lignite B.

If the heating values of the outcrop channel samples of the Pintail coal bed are increased by 35 percent, the resulting values are 8,900 Btu/lb (subbituminous C) for the lower bench and 6,600 Btu/lb (lignite A) for the upper bench. These values suggest possibly higher ranks for the two coal benches than is indicated by the analyses of the outcrop samples, but the values are still considerably lower than the bituminous C rank indicated by the core samples taken in the test holes drilled by the U.S. Department of Energy.

VITRINITE REFLECTANCE

The average vitrinite reflectance (Ro) of several coal samples from the upper and lower coal benches of the Pintail coal bed at locality D (fig. 25) was 0.42 (R. W. Stanton, written commun., 1981). This amount of reflectance places the Pintail coal bed in a subbituminous rank, probably subbituminous B, on a scale of maturation that was published by Dow (1978). The data, however, are from samples of near-surface, weathered coal, and they too may not be reliable.

ULTIMATE ANALYSIS (PERCENT)	U.S. Department of Energy hole: Corehole MSR-10C; NE¼ SE¼ sec. 28, T. 16 N., R. 102 W.	Corehole MSR-14C; SE¼ SE¼ sec. 8, T. 15 N., R. 102 W.	Outcrop channel samples locality D; NE ¼ sec.10, T.16 N., R. 102 W.: Lower coal bench	Carbonaceous shale split	Upper coal bench
Ash	4.90	6.40	5.92	1.72	5.89
Hydrogen	5.64	5.66	29.92	2.74	37.43
Carbon	64.00	64.67	1.04	0.11	1.06
Nitrogen	0.91	0.75	0.36	0.04	0.38
Oxygen	23.61	21.60	49.44	12.41	46.41
Sulfur			13.32	82.98	8.83

FIGURE 66.—Ultimate analyses, in percent (as received), of core samples of the Pintail coal bed from core holes MSR-10C and MSR-14C and from outcrops at locality D.

PROXIMATE ANALYSIS (PERCENT)	Locality D; NE ¼ sec. 10, T. 16 N., R. 102 W.		
	Lower coal bench	Carbonaceous shale split	Upper coal bench
Moisture	39.62	10.93	35.24
Ash	13.32	82.98	8.83
Volatile matter	24.93	6.05	27.90
Fixed carbon	22.13	0.04	28.03
Heating value	5,519.00	298.00	4,427.00

FIGURE 67.—Proximate analyses, in percent (as-received), of weathered outcrop channel samples of the Pintail coal bed and its carbonaceous shale split at locality D. The sampled intervals are indicated in figure 25.

TRACE ELEMENT ANALYSES

Outcrop samples of the Pintail coal bed at locality D were analyzed for major, minor, and trace element content by emmission spectrographic analysis (J.L. Harris and others, written commun., 1983). The data are listed in figure 68, where they are compared to average abundance of elements in coal of all ranks in the United States (Swanson and others, 1976).

COAL DEVELOPMENT POTENTIAL

GRAPHIC SECTIONS AND DESCRIPTION OF COAL OUTCROPS

The Pintail coal bed is fairly well exposed in the study area but it usually has sparse, thin vegetation, such as sage and grass, and a few inches of soil and rock veneer covering it. The coal interval weathers drab gray and is commonly seen in outcrop as a dark-gray, poorly vegetated band within lighter drab-gray and drab-brown, more vegetated slopes. In only a few places is bare coal visible. Where the line of coal outcrops crosses large drainages, such as Salt Wells Creek, the coal may be covered by thick intervals of Quaternary alluvium. The bed most commonly crops out near the base of slopes formed by the weathering of thick, soft shale and thin sandstone that are present between more resistant, topographically higher ridges formed by thick barrier sandstones. The angles of the surface slopes seldom exceed 35°. In only a few places is the coal exposed along the banks or near the bottom of minor drainages or dry washes. Large vegetation, such as the juniper trees common to the region, never grow directly upon the coal.

The Pintail coal bed is generally clean and bright in trenches or channels that are dug along outcrops. Within the study area, the bed thickens and thins, splits, and is burned locally, as indicated on plate 1. The coal is massive (5 ft or more thick) in sections 18, 56–57, 69, 71, 73, 75–80, and 100 (plate 1). It thins to less than 1.3 ft in sections 24–30. Splits in the coal range in thickness from less than 0.2 ft to more than 12 ft and are usually composed of carbonaceous shale. The coal is partly or totally burned in sections 31 and 54 (plate 1), where it weathers dull red and consists of clinkers or black, powdery ash. The coal has primary and secondary sets of nearly vertical cleats that trend in N. 65 E. and N. 20 W.

The rocks that directly overlie the Pintail coal bed are mostly soft, gray or brown carbonaceous shale. The carbonaceous shale in places changes laterally to firmly cemented gray and tan, fine- to medium-grained sandstone, and gray siltstone that may contain fragments of oysters and other mollusk shells. The sandstone and siltstone rarely show evidence at their bases of scouring and removal of the upper part of the underlying coal bed.

The coal bed either rests directly upon the sandstones composing barrier bar G, or is underlain by gray or brown carbonaceous shale. No underclays were identified anywhere in the study area. When the coal rests upon the barrier sandstone, the upper 1–2 ft of the sandstone commonly contains small root casts and molds and is discolored brown to nearly black. The discoloration was caused by humic acids that were present in the Pintail peat beds that migrated downward during coalification into the underlying seat rock composed of highly porous and permeable-barrier sand.

AREAL DISTRIBUTION OF THE COAL AS A RESULT OF THE DEPOSITIONAL ENVIRONMENT

The Pintail coal bed was deposited entirely within the lagoon that formed landward of and lapped seaward onto barrier bar G. The areal distribution of the coal is illustrated by an isopach map that shows net coal thicknesses, excluding splits and partings (fig. 69). The isopach map was prepared from coal measurements along outcrops, from geophysical logs of drill holes, and from interpretations of the geographic distribution of forest swamp (coal-forming) and reed swamp (noncoal-forming) habitats within the lagoon.

A major north-south trend of coal thickening is readily apparent on the isopach map. This trend conforms to the direction of the trend of the shoreline of the Late Cretaceous epeiric sea across the study area, to the direction of facies strike of barrier bar G, and to the

Element	Outcrop samples from locality D: Lower coal bench	Carbonaceous shale split	Upper coal bench	Average for coal in the United States (Swanson and others, 1976)
		Percent		
Si	3.0	33.0	2.8	2.6
Al	2.7	6.5	0.77	1.4
Fe	1.4	1.1	0.48	1.6
Mg	0.027	0.51	0.13	0.12
Ca	0.32	0.055	1.1	0.54
Na	0.012	0.12	0.002	0.06
K	0.059	1.8	0.038	0.18
Ti	0.035	0.37	0.05	0.08
		Parts per million		
As	3.8	6.2	0.4	15.0
B	15.0	50.0	8.5	50.0
Ba	410.0	330.0	120.0	150.0
Cd	0.2	0.09L	0.01L	1.3
Ce	37.0	85L	11L	---
Co	21.0	2.8	3.0	7.0
Cr	9.7	72.0	6.7	15.0
Cu	6.8	35.0	9.4	19.0
Ga	5.4	7.9	7.0	19.0
Hg	0.17	0.13	0.07	0.18
Li	3.0	19.0	3.6	20.0
Mn	13.0	36.0	11.0	100.0
Mo	5.1	1.8L	0.4	3.0
Nb	2.5	11.0	1.2	3.0
Ni	52.0	7.8	4.6	15.0
Pb	5.1	13.0	1.9	16.0
Sb	3.0	7.0	0.1	1.1
Sc	6.8	8.4	1.5	3.0
Se	1.42	---	---	4.1
Sr	570.0	130.0	330.0	100.0
Th	1.4	10.0	1.2	4.7
U	2.5	4.4	0.7	1.8
V	17.0	81.0	5.7	20.0
Y	32.0	19.0	6.2	10.0
Yb	1.9	1.3	0.3	1.0
Zn	34.0	22.0	3.1	39.0
Zr	32.0	100.0	17.0	30.0

FIGURE 68.—Average amounts of major, minor, and trace elements in the Pintail coal bed as compared with an average for coal of all ranks in the United States. Leaders (---) indicate no data; L indicates less than value shown.

configuration of the seaward parts of the lagoon landward of the barrier.

An eastward trend of thinning from the line of outcrops of barrier bar G to the zero isopach line for the coal is also indicated in figure 69. This trend is the result of thinning of the Pintail peat beds in a seaward direction across the back-barrier flats. The zero isopach line marks the location of the wedge-out of the peat beds behind the shorelines of the barrier at the time that the barrier was abandoned (compare figs. 56 and 69).

Several narrow trends of east-west coal thinning cross the major north-south trend of coal thickening. The locations of these trends coincide with the locations of tidal inlets and tidal channels. Saltwater tides entered the lagoon through these inlets and channels and introduced noncoal-forming, reed swamp habitats in which carbonaceous muds were deposited. The carbonaceous muds rested upon or laterally replaced intervals of peat that were forming in forest swamp habitats, and in this way carbonaceous shale splits and partings were introduced into the coal bed. The net thickness of the coal is thinner where the splits and partings are present. An example of a coal thinning at a tidal inlet and tidal channel is present in sec. 14 and 15, T. 16 N., R. 102 W. (fig. 69). In that area the coal consists of thin upper and lower benches that are separated by a thick carbonaceous shale split. The split is lenticular along outcrops and is visible between measured sections 18 and 35 on plates 1*A* and 1*B* (see also fig. 64).

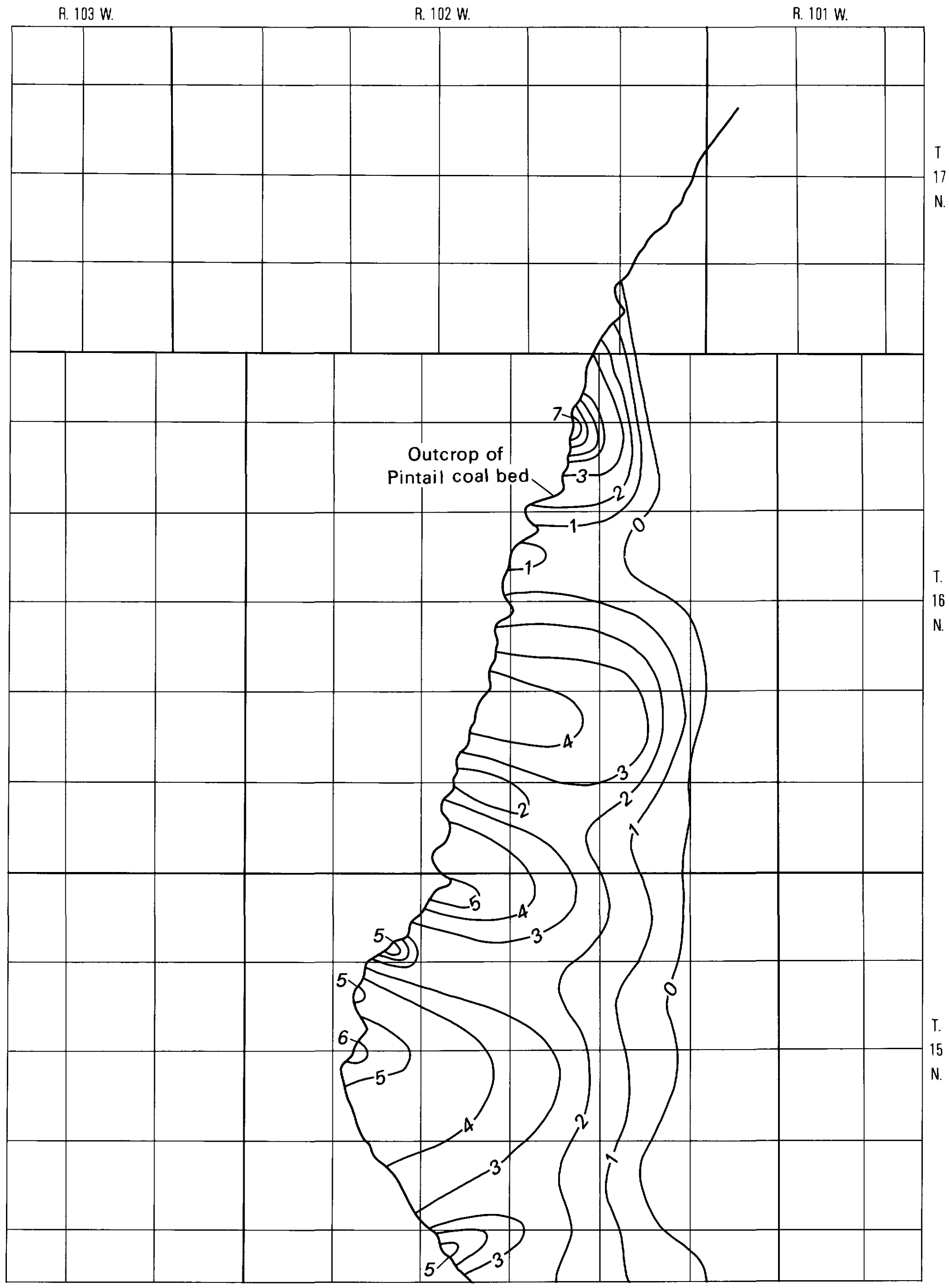


FIGURE 69.—Generalized isopachous map of the Pintail coal bed showing coal thickness in feet, excluding splits and partings. Isopach interval is 1 ft.

The irregular thickening and thinning of the Pintail coal bed in outcrops from sec. 5, T. 15 N., R. 102 W. southward to sec. 28, T. 15 N., R. 102 W. (fig. 69) probably is caused partly by in-filling by peat in channels and in swales that formed across the flood-tidal delta sandstone depicted in figure 54, and partly by later decomposition of the upper part of the peat bed as a result of seawater entering the lagoon through a nearby tidal inlet. Some coal thinning along outcrops in the study area can be attributed to the erosion that was associated with the marine transgression that took place after the barrier system was abandoned (fig. 57) and to the consequent biogenic degradation of the peat beds in those places by saltwater and brackish-water organisms living in the overlying lagoon (note the position of the brackish-water oyster bed (ORM) in sections 10 to 35, on plate 1).

ESTIMATED COAL RESOURCES

The amount of coal in place in the Pintail coal bed in the study area is estimated to be about 77 million short tons. About 30 percent of these resources are located where the bed is more than 2.5 ft thick, and where it is considered minable.

Measured and indicated coal resources for the Pintail coal bed, and for other coal beds in the Almond Formation, in the study area, are listed in Roehler (1979b; 1979c). These resource estimates were derived mostly from outcrop data. Isopach maps of individual coal beds are shown, and the resources are listed by section and township for intervals of coal thickness and overburden. More accurate resources for the Pintail coal bed cannot be computed without additional exploratory drilling and coring to determine the rank and thickness of the coal in areas downdip of outcrops.

MINING METHODS AND PROBLEMS

The Pintail coal bed dips from 5° to 8° eastward in a desert terrain of ridges and valleys; the thickness of the overburden increases rapidly downdip, and the amount of recoverable coal is small. These facts generally preclude surface mining methods, because of the large initial capital investments required for these types of mines, and because of the high costs of overburden removal and site reclamation. The underground mining method that appears most acceptable is a drift mine with a mine opening directly into the coal bed, where the coal can be transported to the surface by track haulage or conveyor. Room and pillar, longwall, or shortwall mining methods could be used, but because of the high mining costs in relation to the amount of recoverable coal, the room and pillar method is probably the best method. One favorable area for mining the coal is downdip of outcrops between measured sections 65 and 97 (fig. 2 and plate 1) in secs. 8, 17, and 20, T. 15 N., R. 102 W. The coal in this area is generally more than 4 ft thick and has no partings. The recoverable coal probably is less than 10 million short tons, but several other minable coal beds situated above and below the Pintail coal bed in the same area (Roehler, 1979c) substantially increase the amount of coal that could be recovered from a single mine having several levels.

Roof conditions have been studied and evaluated by Petranoff and others (1980) in the Stansbury mine in the northern part of the Rock Springs coal field. The rocks overlying the Pintail coal bed closely resemble those investigated in the Stansbury mine, and the roof conditions are expected to be similar. The roof rock of the Pintail coal bed across the northern part of the study area, in outcrops in T. 16–17 N., R. 102 W., is composed of limy, hard, fine-grained sandstone containing oyster shell fragments, or firmly cemented, fine- to medium-grained sandstone in broad, lenticular beds. The roof conditions in this area are rated excellent, based on the studies in the Stansbury Mine. In the southern part of the study area, in outcrops in T. 15 N., R. 102 W., the roof rock is composed of 1–5 ft of carbonaceous shale, which is overlain by 3–6 ft of mudstone. The roof conditions here are rated only good to fair. Areas of poor roof conditions susceptible to roof falls have been identified in a few places along the outcrops of the coal. For instance, if conventional rock bolts are used as roof supports, unsafe conditions apear to be present between measured sections 83 and 94 in secs. 17 and 20, T. 15 N., R. 102 W. In that area the Pintail coal bed is overlain by incompetent soft, rooted, carbonaceous shale and coal in which roof bolts could not be anchored securely.

A more serious problem in underground mining will be possible water flooding because of the proximity of sandstone aquifiers. Barrier bar G and its lateral sandstone equivalents are porous and permeable and underlie the coal nearly everywhere. The confined water in these sandstones is constantly recharged by meteoric water along outcrops. If the aquifiers were penetrated during normal underground mining operations, increased hydrostatic pressures downdip of outcrops could cause mine flooding that would result in property damage and financial loss. The thickest aquifer in the study area is the Ericson Sandstone that underlies the Pintail coal bed at intervals ranging from 400 to 550 ft. The Ericson Sandstone is nearly 1,000 ft thick and is a well known artesian system locally. It provides the freshwater used at the Black Butte coal mine, located 12 mi northeast of the study area.

CONCLUSIONS

Paleogeographic, paleontologic, and sedimentologic studies of the Pintail coal bed and barrier bar G reveal that the plant debris that formed the coal and the barrier sands were deposited at the head of a marine embayment located along the western shores of the Late Cretaceous epeiric sea. The investigations further reveal that the quartzose sandstones composing the barrier coarsen upward and landward, but are dominantly fine grained; that the barrier sandstones prograded along a mesotidal coastline; that associated coal is of lagoonal origin; and that the lagoon had forest swamp and reed swamp habitats. The morphologic characteristics of the barrier and its lagoon are identified by their sedimentary structures and lithofacies.

The geological data acquired in the investigation permit the construction of a model for a barrier-lagoon, coal-forming environment based on the depositional history. The model is illustrated by cross sections in figure 70 that show stages of youth, maturity, old age, abandonment, and marine transgression. The earliest record of barrier-coal deposition, during the stage of youth (timeline A), was marked by the appearance of a narrow, open, saltwater estuary or bay (LA) behind barren sandbanks that emerged from the sea floor 1–2 mi off the Late Cretaceous shoreline. The sandbanks rapidly enlarged to form a chain of barrier islands by the accretion of sediments swept southward by longshore currents. A brackish-water lagoon (LA) subsequently evolved between barrier islands (BB) to the east and a freshwater-coastal plain (CS) to the west. Sparse saltwater and brackish-water vegetation spread across the shores of the lagoon, but the mud substrate was alkaline and aerobic and therefore not conducive to the formation and preservation of peat. The barrier shorelines began to prograde during the stage of maturity (timeline B), and the lagoon (LA) behind the barrier began to expand in landward and seaward directions. The expansion seaward was across the back-barrier flat, and this was accompanied by the weathering and erosion (LU) of the upper, older parts of underlying barrier sands. The saltwater-saturated sands in the older, eroded parts of the back-barrier flat were soon flushed by freshwater of meteoric origin, and dense concentrations of shrubs and trees entered this sand platform to form peat swamps (PS). Similar vegetation and peat swamps encroached upon shallow, freshwater, landward parts of the lagoon. The lagoon continued to expand in landward and seaward directions during the stage of old age (timeline C). Large rivers entered the lagoon from the coastal plain to the west, and this freshwater incursion, accompanied by sediment in-filling of the lagoon, introduced forest swamps and peat deposition in scattered patches across the lagoon. Platforms and islands of peat (PS) formed in this manner, and these were interspersed with and rested upon nonpeat-forming, brackish-water reed swamps and bay-fill muds (BF). Sedimentation slowed and then ceased during the abandonment stage (timeline D), and the barrier was reduced to a narrow, straight, sandy, coastal beach with remnants of a dune field behind it. The lagoon filled in and almost disappeared; it was replaced by extensive freshwater forest swamps and blanket-like peat deposits (PS). Following the barrier-lagoon abandonment the coastline submerged as a result of subsidence and marine transgression. Erosion (MU) accompanied the marine transgression and obliterated nearly all the surface expression of the barrier and removed parts of adjacent peat beds.

The thickness and geometry of the Pintail coal bed are directly related to the lagoonal environment in which it was deposited. The thickest parts of the coal bed trend north-south, in the direction of the facies strikes of the barrier shoreline and the seaward edge of the lagoon. An overall trend of eastward coal thinning and wedge-out is present in the study area along the north-south trend of thickening, where the peat beds lapped eastward from the lagoon onto the back-barrier flat and wedged out near the barrier shoreline. Several minor trends of east-west thinning cross the north-south trend of thickening at nearly right angles, and the trends of thinning coincided with the locations of tidal inlets, tidal channels, and flood-tidal deltas. Petrographic and palynological studies indicate that peat was deposited only in areas of freshwater where forest swamps developed; reed swamps developed and carbonaceous mud was deposited in areas of saltwater or brackish-water influence near tidal inlets, tidal channels, and flood-tidal deltas. The carbonaceous mud that was deposited in the tidal areas (where the coal thins) forms carbonaceous shale splits and partings that are widespread in the lower half of the Pintail coal bed. The splits and partings in the lower part of the bed that change to a massive, laterally persistent bench of coal at the top of the bed are the fundamental identifying characteristics of the coal deposited in the barrier-lagoon environment.

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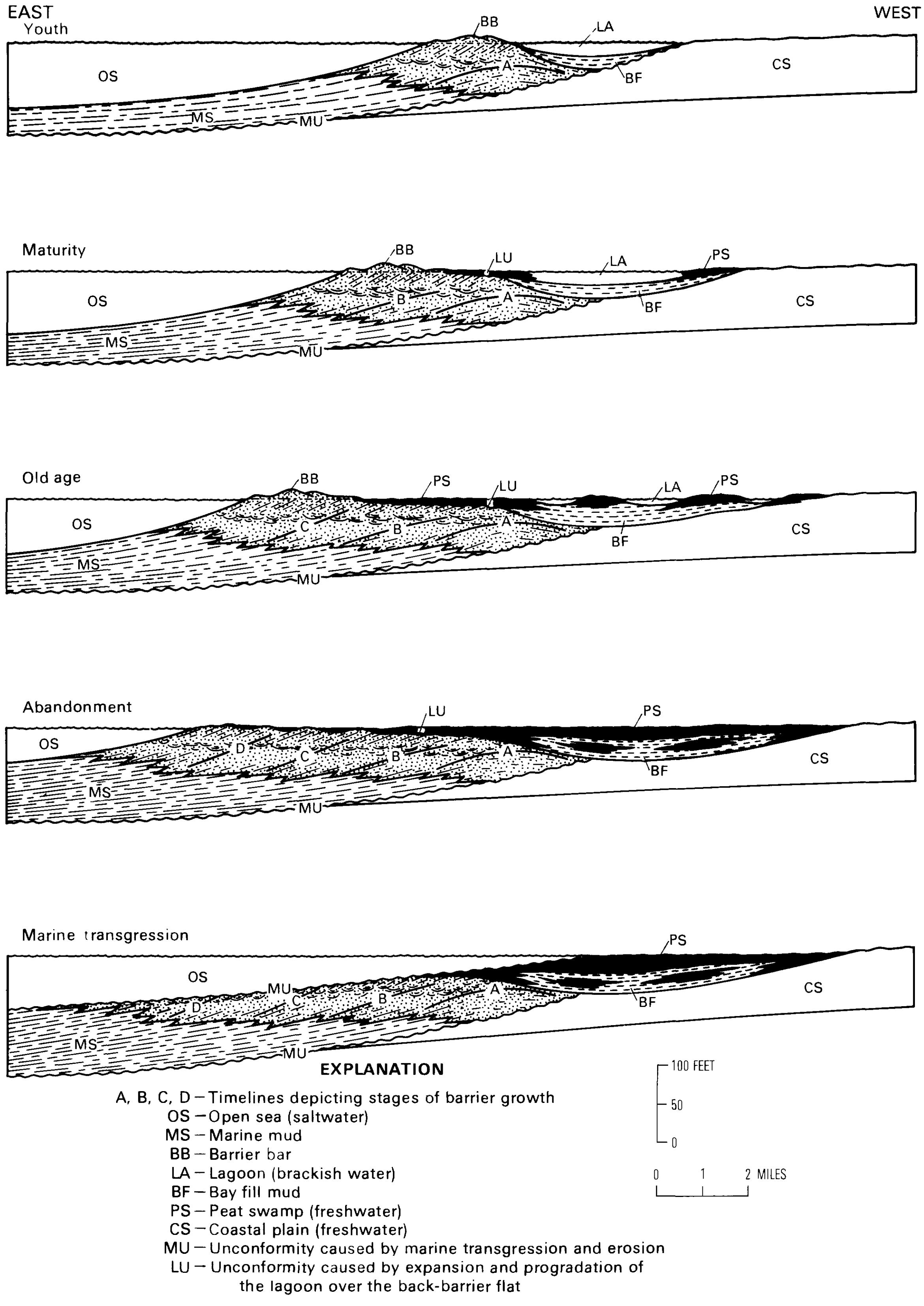

FIGURE 70.—Cross sections showing a model for a barrier-lagoonal, coal-forming environment based on the depositional history of barrier bar G and the Pintail coal bed.

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