

# Depositional Environment of Upper Cretaceous Black Sandstones of the Western Interior

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 994-A



DEPOSITIONAL ENVIRONMENT OF  
UPPER CRETACEOUS BLACK SANDSTONES  
OF THE WESTERN INTERIOR



Black sandstone capping buttes 6 miles (9.6 km) north of Pendroy, Mont. All except two small buttes in the lower background are capped by black sandstone that lies near top of Virgelle Sandstone.

# Depositional Environment of Upper Cretaceous Black Sandstones of the Western Interior

By ROBERT S. HOUSTON *and* JOHN F. MURPHY

UPPER CRETACEOUS BLACK SANDSTONES OF THE WESTERN INTERIOR

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*Cretaceous black sandstone deposits of the  
Western Interior have stratigraphic, structural, textural,  
and mineralogical characteristics helpful in reconstructing  
local and regional depositional environments*



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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1977

**UNITED STATES DEPARTMENT OF THE INTERIOR**

**CECIL D. ANDRUS, *Secretary***

**GEOLOGICAL SURVEY**

**V. E. McKelvey, *Director***

Library of Congress Cataloging in Publication Data

Houston, Robert Stroud, 1923-  
Depositional environment of Upper Cretaceous black sandstones of the Western Interior

(Upper Cretaceous black sandstones of the Western Interior) (Geological Survey Professional Paper 994-A)

Bibliography: p. 28-29.

1. Geology, Stratigraphic--Cretaceous. 2. Sandstone--The West. 3. Placer deposits--The West. I. Murphy, John Francis, 1922- II. Title. III. Series. IV. Series: United States Geological Survey Professional Paper 994-A.

QE685.H76

551.77'0978

77-608083

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For sale by the Superintendent of Documents, U.S. Government Printing Office

Washington, D.C. 20402

Stock Number 024-001-02974-0

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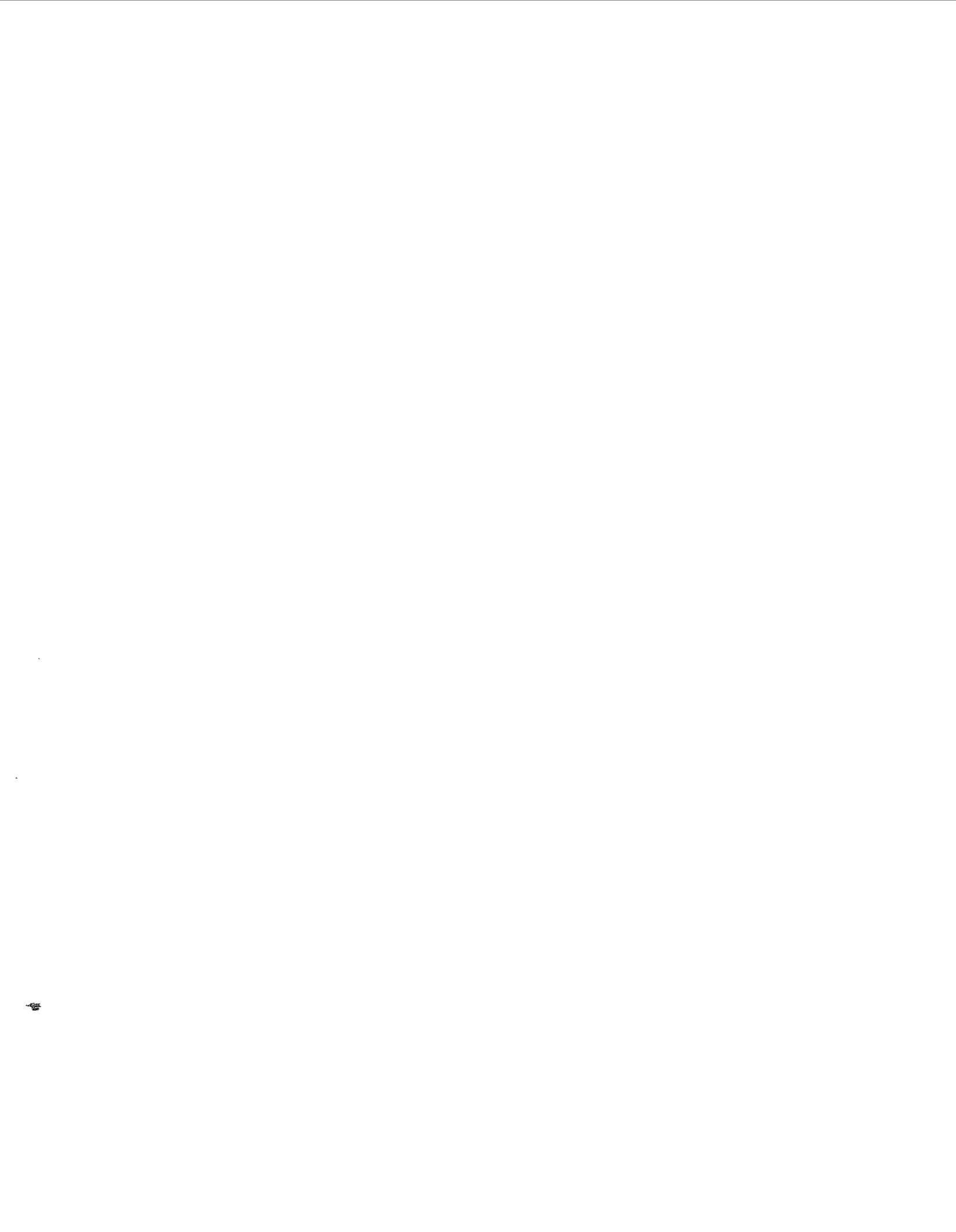
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UPPER CRETACEOUS BLACK SANDSTONES OF THE WESTERN INTERIOR

DEPOSITIONAL ENVIRONMENT OF UPPER CRETACEOUS  
BLACK SANDSTONES OF THE WESTERN INTERIOR

By ROBERT S. HOUSTON and JOHN F. MURPHY

ABSTRACT

Black sandstones of Late Cretaceous age that are fossil marine placer deposits of heavy minerals have been known in the Rocky Mountains since 1914 when Stebinger reported occurrences in northwestern Montana. More than 100 of these deposits have been located in recent years in Alberta, Montana, Wyoming, Utah, Colorado, New Mexico, Arizona, and northeastern Mexico. These deposits are unquestionably of beach placer origin and have many characteristics in common with modern beach placers such as those on the southeast coast of Australia. Study of these deposits in Wyoming and throughout the Rocky Mountains region has provided basic information on Late Cretaceous shoreline trends, beach slopes, and sediment source areas. Recent investigations of better exposed deposits, especially in Montana, have added information and modified earlier concepts.

Black sandstone deposits are characteristically found in regressive sandstones; deposition during regression is evident from internal structure of individual deposits and from general stratigraphic relationships. Typical black sandstone is underlain by white nearshore marine sandstone and is overlain by non-marine fine-grained sandstone, carbonaceous shale, and coal. Oyster-bearing beds, characteristic of lagoon and near-marine swamp deposits, are also fairly common in overlying deposits. In some localities the white nearshore marine sandstone can be divided into three structural units: a lower unit with horizontal laminations and low-angle medium- to large-scale trough and planar cross-lamination which contains nonabraded fossils and which is probably deposited in offshore areas seaward of the breaker zone; a middle unit with low- and high-angle medium-scale trough cross-lamination that may have formed on beach-point bars in the breaker zone; and an upper unit containing the black sandstone marked by large-scale very low angle wedge-planar cross-lamination thought to have developed in the fore-beach.

The black sandstone deposit proper is characteristically a laminated black and white sandstone, averaging about 15 percent heavy minerals at the base, and a massive black sandstone composed of layers containing as much as 90 percent heavy minerals at the top. In some deposits the lower and upper parts of the black sandstone deposit characterized by seaward-dipping large-scale very low angle wedge-planar cross-lamination are separated from one another by crossbedded units with high-angle laminae that dip seaward and landward, with steeper dips, as much as 32°, landward. The lower black and white sandstone, lowermost part in particular, contains worm and possible *Ophiomorpha* burrows. The black sandstone deposit is itself considered to be a regressional deposit; the lower black and white sandstone

is considered to be a foreshore deposit, the high-angle crossbedded middle unit foreshore ridge deposits, and the upper heavy-mineral-rich unit upper foreshore and backshore deposits. By analogy with modern deposits the black and white layers are thought to be deposited by traction processes operating in the swash zone which require constant deposition and reentrainment and which result in an association of light minerals too large to be hydraulic equivalents of associated heavy minerals. The thick black layers rich in heavy minerals deposited at the top of the beach are thought to be storm generated and deposited by combined gravity-shear sorting. This gravity-shear sorting causes a sorting of large light grains to the top of a layer and small heavy grains to the bottom of a layer, and during storms the process is thought to be so effective as to remove most of the upper layer leaving behind a layer composed mostly of heavy minerals.

Black sandstone deposits are not uniformly distributed in the Upper Cretaceous rocks of the Rocky Mountains region. They are most abundant in Montana and northern Wyoming. Major episodes of black sandstone formation took place in the 80-82-m.y. and 71-72-m.y. time span in the northern areas. These episodes of black sandstone formation are thought to be related to igneous activity or to deformation associated with emplacement of the Idaho and Boulder batholiths, or both, in part because minerals of volcanic or igneous origin are more common in these northern area deposits and because the igneous activity could produce a larger supply of heavy minerals. The 80-82-m.y. period of black sandstone formation may relate to a part of the events associated with the Telegraph Creek-Eagle regression that Gill and Cobban believe was caused by tectonism and volcanism in western Montana.

The black sandstone is perhaps the most reliable shoreline marker known in rocks of Cretaceous age. If exposed in three dimensions and if the top of the deposit is uneroded, the thickest and most abruptly terminating part of the deposit is located landward, and the long axis of the deposit is the local shoreline trend. Although black sandstone deposits yield information on local shorelines only, the strike of shorelines deduced from black sandstone corresponds quite well with that determined by Gill and Cobban from regional stratigraphic studies.

The overall shape of a black sandstone deposit and the distribution of heavy minerals along strike may yield clues to storm wind directions during the Late Cretaceous. Tentative models developed in Gardner's study of Australian deposits suggest that black sand deposits should thicken toward headlands that face the direction of storm wind attack and that zircon tends to lag behind other minerals as clastic material is transported toward

the headland. Evidence from black sandstone of Late Cretaceous age, though not conclusive, suggests that storm waves struck the Cretaceous coasts from the southeast.

The extraordinary width of individual black sand lenses perpendicular to strike, the very flat dip of laminae in deposits, and the very fine grain size suggest that Cretaceous beaches, especially in some Montana areas, may have been wide and flat. If subsidence and compaction were negligible, or if a given deposit is a product of progradation only, the thickness of a deposit may be an approximate measure of tidal range. In general, deposits are thicker in the northern Rocky Mountains, suggesting that tidal ranges may have been higher.

### INTRODUCTION

Black sandstones of Late Cretaceous age that

are fossil marine placer deposits of heavy minerals have been known in the Rocky Mountains region since 1914 when Stebinger (1914) reported occurrences in the Horsethief and Virgelle Sandstones of northwestern Montana. Subsequently, similar deposits have been found sporadically, but exclusively, in regressive-type littoral sandstone along the entire belt of Upper Cretaceous rocks that crop out from Alberta southward throughout the Rocky Mountains to Arizona and New Mexico and into northeastern Mexico (figs. 1-5). They occur in southwestern Alberta (Mellon, 1961) in the Belly River Formation; in Wyoming (Houston and Murphy, 1962) in the

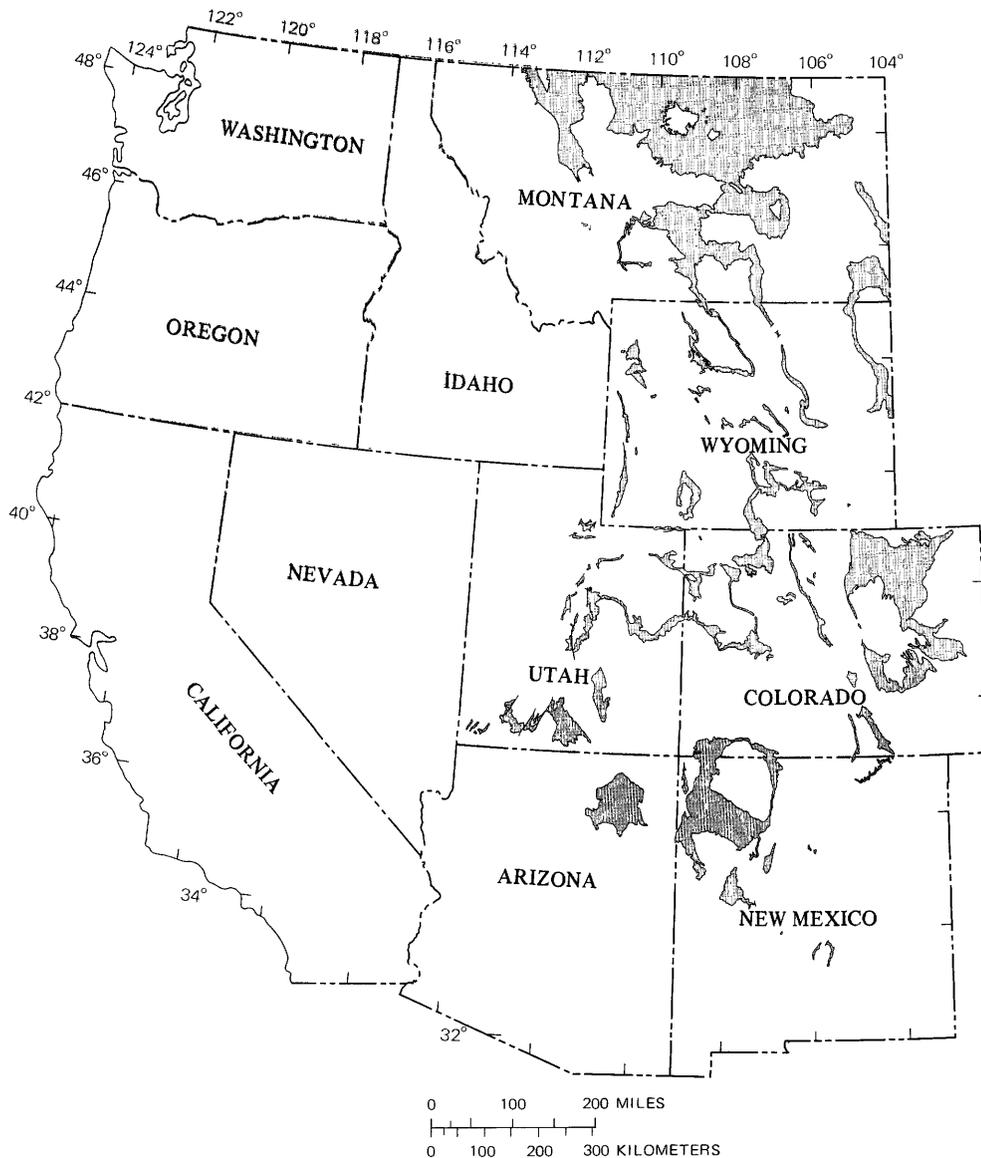
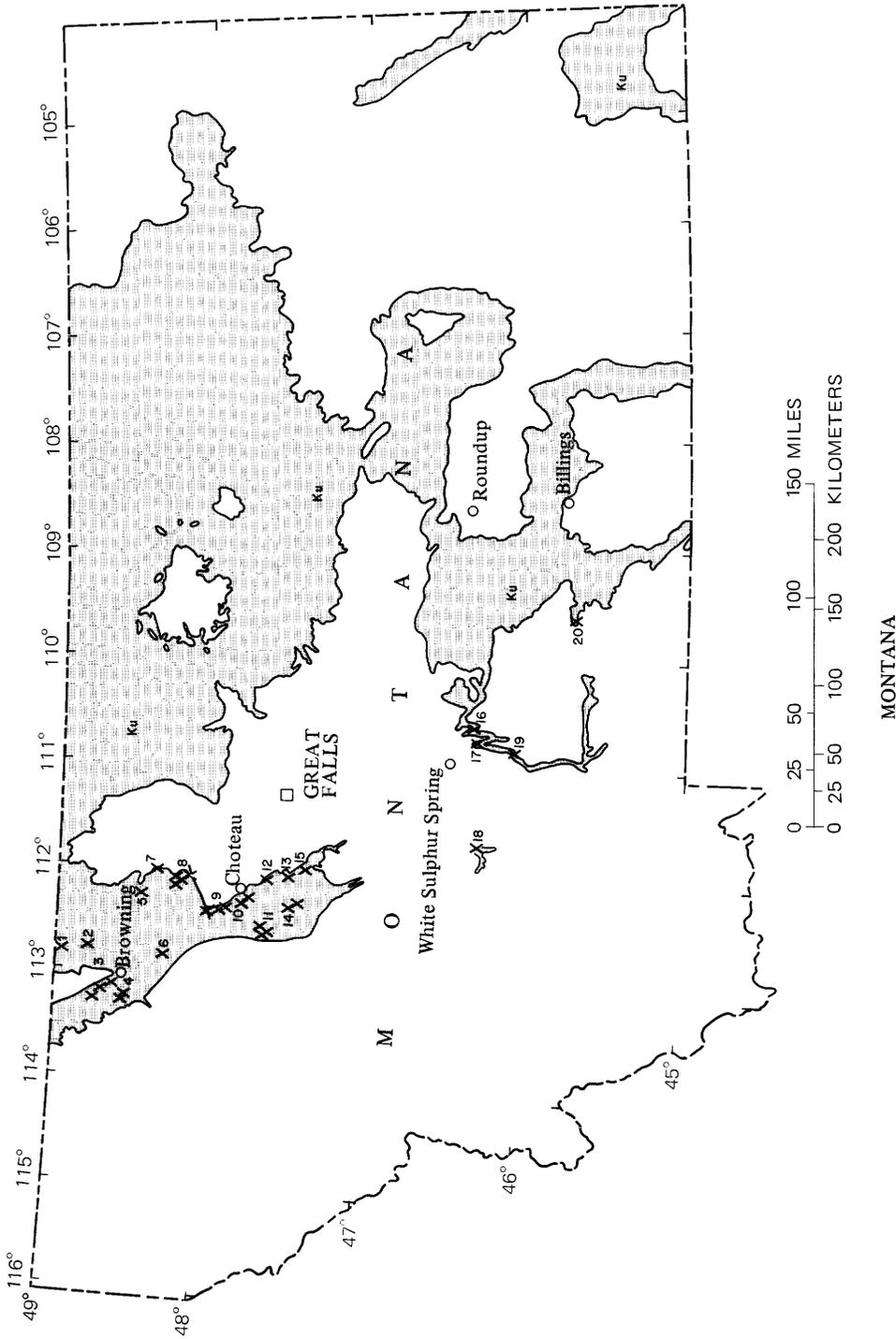


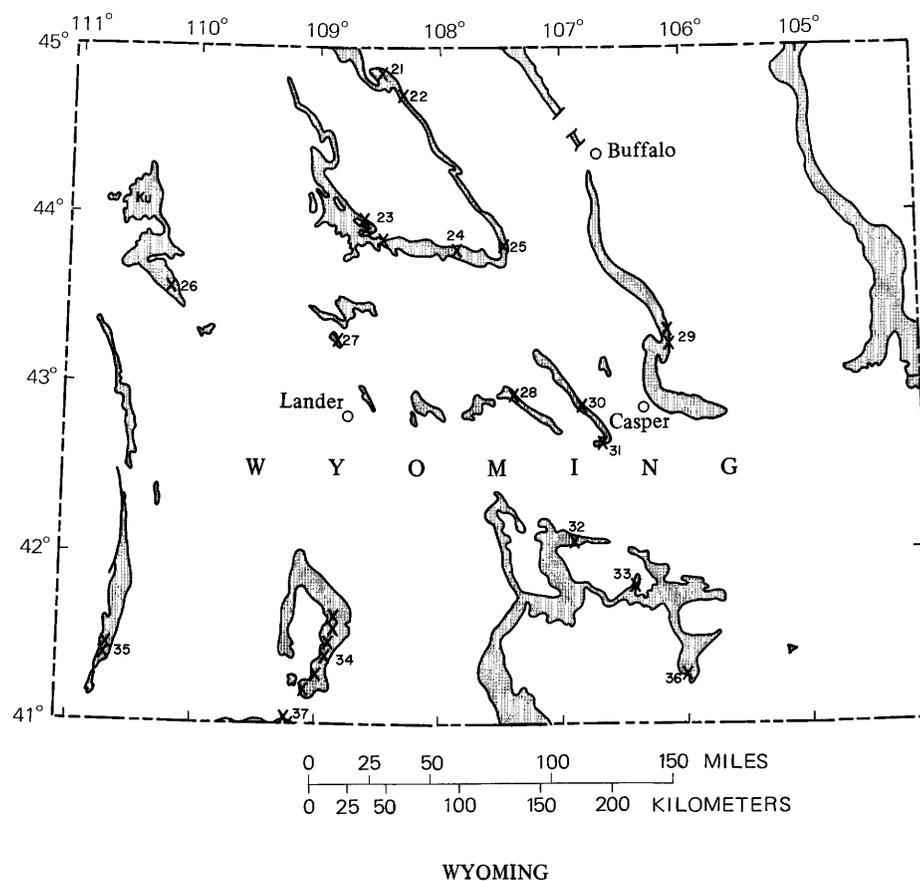
FIGURE 1.—Index map showing distributions of Upper Cretaceous rock (black) in which black sandstone deposits are found in the Rocky Mountains region. Faults are heavy black lines. Modified from Stose and Ljungstedt (1932).



DEPOSIT	STRATIGRAPHIC POSITION	DEPOSIT	STRATIGRAPHIC POSITION
1. Kennedy Coulee	----- Horsethief Sandstone	11. Sun River	----- Horsethief Sandstone
2. Rimrock Butte	----- Do.	12. Freezeout Lake	----- Virgelle Sandstone
3. Browning	----- Do.	13. County Line	----- Do.
4. Kiowa	----- Do.	14. Bee Ditch	----- Horsethief Sandstone
5. Birch Creek	----- Virgelle Sandstone	15. Iron Hill	----- Virgelle Sandstone
6. Heart Butte	----- Horsethief Sandstone	16. Bruno	----- Do.
7. Trunk Butte	----- Virgelle Sandstone	17. Ringling	----- Do.
8. Marias River	----- Do.	18. Iron Cross	----- Slim Sam Formation
9. Choteau	----- Do.	19. Wall Rock Basin	----- Virgelle Sandstone
10. Burd Hill	----- Do.	20. Greycliff	----- Hell Creek Formation

FIGURE 2.—Distribution of Upper Cretaceous rocks (patterned) and black sandstone deposits (X), Montana. Faults are heavy black lines. Modified from Stose and Ljungstedt (1932).

## UPPER CRETACEOUS BLACK SANDSTONES OF THE WESTERN INTERIOR



DEPOSIT	STRATIGRAPHIC POSITION
21. Cowley-----	Mesaverde Formation
22. Lovell-----	Do.
23. Grass Creek-----	Do.
24. Mud Creek-----	Do.
25. Buffalo Creek-----	Do.
26. Dry Cottonwood Creek-----	Bacon Ridge Sandstone
27. Shotgun Bench-----	Mesaverde Group
28. Coalbank Hills-----	Do.
29. Salt Creek-----	Fox Hills Sandstone
30. Poison Spider Creek-----	Lewis Shale
31. Clarkson Hills-----	Mesaverde Group
32. Seminoe-----	Fox Hills Sandstone
33. Fiddlers-----	Lewis Shale
34. Rock Springs-----	Rock Springs Formation
35. Cumberland Gap-----	Frontier Formation
36. Sheep Mountain-----	Mesaverde Group
37. Clay Basin (Utah-Wyoming)---	Rock Springs Formation

FIGURE 3.—Distribution of Upper Cretaceous rocks (patterned) and black sandstone deposits (X), Wyoming. Faults are heavy black lines. Modified from Stose and Ljungstedt (1932).

Mesaverde (also of group rank which locally includes the Rock Springs and Frontier Formations), and in the Lewis Shale; in Colorado (Houston and Murphy, 1962) in the Mesaverde Formation at Grand Mesa; in the San Juan Basin of New Mexico and Colorado (Chenoweth, 1956; Dow and Batty, 1961; Murphy,

1956) where the deposits are in sandstones of the Mesaverde Group including the Gallup, Point Lookout, and Pictured Cliffs Sandstones; in Utah (Dow and Batty, 1961) in the Straight Cliffs Formation and Ferron Sandstone Member of the Mancos Shale; in Arizona (Murphy, 1956) in the Toreva Formation;

DEPOSITIONAL ENVIRONMENT

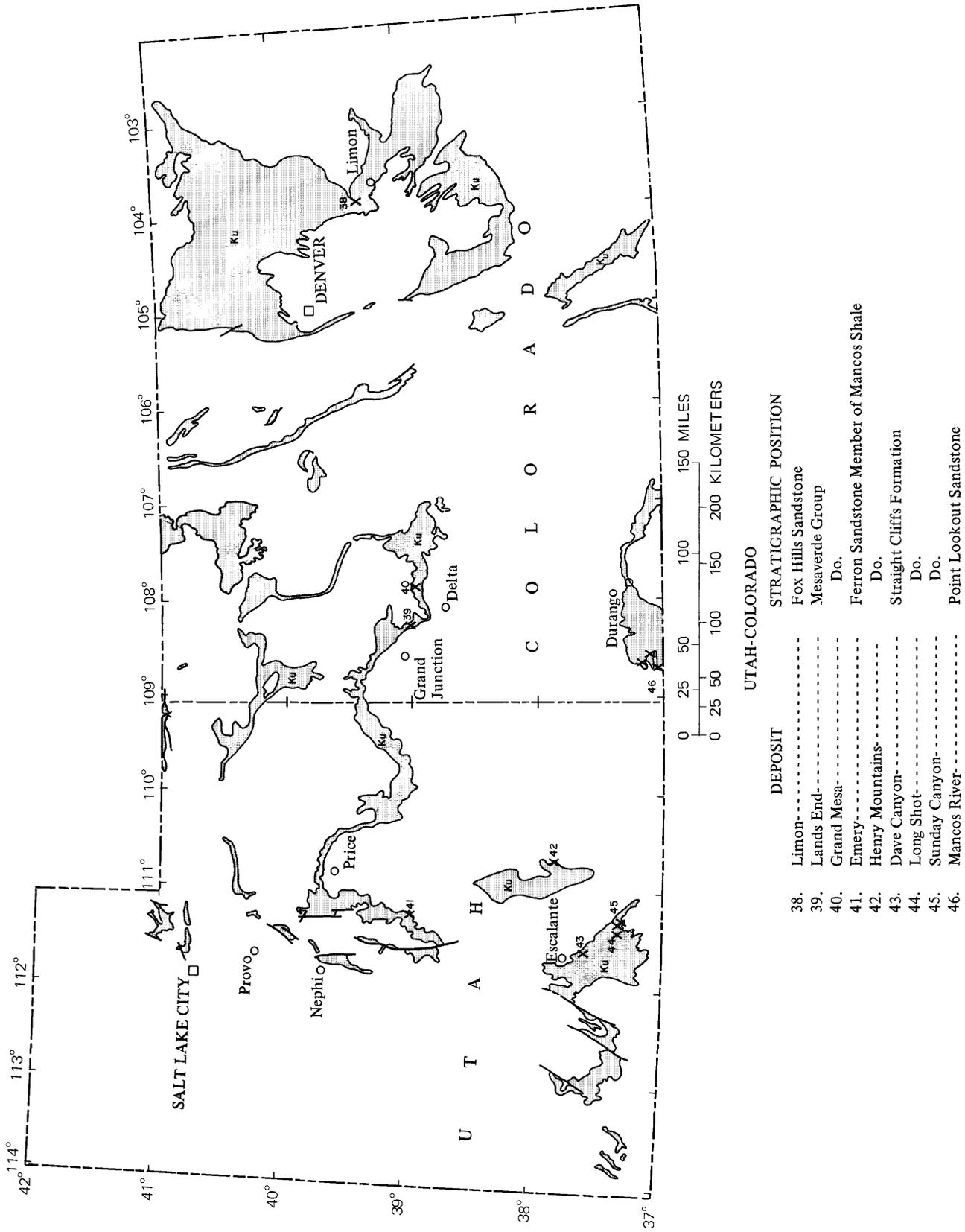


FIGURE 4.—Distribution of Upper Cretaceous rocks (patterned) and black sandstone deposits (·), Utah and Colorado. Faults are heavy black lines. Modified from Stose and Ljungstedt (1932).

UPPER CRETACEOUS BLACK SANDSTONES OF THE WESTERN INTERIOR

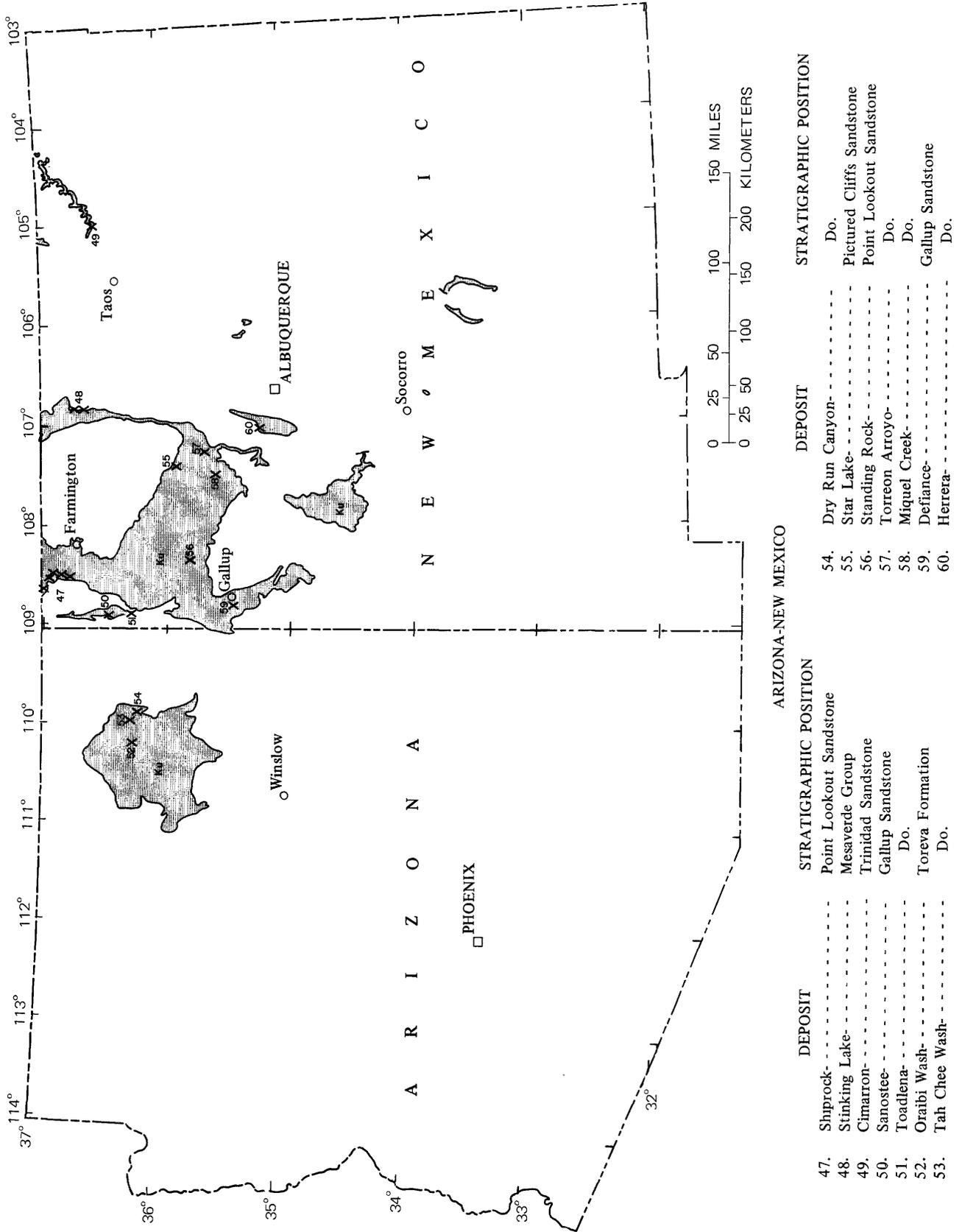


FIGURE 5.—Distribution of Upper Cretaceous rocks (patterned) and black sandstone deposits (X), Arizona and New Mexico. Faults are heavy black lines. Modified from Stose and Ljungstedt (1932).

and in northeastern Mexico where the deposits are at the base of the Upper Cretaceous in Canon Del Tule (Baker, 1970, p. 218-219).

The most abundant heavy minerals in the black sandstone deposits are opaque iron-titanium oxides and zircon. Other minerals of lesser abundance are rutile, chromite, monazite, tourmaline, garnet, staurolite, amphibole, pyroxene, sphene, apatite, allanite, niobium-bearing opaque minerals, anatase, biotite, brookite, chlorite, epidote, kyanite, pyrite, spinel, and gold.

These deposits are unquestionably of beach placer origin and have many characteristics in common with modern beach placers such as those on the southeast coast of Australia (Gardner, 1955; Whitworth, 1959; Connah, 1961). Study of these deposits in Wyoming and throughout the Rocky Mountains region has provided basic information on Late Cretaceous shoreline trends, longshore current directions, beach slopes, and sediment source areas. Some of these features, relative to Wyoming deposits, have been described (Houston and Murphy, 1962), but investigations of better exposed deposits, especially in Montana, have added new information and modified earlier concepts.

#### ACKNOWLEDGMENTS

The late James R. Gill of the U.S. Geological Survey located a number of the black sandstone deposits studied and was most helpful in discussing regional stratigraphic problems. William A. Cobban of the U.S. Geological Survey supplied critical information on the age of deposits from throughout the Rocky Mountains area. Survey colleagues Ralph E. Hunter and Harry A. Tourtelot were responsible for major improvements in the manuscript but are not to be held responsible for its contents.

#### FACTORS CONTROLLING THE DEVELOPMENT AND PRESERVATION OF BLACK SANDSTONE

Black sandstone deposits are not uniformly distributed in Cretaceous beach deposits. They occur in regressive sandstone deposits (Houston and Murphy, 1962, p. 14) and are unknown in transgressive sandstone deposits (fig. 6). In the regressive sandstone beds of some areas, such as the Choteau area of northwestern Montana, black sandstone is very abundant, but in other areas of similar depositional environment, such as the Kaiparowits area of southwestern Utah, it is relatively uncommon.

A critical factor in black sand accumulation is the supply of clastic debris containing heavy minerals that is brought to the sea by rejuvenated

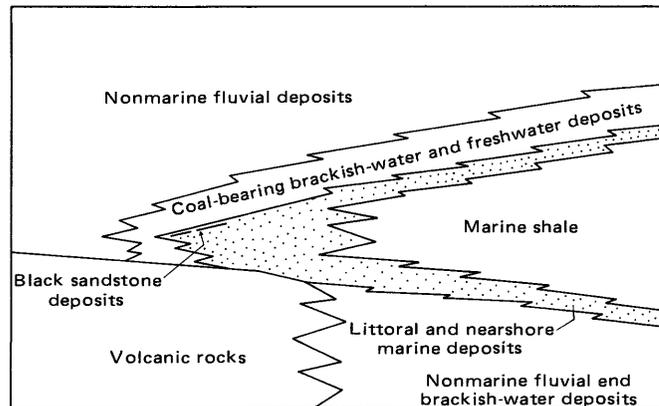


FIGURE 6.—Diagram showing idealized stratigraphic position of major occurrences of black sandstone in Montana.

streams and rivers. For example, although black sand has been reported on most modern beaches, some of the major deposits are on beaches where the geomorphic history suggests that uplift in the source areas, and therefore increased detritus, has preceded the development of the deposits. Gillson (1959) noted that the major black sand deposits of Travancore and MK in India accumulated after uplift and erosion from a piedmont or upland undergoing lateritic weathering, and Gardner (1955, p. 17-33) emphasizes that geologic evidence suggests successive emergence and submergence of the land adjacent to Australian beaches during the Pleistocene and that an emergence of about 25 feet (6.2 m) in Holocene time took place during the development of major black sand deposits on the southeast coast of Australia.

The association of black sand deposits with regressive sandstone beds is in part related to the increase in detritus resulting from stream rejuvenation which was brought about by uplift and retreat of the sea. Evernden and Kistler (1970) have shown a remarkable correlation between Mesozoic plutonic episodes of California and Nevada and regression. They indicate five major episodes of batholithic emplacement and deformation during the Mesozoic and correlate each with a temporary regression of the epicontinental seas in the North American continent.

Temporally and genetically, the black sandstone deposited in Montana and Wyoming during periods of regression suggests relationship with the igneous activity and deformation associated with the emplacement of the Idaho batholith. Like the Mesozoic plutons of California and Nevada, the Idaho batholith is a composite intrusive with a long history of emplacement. Facies of the batholith have

been dated as old as 217 m.y. (million years) and as young as 38 m.y. Although there is a clear overlap in age determinations between rocks of the Idaho batholith and rocks of the Mesozoic plutons of California and Nevada (Larsen and others, 1958), the dating is inadequate to relate the individual pulses of magma emplacement. If a relationship can be inferred, it is that a major magmatic episode in the emplacement of the Idaho batholith may have occurred during the Late Cretaceous in the period 90-79 m.y. ago (Evernden and Kistler, 1970, p. 24, fig. 10). Figure 7 shows that this is the period during which more than 50 percent of the known fossil black sandstone occurrences were deposited. Most of the deposits shown in figure 1 are in Wyoming and Montana, and their mineralogy indicates a significant contribution from igneous and (or) volcanic sources (Houston and Murphy, 1970, p. 246-248). In general, the deposition of black sandstone increases toward the end of the 90-79-m.y. period.

Another major period of black sandstone deposition in Montana occurred between 72 m.y. and 71 m.y. ago (fig. 7). These deposits also contain abundant minerals derived from the intrusive and extrusive rocks associated with the Boulder batholith of Montana. Volcanism associated with the emplacement of the Boulder batholith began 85 m.y. ago, reached maximum intensity about 78 m.y. ago, and ceased about 72 m.y. ago; plutonism began 78 m.y. ago, peaked about 76 m.y. ago, and ceased about 68 m.y. ago (Robinson and others, 1968, p. 551-576).

If the frequency of occurrence of black sandstone reflects in some degree igneous activity and deformation associated with the emplacement of either the Idaho or the Boulder batholith, or both, the deposits are more likely to mirror local events such as those suggested by Gill and Cobban (1973, p. 20-33) than regional events such as those suggested by Evernden and Kistler (1970). The major episodes of black sandstone formation are in the 80-82-m.y. and 71-72-m.y. time span, much briefer episodes than the dating of either batholith indicates (in fact, if Gilluly's plots of the number of ages of salic plutons and volcanics in the North American cordillera (Gilluly, 1973, p. 505) are representative of the regional events, the 80-82-m.y. episode is a regional low in the number of ages reported in the period 45-105 m.y.). The 80-82-m.y. period of black sandstone formation, largely representing deposits in Montana and northern Wyoming, may relate to a part of the events associated with the Telegraph Creek-Eagle regression that Gill and Cobban (1973, p. 20) believe was caused by tectonism and volcanism in western Montana. The 71-72-m.y. period of black sandstone

deposition, largely in Montana, corresponds, in part, to the Fox Hills regression (initial phase) which Gill and Cobban (1973, p. 28) could not relate to either volcanism or tectonism but which they suggested possibly was caused by uplift related to late stages of emplacement of the Boulder batholith.

The absence of black sand deposits in transgressive littoral sandstone is due to the fact that transgressive littoral sandstone bodies are not preserved or were not formed because rates of transgression were more rapid than rates of regression.

It is also quite possible that the black sand concentrating process is more effective, all other factors being equal, if more time is available to work on a given volume of sand before that volume is covered by newly supplied sediment (Ralph E. Hunter, written commun., 1973). This possibility might suggest that some of the major black sandstone concentrations are evidence of temporary stillstands during regression. Perhaps factors that influence outcrop of black sandstone-bearing rocks play as important a role in determining their present known distribution and apparent abundance as any of the preceding considerations, but we consider volcanism the key factor that directly or indirectly causes major black sandstone concentrations in any given area.

#### HOLOCENE BLACK SAND DEPOSITS

Connah (1961, p. 3-5) classified Australian black sand deposits of Holocene age into four types according to origin: (1) storm-wave deposits at top of beach, (2) wind-sorted deposits in dunes, (3) tidal-current interaction deposits, and (4) high-grade dune deposits of unknown origin. The fossil black sandstone deposits of Late Cretaceous age most closely resemble storm-wave deposits at the top or landward edge of the beach. According to Gardner (1955, p. 38) the storm-wave deposits on the southeast coast of Australia are formed by the surf on the upper or landward part of a beach during stormy weather. These deposits are dark layers of heavy minerals 30-50 feet (9.2-15.2 m) wide that may extend along the beach for the greater part of its length. In cross section, they appear wedge shaped, tapering gradually seaward toward the foreshore and dipping seaward at a low angle. In southeast Australia the thickest of these deposits occur in beaches that terminate northward in a headland or other natural barrier. Such deposits may be 5 feet (1.5 m) thick near the headland and taper gradually to the south. Connah (1961, p. 3-5) stated that storm-wave deposits show all degrees of concentration from single to repeated pencil streaks to layers of pure black sand

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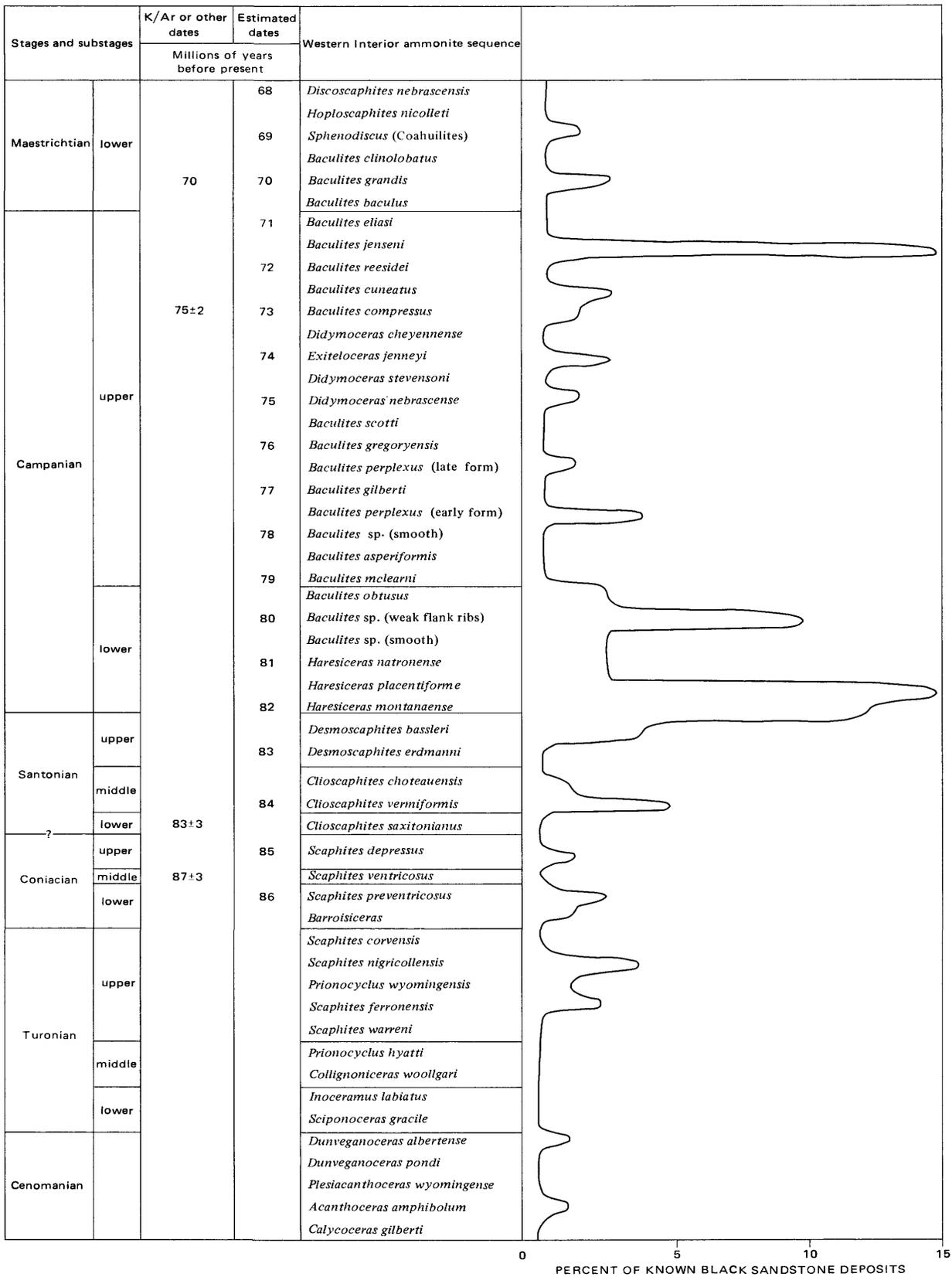
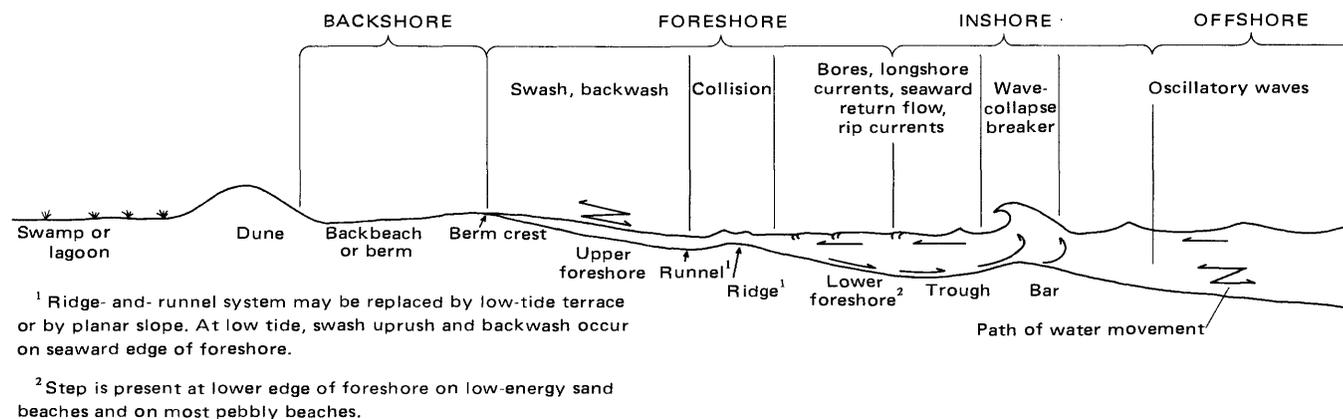


FIGURE 7.—Percentages of known Upper Cretaceous black sandstone deposits of the Rocky Mountains region deposited during time periods represented by Western Interior ammonite zones.

as much as 8 feet (2.4 m) thick. Two or more layers may be deposited successively and overlapping en echelon. By inference Connah (1961, p. 12-13) suggested that where deposits overlap each other the combined thickness of both low-grade (3 percent heavy minerals) and high-grade (as much as 80 percent heavy minerals) layers may exceed 20 feet (6.2 m).

According to Foxworth, Priddy, Johnson, and Moore (1962, p. 35-41), who studied modern black sand deposits on beaches of the Mississippi Gulf Coast, heavy minerals are deposited primarily by wind-generated waves that result from squalls or storms at sea. The heavy minerals may be deposited on different parts of the beach depending on the wave height and tide. Waves generated by winds of low intensity are capable of depositing layers of heavy minerals on the foreshore. (See fig. 8 for beach terminology used in this report.) The heavy and light minerals are carried to the foreshore, and the retreat-

ing low-energy wave returns most of the light minerals, leaving the heavy minerals marooned on the upper foreshore in thin laminae that outline the relatively steep slope in this area of the foreshore. Moderate-intensity waves carry the heavy minerals to and over the berm crest. The heavy minerals are frequently draped over the berm crest and in cross section outline a depositional anticline with dips on one side toward the forebeach and on the other toward the backshore. Erosion and redeposition on these berms (especially on the foreshore side) may result in truncation of one set of black sand beds and redeposition of another set at a slightly different dip. The black sand is interlayered with white quartz-rich layers and shows distinct laminations. High-intensity waves, generated at high tide or during major storms, carry sediment over the berm crest to the backbeach and return light minerals seaward back over the berm crest. Gulf Coast backbeach deposits are rich in heavy minerals and are appar-



Facies	Characteristics
Swamp or lagoon	Burrowed lagoonal silt and clay; rich in organic material; disrupted laminations; small-scale low-angle trough and planar cross-lamination; ripple marks; oyster and coquinoïd lime deposits
Dune	Very fine sand <sup>1</sup> ; trough cross-laminations; vertical root traces; laminated to structureless
Backbeach	Fine sand; low-angle landward, seaward, or horizontal, dipping wedge-planar cross-lamination; channels common; nonfossiliferous
Berm crest	Fine sand; convex laminae; low- to moderate- to high-angle planar cross-lamination; nonfossiliferous
Upper foreshore	Fine sand; low-angle seaward-dipping wedge-planar cross-lamination; rare micro-cross-lamination; burrows present but not abundant
Ridge and runnel	Fine sand; locally coarser and bimodal on ridge; high-angle cross-lamination; trough cross-lamination; burrows uncommon
Lower foreshore	Fine sand; low-angle wedge-planar cross-lamination dipping seaward; burrows common. Coarse sand at lower edge of foreshore
Trough	Fine sand, high-angle trough and planar cross-lamination; shell fragments
Bar	Locally coarser sand; high-angle cross-lamination in some examples. Sand in trough may be coarser than on bar
Offshore	Very fine sand; thin bedded; undulatory wave ripples; plants and animals in growth position; structureless where bioturbated

<sup>1</sup> Grain size may vary in all facies because it is, in part, dependent on material supplied.

FIGURE 8.—Major facies of idealized beach cross section (modified from Ingle, 1966).

ently of the same type formed on Australian beaches. Probably during intense storms, when deposits are formed on the backbeach, preexisting beach ridge and perhaps forebeach deposits are partly destroyed and redeposited on the backbeach to add to the greater heavy mineral concentrations in this area. In the Mississippi Gulf Coastal areas, autumn and winter storm waters may carry heavy minerals inland beyond the backbeach and distribute them among sand dunes.

The preservation of the heavy minerals on various parts of the beach depends on the deposition of protective layers of light minerals soon after formation of the heavy layer. The heavy minerals laid down on the foreshore, especially in the seaward foreshore area, are more subject to erosion than those deposited on the backbeach, which are most likely to be preserved.

#### CRETACEOUS BLACK SANDSTONE DEPOSITS (THE REGRESSIVE SEQUENCE)—MARIAS RIVER EXAMPLE

A typical Upper Cretaceous black sandstone deposit crops out along the Marias River in Montana northeast of Pendroy in sec. 4, T. 28 N., R. 5 W. (fig. 2, No. 8). Where exposed, the deposit is 0.8 mile (1.3 km) long and 0.1 mile (0.16 km) wide. It lies near the top of the Virgelle Sandstone. The long dimension of the deposit trends N. 50° W., which is in agreement with the generalized Late Cretaceous shoreline trends shown by Gill and Cobban (1969). The deposit is about 18 feet (5.5 m) thick in the center and thins northwestward to about 9 feet (2.8 m) where it is concealed by younger sediments; it thins similarly to the southeast. The deposit is wedge shaped in cross section—it is thickest on the southwest (shoreward) and thins northeastward to a feathered edge (fig. 9 shows similar thinning in deposit at Red Creek, Wyo., fig. 3, No. 37).

The Marias River deposit overlies a coarser grained white massive sandstone that is not well exposed in this area. As in most black sandstone deposits the percentage of heavy minerals increases from the base to the top (fig. 10). The lowermost zone of the Marias River deposit, zone A (fig. 11) is generally an iron-stained brown sandstone with a few thin laminae of heavy minerals. This zone, which ranges in thickness from 2 to 5 feet (0.6–1.5 m), is generally structureless at the base and indistinctly bedded near the top. Sporadic casts and molds of burrows are present. Some are small tubular casts that may be worm burrows.

Overlying zone A is a laminated sandstone with

more abundant thin apparently horizontal laminae of heavy minerals—zone B (fig. 11). About 20–50 percent of zone B consists of heavy mineral laminae, some of which show a dip of 4°–5° NE., or seaward. Only one current ripple mark was well enough exposed to determine its orientation—strike N. 30° E. and steep limb facing northwest, which suggests northwest transport. Some layers of heavy minerals are deformed, some of them being almost convolute. Locally the laminae have been faulted, probably penecontemporaneously with deposition inasmuch as the layers are overlain and underlain by undeformed beds. The faults are miniature thrust faults, and most show apparent displacement to the northwest. This zone averages 3 feet (0.9 m) in thickness and is overlain by a similar laminated zone (zone C, fig. 11) with thicker and more abundant laminae of heavy minerals.

Crossbeds outlined by laminae of heavy minerals are common in zone C. The crossbedded units vary in thickness, but most are about 6 inches (15 cm) thick (fig. 12). Most of the crossbedding dips (8°–32°) either northeast or southwest and strikes roughly parallel to the long dimension (shoreline direction) of the deposit (fig. 13). Thick layers (2–8 in. or 5–20 cm) composed almost entirely of heavy minerals occur sporadically in the zone but with greater frequency near the top. Burrows are present, some as large as 2 inches (5 cm) in diameter. The larger burrows, which were probably made by animals “swimming” through the sediment, are as much as 6 inches (15 cm) in length and are U-shaped in cross section with a series of concentric concave layers from bottom to top of the burrow (fig. 14). Other, usually smaller, burrows resemble *Ophiomorpha* (Toots, 1961), a term used for a burrow probably constructed by a decapod crustacean like *Callianassa major*, whose burrows from beaches along the Georgia coast were described by Weimer and Hoyt (1964). Zone C is 5–6 feet (1.5–1.8 m) in thickness.

Overlying zone C is zone D, the uppermost part of the black sandstone deposit and the part richest in heavy minerals. Zone D (fig. 11), which is 4–6 feet (1.2–1.8 m) thick, is characterized by thick massive layers containing 80–90 percent heavy minerals. The layers range in thickness from a few inches to nearly 1 foot (5–30 cm). They are not continuous and may overlap each other or be separated by laminated black sandstone, crossbedded sandstone, or even white almost structureless sandstone barren of heavy minerals. Commonly the higher grade and thickest layers are at the top of zone D. In many deposits this upper zone is overlain by 2–3 feet (60–90 cm) of massive white sandstone which in turn is



FIGURE 9.—Black sandstone deposit in the uppermost sandstone of the Rock Springs Formation at Red Creek. Note distinct thinning of the deposit to the east or right (seaward) and abrupt termination to the west or left. Photograph shows a cross section of the deposit taken nearly at right angle to the shoreline. NE1/4 sec. 22, T. 12N., R. 105 W., Sweetwater County, Wyo.; view looking north.

overlapped from the seaward side of the deposit by another rich heavy mineral zone, perhaps part of another cycle, with characteristics like those of zone D. Burrows are rare in zone D.

Some individual high-grade heavy mineral layers in zone D can be traced in cuts perpendicular to the shoreline nearly to the exposed seaward edge of the deposit where they intertongue with white sand (fig. 15). The layer may be 2–6 inches (15 cm) thick at the landward edge, and an individual layer between marker laminae gradually thins in a sea-

ward direction until it is less than one-sixteenth inch thick. Beds above and below an individual heavy mineral layer appear to parallel the layer when examined in outcrop, but when viewed at a distance, some truncation surfaces dip more steeply than underlying beds, whereas others are flatter than underlying beds. Again when viewed at a distance the entire sequence appears to be stacked seaward, and, overall, beds show a decrease in dip in the seaward direction.

The vertical sequence within deposits A–D can

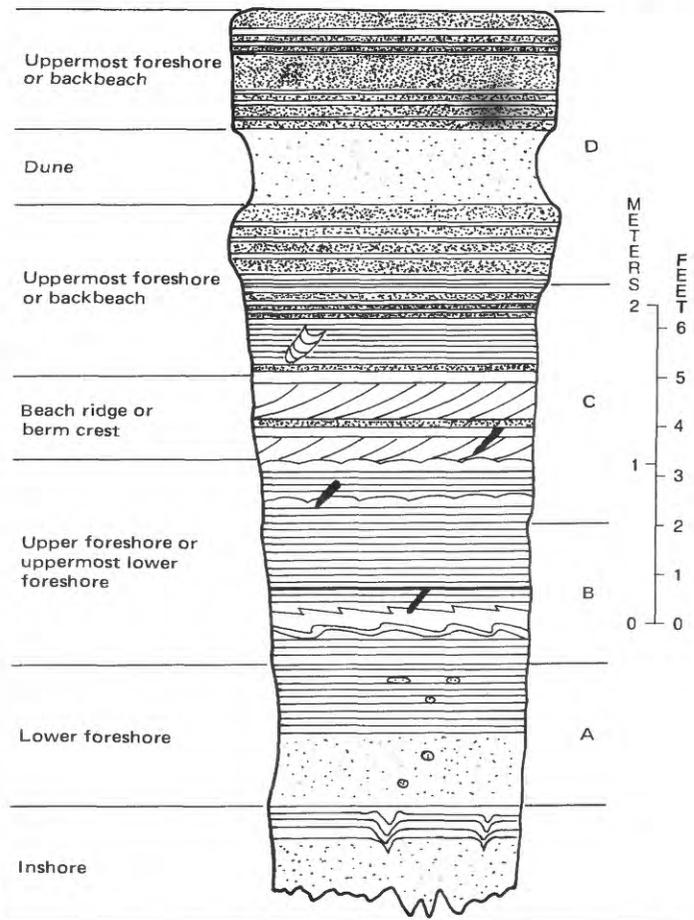


FIGURE 10.—Black sandstone at the top of the John Henry Member of the Straight Cliffs Formation south of Escalante, Utah. The base of the unit is a white burrowed sandstone which is overlain by laminated black and white sandstone capped by thick massive beds very rich in heavy minerals.

be seen, by the lateral tracing of beds, to follow Walther's Law (Walther, 1893) and clearly reflects the regressive environment during which it was deposited. In any given locality the layers represent, successively from base to top, deposits typical of the foreshore to backbeach and possibly including dune remnants.

*Basal white sandstone*

The basal white sandstone that underlies the black sandstone (fig. 16) is massive without distinctive or well-developed structures. Samples of this unit taken a few feet below the black sandstone are coarser grained than the black sandstone. This fact, plus its lack of sedimentary structures, might be used to support the concept that the bulk of the white sandstone was deposited in the inshore or portions of the offshore nearest the beach. Ingle (1966, p. 181) has pointed out that inshore deposits (collision and wave collapse areas) are generally coarser grained than beach sand and that, inasmuch as bedding is



EXPLANATION

- Burrows
- Contorted laminations of organic and inorganic origin
- Crossbedding
- Ripple marks
- Beds containing over 60 percent heavy minerals
- Laminae of heavy minerals in sandstone
- Beds containing less than 4 percent heavy minerals

FIGURE 11.—Typical vertical sequence of black sandstone, Marias River deposit, Montana.

more likely to be disrupted by the action of organisms in the inshore and offshore areas (Hunter and others, 1972), well-developed structure may not be typical of sandstone that was deposited in this environment.

The basal white sandstone is not without structure in all areas, however. High-angle trough cross-lamination can be recognized in some deposits (fig. 4,



FIGURE 12.—Cross-lamination in middle part of black sandstone of Marias River deposit. Landward-dipping cross laminae are curved so that steepest dip is in the central section of the laminae, suggesting bed has undergone little or no truncation. Ruler is 7 in. (18 cm) long.

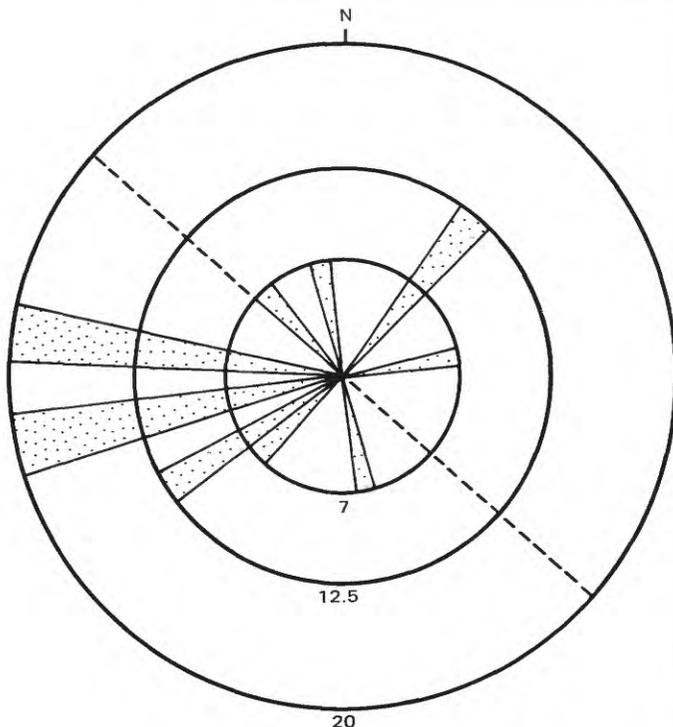


FIGURE 13.—Rose diagram showing direction of crossbedding dip in black sandstone at Marias River deposit, Montana. Data plotted in  $10^\circ$  azimuth classes; radial scale in percent of total number of measurements. Dashed line at N.  $50^\circ$  W. is strike of shoreline in this area; seaward side is to the northeast.

No. 44), and in others the white sandstone has faint thin laminations with very low dip. Burrows (*Ophiomorpha*?) are unusually abundant in some white sandstone (fig. 4, No. 43), and, in still another area, a channel about 2 feet (0.6 m) deep and 10 feet (3 m) wide has been filled with very complex small- and medium-scale cross-laminated sandstone (fig. 2, No. 8). These various organic and inorganic structures could have formed on the lowermost foreshore or inshore. Thin laminae with low dip and burrowed sandstone could be fossil analogs of structures described by Hoyt and Weimer (1963, p. 530) on the lower foreshore of modern beaches at Sapelo Island, Ga. The trough cross-lamination may represent small and large cut-and-fill structures (trough) described in the inshore (surf zone) portion of beaches of Padre Island, Tex. (Jacka, 1970, p. 192-193).

Further indication as to the environment of deposition of the white sandstone was given by Petersen (1969, p. 133), who described a threefold vertical sequence of structures in the John Henry Member of the Straight Cliffs Formation of Utah, where black sandstone occurs in the upper part of barrier sandstone bodies. The lower unit of this sequence is a grayish-orange sandstone with horizontal laminations and low-angle medium- to large-scale trough and planar cross-lamination, and it commonly contains nonabraded fossils. The middle unit is a grayish-orange to light-gray sandstone with



FIGURE 14.—Laminated black sandstone typical of lower part of black sandstone at the top of the Virgelle Sandstone on the north side of the Dry Fork Marias River, sec. 4, T. 28 N., R. 5 W., Pondera County, Mont. Note local disruption of bedding by burrows.

low- and high-angle medium-scale trough cross-lamination. The upper unit contains the black sandstone and is very light gray to white with very low angle medium- to large-scale wedge-planar cross-stratification, and it lacks fossils.

The presence of nonabraded fossils in the lower bedding unit is considered evidence that this part of the vertical sequence formed in offshore areas seaward of the breaker zone where lower flow-regime conditions prevailed (Peterson, 1969, p. 139). The high-angle medium-scale trough cross-lamination of the middle unit may have formed on break-point bars modified by longshore currents in the breaker zone, and laminae may reflect the form of longshore bars and troughs. The large-scale very low angle wedge-planar cross-lamination of the upper unit was interpreted by Peterson (1969, p. 137) as evidence that this sandstone developed on the forebeach.

This same general sequence has been recognized by Jacka (1965, p. 88–89; 1970, p. 214–216) in other areas in his Fox Hills Sandstone, Rock Springs Formation, Almond Formation, and Lazear Sandstone of Wyoming and in his Tocito Sandstone and

Sanostee Members of the Gallup Sandstone, Point Lookout Sandstone, Cliff House Sandstone, and Pictured Cliffs Sandstone of New Mexico.

#### *Black sandstone*

Figure 11 shows the subdivision of a typical black sandstone and suggests the environments of deposition. Zone A was deposited on the lower foreshore, where laminae of heavy minerals are thin and rarely formed or preserved. The low seaward dip of laminae, scarcity of heavy mineral laminae, and presence of worm and possible *Ophiomorpha* burrows all suggest the lower foreshore environment. Zone B may represent the upper foreshore or upper part of the lower foreshore. This interpretation depends on the interpretation of the crossbedded units with high-angle laminae in zone C. Some crossbeds dip seaward and others landward, which suggests structures like those on berm crests described by Foxworth, Priddy, Johnson, and Moore (1962, p. 32) or structures on foreshore ridges located beneath the upper and lower foreshore described by Hoyt (1962) and Hoyt and Weimer (1963). If these are crossbedded units on the berm crest, then units below them are upper foreshore and units above them are backshore deposits, but if the crossbeds were formed on the foreshore ridge, then the units below them would be lower foreshore and units above them upper foreshore.

Figure 13 shows that more beds dip landward than seaward in the crossbedded unit at Marias River. The landward-dipping crossbeds dip as much as  $32^\circ$ . Ridge and runnel systems that develop on flat beaches (Hoyt, 1962) may be modern analogs of these crossbedded structures. Hoyt noted that these ridges commonly originate on the lower foreshore, are 50–150 feet (15.2–46 m) wide, and may extend along a beach for as much as 1 mile (1.6 km). The landward slope of the ridge is steep, as much as  $30^\circ$ , whereas the seaward slope is  $1^\circ$ – $2^\circ$  (Hoyt, 1962, p. 311). The landward-dipping laminae in the Sapelo Island, Ga., deposits studied by Hoyt are well defined by laminae of black heavy minerals that alternate with layers of quartz. The stratification planes are curved, with the steepest dips in the central section, and are virtually identical to similar structures in fossil black sandstone (fig. 12). The landward-dipping crossbedded units in fossil black sandstone deposits are therefore interpreted as being part of fossil foreshore ridges.

In figure 7, a ridge and runnel system is shown separating the lower and upper foreshore of a typical beach, and this is also shown as a collision zone (Ingle, 1966, p. 181), an area where backwash encounters incoming waves. This zone has most recently been described as the “inner rough zone” by

Clifton, Hunter, and Phillips (1971, p. 656), who have studied structures of steep high-energy beaches of the Oregon coast. They found that off steep beaches this inner rough facies consists of a series of steep-sided symmetrical ripples of coarse sand and gravel but that on more gently sloping beaches sets of troughs or depressions develop, 3-6 feet (1-2 m) across and 4-20 inches (10-50 cm) deep, that are parallel to the beach and are separated by broad flat "ridges." According to Clifton, Hunter, and Phillips (1971), the seaward-facing side of these troughs is generally steeper than the landward side, and these structures migrate seaward, which is in direct contrast to the similar structures at Sapelo Island, described by Hoyt, that migrate landward.

Fossil ridges in the fossil black sandstones seem to be of a type that develops on flat low-energy beaches, such as the Sapelo Island example, rather than on steep high-energy beaches, such as the Oregon coast example. If these beach ridges are developed some place on the foreshore, as suggested by Hoyt (1962), the thick beds rich in heavy minerals probably were deposited on the upper foreshore of the Cretaceous beaches, and the laminated beds below the crossbedded unit on the lower foreshore. This hypothesis undoubtedly is an oversimplification for several reasons. Ridge and runnel systems may develop on different parts of flat beaches, and a given beach may have a series of these structures that parallel one another on the lower foreshore and



FIGURE 15.—Landward (A) and seaward (B) portion of a black sandstone at the Marias River deposit. The pencil shown in both photographs is at the base of the same bed that can be traced 200 feet (60 m) in a direction perpendicular to the shoreline. A, The landward portion. The bed above the pencil is a layer of sandstone 3 inches (8 cm) thick composed almost entirely of heavy minerals. The sandstone in the upper half of A is composed of layers containing 80-90 percent heavy minerals, whereas that in the lower half is laminated and more like the beds in B. B, Very thin locally burrowed laminae of heavy minerals typical of the seaward edge of the deposit. Very low angle wedge-planar cross-laminations are shown in the top right. Below the pencil, the laminae are less well developed and burrowed; at the base truncated landward-facing cross-laminae having dark silty layers in the troughs are exposed. The sandstone at the base of B is coarser grained than that at the top.

even on the upper foreshore near the berm. King (1959, p. 341-347) stated that the ridges develop at the upper limit of the swash zone and that their position is related to the tides. At low tide a ridge may develop on the upper part of the lower foreshore, and at high tide on the upper foreshore nearer the berm, but ridges on the upper foreshore are generally poorly developed. All ridges will be marked by steeper landward-facing crossbedding in fossil black sandstone so that their value in separating upper and lower foreshore can be questioned.

A characteristic of the black sandstone at Marias River as well as in other areas in the Rocky Mountains is that the thick heavy-mineral-rich layers at the top of the deposits truncate lower beds and characteristically dip in a seaward direction (fig. 11, zone D). Aside from the crossbedded unit in zone C, landward-dipping beds and landward-dipping wedge-planar structure cut by numerous troughs and channels (McKee, 1957, p. 1712) that are characteristic of the surface of the berm or backshore are not present. In areas subject to severe storms the berm

would have been destroyed, and probably any upper beach ridges would be removed as well. It seems probable that the high-angle crossbedded units of zone C were deposited on foreshore ridges and that the thick beds rich in heavy minerals that lie above these units were deposited on the upper foreshore. Probably, on most Cretaceous beaches where black sandstone occurs, the upper foreshore extended landward to the dunes. In any event the vertical sequence observed in most black sandstone deposits must represent successively higher or landward portions of the beach, and the layers rich in heavy minerals found near the top of virtually all deposits must be deposited on the upper part of the beach. In a regressive sequence these rich layers represent the uppermost true beach deposits of a given regressive sandstone.

An interesting aspect of most black sandstone deposits is the absence of positively recognizable dune deposits overlying the uppermost black sandstone layers. Fine-grained structureless sandstone that may have formed in dunes overlies some black

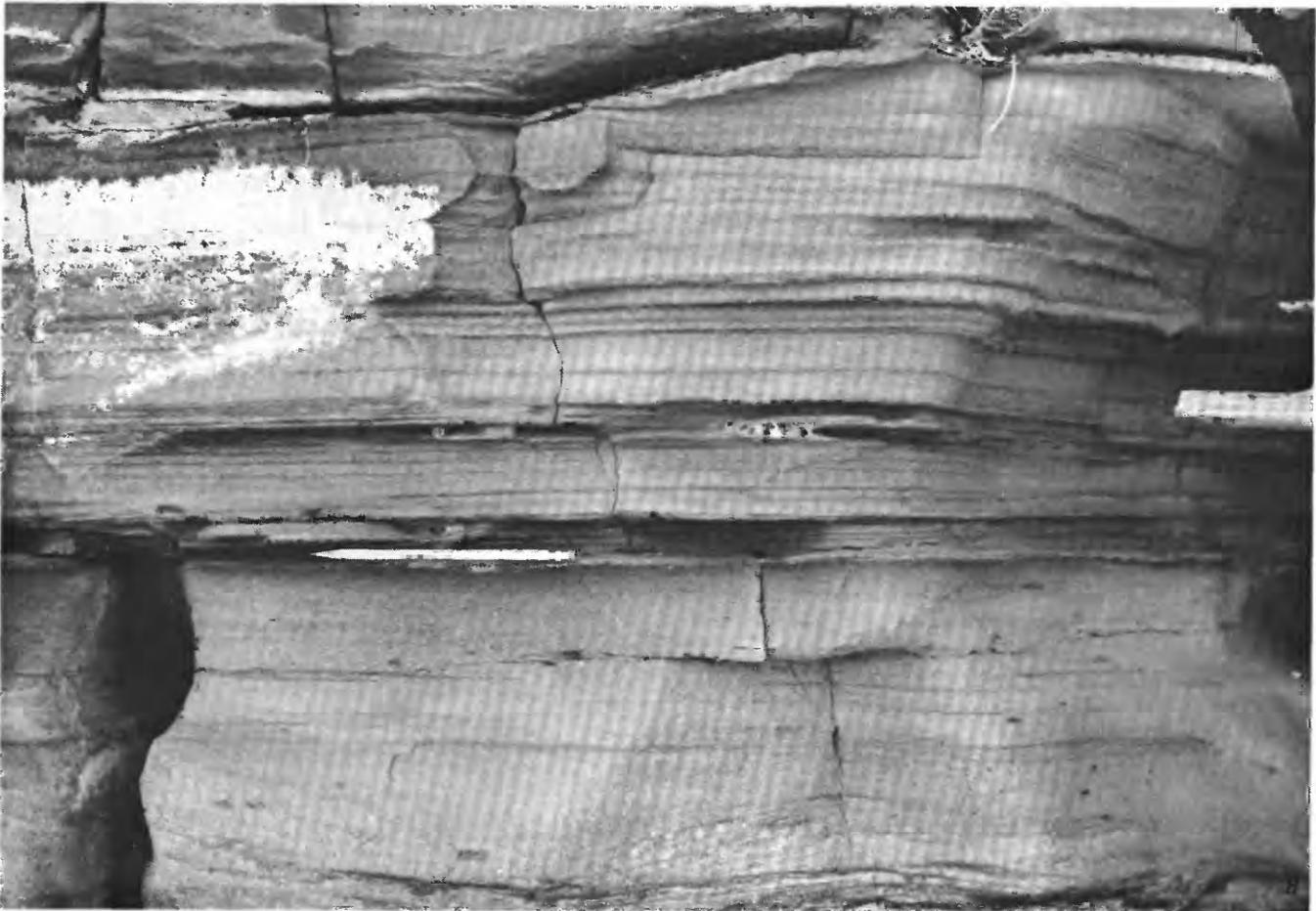


FIGURE 15.—Continued.



FIGURE 16.—Black sandstone at the top of basal white sandstone of the Mesaverde Formation on the north rim of the Grass Creek anticline in Hot Springs County, Wyo. The rocks exposed here are typical of the regressive sequence—a basal white massive sandstone about 150 feet (46 m) thick, overlain by 10–15 feet (3–4.6 m) of black sandstone, which is overlain by nonmarine shale and carbonaceous shale containing lignite and coal beds. Photograph taken looking south.

sandstone and is interbedded with thick heavy-mineral-rich layers at the top of some deposits (fig. 11), but structures characteristic of modern dunes are not present. Perhaps the dunes, being topographically high and thus more prone to erosion, were readily removed and replaced by lagoonal or coastal swamp deposits during regression. It is also possible that sedimentary structures in dunes were destroyed by weathering processes, plant roots, animals, and movement of vadose water as has been shown to be the case on Galveston Island, Tex., by Bernard, LeBlanc, and Major (1962, p. 200).

None of the immediately (?) overlying beds are exposed in the Marias River deposit, but in many deposits the overlying beds are fine-grained sandstone, carbonaceous shale, and coal. Oyster-bearing beds, typical of lagoon and near-marine swamp deposits, are also fairly common.

Figure 17 shows possible stages in the development of the thick wedges of black sandstones on a

relatively flat Cretaceous beach and suggests how the various facies may overlap to develop the typical regressive sequence previously described.

#### SIGNIFICANCE OF GRAIN SIZE

Fossil black sandstones of Late Cretaceous age are very fine grained; modal diameters are related to the proportion of light and heavy minerals in a sample. Samples with a predominance of light minerals have modal diameters that range from 0.15 to 0.21 mm, and samples with a predominance of heavy minerals have modal diameters close to 0.10 mm. Because of the response of heavy minerals to hydraulic factors that influence deposition, heavy minerals are smaller than associated light mineral grains within a black sandstone deposit.

Upward fining from water level to the top of a beach is the general rule in beaches (Miller and Zeigler, 1958) and is especially true of beaches with abundant heavy minerals for reasons cited above.

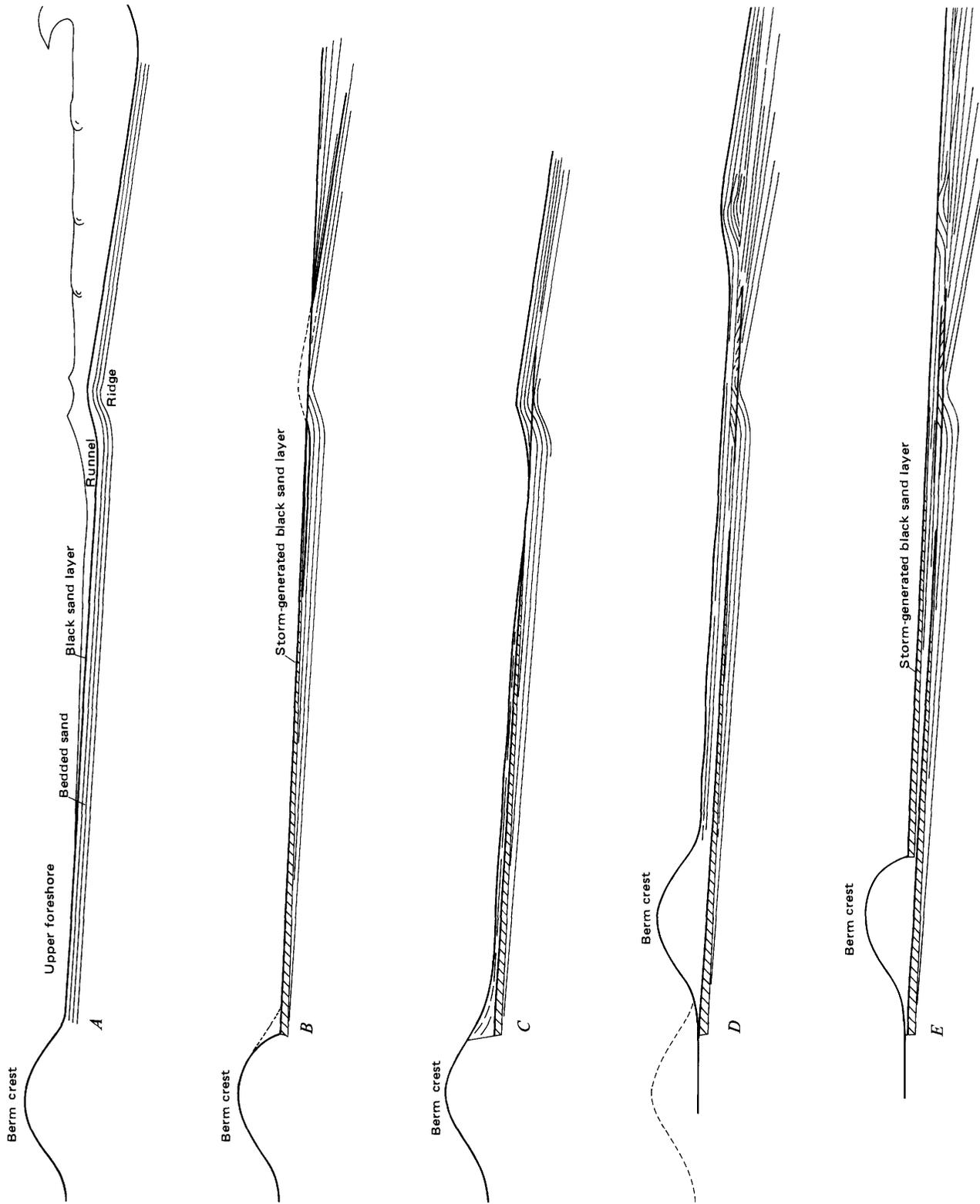


FIGURE 17.—Possible stages of development of black sandstone deposit. *A*, Simplified flat Cretaceous beach showing internal structure of upper beach and ridge-and-runnel system. *B*, Black sand layer, flattening of overall beach gradient, and partial destruction of ridge, all generated by storm. *C*, New ridge developed in attempt to steepen beach gradient. *D*, Shifting of beach facies during regression. *E*, Storm-generated black sand layer formed after regression.

Thus the forebeach environment, and black sandstone in particular, is an exception to the general trend of upward increase in grain size in a regressive marine sequence (Sabins, 1965).

In many of the black sandstone deposits the principal heavy mineral is magnetite and the principal light mineral is quartz. The modal diameter of the heavy minerals is 0.10 mm, whereas the modal diameter of associated light minerals varies depending on the percentage of heavy minerals of the sample. Light minerals in samples with alternating laminae of black and white sand that average more than 50 percent light minerals have modal diameters of 0.21 mm. Light minerals in samples composed largely (more than 60 percent) of heavy minerals have modal diameters that average 0.15 mm (fig. 18; also Houston and Murphy, 1962, fig. 4, pl. 3; Mellon, 1961, table 1). Grains transported in suspension and deposited as current velocity decreases should have the same settling velocity (Rubey, 1933) or be hydraulic equivalents (Rittenhouse, 1943). Light and heavy minerals in fossil black sandstone approximate this ideal in that the heavier mineral grains are smaller than light mineral grains, but they are not exact hydraulic equivalents. Ideally, a single lamina (depositional unit of Apfel, 1938) should be used to test for hydraulic equivalency so that grains de-

posited together may be compared. The higher grade (60–90 percent heavy minerals) samples are from single layers rich in heavy minerals, and they should be ideal depositional units; for example, if the dominant heavy and light minerals, magnetite (sp. gr. 5.18) and quartz (sp. gr. 2.67), are used to test for hydraulic equivalency, and assuming the grains to be spherical, a magnetite grain of 0.10 mm diameter should be associated with a quartz grain 0.16 mm in diameter. The observed modal size of the light minerals is 0.15 mm and therefore is slightly smaller than it should be. Quartz in black sandstone (fig. 18*F*, *C*) has a modal diameter of 0.21 compared to the 0.10 of the associated heavy minerals, somewhat larger than would be expected if deposition was controlled by settling velocities.

Clifton (1969) has demonstrated that heavy minerals are deposited in the swash zone of Oregon beaches as a type of reverse graded depositional unit. The base of a unit is a fine-grained layer rich in heavy minerals, and this grades upward into a coarser grained light-colored layer with a high proportion of light minerals. Constant erosion and redeposition in the swash zone causes this layering to vary, in that part or all of some layers are removed so that individual depositional units may not be complete, but the process results in the development of alternating light and dark laminae very much like that in the lower parts of black sandstone deposits. Clifton suggested that the reverse graded bedding is formed by sorting action that takes place as sediment is transported by traction. He stated (Clifton, 1969, p. 557) "segregation between coarse and fine grains, and between light and heavy grains occurred very quickly within a moving layer of sand following the maximum erosion during backwash." This general type of sorting in dense layers of sand has been discussed from a theoretical viewpoint by Bagnold (1954, p. 62), who stated that when grains of mixed sizes are sheared together the larger grains should drift toward the zone of least shear (top of the layer). It is also reasonable to assume (Clifton, 1969, p. 557) that grains of higher density will work their way to the bottom of a layer even if all grains are of equal size. This general process of combined gravity-shear sorting has been observed not only by Clifton but by many others including Inman (1949) and Krumbein (1944).

Hand (1967) has demonstrated by use of settling tube techniques that heavy minerals are too small to be the hydraulic equivalents of light grains on New Jersey beaches. He noted that once a grain is entrained, the distance it will travel should be controlled by settling velocities and that under these circumstances grains that are deposited in a given area should be hydraulic equivalents, but he stressed

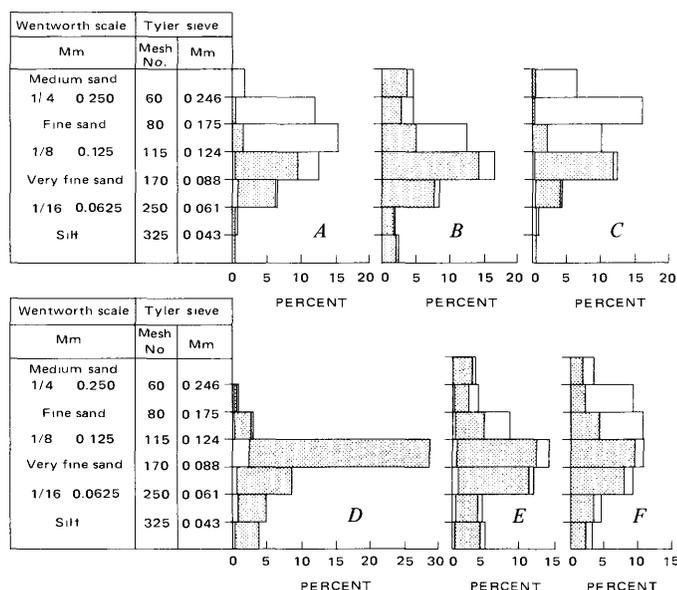


FIGURE 18.—Histograms relating grain-size variation to light (no pattern) and heavy (black) mineral fractions in black sandstone deposits. Line pattern represents ferromagnetic fraction (ferric iron and carbonate matrix removed by 10 percent HCl). *A*, Rollins(?) Sandstone Member of Mesaverde Formation, Grand Mesa, Colo. *B*, Straight Cliffs Formation, Escalante, Utah. *C*, Point Lookout Sandstone (of Shiprock deposit), Salt Creek Wash, N. Mex. *D*, Gallup Sandstone, Sanostee, N. Mex. *E*, Gallup Sandstone, Toadlena, N. Mex. *F*, Toreva Formation, Tah Chee Wash, Ariz.

the point that an additional and perhaps more important control on whether a grain will remain in a particular place is the ability of the existing current to remove it—the process of reentrainment. He noted that if two grains have the same settling velocity but different densities, the denser grain will be smaller, and that since a small particle among larger ones is physically removed and shielded from high velocity flow, its movement will be blocked by the larger grains. He further stated (Hand, 1967, p. 516)

It follows that in a mixture of quartz (S.G. 2.65) and garnet (S.G. 4.0), all of whose grains had the same settling velocity, the quartz should be less likely to remain as part of the permanent deposit than the garnet. To make the garnet equivalent to the quartz in a true sense, it would be necessary to decrease the settling velocity (grain size) slightly. With only a slight change, the geometric disadvantage of the garnet will not be greatly increased, but the ratio of fluid drag to grain mass will be substantially increased. When the probability of entrainment for garnet just equals that for associated quartz, the grains should be truly equivalent.

Hand's concept therefore emphasizes the role of reentrainment in controlling grain size of associated minerals of different specific gravity and would seem to apply best to areas on a beach where there is constant erosion and redeposition of grains—the swash zone. The overall tendency with time might be an association of heavy minerals that are too small or light minerals that are too large to be hydraulic equivalents in the sense of having equal settling velocities.

The preceding discussion suggests that there may have been two processes at work on the Cretaceous beaches: one that resulted in the deposition of alternating black and white sand on the forebeach (swash zone) where light minerals are too large to be hydraulic equivalents of associated heavy minerals and one that resulted in the deposition of black layers composed of at least 60 percent heavy minerals, and often more than 80 percent heavy minerals, on the landward edge of the beach where associated heavy and light minerals are nearly hydraulic equivalents. Deposition of the black and white sand on the forebeach may be the result of the traction processes described by Clifton (1969) and Hand (1967), but deposition of the black layers on the landward edge of the beach may be the result of a different process.

The thick black layers rich in heavy minerals found at the top of the black sandstone deposit are thought to be storm generated. High-energy storm waves are capable of destroying and flattening parts of the forebeach, and they probably carry in suspension grains that were previously deposited on the forebeach plus other clastic particles picked up seaward of the forebeach. When this material is carried to the top of the beach, the wave energy decreases

and grains must begin to settle from suspension as the wave moves along the beach. As the wave moves along the beach and eventually returns seaward, traction processes may take over and the mechanism of combined gravity-shear sorting as discussed by Clifton (1969) may be carried almost to completion with the removal of most of the upper coarser grained light-colored layer, leaving only the black fine-grained layer rich in heavy minerals. The process of combined gravity-shear sorting would be carried to completion because of the higher energy of the storm wave as it moves along the beach and eventually seaward.

Light and heavy minerals in the lower layer of a storm-generated deposit of this type would not be affected by the reentrainment process of Hand and would therefore be closer to hydraulic equivalents.

#### SHORELINE TRENDS

The black sandstone is perhaps the most reliable shoreline marker known in rocks of Cretaceous age. If exposed in three dimensions and if the top of the deposit is uneroded, the thickest and most abruptly terminating part of the deposit is located landward (fig. 9). The deposit thins and feathers out seaward or may be made up of an en echelon series of black sand lenses that are repeated slightly higher in the section seaward. The long axis of the deposit is the local shoreline trend. However, if the deposit is made up of lenses that are en echelon in a horizontal plane as well as in cross section, the long axis of the deposit may diverge from the shoreline direction, and the observer should thus make certain that he considers a single black sand lens when a shoreline direction is determined.

Table 1 compares shoreline trends deduced from black sandstone deposits with those determined by Gill and Cobban (1969) from regional stratigraphic studies. Although the comparison cannot be made at exactly the same instant of Late Cretaceous time, there is reasonably close agreement. Significant departures between the two methods occur only where there are known major age differences between the black sandstone and the stratigraphic unit used by Gill and Cobban.

#### SOME AREAS FOR FUTURE RESEARCH

In the course of this study, which was primarily to consider the economic potential of fossil black sandstone, a number of concepts were considered that we believe will be useful in determining more about the Late Cretaceous environment. The results of studying these concepts were not conclusive partly because detailed information on modern black sandstone deposits is not available and partly because of less than adequate study of fossil

TABLE 1.—Trends of Upper Cretaceous shorelines determined from black sandstone as compared with trends of shorelines established by Gill and Cobban (1969) from regional stratigraphic and paleontologic study

Stages and substages	Age from Western Interior ammonite sequence	Location of black sandstone deposits	Stratigraphic unit	Shoreline trend from black sandstone	Shoreline trend of closest age from Gill and Cobban (1969)	
Maestrichtian	Lower	<i>Sphenodiscus (Coahuilites)</i>	Colorado (northwest of Limon)	Fox Hills Sandstone	North-northwest (approx.)	Northwest (approx.) ( <i>Baculites clinolobatus</i> )
		<i>Baculites clinolobatus</i>				
		<i>Baculites grandis</i>	Wyoming (southeast of Midwest)	Fox Hills Sandstone	N. 10° W.(?)	North (approx.) ( <i>Baculites clinolobatus</i> )
		<i>Baculites baculus</i>				
		<i>Baculites jenseni</i>	Montana (north of Browning)	Horsethief Sandstone	N. 25°-30° W.	N. 25° W. ( <i>Baculites reesidei</i> )
			Montana (west of Browning Kiowa Junction area)	Horsethief Sandstone	N. 40° W.	N. 25° W. ( <i>Baculites reesidei</i> )
		<i>Baculites reesidei</i>				
		<i>Baculites cuneatus</i>	Northern Montana (near Augusta)	Horsethief Sandstone	N. 65° W.	N. 30° W. ( <i>Baculites reesidei</i> )
		<i>Baculites compressus</i>	New Mexico (Star Lake Trading Post)	Fruitland Formation	N. 60° W.	N. 55° W. ( <i>Baculites reesidei</i> )
		<i>Didymoceras cheyennense</i>				
	<i>Exiteloceras jenneyi</i>					
Upper		<i>Didymoceras stevensoni</i>	Wyoming (west of Laramie)	Mesaverde Group	North-northwest (approx.)	North ( <i>Baculites scotti</i> )
		<i>Didymoceras nebrascense</i>				
		<i>Baculites scotti</i>				
		<i>Baculites gregoryensis</i>				
		<i>Baculites perplexus</i> (late form)	Wyoming (southwest of Casper)	Parkman Sandstone Member of Mesaverde Formation	North	North ( <i>Baculites scotti</i> )
		<i>Baculites gilberti</i>				
		<i>Baculites perplexus</i> (early form)	Wyoming (south of Tensleep)	Mesaverde Formation	N. 15° E.	North ( <i>Baculites scotti</i> )
			Wyoming (south of Hiland)	Mesaverde Formation	Northwest	North ( <i>Baculites scotti</i> )
		<i>Baculites sp.</i> (smooth)				
		<i>Baculites asperiformis</i>				
Campanian		<i>Baculites mclearnii</i>				
		<i>Baculites obtusus</i>	Wyoming (northern Bighorn Basin)	Mesaverde Formation	N. 45° W.	N. 45° W. ( <i>Baculites mclearnii</i> )
		<i>Baculites sp.</i> (weak flank ribs)	Wyoming (southeast of Rock Springs)	Rock Springs Formation of Mesaverde Group	Northeast	Northeast ( <i>Baculites mclearnii</i> )
	Lower	<i>Baculites sp.</i> (smooth)	New Mexico (northeast of Shiprock)	Menefee Formation	N. 70° W.	N. 70° W. ( <i>Baculites sp.</i> [smooth])
		<i>Haresiceras natronense</i>	Wyoming (southeast of Bighorn Basin)	Mesaverde Formation	N. 15° W.	N. 15° W. ( <i>Baculites sp.</i> [smooth])

deposits; however, these results are discussed below | helpful in the study of fossil black sandstone and to suggest areas where future research may be | modern analogs. Interpretations are tentative, and it

TABLE 1.—Trends of Upper Cretaceous shorelines determined from black sandstone as compared with trends of shorelines established by Gill and Cobban (1969) from regional stratigraphic and paleontologic study—(Continued)

Stages and substages	Age from Western Interior ammonite sequence	Location of black sandstone deposits	Stratigraphic unit	Shoreline trend from black sandstone	Shoreline trend of closest age from Gill and Cobban (1969)
Lower (Con.)	<i>Haresiceras placentiforme</i>	Wyoming (northwest Wind River Basin)	Mesaverde Formation	North	North ( <i>Baculites</i> sp. [smooth])
		New Mexico (northeast of Shiprock)	Point Lookout Sandstone	N. 60°–70° W.	N. 60°–70° W. ( <i>Baculites</i> sp. [smooth])
		New Mexico (Standing Rock Trading Post)	Point Lookout Sandstone	N. 54° W.	N. 50° W. ( <i>Baculites</i> sp. [smooth])
	<i>Haresiceras montanaense</i>	New Mexico (west of Cabezon)	Point Lookout Sandstone	N. 50° W.	N. 50° W. ( <i>Baculites</i> sp. [smooth])
		Montana (east of Valier)	Virgelle Sandstone	N. 55° W.	N. 50° W. ( <i>Baculites</i> sp. [smooth])
		Montana (northeast of Pendroy)	Virgelle Sandstone	N. 55° W.	N. 50° W. ( <i>Baculites</i> sp. [smooth])
		Montana (near Choteau)	Virgelle Sandstone	N. 45° W.	N. 50° W. ( <i>Baculites</i> sp. [smooth])
Santonian	Upper <i>Desmoscaphites bassleri</i>	Utah (south of Escalante)	Straight Cliffs Formation	N. 15° W.	N. 20° W. ( <i>Desmoscaphites</i> )
	<i>Desmoscaphites erdmanni</i>				
	Middle <i>Clioscaphtes choteauensis</i>				
	<i>Clioscaphtes vermiformis</i>	Utah (southeastern Kaiparowits Plateau)	Straight Cliffs Formation	N. 35° W.	N. 40° W. ( <i>Desmoscaphites</i> )
	Lower <i>Clioscaphtes saxitonianus</i>				
Coniacian	Upper <i>Scaphites depressus</i>				
	Middle <i>Scaphites ventricosus</i>				
	Lower <i>Scaphites preventricosus</i>	Arizona (north of Pinon)	Toreva Formation of Mesa-verde Group	Northwest	N. 55° W. ( <i>Desmoscaphites</i> )
		Arizona (Tah Chee Wash)	Toreva Formation of Mesa-verde Group	Northwest	N. 55° W. ( <i>Desmoscaphites</i> )
	<i>Barroisiceras</i>	New Mexico (west of Laguna Pueblo)	Gallup Sandstone	N. 30° E.(?)	N. 65° W. ( <i>Desmoscaphites</i> )
	<i>Scaphites corvensis</i>				
	<i>Scaphites nigricollensis</i>	New Mexico (Sanostee)	Gallup Sandstone	N. 25° W.	N. 60° W. ( <i>Desmoscaphites</i> )
Turonian	Upper <i>Prionocyclus wyomingensis</i>	New Mexico (southwest of Gallup)	Gallup Sandstone	N. 25° W.	N. 60° W. ( <i>Desmoscaphites</i> )
	<i>Scaphites ferronensis</i>	Arizona (north of Black Mountain Trading Post)	Toreva Formation of Mesa-verde Group	Northwest	N. 55° W. ( <i>Desmoscaphites</i> )
		Utah (southeast of Emory)	Ferron Sandstone Member of Mancos Shale	N. 40° W.	North ( <i>Desmoscaphites</i> )
	Utah (south of Mount Hillers)	Ferron Sandstone Member of Mancos Shale	N. 27° W.	North ( <i>Desmoscaphites</i> )	

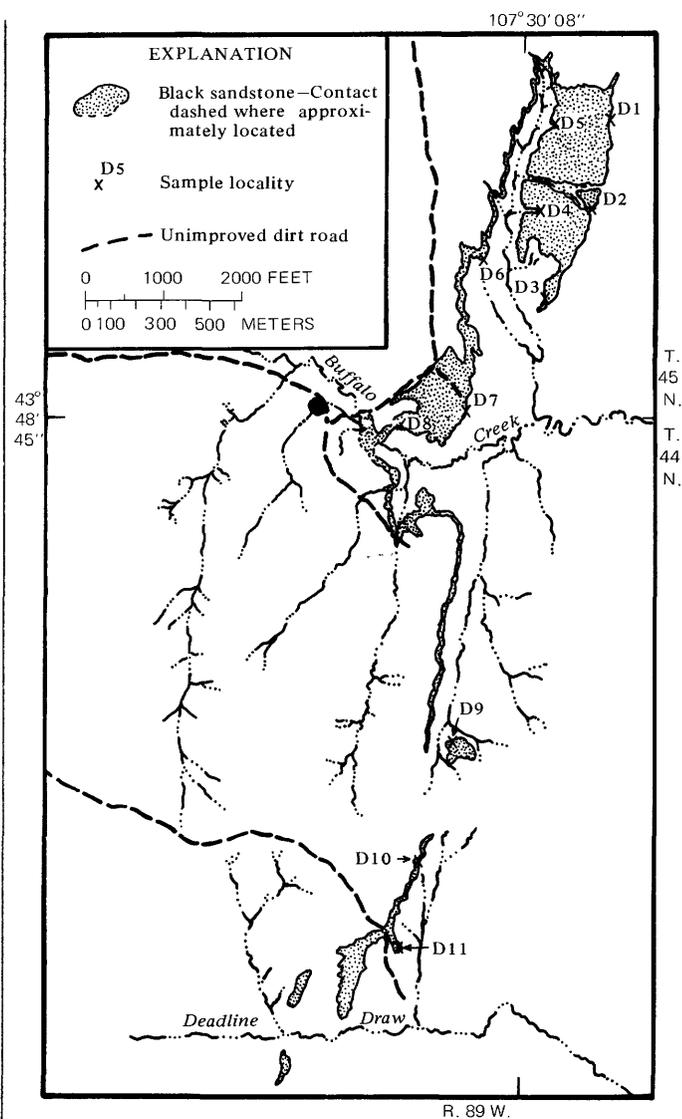
will be clear to the reader that comparisons with modern analogs are inconclusive and that similarities and differences may cancel each other in our present state of knowledge.

POSSIBLE WIND DIRECTIONS DURING  
LATE CRETACEOUS STORMS

In an earlier study (Houston and Murphy, 1962, p. 72-74) it was suggested that the form and shape of

black sandstone deposits and their heavy mineral distribution might give clues as to prevailing storm-wind directions. This suggestion was based on the work of Gardner (1955), who reported a relationship between shape of black sand deposits and mineral distribution in black sand deposits in Australia and the direction that storm waves strike the Australian beaches. Gardner (1955, p. 38) stated that the width (plan view) of a seam of heavy minerals is 30-50 feet (9.2-15.2 m) and that the thickest deposits (cross section) occur on beaches that terminate northward at a headland or other natural barrier. This type of deposit may be 5 feet (1.5 m) thick near the headland and thins gradually toward the south. Gardner did not state whether the entire beach interval thickens northward or just the heavy mineral deposits. Gardner (1955, p. 53-61) also stated that heavy minerals in Australia deposits are distributed according to their relative rates of transport, all other factors being equal. He ranked zircon slowest, ilmenite as intermediate, and rutile as having the most rapid rate of transport. He demonstrated that in deposits that terminate in a headland or creek mouth there is a small but steady decrease in zircon and increase in rutile from south to north. The Australian deposits studied by Gardner are on north-trending beaches located on the southeast coast. Storm waves strike this coast from the southeast, and Gardner believed that both the increase in thickness toward headlands at the northern termination of a deposit and the mineral distribution result from northern transport of sediment during storms.

Information on both shape and mineral distribution in Upper Cretaceous black sandstone is limited to two deposits, one in Wyoming and one in New Mexico. The best exposed deposit in Wyoming is at Buffalo Creek (secs. 34 and 35, T. 45 N., R. 89 W., and secs. 2 and 11, T. 44 N., R. 89 W.; fig. 19; fig. 3, No. 25) in the southeast Bighorn Basin. This deposit is thin at its southern end and gradually increases in thickness (cross section) to the north, which suggests northern transport using the Australian analog. At Buffalo Creek zircon decreases in abundance to the north (table beneath fig. 19), again suggesting northern transport using the Australian analog. At Buffalo Creek, however, the northern decrease in abundance of zircon is with respect to magnetite rather than ilmenite and rutile as is the case with the Australian analog. If the ratio of rutile to zircon is considered, a first approximation might be to assume that the lighter mineral rutile is being transported farther, but if the ratio of zircon to magnetite is considered, the reverse would have to be true or we must state that transport is southerly in the Wyo-



Sample locality	Ratio of zircon to total opaque minerals	Ratio of euhedral to well-rounded zircon
North D-5	0.014	0.11
D-4	.025	.09
D-6	.017	.36
D-3	.056	.72
D-8	.020	.23
D-9	.120	.55
D-10	.097	.45
South D-11	.096	.30

FIGURE 19.—Planetable map of Buffalo Creek black sandstone deposit, Washakie County, Wyo.

oming deposit according to mineral distribution evidence and northerly according to deposit shape. We believe that size is a more important factor in the transport of a mineral than specific gravity, as reviewed in the discussion on significance of grain

size. Zircon is significantly smaller than magnetite in the Upper Cretaceous black sandstone (Houston and Murphy, 1962, p. 35, fig. 8; Mellon, 1961, p. 95). Therefore, if processes of combined gravity-shear sorting are operative on beaches during storms, larger magnetite may be selectively winnowed from smaller zircon despite the higher specific gravity of magnetite.

A well-exposed deposit in New Mexico near the Sanostee Trading Post (fig. 5, No. 50; fig. 20; lat 36°27'–36°28', long 108°53'45"–108°54'45") is thicker in the southeast, suggesting southerly transport; the deposit is probably a series of overlapping lenses (Bingler, 1963), and it is questionable how far each lens extends in the shoreline direction. A series of localities distributed along the length of the Sanostee deposit (shoreline) were sampled vertically at 2-foot (0.6-m) intervals. These samples were

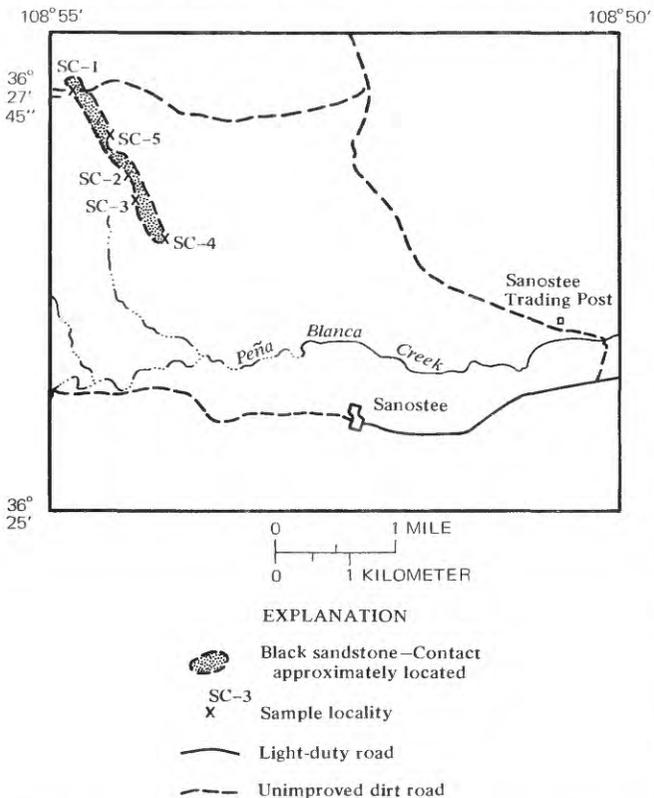
averaged, and heavy mineral grain counts were made (table beneath fig. 20). Zircon is more abundant in the south, and a euhedral variety of zircon is more abundant than a well-rounded variety in the south. At Sanostee the distribution of zircon is compared with that of ilmenite, and from size, shape, and specific gravity the distribution suggests northerly transport. However, inasmuch as the Sanostee samples may not come from the same lens, the significance of the mineral distribution is questionable.

Other deposits in the Rocky Mountains region have some characteristics that may be helpful in determining storm transport directions. For example, a well-exposed deposit in Montana near Castle Rock, in sec. 22, T. 28 N., R. 5 W., is thinner in the southeast and thicker at the northwestern end, suggesting northern transport. A vertically dipping Montana deposit east of Ringling, in sec. 17, T. 7 N., R. 9 E., is well exposed along the strike probably parallel to the ancient shoreline. It consists of a series of overlapping lenses of black sandstone that rise stratigraphically to the southeast. This configuration suggests that as the beach regressed seaward (northeast) it also migrated to the southeast and thus that there is a general southeast transport of material. Each individual black sandstone bed in this deposit thickens to the northwest (fig. 21). If the lenses of black sand rise in section as the sea regresses, the fact that the lenses rise in section to the southeast in the deposit near Ringling suggests that the direction of beach migration and sediment transport is to the southeast. The thickening of individual layers of black sandstone and overall thickening of deposits to the northwest suggests northwest transport of sand during storms. Perhaps the primary direction of longshore current movement was southeast, but during storms transport was in the opposite direction.

Other deposits appear thicker in the center and thinner at each end. Undoubtedly, the various configurations are related to the position of a deposit on the coast and its location with respect to headlands. Deposits on long stretches of beach at some distance from headlands or river mouths or other barriers might be expected to thin at each end.

*Sediment source areas*

The formation of a black sand deposit is controlled in good part by the availability of a major supply of heavy minerals. On some modern beaches, black sands are in greater abundance near deltas and distributaries (Higazy and Naguib, 1958; Mahadevan, 1958). Some of the large concentrations



Sample locality	Ratio of zircon to total opaque minerals	Ratio of euhedral to well-rounded zircon
North SC-1	0.39	0.07
SC-5	.27	.12
SC-2	.55	.21
SC-3	.67	.23
South SC-4	.71	.43

FIGURE 20.—Sketch map of black sandstone deposit, Sanostee, San Juan County, N. Mex.



FIGURE 21.—Wedge-shaped body of black sandstone that pinches out to the southeast and thickens to the northwest (behind viewer) in the upper part of the Virgelle Sandstone. White objects in the background of both photographs are sample bags approximately 9 by 5 inches (23 by 13 cm) in size. NE¼, sec. 17, T. 7 N., R. 8 E., east of Ringling, Mont., view toward southeast. Beds strike N. 30° W. and dip 80°–90° E.

are on shorelines located on the lee side of deltas with respect to the direction of longshore current movement (Mahadevan, 1958).

In southwestern Wyoming, about 34 miles south of Kemmerer, secs. 18, 19, and 30, T. 18 N., R. 116 W., and W1/2 sec. 25, T. 18 N., R. 117 W. (fig. 3, No. 35), a number of black sandstone deposits are in the lower sandstone units of the Frontier Formation (120 and 355 ft above the base of the formation) that are probably late Belle Fourche or early Greenhorn in age. The deposits lie south of a postulated major distributary (McGookey and others, 1972, p. 209) that may have developed in the area between early Belle Fourche and middle Greenhorn time. This same deltaic system is believed (McGookey and others, 1972) to have been present in late Coniacian time, and, from micropaleontologic evidence, Kent (1968) has postulated a southward drift of longshore currents.

Possible relationships of other black sandstone

deposits to deltas or distributaries are conjectural, but the deposits may be useful in locating distributaries or may eventually correlate with distributaries as detailed paleogeographic data become available.

#### WIDTH OF CRETACEOUS BEACHES AND TIDAL RANGES

Certain features of black sandstone deposits may indicate the widths and tidal ranges of Cretaceous beaches. These features include width of individual black sand lenses, grain size, dip of long traceable beds, and structure in the deposits.

Obviously, the width of an individual black sandstone deposit cannot be used as a measure of the width of the beach at any time. For example, the deposit at Choteau, Mont. (fig. 2, No. 9, T. 25 N., Rs. 5 and 6 W.) is 1¼ miles (2 km) wide, but it represents at least three distinct shifts of the shoreline in a seaward direction. At the Marias River deposit in Montana, however, it is possible to trace individual heavy-mineral-rich layers that cut obliquely across the deposit from its top in the landward direction to its base in a seaward direction. The minimum width of one of these layers has been found to be 200 feet (60 m). This is about four to six times the width of similar black sand layers in Australia (Gardner, 1955). The total width of Australian beaches varies, and there is little information on the width of a beach from the dune edge to mean low water in Australian deposits; however, Gardner (1955, p. 15) stated that a typical beach is 100–200 feet (30–60 m) wide, depending on the weather and tide. A direct comparison based on comparable width of black sandstone would suggest that the Cretaceous beach at the present site of the Marias River deposit was 800–1,000 feet (240–300 m) wide. Although other factors, such as storm intensity, are known to affect the width of a black sand lens, the ancient beach of the Marias River area undoubtedly fell within the flat beach classification of Bascom (1964, p. 194).

Additional support for the flat beach concept is the 4° dip of long traceable beds on the upper foreshore at Marias River; the dip decreases seaward and seems to flatten to less than 1°. Grain size may also be a clue to the slope of a beach for, as Bascom (1964, p. 199–201) has shown, where other factors are equal, flat beaches have fine sand and steep beaches coarse sand. The very fine grain size of sandstone of the Late Cretaceous beaches thus suggests a flat beach.

In inland seas, such as the Gulf of Mexico and the Mediterranean, the amplitude of tides is small except perhaps in narrow straits or estuaries. Small tidal amplitudes may have characterized much of

the Cretaceous seaway. Hayes (1971) classified depositional coasts that have strong downwarp and rapid sedimentation (Hayes, 1964) into hypotidal [tidal range 0–5 ft (0–1.5 m)], mesotidal [tidal ranges 5–10 ft (1.5–3 m)], and hypertidal [tidal ranges greater than 10 ft (3 m)]. Hayes noted that, as a rule, coasts with small tidal ranges are dominated by wave energy and that they are characterized by well-developed deltas of the arcuate and cusped types at the mouths of major rivers. Between major rivers, long barrier islands are present with beaches marked by a series of breakpoint bars parallel to the beach. Hayes cited the Gulf Coast of the United States, the southern Baltic coast, and coasts of southern Australia and the Mediterranean as having beaches of this type.

The Late Cretaceous beaches, especially those of New Mexico and Utah, seem to fit the hypotidal category very well; Peterson's (1969, p. 193) reconstruction of the paleogeography during the time of deposition of the John Henry Member of the Straight Cliffs Formation of southwestern Utah is an almost perfect analogy of a hypotidal coast.

The landward-facing foreshore ridges that are well substantiated in Montana have been considered by King (1959, p. 338) to be typical of very flat beaches with high tidal ranges. According to King, the development of a ridge-and-runnel system depends on several factors:

1. The beach should be very flat and have a high tidal range.
2. The ridge-and-runnel system is developed on flat beaches where waves striking the beach have a short fetch because there is an attempt to steepen the beach gradient to adjust to shorter waves. Flat beaches exposed to the open ocean may not develop ridge-and-runnel systems because the long fetch of the waves may adjust more readily to the flatter beach.
3. Ideally a large supply of sand-sized material also enhances the development of beach ridges, as the sand is needed to build up the gradient in response to the short fetch waves.

King's criteria seem opposed to those used to support the classification of the southern Cretaceous beaches as hypotidal, but Davis, Fox, Hayes, and Boothroyd (1972) cited evidence that suggests that ridge-and-runnel systems may develop on beaches with low tidal ranges. They compared beaches on Lake Michigan where tidal ranges are small with beaches of the northern Massachusetts coast where tidal ranges are large, and they showed that both

types of beaches may have well developed ridge-and-runnel systems. Davis, Fox, Hayes, and Boothroyd (1972, p. 416) showed that ridge-and-runnel systems develop after storms when erosion of the beach and adjacent dune areas supplies a source of sediment for ridge development. Therefore the presence of a foreshore ridge does not seem definitive of tidal range.

If subsidence during progradation was negligible and postdepositional compaction is negligible, the thickness of a black sandstone deposit may be used to approximate tidal range. The thickness may be representative of the height of a beach from the lower foreshore to the base of the dune, if the environmental interpretations are correct. The thickness, therefore, may be an indicator of tidal range plus height of swash. The 18-foot (5.5-m) thickness of the Marias River deposit suggests a substantial tidal range or that the beach was subject occasionally to very large waves. We do not suggest that the thickness of individual black sandstone deposits is a direct measure of tidal range because we are not certain that subsidence was negligible, compaction was negligible, or that a given deposit is a product of progradation only, but if the same general processes operate to form the various deposits, thicker deposits may be indicative of higher tidal ranges. In general, thicker deposits are in northern Wyoming and Montana, although thickness varies greatly even in a local area.

Summarizing, the hypotidal classification seems appropriate for the overall characteristics of the Utah, New Mexico, and perhaps the southern Wyoming beaches as they have been described, but evidence from the black sandstone deposits suggests that tidal ranges may have been higher in northern Wyoming and Montana.

#### SUMMARY

Fossil black sandstones may aid in reconstructing the characteristics of beaches of the Late Cretaceous seaway of the Rocky Mountains region. Although the character of the deposits varies considerably from one locality to another, most of the interpretations have been formulated through study of the better exposed deposits in Montana and Wyoming, and these deposits are different from those in Utah, New Mexico, and Arizona. Certain characteristics of Upper Cretaceous black sandstones seem common to all or most deposits and are reasonably well documented:

1. The deposits occur only in regressive sandstone where a large supply of heavy-mineral rich detritus was available.

2. The black sandstone deposit is itself a small-scale example of a regressive unit. Each deposit typically has a laminated sandstone at the base overlain by thick beds rich in heavy minerals. The laminated black sandstone was deposited on the lower part of the beach, and the heavy-mineral-rich layers on the upper part. Each deposit is typically overlain by carbonaceous shale, coal, or oyster beds deposited in lagoons or swamps during regression.
3. The upper heavy-mineral-rich layers are probably formed during major storms. Berm crests and structures typical of the backshore are largely destroyed during the storms, and so most laminae dip seaward.
4. Evidence of original dune deposits is lacking; presumably the dunes were destroyed during regression by lateral planation or by action of plants and ground water.
5. Processes of reentrainment and gravity-shear sorting may have played major roles in the deposition of laminated black sandstone. The heavy-mineral-rich layers probably resulted chiefly from gravity-shear sorting.
6. Well-exposed black sandstone deposits are useful in determining local shoreline directions.
7. The very fine grain size and low dip of laminae of most black sandstone suggests deposition on flat beaches.

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