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TITANIFEROUS BLACK SANDSTONE DEPOSITS OF WYOMING

By

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Black sandstone deposit on the northeast rim of the Grass Creek anticline, Grass Creek, Wyoming. The deposit is underlain by white littoral-type sandstone, and is overlain by a slope-forming non-marine sequence of carbonaceous shale, fluviatile channel sandstone, and coal. View looking southeast.

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By

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ABSTRACT

Black sandstone deposits are highly indurated concentrations of heavy minerals that accumulated on ancient beaches. Fourteen deposits in Wyoming were examined, and their mineralogy was studied by petrographic, X-ray, chemical, and other methods.

With the exception of one deposit in the Stump sandstone of Late Jurassic age, all the known deposits in Wyoming are in rocks of Late Cretaceous age. They occur in regressive sandstone units of the Frontier formation, Rock Springs formation, Mesaverde formation, and Lewis shale at localities in the Green River, Big Horn, Laramie, and Wind River Basins.

The heavy minerals, which comprise as much as 80 percent of the black sandstone, include anatase, apatite, biotite, chlorite, epidote, garnet, monazite, magnetite, ilmenite, "ferrian ilmenite," pyroxene, rutile, sphene, spinel, staurolite, tourmaline, zircon, and radioactive opaque minerals.

Ilmenite, "ferrian ilmenite," monazite, rutile, zircon, and the radioactive opaque minerals have potential economic value. The "ferrian ilmenite" is the most abundant mineral in the black sandstone deposits in Wyoming. It is partly altered to an anatase-hematite-goethite mixture. As a result of this alteration, the TiO_2 content is increased but is still low, averaging 35 to 40 percent. Iron-poor ilmenite is highly altered and is enriched in TiO_2 to an average of about 60 percent, but is not abundant enough to warrant exploitation of the deposits.

Monazite, rutile, and the radioactive opaque minerals occur in minor amounts but may be valuable as by-products. Zircon, containing hafnium, comprises as much as 16 percent of the heavy-mineral content of some deposits, and as such, may constitute a commercial source of zirconium or hafnium.

Two varieties of zircon, a well-rounded violet variety and a euhedral colorless variety, have been dated by the lead-alpha method as 750 million and 100 million years old, respectively. The original source of the well-rounded zircon is an area of Precambrian rocks, whereas the source of the euhedral zircon is probably the igneous rocks of Cretaceous age in the Idaho batholith. The euhedral colorless variety of zircon is abundant in older black sandstone deposits, thus providing evidence that the younger igneous rocks were exposed to erosion very early in the Laramide orogeny and provided a major part of the detritus.

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INTRODUCTION

The term "black sand" is ordinarily used to describe local accumulations of dark-colored heavy minerals which have been concentrated along beaches by the action of wind and waves. The "black sand" discussed in this paper, however, has become indurated through geologic time, and thus is called "black sandstone."

The earliest reference to indurated black sand in the Rocky Mountain region was by Stebinger (1914, p. 329-337), who made a study of titaniferous magnetite deposits on the Blackfeet Indian Reservation, Montana. Stebinger attributed the deposits to deposition along ancient beaches and compared them to deposits along present sea beaches. He concluded that the deposits were not of commercial value as sources of iron because of the high titanium content. The deposits to which Stebinger referred occur at the top of what is now termed the Horsethief sandstone (Upper Cretaceous). In a later report, Stebinger (1918, p. 165) briefly mentioned similar black sandstone in the upper part of the Virgelle sandstone (Upper Cretaceous) in the Birch Creek-Sun River area, Montana. The Virgelle deposits were reported to be thinner and less extensive than those in the Horsethief sandstone.

No known mention of black sandstone deposits is made in the literature covering the next twenty-eight years of geologic study in the Rocky Mountain region.

In 1942, a deposit 9 miles northwest of Choteau, Mont., was examined by a U. S. Bureau of Mines engineer, and an exploration project was recommended. Core-drilling exploration was undertaken in the summer of 1945 by the Bureau of Mines, and the data obtained from the project were released the following year (Wimmler, 1946). In that report the titaniferous magnetite was described as "very extensive, although the greatest concentration was apparently confined mainly to certain parts or localities in the form of beach placers, channels, or bars." Extensive metallurgical tests were conducted by the Bureau of Mines and, for the most part, the results of these tests indicated the difficulties likely to be encountered in beneficiation processes.

The renewed interest in black sandstone and the large number of deposits discovered in recent years have been primarily the result of widespread prospecting for uranium. Inasmuch as the black sandstone is somewhat radioactive, many deposits have been reported as possible uranium discoveries. Subsequent chemical analyses, however, showed that the deposits contain only small amounts of uranium.

The initial discovery of black sandstone in Wyoming was made at Grass Creek late in 1952 through use of airborne radiation equipment of the U. S. Atomic Energy Commission. The deposit was subsequently examined on the ground for its possible uranium content by D. C. Barrett (unpublished data, 1953) but no attention was given to its titanium content.

According to the records of Dr. H. G. Fisk, then of the Wyoming Natural Resources Research Institute, the Grass Creek deposit was brought to his attention in January, 1953, when he received a sample and a request for analysis from Mr. Worthington of Casper, Wyo. Mr. Worthington, since deceased, obtained a State lease on a part of the deposit (sec. 16, T. 46 N., R. 98 W.).

The writers first became aware of indurated black sand in Wyoming in January, 1954, when a sample from Grass Creek, Wyo., was submitted to the U. S. Geological Survey by Mr. P. J. Hillberry of Riverton, Wyo. Mr. Hillberry's discovery, which was apparently independent of those made earlier, was accomplished by an unusual approach to prospecting. A radiation-detection instrument was given to a sheepherder in his employ, with instructions to locate anomalous radioactivity while herding the sheep from place to place. In doing this, the herder detected the radioactivity emanating from the small uranium and thorium content of the Grass Creek black sandstone deposit. Several miles distant, a smaller deposit was located by the same method near the intersection of Cottonwood Creek and Wyoming State Highway 120.

Inasmuch as all Grass Creek samples analyzed up to 1954 had contained approximately 30 percent titanium dioxide, it was decided that the deposit was worthy of further investigation. It was subsequently examined by a field party of the U. S. Geological Survey and representative samples were collected for analyses. The results of this examination, and the analytical determinations that followed, were encouraging, and this, coupled with reports of additional black sandstone discoveries in Wyoming and adjacent areas, led to the conclusion that research studies of black sandstone should be expanded. In October, 1954, a cooperative project between the Geological Survey of Wyoming and the U. S. Geological Survey was initiated for this purpose.

Between early 1954 and 1957, deposits at fourteen different localities in Wyoming (fig. 1) were examined. Several others have been reported but were not examined. Two preliminary reports have been published about black sandstone deposits in western Wyoming (Murphy and Houston, 1955, and Houston and Love, 1956).

During 1955 and the early part of 1956, many deposits of radioactive black sandstone were reported in northwestern New Mexico, southwestern Colorado, and northeastern Arizona (pl. 9). Most of these deposits were located by airborne radiation-detection equipment operated by personnel of the U. S. Atomic Energy Commission. Samples of these deposits were submitted to the authors by W. L. Chenoweth and Bryan Archer of the Atomic Energy Commis-

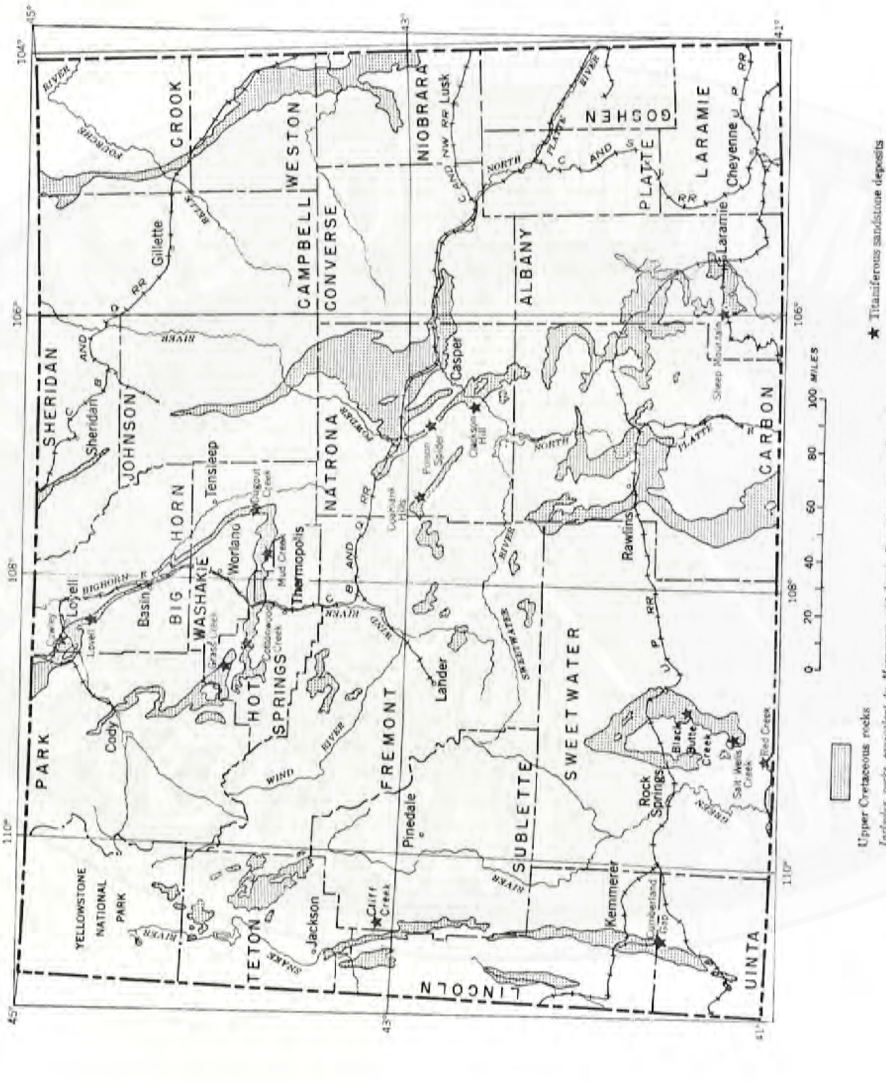


Figure 1. Index map of Wyoming showing geologic and geographic setting of titaniferous sandstone deposits.

sion, and J. F. Murphy later made a reconnaissance study of many of the deposits. The regional setting and the general physical characteristics of these deposits have been reported by Chenoweth (1956, p. 1792) and Murphy (1956), and the mineralogy of a deposit near Gallup, N. Mex. has been discussed by J. E. Allen (1956, p. 1789). Early in 1956, Murphy and R. B. O'Sullivan, also of the U. S. Geological Survey, visited and sampled other reported deposits in the southern San Juan Basin of New Mexico and the Black Mesa Basin of Arizona. Samples of most of these deposits outside of Wyoming have been studied in considerable detail for comparison with occurrences of black sandstone within the State.

Since the completion of the present manuscript, two significant reports have been published which add materially to the knowledge of Upper Cretaceous black sandstone deposits in the Rocky Mountain region. One of these reports, by V. T. Dow and J. V. Batty (1961) of the U. S. Bureau of Mines, discusses many of the deposits listed in the present report, but in the main, it emphasizes tonnage, grade, and economic potential of the deposits. The second report, by G. B. Mellon (1961), discusses deposits in the Crowsnest Pass region of southwestern Alberta which are similar stratigraphically and mineralogically to those described in this report. Both reports are cited in the general references of this bulletin but at the time of their publication, the present report was too far advanced to permit adequate reference within the text which would otherwise be desirable and helpful to the reader.

Chemical and spectrographic analyses for this investigation were furnished by personnel of the U. S. Geological Survey. Mr. L. B. Riley of the U. S. Geological Survey has been especially helpful in offering advice and encouragement on all phases of analytical work. Mr. J. F. Smith of the U. S. Bureau of Mines provided valuable X-ray data. Dr. H. G. Fisk of the Wyoming Natural Resources Research Institute gave freely of his time in the discussion of problems involving the mineralogy of the deposits. Mr. L. E. Lynd generously furnished samples of altered ilmenite from black sand deposits in Florida and Quilon, India. Personnel of the U. S. Atomic Energy Commission have been especially cooperative in all phases of the investigation. Dr. H. D. Thomas, State Geologist of Wyoming, and Dr. W. H. Wilson, Assistant State Geologist, have critically read the manuscript, and with Dr. D. L. Blackstone, Jr., of the University of Wyoming, have offered many helpful suggestions. Dr. S. H. Knight generously permitted the use of the many facilities of the Department of Geology, University of Wyoming. All sample preparation and some of the analytical work were done by Mr. B. L. Short, and the illustrations were drafted by Shirley H. Jereb, Lorraine D. Christensen, and Beth Van Blair. Betty Jo Doyle was especially helpful in many stages of manuscript preparation including typing, assembling, and proofreading. The permission of the many claim owners to sample the rocks on their claims is gratefully acknowledged.

METHOD OF STUDY

FIELD

Fourteen deposits of black sandstone in Wyoming have been examined since the beginning of the investigation. Where possible, the deposits were mapped on aerial photographs or topographic base maps. When photographs or topographic maps were not available, sketch maps were made using the pace and compass method.

Each deposit was systematically sampled, but because of the highly indurated state of most of the black sandstone, chip samples were generally collected at several places along the length of each black sandstone lens. An effort was made to sample the thickest, intermediate, and thinnest parts of each deposit, and also to select samples of the high-grade, low-grade, and barren zones. With the exception of a few random grab samples, sampling was done at regular intervals across fully exposed sections of the lens, the interval depending largely on the grade, bedding, and thickness of the deposit. Where the deposit was thin and showed thin-bedded alternations of high- and low-grade rock, samples were taken at 6-inch intervals; where the bedding was thick or massive and the rock appeared to be of relatively constant grade, samples were taken at 1- or 2-foot intervals. Equal volumes of the samples from each point were later combined in the laboratory to determine as accurately as possible the average grade.

To study the effects of weathering, a suite of samples representing both the least and the most weathered rocks in each deposit was collected. Two of the deposits had been drilled or excavated by prospectors, and fresh, relatively unaltered samples were available, but for the most part, the samples collected were surface rocks in varying degrees of alteration.

LABORATORY

Standard laboratory methods, such as those used by Hutton (1950, p. 637-646) in an analysis of New Zealand unconsolidated black sand, were followed in this study. The general procedure used is outlined in figure 2. The black sandstone, however, differs from most of the previously studied unconsolidated black sand in that most samples are hard and coherent, and in general, most of the opaque minerals are highly altered. For example, part of the iron oxide and titanium oxide was removed from the opaque minerals during alteration and subsequently became a part of the cement. This abundance of ferric oxide cement, and the coherence of the samples, makes disaggregation difficult. The samples were first broken down by pounding in a steel mortar, and then by boiling in 1:6 hydrochloric acid for at least one hour until individual grains were free of iron stains (fig. 2). The acid probably caused some loss

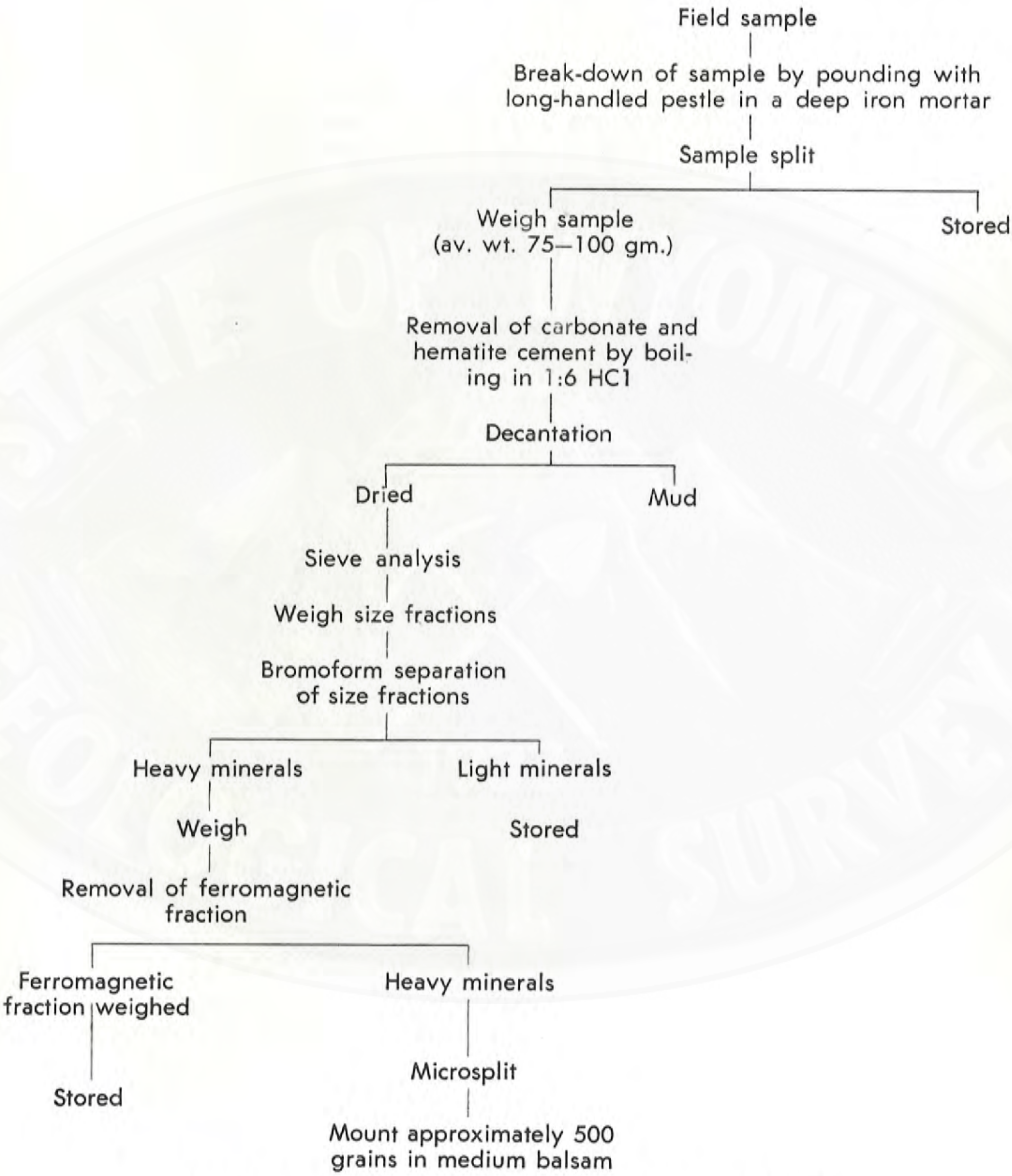


Figure 2. Procedure for preparation of field samples for mineral analyses.

of acid-soluble heavy minerals, but the amount is believed negligible. For example, quantitative analyses for monazite show very little difference between the samples that were boiled in acid and those that were not.

Mechanical analyses of most samples were made with Tyler sieves of 60, 80, 115, 170, 250, and 325 mesh. Bromoform separations of heavy minerals were made using the flat-bottom Coors dish. Ferromagnetic fractions were removed from heavy-mineral suites by passing an electromagnet over grains scattered on a surface of sheet aluminum. The electromagnet was especially designed to separate pure magnetite from pure ilmenite.

Identification of nonopaque minerals was made with standard immersion methods using the petrographic microscope. Index measurements were checked with a Leitz-Jelly microrefractometer. Opaque minerals were studied for the most part by polished-section methods, although supplementary information on specific minerals was obtained by X-ray diffraction, X-ray spectrographic, differential thermal, and chemical analyses. Grain counts were made on an average of seven samples from each of the deposits in Wyoming; at least 1,200 heavy mineral grains, 400 in each of the 115-, 170-, and 250-mesh sizes, were counted from each sample; thus, a total of approximately 8,400 grains were counted from a single deposit. It should be emphasized that only one sample was studied from each of the deposits in areas outside of Wyoming, and therefore the mineral percentages given for these deposits may be less representative of the deposit as a whole.

ELECTROMAGNETIC FRACTIONATION

Magnetic separations of the nonferromagnetic fraction were made with the Frantz magnetic separator. Both Hutton (1952, p. 13-16) and MacKay (1949) have listed the ampere range for the extraction of various common minerals using the Frantz separator. Figure 3 shows these ranges and ranges for several other minerals that were determined during the present study.

MINERAL CONCENTRATION TECHNIQUES

The Frantz magnetic separator was also used to concentrate minerals for chemical, X-ray, and spectrographic analyses, but precise mineral separation for these purposes was hampered because many of the opaque mineral grains were partially altered. Magnetic susceptibility of the opaque minerals decreases as the degree of alteration increases and, because the degree of alteration was highly variable, some opaque mineral grains separated out in every magnetic fraction. The problem of contamination was partly overcome by the use of simple electrostatic methods as outlined by Holmes 1930, p. 96).

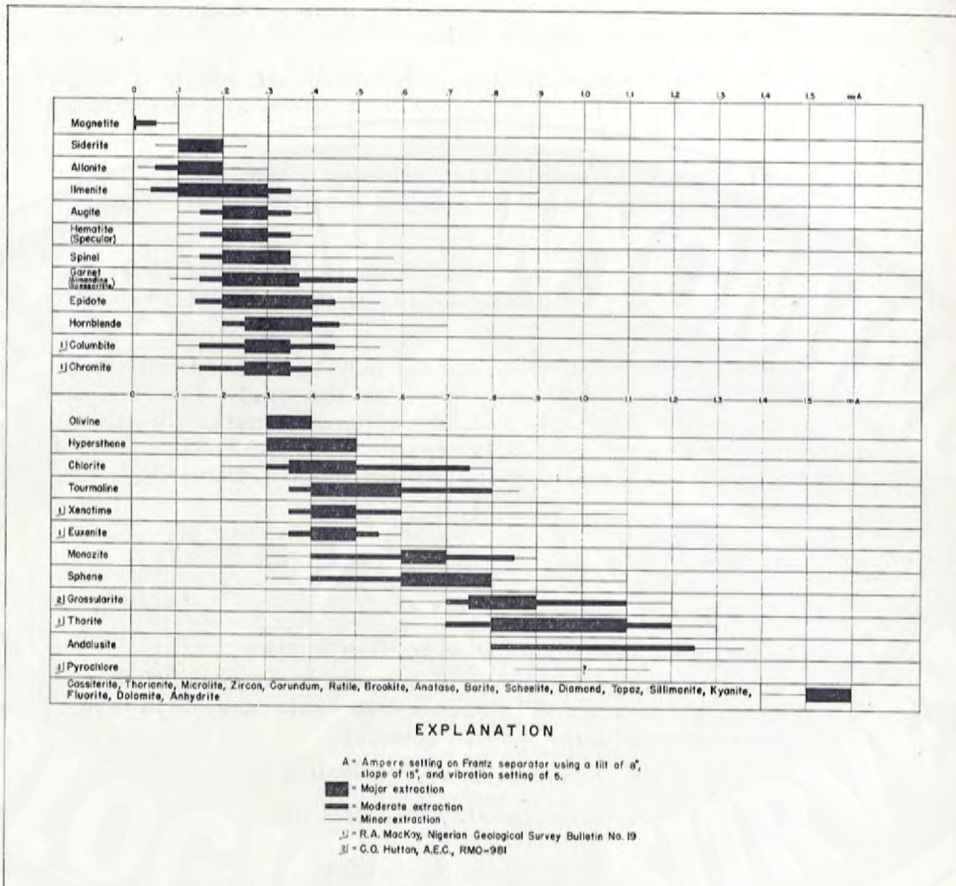


Figure 3. Magnetic susceptibility of common heavy minerals.

The most difficult problem in mineral concentration was the separation of two varieties of zircon for age determination. Both varieties have equal magnetic susceptibility, and hence, could not be separated by magnetic methods. Although considerable handpicking was required, the difference in rounding between the two varieties was of some advantage. The minerals were scattered over sheet aluminum, and by tapping the sheet, a rough separation of round versus euhedral grains was achieved.

Statistical Computations

Quartile measures were used to compare data of grain-size analyses. Standard procedure for computation of these measures involves computation of three values, as follows:

(1) Md, the median diameter; that diameter which is larger than 50 percent of the diameters of distribution, and smaller than the other 50 percent.

(2) Q_1, the first quartile; that diameter which has 25 percent of the distribution by weight smaller than itself and 75 percent larger than itself.

(3) Q_3, the third quartile; that diameter which has 75 percent of the distribution by weight smaller than itself and 25 percent larger than itself.

The median diameter and the quartiles may be taken directly from a plotted cumulative frequency curve. In this study, however, the median diameter and quartile measures were computed arithmetically, following a procedure outlined by Bryant (1953, p. 35-41). The following formula was used in computing the median diameter:

$$Md = L + \frac{(g)\,c}{f}$$

where:

Md=median diameter

L=lower boundary of estimated median interval

g=one-half the total number of frequencies in the distribution minus the number of frequencies up to the median interval

f=the frequency of the median interval

c=the size of the class interval of the median interval

For computation of the quartile measures the same formula was used as follows:

$$Q_1 \text{ or } Q_3 = L + \frac{(g)\,c}{f}$$

where:

Q_1=first quartile

Q_3=third quartile

L=lower boundary of quartile interval

g=one-fourth the total number of frequencies for Q_1 and three-fourths the total number of frequencies for Q_3, minus the total number of frequencies up to the quartile interval

c=class interval of the quartile interval

f=the number of frequencies of the quartile interval

The sorting and skewness coefficients were computed from the quartile measures and median diameter. The sorting coefficient (So) is defined as a mathematical measure of the degree of sorting of a sediment (Trask, 1932, p. 26). It is computed using the following formula:

$$So = \sqrt{Q_3/Q_1}$$

The coefficient of skewness (Sk) is defined as a measure of the dissymmetry in the size distribution of the particles in a sediment (Trask, 1932, p. 27) and can be computed using the following formula:

$$Sk = Q_1\ Q_3/(Md)^2$$

GEOGRAPHIC DISTRIBUTION

Black sandstone deposits are known in Montana, Wyoming, Colorado, Utah, New Mexico, and Arizona. Although outcrops of the sedimentary formations that contain these deposits are widespread throughout the Rocky Mountain region, the black sandstone deposits are sporadic in their occurrence. The distribution of the black sandstone and information concerning environment of deposition suggest the likelihood of many more deposits beneath younger rock units in areas where Upper Cretaceous strata are not exposed.

In Montana, the known deposits are located in the northwestern part of the State in a belt lying between the eastern front of the Rocky Mountains and the Sweetgrass arch. Most lie west of Cut Bank and northwest of Choteau. They are readily accessible by road and are within convenient distance of branch lines of the Great Northern Railway.

In Wyoming, the known black sandstone deposits crop out along the peripheries of the intermontane basins (fig. 1). Deposits in the Bighorn Basin are near Cowley and Lovell in the north, near Grass Creek in the southwest, and near Tensleep in the southeast. Three deposits are exposed in the extreme eastern part of the Wind River Basin. In the Laramie Basin of southeastern Wyoming, a deposit crops out at the north end of Sheep Mountain, about 25 miles west of Laramie. In southwestern Wyoming are at least four deposits along the margins of the Rock Springs uplift, and another near Cumberland Gap, about 17 miles south of Kemmerer. Northwestern Wyoming has a single known deposit near Cliff Creek, about 20 miles southeast of Jackson. The Cliff Creek deposit is unique in that it occurs in the Stump sandstone of Late Jurassic age.

The known deposits in Colorado are in the western part of the State. One is on the south flank of Grand Mesa, about 30 miles southeast of Grand Junction, and six are in southwestern Colorado near the Mancos River (Murphy, 1956). Nearly all these deposits are close to paved highways or passable dirt roads.

Two deposits have been reported in southern Utah. One of these is on the Kaiparowits Plateau, about 25 miles west-northwest of the confluence of the Colorado and San Juan Rivers. The other is on the south flank of the Henry Mountains, about 10 miles southwest of Mount Hillers. The accessibility of the Utah black sandstone deposits is not known to the writers, but the deposits lie in rugged plateau country that is dissected with steep-walled canyons.

Many deposits crop out around the periphery of the San Juan Basin in northwestern New Mexico. The greatest concentration of black sandstone lenses in that region lies northeast of Shiprock and northwest of Farmington (Murphy, 1956), and isolated deposits are present near Sanostee, Toadlena, Gallup, Crown Point, Star Lake, Miguel Creek Dome, Cabezon, and Stinking Lake. Most of the New Mexico deposits are accessible by paved or passable dirt roads.

The known Arizona deposits are in the northeastern part of the State (Murphy, 1956) in Black Mesa Basin. Two deposits are located 5 and 9 miles, respectively, north of the Black Mountain Trading Post on the Apache Indian Reservation. Another, on the Hopi Indian Reservation, is about 10 miles north of the Pinon Trading Post. These deposits can be reached by graded or unimproved dirt roads.

GEOLOGY

With the exceptions of black sandstone in the Frontier formation and the Stump sandstone, all deposits were laid down during regressions of the Late Cretaceous sea. The paleogeological environments of deposition of the Frontier and Stump deposits are not thoroughly understood, and hence, the following remarks are largely confined to the remainder of the known Wyoming deposits.

In the Rocky Mountain region the black sandstone deposits have very similar characteristics, which is not surprising inasmuch as they are all fossil beach placers laid down in nearly identical environments. Stratigraphically, they are almost everywhere associated with rocks deposited in a normal regressive sequence. The original long axes of the deposits were parallel to the direction of the strand lines of the Late Cretaceous sea.

The gross mineralogic characteristics are also the same from one deposit to another, regardless of the geographic locality. This is not unusual, however, even though many widely different source areas along the Cordilleran geanticline must have contributed debris to the vast Late Cretaceous sea. The black sandstone deposits are largely concentrations of heavy minerals having specific gravities greater than 4.0, and there are but few common rock-forming minerals of such density.

STRATIGRAPHIC ENVIRONMENT

The normal stratigraphic succession of rocks associated with black sandstone deposits is threefold; it includes a lower marine shale or sandy shale, an overlying littoral sandstone, and an upper nonmarine sequence of coal, carbonaceous shale, and fluviatile channel sandstone. These rocks were deposited during the regressive stages of the last great sea that inundated the Rocky Mountain region. The easterly retreat or regression of this sea was caused primarily by a rising land mass to the west accompanied by a subsidence of the trough of deposition occupied by the sea. The great volume of rock debris eroded from the rising land mass was transported by rivers and streams to the sea, where it accumulated along the beaches and in the shallow-water areas. Upon reaching the sea, the debris was reworked and winnowed by wave action, and the coarser sand fraction was deposited along the shore in the form of beaches, bars, and spits. Finer grained sand and silt fractions were carried progressively farther seaward, where they were deposited as near-shore sands and off-shore muds. Hence, a layer of sediments deposited during any given time interval shows a decrease in grain size in a seaward direction.

During this period of regression the land area adjacent to the coastline had a very gentle gradient toward the sea, comparable perhaps to the coastal areas around the present Gulf of Mexico. Vast flood plains extended landward from the coast lines. The drainage across these flood plains was normally sluggish, and directly behind dunes and bars of the beach area, large swamps and lagoons formed. Lush vegetative material deposited in these swamps was later to become extensive coal deposits. As the beaches and bars built farther eastward, the coastal-swamp and flood-plain environments also shifted eastward, and deposits of carbonaceous silt and channel sand were laid down upon the sands of the beach environment. This pattern of deposition resulted in the typical sequence of regressive deposits now observed in parts of the Upper Cretaceous section throughout much of the region.

The marine shale, which forms the lower part of the threefold succession, is grayish buff to dark gray, very thinly bedded, locally glauconitic, and in some places highly fossiliferous. The shale generally thickens in an easterly direction and in places exceeds 4,000 feet. For the most part, the shale was deposited as mud and silt in shallow water, but at a great distance from the shoreline. Where deposition took place nearer shore, the shale is more sandy and somewhat lighter in color. Throughout most of Colorado, Utah, New Mexico, and Arizona the sequence is represented by the Mancos shale. In Wyoming, it is variously termed Cody, Steele, Baxter, or Hilliard shale. In western Montana, the name Colorado shale has been in common usage, but it has been replaced by the term Marias River shale of the Colorado Group (Cobban and others, 1959). All along the eastern front of the Rocky Mountains the name Pierre shale is used exclusively.

The contact between the marine shale and the overlying littoral sandstone is transitional. Sediments in the transition zone were deposited in near-shore waters, probably below low-tide level, and represent the sand-mud transition between beach sand and off-shore mud. In some places the transition zone consists of 100 feet or less of interbedded shale and very fine grained sandstone. In other places, the transition was much more gradual and includes as much as 2,000 feet of sandy shale. The upper contact is usually placed at the base of the lowermost massive sandstone in the section. Generally, the entire transition zone is included as part of the underlying shale sequence and is, at some places, given a formal name as a member of the shale formation. In many parts of Wyoming, the transition zone attains a thickness of as much as 2,000 feet and is called the sandy member of the Cody shale (Troyer and Keefer, 1955). Less commonly, the transition zone is included as the basal part of the overlying formation. In the Durango area, Colorado, Zapp (1949) termed the transitional beds the lower member of the Point Lookout sandstone.

The sandstone that directly overlies the transition zone is the host rock for the black sandstone deposits. This sandstone is for the most part a true littoral deposit in that it was deposited in the immediate vicinity of the beach. It typically consists of a fine-grained massive cliff-forming sandstone in which bedding features are inconspicuous or absent. In places, however, several thick layers can be recognized. The bedding features are probably obscured in part by the homogeneous lithology and grain size which resulted from the selective winnowing action of the waves. The sandstone generally maintains a uniform appearance and thickness, but locally it is absent. The thickness and uniformity of the sandstone were probably dependent upon the rate of trough subsidence and the supply of debris. For the most part, the sandstone is light tan but locally it is light gray to white. The white color, frequently called "white cap," is believed by Spieker (1949, p. 64) to indicate an overlying coal zone. During deposition in the coastal-swamp environment, leaching by swamp waters removed ferruginous matter from the underlying littoral sandstone. One of the most characteristic features of the littoral regressive sandstone deposits is the sharply defined upper contact. This feature has been discussed by Spieker (1949, p. 64), who attributes the clear-cut tops of the sandstone beds to subaerial gradation across successive beaches as the debris from adjacent land areas was swept into the sea and reworked by waves.

In many areas in Montana, Colorado, Utah, and New Mexico, the littoral sandstone sequence has been given formational status. This is also true in some parts of Wyoming, but generally the littoral sandstone is considered the basal sandstone of the Mesaverde formation. Two of the littoral regressive sandstone deposits that have been given formal status in Wyoming are the Lazeart sandstone member of the Adaville formation and the Fox Hills sandstone. At least the lower parts of the Parkman and Bacon Ridge sandstones are also littoral regressive deposits. The terminology and stratigraphic position of those in adjacent Rocky Mountain States is shown on plate 1 (in pocket).

At most places, the black sandstone deposits occur at the top of the littoral regressive sandstone. They do not overlie the regressive sandstone, but rather they comprise the uppermost stratum for short distances. A few of the black sandstone deposits, however, are lenses within the regressive sandstone, but these also are in the upper part. In general, the contacts of each black sandstone deposit with the host sandstone are well defined, largely because of the marked color contrast (frontispiece), but the base of each deposit is somewhat gradational with the underlying sandstone.

With few exceptions, the littoral regressive sandstone or the black sandstone deposits are directly overlain by a nonmarine sequence of carbonaceous shale, fluviatile sandstone, and commonly coal. The carbonaceous shale and coal are gray, black, and grayish brown, depending largely on the abundance of carbonaceous material.

The carbonaceous shale was deposited as silt and mud in coastal swamps directly inland from the beach area. During long periods of shoreline stability, deposition in the swamp areas was probably at a minimum, thus allowing a heavy vegetative growth to thrive. This accounts for the thick coal beds that are common in this part of the stratigraphic section. At many places the coastal swamps were apparently invaded periodically by marine waters. As a result, fossils indicative of brackish water and lagoonal environments are common in the lower part of this sequence. Farther inland, on the flood plain away from the sea, fewer and less extensive swamps existed and hence, fewer coal deposits were formed.

The sandstone beds of the nonmarine sequence are light tan to light gray, fine grained, lenticular, cross laminated, and thin to thick bedded. They were deposited in the channels of sluggish meandering river systems which drained the land areas to the west. Sandstone beds in this sequence are commonly coarser grained to the west and in some places are conglomeratic.

The thickness of the carbonaceous shale and sandstone sequence is as much as several thousand feet, but it varies greatly from place to place. Generally, it thickens in a westward direction and thins, in many areas to a wedge-edge, in an eastward direction.

Throughout most of Wyoming the carbonaceous shale and fluviatile sandstone sequence is represented by the part of the Mesaverde formation directly overlying the basal regressive sandstone. In the Rock Springs uplift this sequence is included in that part of the Rock Springs formation directly overlying the basal sandstone (Sears, J. D., 1926). In some Wyoming areas, however, the nonmarine rocks are given member status and are variously called the middle member of the Mesaverde formation (Dobbin and others, 1929, p. 18) and the Coaly sequence of Upper Cretaceous rocks in northeastern Teton County, Wyo. (Love and others, 1951).

The stratigraphic units that overlie the threefold sequence are highly varied in lithology and color and with only minor exception they are of continental origin. The exceptions occur in areas where the sea readvanced sufficiently to permit the transgression of marine sediments upon the preexisting nonmarine sediments. These transgressions probably occurred whenever trough subsidence took place at a greater rate than deposition. They were commonplace during Late Cretaceous time, but for the most part they were minor and the resulting marine sediments did not greatly affect the stratigraphic succession. The most significant and widespread readvance of the Late Cretaceous sea in the Rocky Mountain region is represented by the Lewis shale (pl. 1). Each readvance of the sea was followed by a retreat during which the regressive cycle of deposition was repeated.

GENERAL FEATURES

The individual black sandstone deposits are elongate lenticular bodies, resembling in many respects accumulations of black sands found along modern beaches. In cross section the deposits generally have a flat upper surface and a convex lower surface. At most places the size and shape of the deposits are difficult to estimate because of cover by younger strata or removal by recent erosion. In other places, however, such as at Grass Creek and Dugout Creek, the deposits are well enough exposed to permit a partial reconstruction of their original size and shape. At Grass Creek, the original deposit was probably at least 4 miles in length, and possibly longer. Each end is now covered by younger strata. The width of the deposit is about 800 feet and it has a maximum thickness of 16 feet. The Dugout Creek deposit is about 2.7 miles long and about 1,750 feet wide. The width of the Dugout Creek deposit has probably been slightly decreased by recent erosion, but the length is believed to be essentially the original length of the deposit. The maximum exposed thickness of the deposit is 25 feet, but core drill data indicate an even greater thickness.

The deposits may be divided into two types: 1) high grade, containing more than 20 percent heavy minerals and 2) low grade, containing less than 20 percent heavy minerals. Many deposits contain both high- and low-grade material (pl. 2), but generally each deposit is mainly one or the other. The grade of the black sandstone bears no relation to the size of the deposit. For example, the Dugout

PLATE 2
Interbedded high- and low-grade sandstone lenses in the Grass Creek deposit.

Creek deposit contains the largest known tonnage of all Wyoming deposits, but the maximum sample assay from the Dugout Creek deposit is 14.8 percent heavy minerals, whereas a sample of the Salt Wells Creek deposit, which is apparently one of the smallest Wyoming deposits, contains 98 percent heavy minerals after removal of the acid-soluble matrix. On the other hand, many samples taken from the large deposit at Grass Creek contain in excess of 95 percent heavy minerals after removal of soluble matrix, and many samples of small deposits contain less than 20 percent heavy minerals.

The long axes of the black sandstone lenses have a general northerly trend in all Wyoming deposits where exposures are sufficient to permit reconstruction of the approximate original shape of the lens. This presumably is parallel to the trend of the strand line during Late Cretaceous time. Folding and erosion have made reconstruction difficult or impossible for many of the Wyoming deposits, but an excellent case for parallelism between long axes and strand lines can be demonstrated for deposits in the San Juan Basin of New Mexico and southwestern Colorado (Murphy, 1956, p. 6). Regional strand-line directions at various stages of advance and retreat of Late Cretaceous seas in the San Juan Basin have been worked out by Sears and others (1941, pl. 26), and by Pike (1947, p. 94). The long axes of black sandstone deposits in the Pictured Cliffs, Point Lookout, and Gallup sandstones align almost precisely with the trends indicated by these previous studies.

The direction of the long axes can be determined in both the Grass Creek deposit, where it is about N. 15° W., and in the Dugout Creek deposit, where it is about N. 15° E. The long axis of the Lovell deposit trends about N. 30° W., but the deposit may be only a small remnant of the original. The general northerly trend of these and other Wyoming deposits might guide drilling in the search for extensions of the deposits beneath overburden.

The exposed upper surfaces of most of the black sandstone deposits are irridescent black to purplish maroon. These dark colors stand out conspicuously against the white to light-tan sandstone upon which the deposits lie (frontispiece). In many places the deposits are overlain by a nonresistant sequence of coal, carbonaceous shale, and lenticular sandstone. At most places, these rocks are readily stripped back by erosion, leaving the highly indurated black sandstone as the caprock on ridges and mesas. At places where the black sandstone has been stripped of its overburden, it is clearly visible from the air or on aerial photographs because of its dark appearance. Some deposits, such as most of those found on the Rock Springs uplift, are overlain by thick beds of sandstone and lesser amounts of coal and shale. These sandstone beds are not so easily eroded, and the black sandstone deposits are exposed as dark lenses on steep hillsides or cliffs. The Salt Wells Creek and Black Butte Creek deposits are of this type.

The color of black sandstone samples taken from below the surface is largely dependent upon the depth of weathering and oxidation by ground water. In most deposits a zone of highly altered brownish-red to brick-red rock lies directly below the surface. Below this red zone is a zone of less altered rust-brown sandstone. These colors are caused largely by alteration products such as hematite and goethite. Unaltered samples from deep cuts or core holes are generally black or gray depending on the percent of dark heavy minerals.

Where the upper surface of the deposits is exposed to weathering, it generally has a flaggy fracture, and the surface is littered with broken slabs of extremely indurated black sandstone (frontispiece). This is particularly true of deposits that have been exposed to oxidation and weathering for a long time. The crustlike surface induration is caused by a chemical breakdown of the opaque minerals, particularly ilmenite and magnetite, and subsequent transfer of iron from the mineral grains to the matrix, where it acts as cement. This alteration is most intense at the surface, and hence, the induration is most extreme at the surface. The undersides of some of the fractured slabs of black sandstone that litter the surface of the deposits are coated with white carbonate, which is caliche precipitated from ground water.

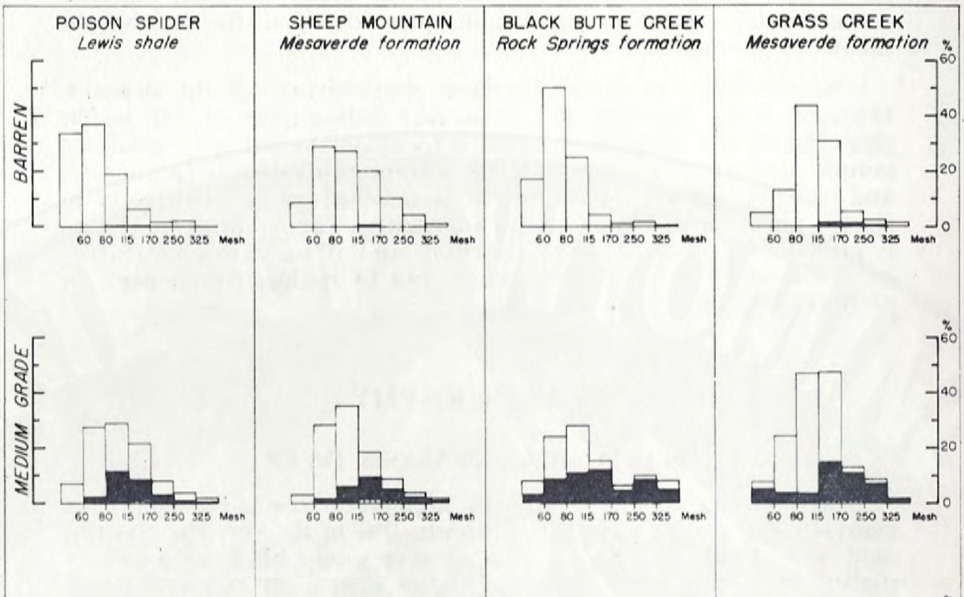
Bedding planes are discernible only where the abundance of heavy minerals changes markedly. The high-grade deposits are relatively homogeneous sandstone that generally lacks distinct bedding planes; but low-grade deposits have many alternations between high and low concentrations of heavy minerals, and bedding is generally well-defined. Bedding in low-grade deposits is further accentuated by a greater induration of the beds containing high concentrations of heavy minerals; these beds form resistant ledges that stand out conspicuously.

Conspicuous cross lamination is uncommon in black sandstone deposits. The cross lamination is mostly in low-grade deposits or in low-grade zones marginal to higher grade deposits. Cross laminae found in high-grade rock are inconspicuous because of the homogeneity of the black sandstone.

The deposits tend to be well sorted. Histograms (fig. 4 and pl. 3) show a distinct peak between the 115- and 170-mesh sizes, which is in the range of very fine grained sand.

With the exception of the euhedral variety of zircon, all the mineral grains are well rounded and have moderate sphericity. In many hand specimens the roundness of the grains is so conspicuous that the rock superficially resembles an oolite.

Owing to the very fine grain size of the constituents in the black sandstone, few minerals can be identified without laboratory study. Zircon, black opaque minerals, and quartz can be recognized in most samples with a hand lens. Samples rich in zircon sparkle in sunlight



E X P L A N A T I O N

Tyler Sieves		Wentworth Grade Scale, Mm.
Mesh	Mm.	
60	.246	.250 (1/4) Fine sand
80	.175	
115	.124	.125 (1/8) Very fine sand
170	.088	
250	.061	062 (1/16) Silt
325	.043	

(Ferric iron and carbonate matrix removed by 10% HCl)

Figure 4. Histograms showing variation in grain size with grade of the sample.

because light is reflected by crystal faces. Under shortwave ultra-violet light the euhedral zircons emit an orange fluorescence which is helpful in estimating the zircon content of the samples. Other minerals are generally present in such small quantities that they cannot be identified in the field.

Radioactivity is another marked characteristic of the deposits. Wyoming black sandstone has an average radioactivity of 0.10 mr/hr above background where measured directly on the outcrop. Analyzed samples contain an average of 0.008 percent equivalent uranium (eU) and 0.002 uranium. The uranium is believed to be principally in zircon, but a small amount is in monazite. The uranium in zircon is probably in radioactive equilibrium, and if so, excess radioactivity is caused by thorium in monazite and by radioactive elements in niobium-bearing opaque minerals.

PETROGRAPHY

MECHANICAL-ANALYSIS DATA

Modal diameters of grains in high-grade black sandstone are generally between 1/8 and 1/16 mm., which is in the very fine grained sand size of the Wentworth scale. Lower grade black sandstone is slightly coarser grained than the higher grade. It contains grains with modal diameters between 1/4 and 1/8 mm., which is in the fine-grained range. Associated barren sandstone is slightly coarser than low-grade sandstone but the grain size is still within the fine-grained range (fig. 4). The average median diameter for grains in the black sandstone is 0.132 mm., and for associated barren sandstone 0.170 mm. figs. 5 and 6).

The average sorting coefficient for Wyoming black sandstone is 1.40 and for associated barren sandstones 1.29 (fig. 5). As might be expected for a well-sorted sediment, the black sandstone has skewness or symmetry approaching unity. In general, the finer grained fractions are larger than the coarse grained, but there are some exceptions.

MATRIX

The matrix of black sandstone containing abundant opaque minerals is chiefly iron oxides, anatase, and rutile, whereas the matrix of sandstone containing minor amounts of opaque minerals is chiefly carbonate (pl. 4A). A detailed study was made of the insoluble part of the matrix of a sample from the Black Butte Creek deposit on the east flank of the Rock Springs uplift. After the sample had been disaggregated by boiling in hydrochloric acid, the solvent was decanted and the fine fraction (less than 325 mesh) was separated. X-ray and differential thermal analyses of the fine fraction showed it to be com-

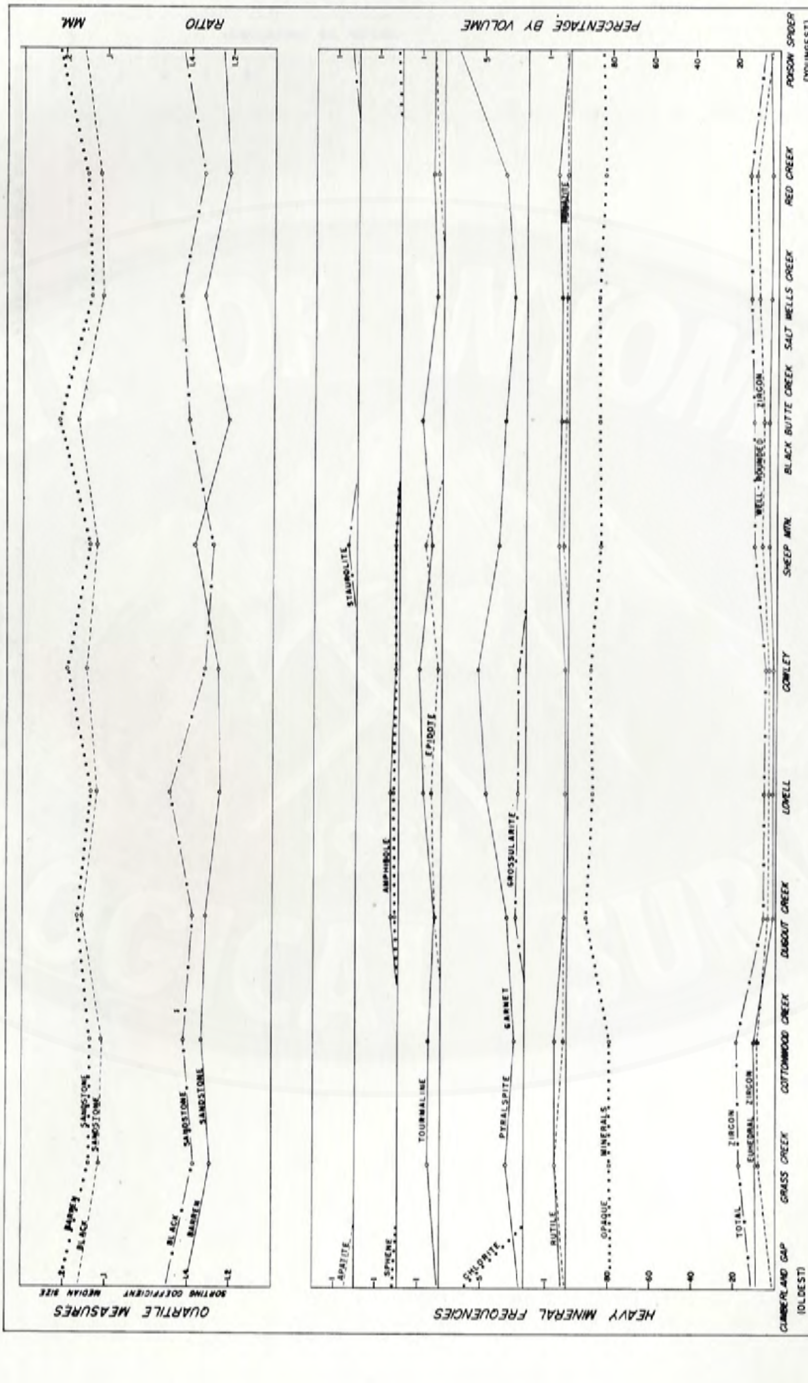


Figure 5. Quartile measures and heavy-mineral frequencies of Wyoming Upper Cretaceous black sandstone deposits arranged according to age.

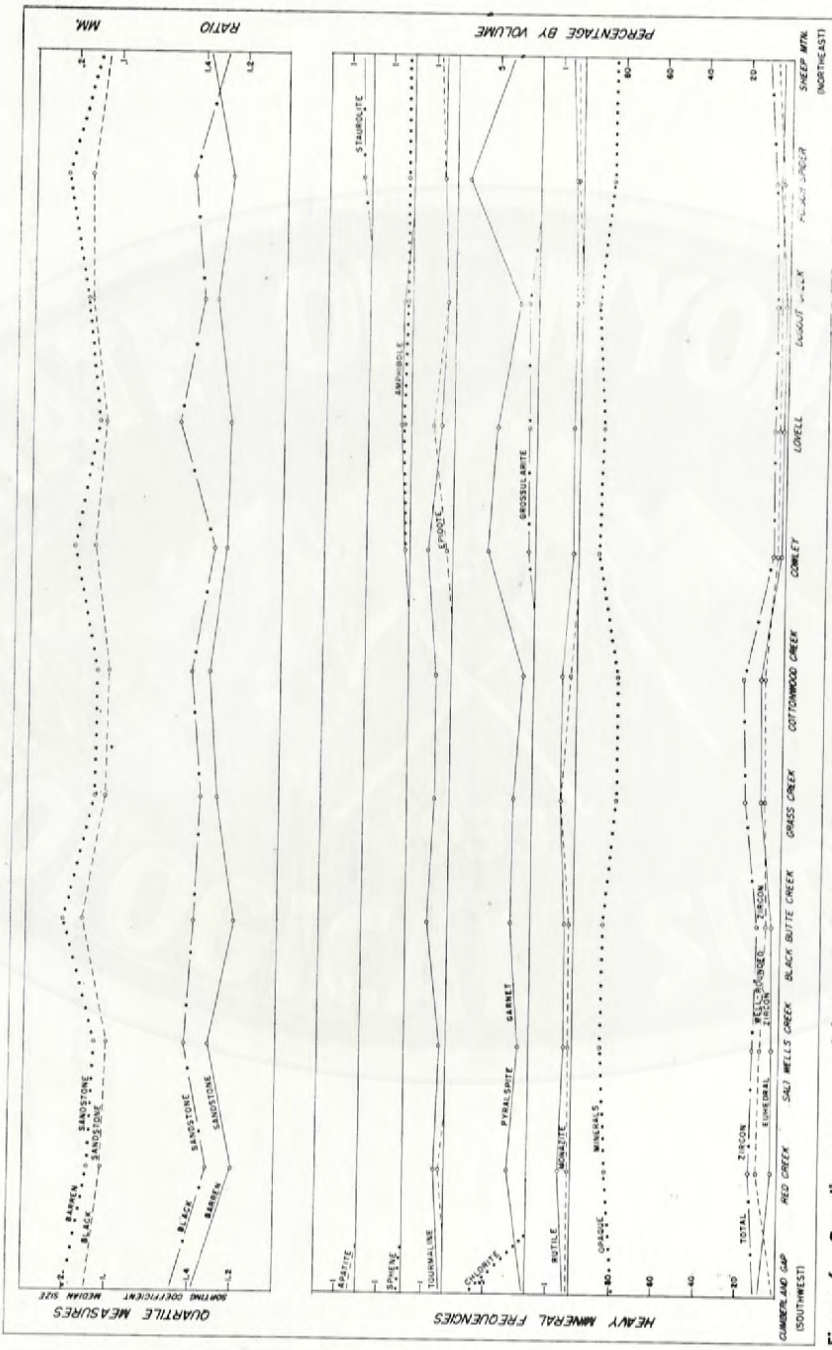
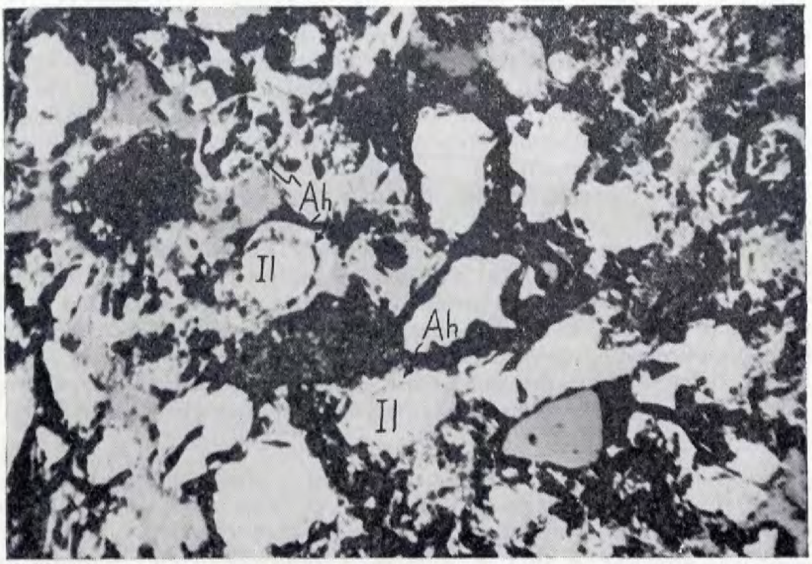


Figure 6. Quartile measures and heavy-mineral frequencies of Wyoming Upper Cretaceous black sandstone deposits. Deposits are arranged from southwest to northeast.

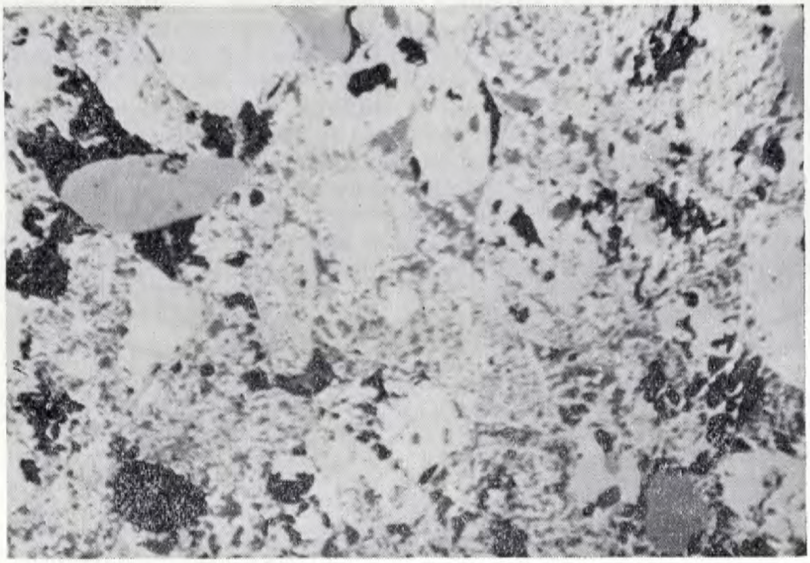
posed of anatase (TiO_2), hydrated iron oxides, quartz, and kaolinite(?). X-ray diffraction patterns indicated anatase and quartz, as well as other constituents that could not be readily identified. The most distinct X-ray lines were those of anatase, suggesting that it was either the most abundant or best crystallized constituent in the insoluble part of the matrix. A differential thermal analysis indicated a pronounced endothermic reaction at 285°C., followed by an exothermic reaction at about 420°C. This is believed to be caused by the breakdown of the iron oxides, goethite and lepidocrocite. Thermal analyses of mixtures of these two oxides by Kulp and Trites (1951, p. 34-37) produced very similar curves (fig. 12), but the reactions occurred at 360°C. and 460°C. The oxides analyzed by Kulp and Trites were ground to 180 to 200 mesh, while those analyzed for this study were smaller than 325 mesh. Inasmuch as finer grained samples tend to react at lower temperatures, the variations are probably the result of the differences in the mesh sizes analyzed. Additional reactions, believed to be caused by kaolinite, were detected at 575°C. and 950°C. (fig. 12).

A chemical analysis of the matrix of a single high-grade bulk sample from Grass Creek showed 32.4 percent TiO_2, 53.1 percent Fe_2O_3, and 14.5 percent of undetermined other constituents. A mineralogical analysis of this sample, after removal of the acid-soluble part of the matrix, indicated only a trace of light minerals; this suggests that the 14.5 percent of undetermined other constituents shown in the chemical analysis was largely zircon and other heavy minerals common to the black sandstone. The mineralogical analysis showed that 26.7 percent of the high-grade sample was matrix composed of both soluble and insoluble materials finer than 325 mesh. The insoluble fraction, which consisted largely of opaque minerals and zircon, was subdivided into fractions of different magnetic susceptibility, and then each magnetic fraction was chemically analyzed for TiO_2. The average TiO_2 content of the entire insoluble heavy fraction in the matrix, including all opaque oxides and zircon, was 33 percent. This closely agrees with the 32.4 percent TiO_2 determined in the chemical analysis of the bulk sample, and indicates that the matrix was probably derived from the original oxides by weathering.

PLATE 4



A. Photomicrograph of polished section of black sandstone from Grass Creek, Wyo. Ferrian ilmenite (Il) with rims of anatase (Ah) in a matrix of hematite and carbonate. Ordinary light x 130.



B. Photomicrograph of polished section of altered black sandstone from Grass Creek. Ferrian ilmenite (light) almost entirely altered to anatase and hematite in a matrix of hematite, anatase, and carbonate. Dark grains are quartz. Ordinary light x 150.

MINERALOGY

The following heavy-mineral suite has been identified in the black sandstone and interbedded barren sandstone:

Amphibole group	Hornblende Oxyhornblende
Anatase	
Apatite	
Biotite	
Brookite	
Chlorite	
Epidote	
Garnet	
Monazite	
Opaque minerals	Magnetite Ilmenite Ferrian ilmenite Magnetite-ilmenite intergrowths Radioactive opaque minerals
Pyroxene	
Rutile	
Sphene	
Spinel	
Staurolite	
Tourmaline	
Zircon	

The mineral composition of the black sandstone deposits is simple in some respects and complex in others. It is simple in that the list of heavy minerals is relatively short and includes few unusual mineral species. This is probably due mainly to two factors: 1) nonresistant minerals and the heavy minerals of lower specific gravity were removed during the selective process of concentration, and 2) chemically unstable minerals were removed from the black sandstone by the post-depositional action of artesian and surface water. The mineral composition of the black sandstone is complex in the sense that some of the mineral species are represented by several varieties, which are believed to indicate differences in provenance.

The heavy minerals in the deposits are relatively resistant to weathering and solution and, for the most part, are included in the relatively stable heavy minerals listed by Pettijohn (1941, p. 619) as being common in Mesozoic rocks.

Figure 5 shows heavy-mineral frequencies of Wyoming black sandstone deposits arranged according to age. There is no apparent systematic variation with age, but there is a suggestion that mineralogically the deposits are comprised of two types:

1. Those containing a very simple mineral suite: zircon, garnet, tourmaline, rutile, monazite, and opaque minerals. De-

posits of this type are Grass Creek, Cottonwood Creek, Black Butte Creek, Salt Wells Creek, and Red Creek.

2. Those containing a more complex mineral suite: zircon, garnet, tourmaline, rutile, opaque minerals, sphene, amphibole, epidote, and possibly monazite, chlorite, staurolite, and apatite. Deposits of this type are Cumberland Gap, Dugout Creek, Lovell, Cowley, Sheep Mountain, and Poison Spider.

Figure 6 shows heavy-mineral frequencies of Wyoming black sandstone deposits arranged according to geographic locality from southwest to northeast. With the exception of the Cumberland Gap deposit, those containing the more complex mineral suites are all in eastern Wyoming.

These mineralogical variations may reflect progressive denudation of different rock types at the source or a change to a different source area, but other factors, unrelated to the provenance of the black sandstone, such as current velocity, sorting, or volcanism, may also cause these variations. Rubey (1933) and Rittenhouse (1943) described methods that might be used in the study of heavy minerals which would tend to minimize the effect of current velocity, sorting, and other factors on heavy-mineral percentages, in order that comparisons of such percentages might be directly related to provenance. However, the degree of change in the percentages of varieties of minerals of the same species was considered a more reliable approach in this study, particularly because two varieties of zircon could be identified in all deposits.

Obviously the main influence in variations of heavy-mineral percentages in different black sandstone deposits is the effectiveness of the sorting process in removing light minerals. If the sorting process continues for an unusually long time, then even some of the lighter heavy minerals are removed. A high-grade sample (one containing more than 30 percent heavy minerals) commonly has different heavy-mineral percentages than a low-grade or barren sample from the same deposit. For example, a higher grade sample from the Black Butte Creek deposit contains 80 percent heavy minerals. Of these heavy minerals, 11.0 percent is zircon, 0.8 percent garnet, and 0.3 percent is tourmaline. A low-grade sample from the same deposit contains less than 1.0 percent heavy minerals, but of these, 7.0 percent is zircon, 2.7 percent garnet, and 5.3 percent is tourmaline. This same relation between grade and heavy-mineral percentage has been observed in several other black sandstone deposits in Wyoming. The high-grade samples contain zircon, garnet, rutile, tourmaline, and opaque minerals. The low-grade samples contain these same minerals together with small amounts of chlorite, epidote, and amphibole. This increase in the complexity of the mineral suite and in the percentage of low specific gravity heavy minerals (e.g. garnet and tourmaline) as the grade decreases is especially evident in figure 7.

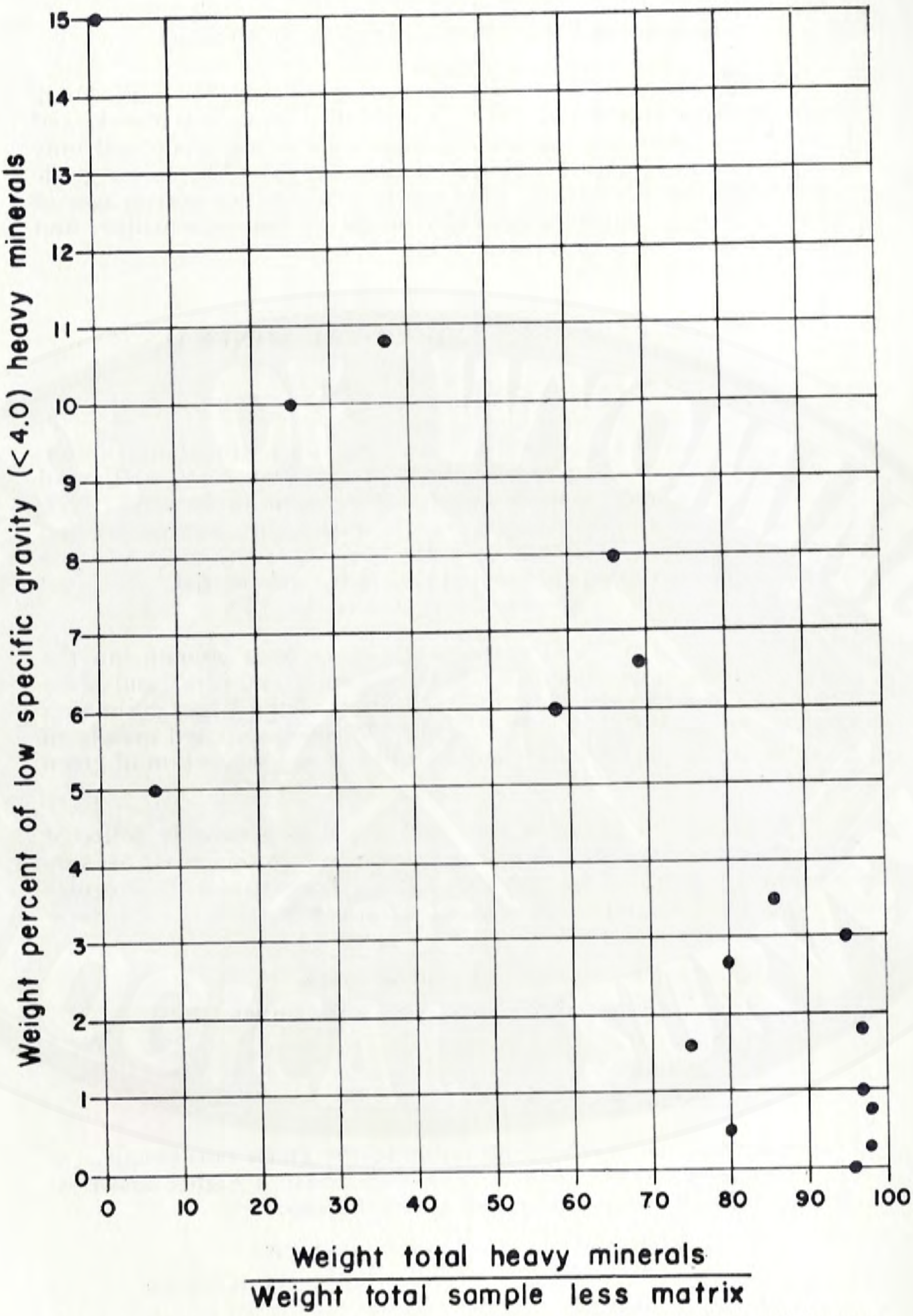


Figure 7. Chart showing decrease in heavy minerals of low specific gravity with increase in total heavy-mineral content. Based on 17 samples from 7 localities; Grass Creek, Cottonwood Creek, Poison Spider, Black Butte Creek, Salt Wells Creek, Red Creek, and Sheep Mountain.

Similar variations are seen in comparing different deposits. High-grade deposits, as at Grass Creek, Salt Wells Creek, Red Creek, and Cottonwood Creek, are marked by an abundance of zircon and only small amounts of garnet and tourmaline (fig. 5). The lower grade deposits, on the other hand, consistently have smaller percentages of zircon, relatively larger percentages of garnet and tourmaline, and generally more complex mineral suites.

DESCRIPTIONS OF INDIVIDUAL MINERALS

Amphibole group

Members of the amphibole group are fairly abundant in low-grade samples and are generally absent in the high-grade well-sorted samples. Amphiboles comprise less than 0.5 percent of the total heavy-mineral suite in all deposits except at Clarkson Hill, where they constitute 11.0 percent. The Clarkson Hill deposit is the only one containing amphibole adequate for optical study, and the data presented here are based entirely on samples from that locality.

Green hornblende and oxyhornblende are both present, but the green is much more abundant. Both types are anhedral and show only slight rounding of edges of crystals even in the larger grain sizes (between 80 and 60 mesh). The amphibole is concentrated mainly in the 0.2 to 0.4 ampere Frantz fractions without any separation of green and oxyhornblende.

The green hornblende is very dark green to opaque in reflected light. Except in coarser fractions, where the grains may be subrounded, the particles are usually cleavage fragments with irregular outlines. Optical properties of green hornblende from the Clarkson Hill deposit are as follows:

$N_z = 1.680 \pm .003$	dark green
$N_x = 1.656 \pm .003$	very light brown
$N_z\text{-}N_x = .024$	
$Z_\wedge c = 13\text{-}15°$	
Absorption $Z>Y>X$	

Oxyhornblende is similar in habit to the green hornblende, except that the grains are reddish brown and have a higher luster in reflected light. Optical properties are as follows:

$N_z = 1.730 \pm .003$	deep red-brown
$N_x = 1.670 \pm .003$	colorless to faint brown
$N_z\text{-}N_x = .060$	
$Z_\wedge c = 0\text{-}2°$	
Absorption $Z>Y>X$	

Anatase

Anatase is one of the most abundant constituents of the black sandstone and has been identified in one form or another in all deposits examined. Its abundance depends on the degree of alteration, which varies considerably even within a single deposit. Altered black sandstone, rich in anatase, is generally dark brown, in contrast to the less altered sandstone which is almost black.

All the anatase identified, with the possible exception of some large platy crystals found in the Cumberland deposit, is considered to be authigenic. X-ray studies show a direct relation between the amount of anatase and the degree of alteration (fig. 11) which suggests that the anatase was formed by alteration of iron-titanium oxides. Anatase may occur both as an integral constituent of altered iron-titanium oxides, where it is in the form of resinous shells pseudomorphic after the oxides, and as very fine grained (between 325 and 250 mesh) aggregates. The resinous shells are composed in part of submicroscopic anatase and in part of darker anatase crystals. The fine-grained aggregates consist chiefly of fragments of the resinous shells, and, therefore, are partly submicroscopic and partly crystalline. Although the authigenic anatase crystals can be recognized under the microscope, they are so small that it is impossible to get a three-dimensional view of individual crystals at the magnification necessary for study. However, they appear to be largely platy crystals, some of which are marked by geometrical patterning on basal (001) plates.

Pure anatase is nonmagnetic and should be separated with the minus 1.5-ampere Frantz fraction; however, anatase appears in all magnetic fractions from 0.6 to 1.5 amperes. Iron, either in the anatase lattice or as very fine grained crystalline oxides in the submicroscopic aggregates, is probably responsible for the wide range of magnetic susceptibility.

X-ray analyses of anatase from the deposit at Grass Creek, Wyo., and from a deposit at Binnental, Valais, Switzerland, are compared in table 1. The intensities and *d* values correspond very closely except for extra lines in the Grass Creek patterns, which probably represent the common ilmenite alteration products, goethite and rutile.

The larger anatase grains found in the black sandstone from the Cumberland Gap deposit are in the form of platy crystals which tend to lie on basal pinacoid (001) faces, and hence, give well-centered uniaxial negative interference figures.

A few grains of anatase in the Cumberland Gap deposit appear to be slightly abraded, and may be of detrital origin.

Table 1.—Powder patterns of anatase (0.75 ampere minus 0.6 ampere Frantz fraction filtered Cu radiation).

Explanation: I, comparison of peak intensities above background; *d*, interplanar spacing of the crystal lattice; BL, broad line; g, goethite; r, rutile.

[Binnental, Switzerland, data from card No. 4-0479, Am. Soc. for Testing Materials file on X-ray powder data.]

Grass Creek, Wyo.		Binnental, Switzerland	
I	*d*	I	*d*
13	3.93 BL		
	4.20		
100	3.544	100	3.510
19	3.340		g
11	3.240		r
5	2.597		
4	2.533		
7	2.499		r
5	2.453		
5	2.433	9	2.435
21	2.390	22	2.379
8	2.348	9	2.336
7	2.190		r
27	1.897	33	1.891
22	1.702	21	1.699
19	1.670	19	1.665
		4	1.494
16	1.484	13	1.480
9	1.363	5	1.367
4	1.339	5	1.337
4	1.260	10	1.264

Apatite

Apatite is a rare constituent of the black sandstone deposits. It occurs as white, well-rounded grains that are elongate parallel to the *c* axis. Grain surfaces are pitted and have a frosted appearance, but this may have been caused in part by hydrochloric acid which was used to eliminate iron stain. Prism faces can be recognized on a few grains and a number of grains show moderately well developed basal cleavage. The mineral is nonmagnetic and is separated with the minus 1.5-ampere Frantz fraction with rutile and zircon.

Inclusions are not common, but a few grains contain trains of opaque material. Inclusions of zircon and possibly sphene have been observed. Refractive index measurements of apatite from the Clarkson Hill deposit are as follows:

$$N_e = 1.630 \pm .003$$
$$N_o = 1.634 \pm .003$$
$$N_o\text{-}N_e = 0.004$$

The mineral is probably normal fluorapatite.

Biotite

Biotite is present in small quantities in most of the deposits, but it is abundant only in the Cumberland Gap deposit. At Cumberland Gap, mica can be easily identified in hand specimens by its pseudohexagonal crystal habit. In thin sections, less altered mica appears to be dark-green biotite. Most of the mica grains, however, are highly altered, some to chlorite and others to a deep-red mineral that consists of fibrous aggregates. This red fibrous alteration product is also common in the matrix of rocks that contain abundant biotite and/or chlorite. It may be a variety of secondary chlorite or mica rich in iron and titanium, or some highly iron stained secondary mineral. The individual fibers have parallel extinction.

Brookite

Brookite was not recognized in any of the Wyoming black sandstone deposits, but it has been identified by X-ray analyses of altered ilmenite in similar black sandstone in the Hosta tongue of the Point Lookout sandstone at Miguel Creek, N. Mex. It is authigenic, forming from ilmenite, and is similar in occurrence to anatase. At Miguel Creek, alteration of ilmenite to brookite has not proceeded far enough to form recognizable crystals of brookite. Ilmenite grains that are partly altered to brookite are usually deep reddish brown in contrast to the brownish yellow of crystals that have been altered mainly to anatase. Authigenic brookite has also been reported from a black sandstone deposit in the Gallup sandstone near Gallup, N. Mex., Sun and Allen (1957, p. 265-270).

Chlorite

Although chlorite is not an abundant constituent, a few grains are found in most Wyoming black sandstone deposits. The mineral was not studied petrographically, but a description of a chlorite-like mineral, believed to have been derived from biotite, is given in the discussion of biotite.

Epidote

Epidote is most abundant in low-grade samples where it constitutes as much as 5 percent of the total heavy minerals.

Epidote is greenish yellow and it has an apple-green fluorescence when activated by a mercury vapor light. This color as well as the fluorescence is also characteristic of monazite. The similarity in fluorescence is probably due to cerium in both minerals. Despite these similarities, the minerals may be easily separated magnetically; epidote is extracted in the fraction between 0.2 and 0.4 ampere and monazite between 0.6 and 0.7 ampere. Another distinguishing characteristic is the degree of rounding; epidote is irregular in shape and is usually found as cleavage fragments, whereas monazite is very well rounded.

Refractive index measurements of epidote from all Wyoming deposits show a variation of N_y from 1.750-1.758. A spectrographic analysis of epidote from the Poison Spider deposit is shown in table 2.

Table 2.—Semiquantitative spectrographic analysis of epidote from the Poison Spider deposit.

[Analyst: R. Havens, U. S. Geological Survey.]

Percent	Element
10.0	Al, Ca
4.646-10.0	Fe
0.215-0.464	Sr
0.10-0.215	Ti, Mn, Ce
0.0464-0.10	Mg, La, Nd
0.0215-0.0464	V, Zr
0.010-0.0215	Y
0.00464-0.010	Ba, Cr, Ga, Pb, Sc
0.00215-0.00464	Cu
0.001-0.00215	Yb
0.000464-0.0010	Ag

Not looked for: Si, Na.

Looked for but not detected: As, Au, B, Be, Bi, Cd, Co, Dy, Er, Gd, Hf, Hg, In, Ir, K, Li, Mo, Nb, Os, P, Pd, Pt, Re, Rh, Ru, Sb, Sn, Sm, Ta, Th, Tl, Te, U, W, and Zn.

Garnet

Garnet is present in all Wyoming black sandstone deposits, but it is not abundant except in the Poison Spider deposit where it makes up 9 percent of the total heavy fraction (fig. 5). Elsewhere, the heavy fraction ordinarily contains only 1 or 2 percent garnet. An equally small percentage is found in Montana and Colorado deposits, but in northwestern New Mexico deposits and at the Tah Chee Wash deposit in Arizona, garnet comprises as much as 30 to 40 percent of the total heavy fraction.

Garnet tends to increase in abundance in the coarser screen fractions and reaches a maximum between 60 and 115 mesh (fig. 8). It is also more abundant in the lower grade than in the higher grade deposits, as shown in figure 7.

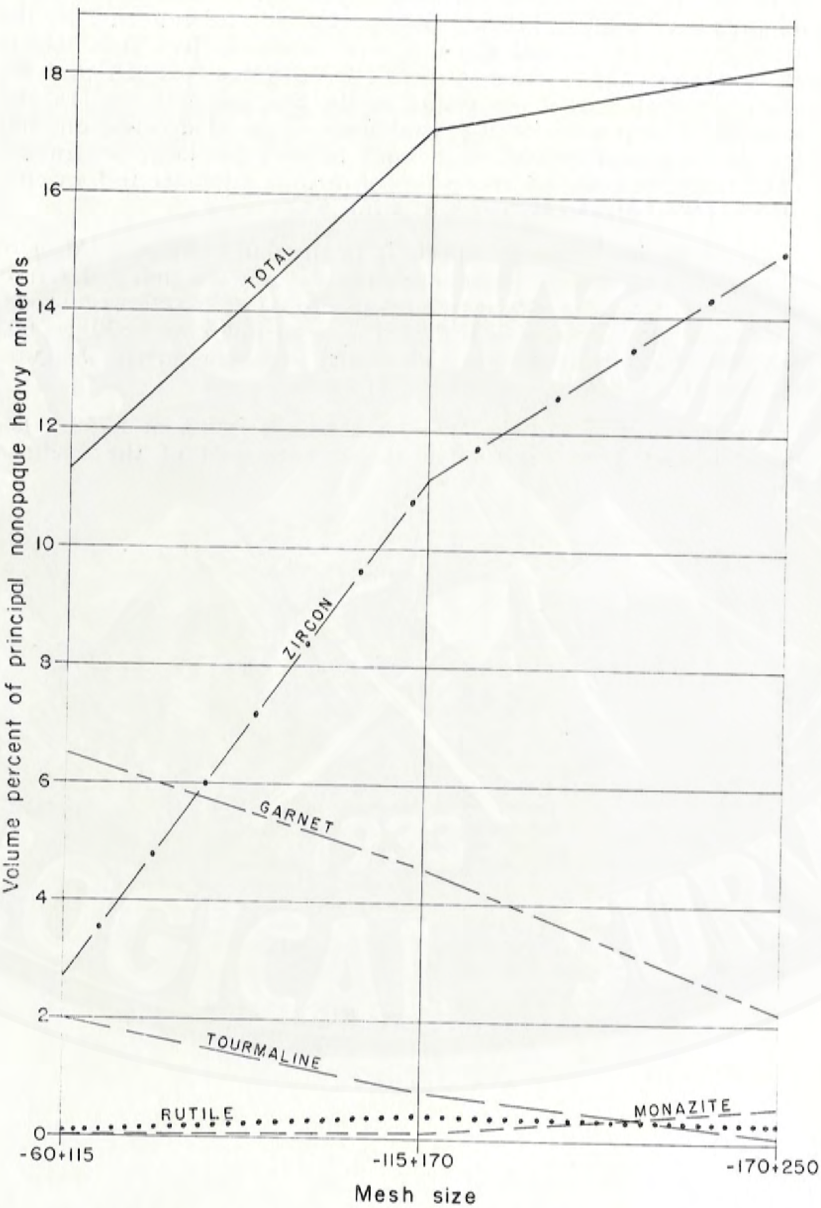


Figure 8. Relation of grain size to abundance of principal nonopaque heavy minerals. Average of 23 samples from 5 localities; Grass Creek, Cottonwood Creek, Poison Spider, Black Butte Creek, and Sheep Mountain.

In the Wyoming deposits, almost all the garnet is isotropic pyralspite (Winchell and Winchell, 1951, p. 486-489) as indicated by the optical data (table 3) and the magnetic susceptibility. It is mostly pink or orange. The shape is distinctly irregular (pls. 5A and B). Euhedral, colorless garnet is found in the fraction between 115 and 170 mesh. The predominant crystal form is the dodecahedron, but trapezohedrons and crystals with both forms have been recognized. The garnet commonly has inclusions of opaque minerals and sericite; it also has wormlike tubular cavities (pl. 5A).

Zoning is also common, especially in the darker variety. Most of the colorless garnet has a faint birefringence, but the index of refraction (table 3) indicates that it is a pyralspite type. A yellowish-brown garnet from the Clarkson Hill deposit has an index of $1.879 \pm .003$ and a very faint birefringence. This garnet may be a variety of ugrandite, possibly andradite.

Isotropic, colorless grossularite that has an index of $1.750\pm$ has been identified from deposits in the western part of the Bighorn Basin.

Table 3.—Properties of garnet

Location	Color	Index of refraction	Specific gravity	Form	Remarks
Black Butte Creek	Colorless	1.798±.003		Dodecahedron	Faint birefringence, numerous opaque inclusions
Do	Orange	1.808±.003		Trapezohedron dodecahedron	Isotropic
Grass Creek	Yellow	1.800±.003			Faint birefringence, relatively free of inclusions
Do	Pink	1.798±.003	4.0		Isotropic
Do	Orange	1.801±.003			Do
Sheep Mountain	Pink	1.799±.003			Do
Do	Colorless	1.780±.003		Dodecahedron	Faint birefringence, numerous inclusions
Dugout Creek	Do	1.750±.003			Grossularite
Lovell	Do	1.755±.003			Do

PLATE 5

A. Photomicrograph of irregular-shaped pyralspite garnet from the Grass Creek deposit showing various types of inclusions. Ordinary light x 205.

B. Photomicrograph of irregular-shaped pyralspite garnet from the Poison Spider deposit showing facets and pits. Ordinary light x 205.

C. Photomicrograph of augite from the Clarkson Hill deposit showing serrate borders or "hacksaw structure." Ordinary light x 240.

Monazite

Monazite is a common constituent of the black sandstone and is one of the main sources of radioactivity. It has been recognized in most of the deposits in Wyoming, Montana, Colorado, New Mexico, and Arizona. Unlike zircon and garnet, which are present in every sample examined, monazite is rather erratic in distribution. It may be found in fairly large amounts, as much as 3 or 4 percent of the heavy fraction in some samples, but it may be entirely absent in other samples from the same deposit. The erratic distribution is usually reflected by variations in the radioactivity of the samples.

The monazite grains tend to be concentrated in the finer grained fractions between 170- and 250-mesh sizes (fig. 8) and to be more highly concentrated in the well-sorted higher grade samples. Because of its low concentration, monazite cannot be recognized by its fluorescence in hand specimens, but concentrates of the mineral emit a distinct apple-green color when activated by a mercury vapor light. As previously noted, cerium-bearing epidote may also emit a similar fluorescence.

Monazite grains are typically well rounded. All grains are yellow in transmitted light. Inclusions are common and include opaque particles and masses and a clear rodlike mineral with parallel extinction which may be apatite. Optical data for monazite from the Grass Creek, Wyo., deposit are as follows:

$$N_x = 1.788 \pm .003$$
$$N_z = 1.838 \pm .003$$
$$N_z - N_x = .050$$

A qualitative X-ray fluorescence analysis of monazite from the Grass Creek deposit shows the following heavy elements in order of abundance: cerium, neodymium, thorium, and yttrium, and minor amounts of iron, titanium, hafnium(?), uranium, and zirconium. A semiquantitative spectrographic analysis gives similar results and indicates an approximate thorium content of 7.0 percent (table 4).

Opaque Minerals

Opaque mineral grains are by far the most abundant constituents of the black sandstone. They are separated principally in the size fractions between 115 and 250 mesh. Individual grains are almost always well rounded, but subrounded grains and euhedral crystals are also present.

The opaque minerals are much more difficult to identify and distinguish from each other than are the nonopaque minerals. This is especially true for opaque grains that are well rounded and extensively altered by weathering and solution. These grains have lost many of their original characteristics, such as color and form. Furthermore, some opaque minerals have undergone different degrees of alteration,

Table 4.—Semiquantitative spectrographic analysis of monazite from the Grass Creek deposit.

[This sample was analyzed by a dilution technique and usual sensitivities do not apply. U. S. Geological Survey Lab. No. 243637. Analyst: Nancy M. Conklin, U. S. Geol. Survey.]

Percent	Element
10.0	P, Ce, La, Nd
7.0	Th
3.0	Pr, Sm, Y
1.5	Ca, Gd
0.7	Dy, Zr
0.15	Ti, Eu
0.07	Fe, Yb
0.02	Cu

Looked for but not detected: Al, Mg, Na, K, Mn, Ag, As, Au, B, Ba, Be, Bi, Cd, Co, Cr, Er, Ga, Ge, Hf, Hg, Ho, In, Ir, Li, Lu, Mo, Nb, Ni, Os, Pb, Pd, Pt, Re, Rh, Ru, Sb, Sn, Sr, Ta, Tb, Te, Ti, Tm, U, V, W, Zn.

and the color and physical properties of the less altered grains may be entirely different from those of the more highly altered grains.

The object of the opaque mineral study was to isolate each of the primary mineral species and to study its characteristics, and to study the changes in the mineral caused by weathering and solution. Opaque minerals from selected localities were first separated from nonopaque minerals by electrostatic methods and hand picking to render the opaque fraction of the heavy minerals 90 to 95 percent pure. Then the minerals were separated magnetically into the following fractions:

(1) *Ferromagnetic fraction*—Essentially pure magnetite attracted by an electromagnet wound to separate magnetite from all other less magnetic minerals.

(2) *Individual magnetic susceptibility fractions*—Opaque minerals excepting pure magnetite attracted at Frantz separator settings of 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.00, 1.10, 1.20, 1.30, 1.40, and 1.50 amperes, respectively.

The separate magnetic fractions were weighed and tested for radioactivity, and their specific gravity was determined by the pycnometer method. Following this, the separate magnetic fractions were studied by X-ray, polished-section, thermal, and chemical analyses. Semiquantitative spectrographic analyses were made of the separate fractions where necessary. Inasmuch as altered ilmenite is the principal opaque constituent of most black sandstone, concentrates of altered ilmenite from modern beach sands in Florida and India were also studied for comparison.

Magnetic properties.—In figure 9, concentrates of opaque minerals from Grass Creek and Black Butte Creek, Wyo., Cut Bank Creek, Mont., and Toadlena, N. Mex., are compared with concentrates of

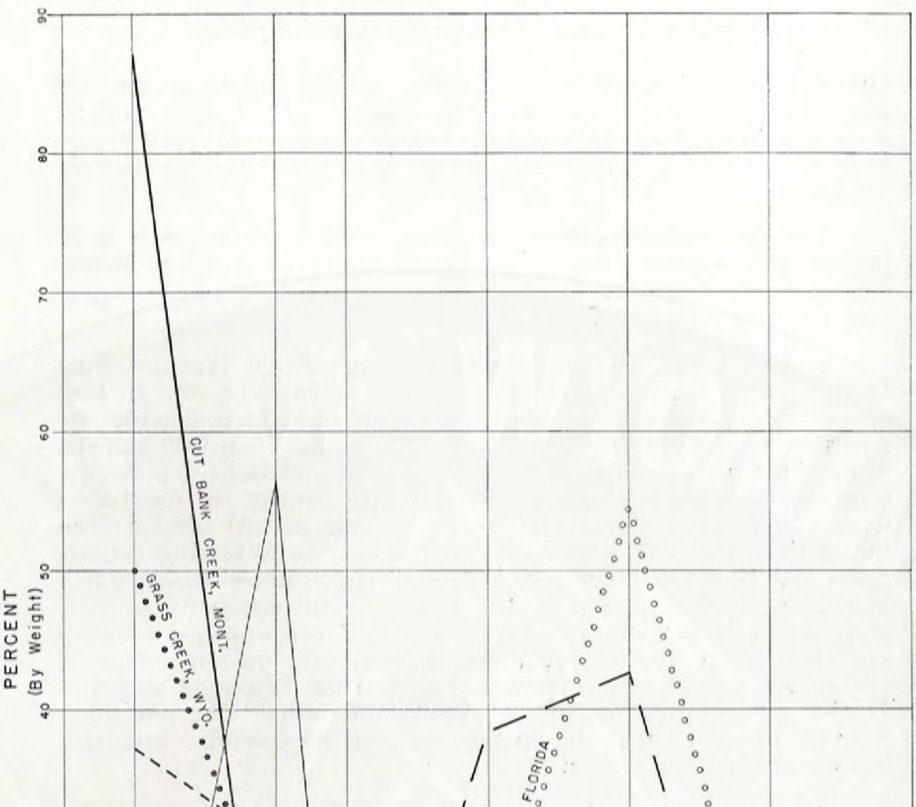


Figure 9. Percentage of opaque minerals separated at increasing amperage on Frantz Magnetic Separator. (Percentage based on total weight of opaque minerals separated at all settings up to 0.5 ampere.

altered ilmenite from Florida and India. A total sample, or 100 percent by weight, is represented by that part of the opaque mineral suite separated at all the magnetic intensity settings up to 0.50 ampere; these fractions include most of the opaque minerals in the concentrates.

The Montana concentrate of opaque minerals is as much as 87 percent ferromagnetic; Wyoming concentrates range from 6 to 50 percent ferromagnetic; and the New Mexico concentrate is only 12 percent ferromagnetic (fig. 9).

As would be expected, concentrates of altered ilmenite from Florida and India are essentially nonferromagnetic (fig. 9). In fact, only a small percentage of opaque minerals from these deposits are separated by the Frantz magnetic separator at less than 0.20 ampere. Most of the opaque minerals from the Florida and India deposits are separated between settings of 0.20 and 0.30 ampere on the Frantz separator; 76 percent from the Florida deposits and 81 percent from the India deposits. Twenty-seven percent of the Wyoming concentrates and 48 percent of the New Mexico concentrates are separated in the same range of 0.20 to 0.30 ampere. This similarity in magnetic properties between Wyoming and New Mexico opaque minerals and those from Florida and India suggests that the same type of altered ilmenite may be present in a part of the Wyoming and New Mexico deposits as is present in Florida and India. The possibility remains, of course, that the opaque minerals have similar magnetic, but dissimilar chemical properties.

Specific gravity.—Other investigators (Tyler and Marsden, 1938, p. 56, and Spencer, 1948, p. 18) have demonstrated that highly altered ilmenite is less magnetic and has lower specific gravity than normal ilmenite. Normal ilmenite has a specific gravity of 4.72, but altered ilmenite is as low as 3.50.

As shown in figure 10, the specific gravity of the opaque minerals studied tends to decrease with decreasing magnetic susceptibility. The least magnetic grains, presumably the most highly altered, have relatively low specific gravity. Nevertheless, minerals from different deposits may separate at the same magnetic setting, yet have significantly different specific gravities. For example, altered ilmenite from India, separated at 0.30 ampere, has a specific gravity of 4.35, but the opaque minerals separated at the same amperage from Grass Creek, Wyo., have an average specific gravity of 4.15. The same fraction from Toadlena, N. Mex., has a specific gravity of 4.15, and from Black Butte Creek, Wyo., a specific gravity of 3.90. Another noteworthy relation shown by figure 10 is the sharp decrease in specific gravity of minerals from most deposits separated at 0.10 ampere.

Radioactivity and rare earth elements.—The radioactivity of black sandstone is attributed to radioactive elements in monazite, zircon, and in an unidentified opaque mineral. Spectrographic analyses

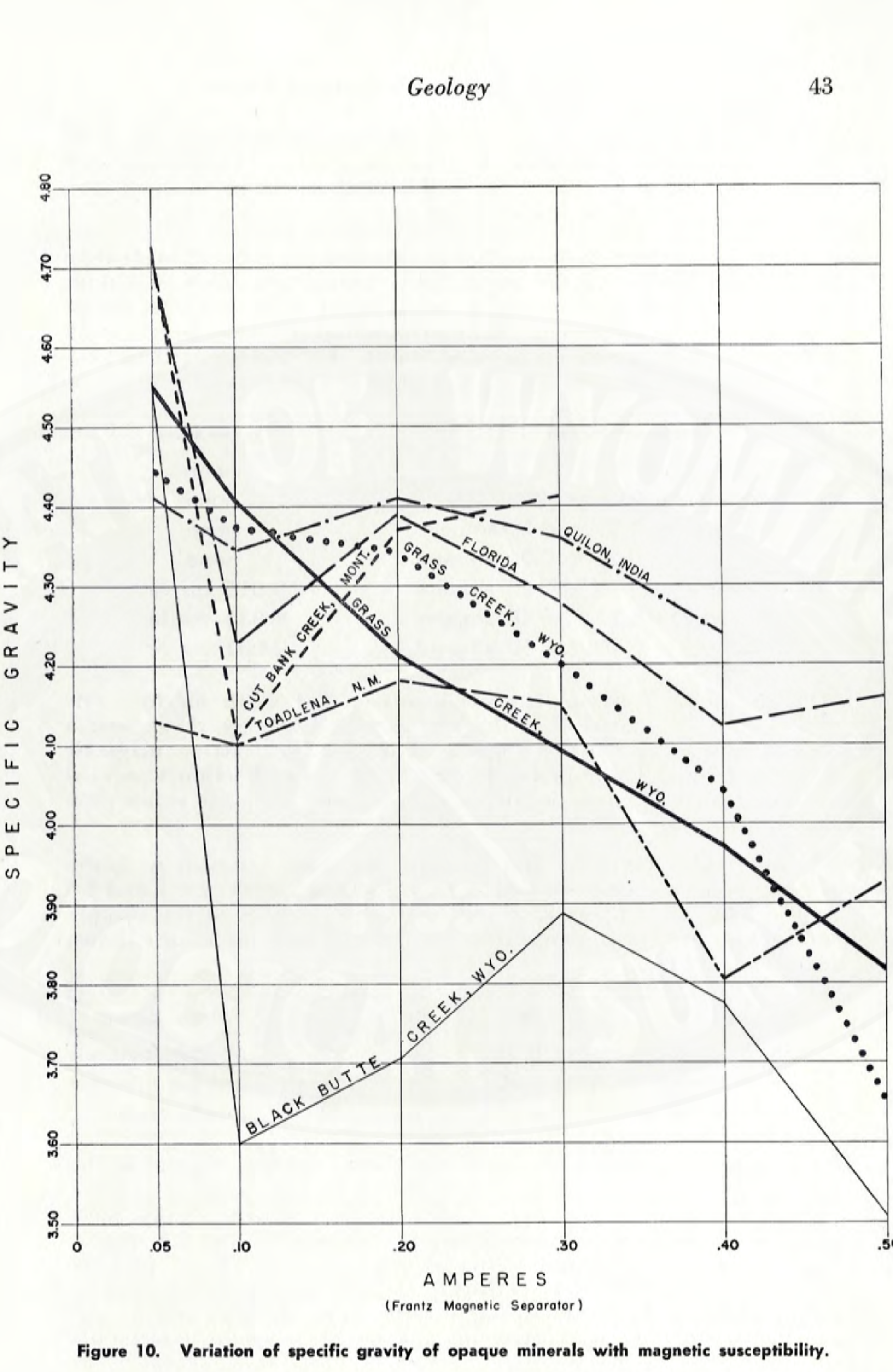


Figure 10. Variation of specific gravity of opaque minerals with magnetic susceptibility.

of bulk samples show the rare earths cerium, neodymium, and ytterbium, and minor quantities of uranium, yttrium, lanthanum, hafnium, and niobium. Except for niobium, these elements are present in zircon and monazite (tables 4 and 7).

Heavy minerals in the size range between 115 and 170 mesh from a 400-gram sample of the most highly radioactive black sandstone from Grass Creek were separated magnetically in an effort to isolate the radioactive constituents. Before separation the total sample registered 0.05 mr/hr above background count. The radioactivity of each of the magnetic fractions up to 0.50 ampere is as follows:

Magnetic fraction	Radioactivity
Ferromagnetic	none
Magnetic at 0.05 ampere	none
Magnetic at 0.05 to 0.10 ampere	none
Magnetic at 0.10 to 0.20 ampere	none
Magnetic at 0.20 to 0.30 ampere	0.015 mr/hr
Magnetic at 0.30 to 0.40 ampere	0.030 mr/hr
Magnetic at 0.40 to 0.50 ampere	0.003 mr/hr

The remaining fraction had a radioactivity of 0.015 mr/hr. The maximum radioactivity is in the 0.20 to 0.40 amperage range, and a second peak of radioactivity was recorded for the fraction magnetic between 1.0 and 1.5 amperes. Radioactivity of the fraction separated at more than 1.0 ampere is attributed to zircon. Monazite is not present in this sample.

Columbite, tantalite, and euxenite, the most common niobium-bearing minerals, are separated at Frantz settings between 0.1 and 0.5 ampere (fig. 3). Quantitative spectrographic analyses of the opaque minerals in this range were made for niobium with the results shown below:

Magnetic fraction	Nb	Ce	La	Mineral Content
0.05 to 0.15 ampere	0.03	0	0	opaque minerals
0.25 to 0.45 ampere	0.30	.x	.x−	opaque minerals
1.2 to 1.5 amperes	0	0	0	mostly zircon

This shows the presence of a niobium-bearing opaque mineral in the 0.25 to 0.45 magnetic range, which also is in the range of greatest radio-activity. In an attempt to identify this mineral, X-rays were taken of the magnetic fraction separated between 0.3 and 0.4 ampere from the more highly radioactive samples, but the X-ray patterns within this range were very poor (fig. 11), and no lines corresponding to the common niobium-bearing opaque minerals were noted. Because many of the radio-active opaque minerals are in a metamict state, a part of the fraction was placed in a differential thermal unit and heated to 1150°C. X-rays of this fraction give excellent patterns for rutile and good patterns for ilmenite and brookite, but no pattern could be detected for a radioactive niobium-bearing opaque mineral.

Although the radioactive opaque mineral was not identified, the presence of cerium and lanthanum as well as niobium are suggestive of euxenite.

Chemical, X-ray, and polished-section analyses.—Chemical analyses were made of cleaned, magnetically separated, opaque minerals from the Grass Creek, Black Butte Creek, and Sheep Mountain deposits in Wyoming, the Sanostee deposit in New Mexico, the Cut Bank Creek deposit in Montana, and altered ilmenite concentrates from Florida and India. The process used to clean the samples prior to analysis involved treatment by a dilute HCl solution. The process is not believed to have leached a significant amount of iron, because the physical character as shown in polished sections was identical before and after treatment.

The samples were chemically analyzed for TiO_2 and total iron as Fe_2O_3, and where adequate sample was available, analyses were also made for FeO and Fe_2O_3 separately (table 5). Titanium and iron oxides constitute more than 90 percent of most of the samples. In general, an increase in TiO_2 and a decrease in FeO is accompanied by a decrease in magnetic susceptibility; this is readily apparent in all samples except those from Montana. Total iron oxide also decreases as TiO_2 content increases.

The low-titanium content of the opaque mineral fraction separated at low amperage from black sandstone of Montana and Wyoming is especially significant, because this fraction includes 98 percent of the opaque minerals of the black sandstone from Montana and about 75 percent of the opaque minerals of the black sandstone from Wyoming. This indicates that both the Montana and Wyoming deposits are largely high-iron, low-titanium types, but that the Wyoming deposits contain less iron than those in Montana.

The ferromagnetic fraction from Cut Bank Creek, Mont., gives a good X-ray pattern for magnetite. Chemical analysis, however, shows that the opaque minerals in this fraction contain 19.25 percent TiO_2 (table 5). It is therefore considered to be a high-titanium titaniferous magnetite. Less-magnetic fractions from Cut Bank Creek show X-ray patterns for ilmenite, and magnetite-ilmenite exsolution lamella in magnetite can be recognized in polished section. As would be expected, these fractions also contain a higher percentage of TiO_2 (table 5).

The ferromagnetic fraction from Grass Creek, Wyo., gives a good pattern for ilmenite and very poor patterns for magnetite and anatase (fig. 11). This suggests that the major mineral in this deposit is

Table 5.—Chemical analyses of magnetic fractions of opaque minerals.

[Percent Fe_2O_3 is calculated from the difference of percent total iron as Fe_2O_3 and percent FeO as Fe_2O_3. TiO_2 was analyzed by colorimetric method. Fe_2O_3 was analyzed by volumetric method. Asterisk (*) indicates analysis by Neal Rice, Nat. Res. Research Inst., Univ. Wyoming. Other analyses by D. L. Skinner, W. D. Goss, and E. C. Mallory, U. S. GeologicalSurvey.]

Locality	Analyzed for	Ferro-magnetic	Magnetic at 0.05 amp.	Magnetic at 0.10 amp.	Magnetic at 0.20 amp.	Magnetic at 0.30 amp.	Magnetic at 0.40 amp.	Magnetic at 0.50 amp.	Magnetic at 0.75 amp.	Magnetic at 1.20 amp.
Florida	**Lab. no.......**		**242836**	**242837**	**242838**	**242839**	**242840**	**242841**		
	TiO_2		57.27	53.96	57.74	58.82	60.04	68.36		
	FeO		[1]11.25	[2] 9.97	[2]11.72	[2] 4.65	[2] 0.91	[1] 0.85		
	Fe_2O_3		25.91	28.90	28.31	31.12	29.82	20.22		
	Total Fe as Fe_2O_3.		38.41	39.98	41.34	36.29	30.83	21.16		
Quilon, India	**Lab. no.......**		**242849**	**242850**	**242851**	**242852**	**242853**			
	TiO_2		59.26	58.97	56.83	60.19	63.83			
	FeO		[1]10.73	[2]10.82	[2]15.34	[1] 7.50	1.81			
	Fe_2O_3		27.12	26.83	25.63	28.42	30.48			
	Total Fe as Fe_2O_3.		39.05	38.86	42.68	36.76	32.49			
Cut Bank Creek, Mont.	**Lab. no.......**		**251845**	**251846**	**251847**	**251848**				
	TiO_2	*19.25	28.99	27.18	18.34	24.08				
	FeO									
	Fe_2O_3									
	Total Fe as Fe_2O_3.		73.10	74.47	80.20	72.47				
Grass Creek, Wyo.	**Lab. no.......**		**242842**	**242843**	**242844**	**242845**	**242846**		**242847**	**242848**
	TiO_2	*23.95	32.55	35.11	36.02	50.37	66.50		69.98	71.29
	FeO		[2]17.73	[2]15.97	[2]11.17	[2] 3.14	[1] 0.24		[1] 0.51	[1] 2.37
	Fe_2O_3		39.00	44.54	35.36	35.95	26.25		6.95	2.37
	Total Fe as Fe_2O_3.	*76.15	58.71	62.29	47.77	39.44	26.52		7.52	5.00

Black Butte Creek, Wyo.	**Lab. no.**		**251853**	**251854**	**251855**	**251856**	**251857**
	TiO_2	*15.73	44.33	45.93	37.44	32.51	47.57
	FeO						
	Fe_2O_3						
	Total Fe as Fe_2O_3.	*80.15	50.60	47.05	38.82	41.58	37.39
Sheep Mountain, Wyo.	**Lab. no.**		**251859**	**251860**	**251861**	**251862**	
	TiO_2	*31.50	31.88	34.24	38.40	5.61	
	FeO						
	Fe_2O_3						
	Total Fe as Fe_2O_3.	*57.50	71.89	65.91	61.21	52.13	
Grand Mesa, Colo.	**Lab. no.**		**251849**	**251850**	**251851**	**251852**	
	TiO_2		45.91	47.11	57.58	65.43	
	FeO						
	Fe_2O_3						
	Total Fe as Fe_2O_3.		60.04	56.98	41.98	30.14	
Sanostee, N. Mex.	**Lab. no.**		**251841**	**251842**	**251843**	**251844**	
	TiO_2		46.71	52.81	50.19	59.39	
	FeO						
	Fe_2O_3						
	Total Fe as Fe_2O_3.		50.48	47.52	44.00	34.30	

[1] Sample too small for reliable ferrous iron determination.

[2] Ferrous iron result is from second determination after finer grinding.

ilmenite, but chemical analysis of this fraction shows the opaque minerals contain only 23.95 percent TiO_2 (table 5), and neither magnetite nor ilmenite, nor intergrowths of these two minerals could be definitely identified in polished section. X-ray patterns of less-magnetic fractions from Grass Creek suggest a transition to anatase, rutile, and goethite, but do not yield additional information on the primary minerals (fig. 11). Chemical analyses of less-magnetic fractions (table 5) show an increase in TiO_2 and Fe_2O_3 which is considered to have resulted from alteration.

The primary mineral at Grass Creek seems to be a form of ilmenite according to X-ray patterns, but it does not contain enough TiO_2. It is also deficient in FeO if the fraction separated at 0.05 ampere (table 5) is used as an example. On the other hand, it is too high in TiO_2 to be titaniferous magnetite, and it does not give a good magnetite pattern. For lack of a more definitive term, the mineral is herein called ferrian ilmenite(?) for descriptive purposes.

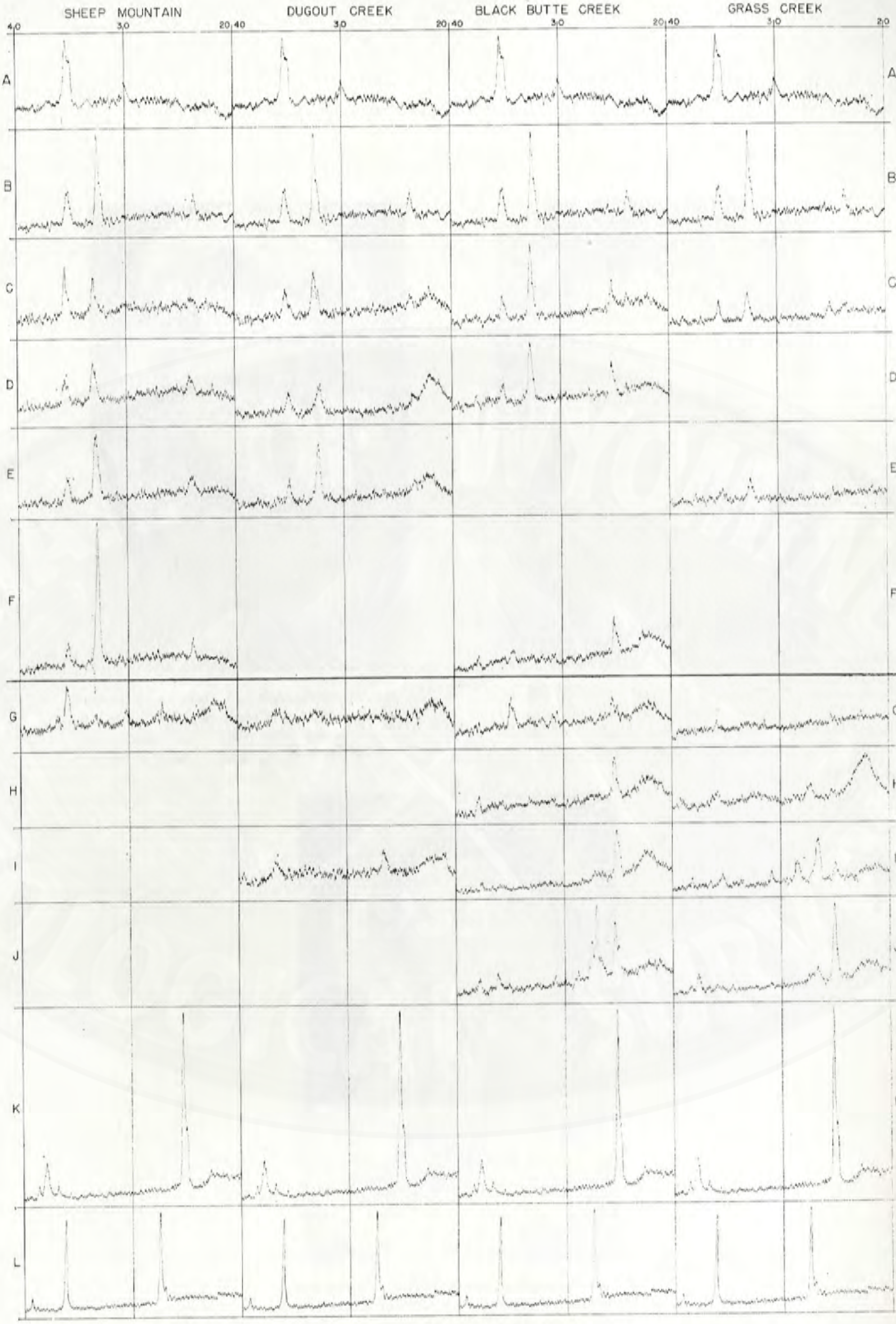
The ferrian ilmenite(?) is blue-gray in polished section and somewhat resembles hematite in color except that it is darker (pls. 6 and 7A).

In the more highly altered (less-magnetic) fractions this mineral has alteration rims of anatase and secondary iron oxide minerals. In addition to the ferrian ilmenite(?), the opaque fractions separated at 0.30 ampere and higher contain highly altered grains of uncertain origin which are marked by a yellowish internal reflection. These grains may be altered ilmenite and may account for the higher TiO_2 content of these fractions (table 5).

Opaque minerals from Black Butte Creek and Sheep Mountain, Wyo., are similar to the ferrian ilmenite(?) from Grass Creek, Wyo. (table 5, fig. 11) except that the Black Butte Creek minerals are generally more highly altered and contain more TiO_2. However, the highly altered grains noted in the 0.30 ampere fraction at Grass Creek are not present in the same fractions in the Black Butte Creek and Sheep Mountain deposits, which may account for their low TiO_2 content (table 5).

The ferrian ilmenite(?) common to these three Wyoming deposits probably contained in its original form 25 to 30 percent TiO_2 and 70 to 85 percent total iron oxides. Through alteration, most of the iron has been converted to ferric iron and in the more highly altered grains a part of the iron has been removed, with the result that the mineral is enriched in TiO_2. The ferrian ilmenite(?) is believed to constitute almost all of the opaque minerals of the Sheep Mountain and Black Butte Creek deposits. At Grass Creek, however, an additional opaque mineral is present in minor amounts, and because of its high TiO_2 content, it is thought to be altered ilmenite.

It should be noted that opaque minerals from only three Wyoming deposits have been studied in detail, and it is possible that



A = Magnetite, Iron Mountain, Wyoming
B = Ilmenite, Arendal, Norway
C = Ferromagnetic opaque minerals
D = Opaque minerals at .05 ampere setting on Frantz
E = Opaque minerals at .10 ampere setting on Frantz
F = Opaque minerals at .20 ampere setting on Frantz
G = Opaque minerals at .30 ampere setting on Frantz
H = Opaque minerals at .40 ampere setting on Frantz
I = Opaque minerals at .50 ampere setting on Frantz
J = Opaque minerals at .75 ampere setting on Frantz
K = Anatase, Binnental, Switzerland
L = Rutile, Ceára, Brazil

Figure 11. X-ray diffraction patterns of opaque minerals from Wyoming deposits compared with standard patterns (A, B, K, and L) of magnetite, ilmenite, anatase, and rutile.

PLATE 6

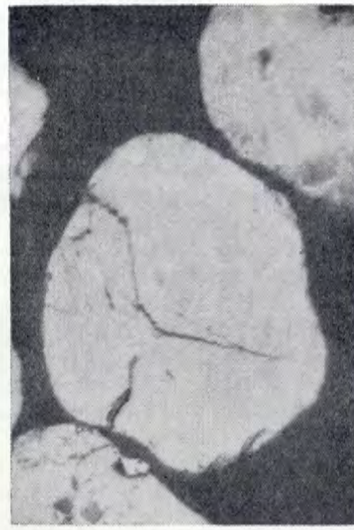
A. Photomicrograph of ferrian ilmenite (?) from the Grass Creek deposit, showing narrow alteration rims. Separated at 0.05 ampere. Ordinary light x 405.

B. Photomicrograph of ferrian ilmenite (?) from the Grass Creek deposit (showing well-developed alteration rims. Separated at 0.10 ampere. Ordinary light x 405.

C. Photomicrograph of highly altered ferrian ilmenite(?) from the Grass Creek deposit. Separated at 0.20 ampere. Ordinary light x 405.

PLATE 7

A. Photomicrograph of anatase-rutile-hematite-goethite mixture from the Grass Creek deposit showing remnant of ferrian ilmenite(?) in core. Separated at 0.30 ampere. Ordinary light x 405.



B. Photomicrograph of anatase-rutile-hematite-goethite mixture from the Grass Creek deposit pseudomorphic after ferrian ilmenite(?). Separated at 0.40 ampere. Ordinary light x 405.

other deposits may have different species of these minerals. For example, the ratio of iron to titanium in bulk samples in the Cowley, Lovell, Dugout Creek, and Poison Spider deposits is higher (table 13) and these deposits have a generally higher percentage of ferromagnetic minerals than in the three deposits studied in detail. This may indicate (at least prior to alteration) considerable magnetite or some other iron-rich oxide.

Opaque minerals from Grand Mesa, Colo., and Sanostee, N. Mex., are similar to altered ilmenite from India and Florida in chemical composition (table 5). Comparable magnetic fractions in the lower ampere ranges do not contain so much TiO_2 as is found in altered ilmenite from Florida and India, but otherwise the chemical properties are similar.

Thermal analyses.—Thermal analyses have been made to determine the minerals in the matrix of the black sandstone and to study the hydrated iron oxide alteration products of the opaque minerals. Previous work on ilmenite from modern beach placers has indicated that ilmenite alters to a mixture of rutile, brookite, and hematite, of which the most common are rutile and hematite. In the samples collected for the present study, the opaque oxide minerals had been subjected to long periods of weathering at ordinary temperature and pressure which resulted in the formation of the hydrated iron oxides goethite and lepidocrocite.

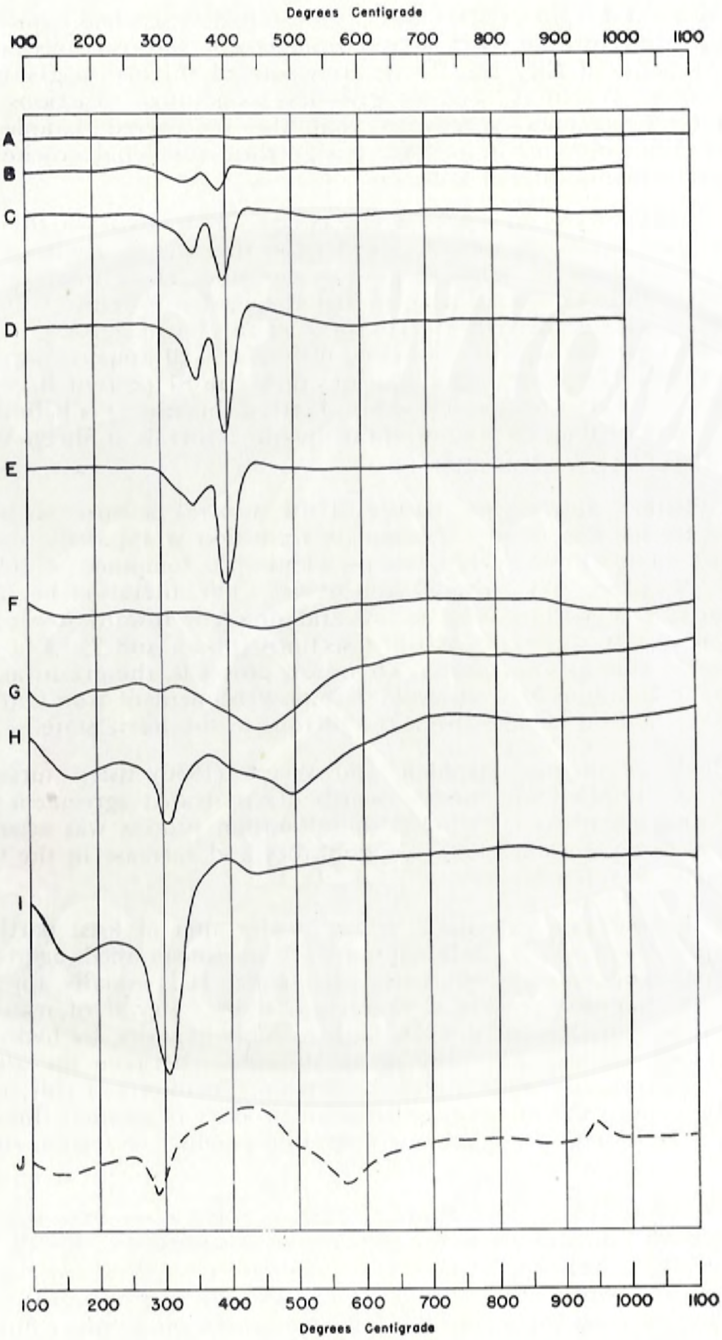
X-ray diffraction patterns of various oxides of different magnetic susceptibilities have broad lines giving *d* values between 4.07-4.20 (fig. 11), which may indicate the presence of goethite, but no pattern could be definitely assigned to it. On the other hand, thermal analyses indicate that the same samples contain mixtures of goethite, lepidocrocite[1], and hematite. Kulp and Trites (1951) show that mixtures of goethite and lepidocrocite give a minor endothermic reaction at 350°C. and a major endothermic reaction at about 435°C. (fig. 12). Typical thermal curves of the Wyoming opaque oxides are similar to those of Kulp and Trites, except that the reactions take place at lower temperatures. The samples studied by Kulp and Trites were between 50 and 80 mesh, whereas those from the Wyoming deposits were finer than 325 mesh. The quantitative effect of differences in size and crystallinity is not known, but the work of Speil, Berkelheimer, Pask, and Davies (1945) on kaolinite indicates a significant decrease in temperature of reaction with smaller particle size, and according to Grimshaw, Heaton, and Roberts (1945) the temperature decrease may be as much as 30°C. for poorly crystallized kaolinite as compared with well-crystallized kaolinite.

[1]Kelly (1958, p. 12) has studied differential thermal curves of gossan goethite and he notes that thermal curves for goethite, for lepidocrocite, and for goethite-lepidocrocite mixtures can be produced by goethite alone.

Figure 12. Differential thermal curves of iron-titanium oxides from Wyoming deposits compared with artificial mixtures of goethite, lepidocrocite, and hematite.

*A. Hematite (50-80 mesh)
*B. 10% goethite, 20% lepidocrocite, and 60% hematite (50-80 mesh)
*C. 30% goethite, 30% lepidocrocite, and 40% hematite (50-80 mesh)
*D. 40% goethite, 40% lepidocrocite, and 20% hematite (50-80 mesh)
*E. 60% goethite, and 40% lepidocrocite (50-80 mesh)
F. Iron-titanium oxides separated at 0.30 amperes, Grass Creek deposit (<325 mesh)
G. Iron-titanium oxides separated at 0.40 amperes, Grass Creek deposit (<325 mesh)
H. Iron-titanium oxides separated at 0.40 amperes, Black Butte Creek (<325 mesh)
I. Iron-titanium oxides separated at 0.50 amperes, Dugout Creek (<325 mesh)
J. Matrix of high grade sample from Black Butte Creek (<325 mesh)

* Kulp and Trites (1951, figs. 4 and 5)


Degrees Centigrade
100
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1000
1100
Degrees Centigrade

Kulp and Trites (1951) also demonstrated that when hematite is added to mixtures of goethite and lepidocrocite the reactions become less pronounced (fig. 12). Moderately altered (higher magnetic susceptibility) Wyoming samples give less-pronounced reactions than highly altered ones, suggesting that the less-altered samples are either richer in hematite or have less goethite and lepidocrocite than the more highly altered samples.

Discussion and summary.—The opaque minerals from the Wyoming black sandstone deposits are ferrian ilmenite(?), altered ilmenite, and a radioactive mineral, possibly euxenite. Data from the three deposits studied in detail suggest that the ferrian ilmenite(?) is most abundant and is the major constituent of the ferromagnetic fraction and the fractions separated at 0.05, 0.10, and 0.20 ampere in almost all deposits. These magnetic fractions make up 81 percent by weight of the Grass Creek opaque minerals. Ferrian ilmenite(?) is believed to make up more than 90 percent of the opaque minerals at Sheep Mountain and Black Butte Creek.

Whatever the original nature of the mineral or minerals herein called ferrian ilmenite(?), a complete transition is apparent from its slightly altered form to complete pseudomorphs composed of anatase, rutile, hematite, and hydrated iron oxides. The alteration begins on the surface of well-rounded grains and proceeds inward toward the core as clearly shown in polished sections (pls. 6 and 7). Chemical analyses (table 5) show that as alteration proceeds, the grains are enriched in titanium by a progressive impoverishment of iron and that some of the iron changes from the ferrous to the ferric state.

Bailey, Cameron, Spedden, and Weege (1956) listed successive stages of alteration of ilmenite, which demonstrated agreement with Lynd and coworkers (1954) that the alteration process was accompanied by decrease in magnetic susceptibility and increase in the titanium oxide-iron oxide ratio.

It is clear that the titanium-iron oxides alter at least partly by recrystallization of the original mineral to fine-grained aggregates of pure titanium oxide and ferric iron oxide. It is equally apparent that the alteration process is characterized by removal of iron and consequent enrichment in TiO_2 and, in some deposits, by hydration of the iron oxides. The only major difference between the altered ilmenite previously studied and the ferrian ilmenite(?) of this report is that rutile is the dominant alteration product of normal ilmenite, whereas anatase is the dominant alteration product of ferrian ilmenite(?).

Overholt, Vaux, and Rodda (1950, p. 117) state that the end products of ilmenite alteration depend on temperature. Rutile may be a comparatively high temperature deuteric or hydrothermal alteration product of ilmenite, formed prior to weathering of source rocks, and anatase may be a low-temperature alteration product formed after deposition. Bailey and co-workers (1956, p. 278) point out that, although temperature may be a factor, peripheral alteration of well-rounded ilmenite grains to rutile is common in beach sands and must have taken place either during the latter stages of transportation or after deposition. This is further substantiated by Cannon (1950, p. 210) who shows that ilmenite in deposits at Trail Ridge, Fla. is altered to leucoxene, which is an amber microfine crystalline rutile. According to Cannon, this type of alteration takes place at a rate five to six times faster above the water table than below. It seems, therefore, that the rutile type of alteration must continue for some time after deposition of black sands, and that factors other than temperature and pressure must be considered before a satisfactory explanation of rutile-versus-anatase alteration can be found. In this connection Hartman (1959, p. 1399-1402) has studied altered ilmenite in bauxite deposits where alteration presumably has taken place under low temperature, pressure conditions. He notes that both anatase and rutile are pseudomorphs after ilmenite and he suggests that pH, rate of alteration, or impurties may be factors that determine which polymorph develops during alteration. The role of pH and impurties could not be evaluated but Hartman (1959, p. 1401) states that if alteration is rapid the titanium ions might not become oriented in the most stable sites and the less stable polymorph, anatase, might form. However, he believes that, in time, anatase would revert to rutile.

Pyroxene

Pyroxene is a rare constituent of the black sandstone, but it is present in the associated barren sandstone. The only deposit containing enough pyroxene for adequate optical study is at Clarkson Hill, Wyo., where augite comprises 7 percent of the total heavy-mineral fraction.

The augite is irregular in shape and has well-developed "hacksaw" or "cockscomb" terminations (pl. 5C) that are believed to be due to post-depositional changes. This type of termination has been described by Ross, Miser, and Stephenson (1929), who attribute it to partial replacement of augite by calcite.

In a comparison of the magnetic susceptibility of amphibole and pyroxene at Clarkson Hill, the amphibole is separated between 0.3 and 0.4 ampere and the pyroxene between 0.4 and 0.5 ampere. Hutton (1952, p. 20), in a study of California beach sands, demonstrated that amphibole has a higher susceptibility than pyroxene for "crystals devoid of opaque ferruginous and/or titaniferous inclusions."

Augite from Clarkson Hill is faint green in reflected light, and colorless in polarized light. The mineral has the following optical properties:

$N_x = 1.678 \pm .003$ colorless
$N_z = 1.699 \pm .003$ colorless

Rutile

All samples of black sandstone in the Rocky Mountain region that have been examined in this study contain minor amounts of rutile. Despite its ubiquitous occurrence, it rarely constitutes more than 2 percent of the heavy-mineral fraction and in Wyoming deposits, it averages less than 1 percent.

Rutile occurs as subrounded elongate crystals that are usually deep red or orange. Some individual crystals range from dark red at one end to black or lighter reddish-orange at the other. Many of the crystals are conspicuously striated parallel to the length, and some show rutile or penetration twinning.

Sphene

Sphene occurs in all deposits in eastern Wyoming and also in the Cumberland Gap deposit in the western part of the State. It is fairly abundant at Clarkson Hill, where it makes up 6 percent of the heavy-mineral fraction. Most grains of sphene are subrounded, and only one or two crystal faces were observed.

Sphene is only moderately magnetic and is extracted in the 0.75 to 1.00 ampere Frantz fractions. It is pleochroic from orange-brown to faint green. The grains examined were biaxial positive with a small $2V$ and very high dispersion. Refractive index measurements are as follows:

$N_x = 1.894 \pm .003$ colorless
$N_z > 2.008$ brownish orange
Disp. strong $r > v$

Spinel

Spinel is widely distributed and occurs in very small amounts in every Wyoming deposit studied. Most grains are irregular in shape and subrounded. Some grains have crystal faces preserved, but rarely are there more than two or three on a single grain. Conchoidal fracture is common.

The grains are green to bluish green. They are separated over a fairly wide magnetic range but mainly between 0.2 and 0.4 ampere.

Optical data for spinel from various deposits is listed in table 6. Most of the spinel has an index of refraction of 1.78-1.79 and probably contains about equal amounts gahnite, hercynite, and normal spinel. Spinel from the Poison Spider deposit has an index of refraction of 1.740 and is probably normal.

Because of the small amounts of spinel available for study, it was not possible to determine definitely the composition by specific gravity or microchemical tests, but a few grains were heated to ascertain whether they might be metamict gadolinite. As pointed out by Hutton (1950, p. 677), spinel and gadolinite may be easily confused, but upon heating, spinel will remain isotropic whereas gadolinite becomes strongly anisotropic because its metamict condition is destroyed. A few deep-green grains were heated but they retained their isotropism; therefore, they are probably normal spinel.

Table 6.—Optical properties of spinel from Wyoming black sandstone deposits.

Deposit	Color	Index of refraction	Remarks
Poison Spider	Bluish green	1.740	Some opaque inclusions
Grass Creek	Green	1.787	
Red Creek	do	1.791	
Sheep Mountain	do	1.78-1.79	

Staurolite

Staurolite is present in the younger deposits, such as Sheep Mountain, Poison Spider, and Clarkson Hill in Wyoming and Grand Mesa in Colorado. It seems to be most abundant in the poorly sorted lower grade samples; at Grand Mesa, Colo., there is a distinct increase in staurolite in the coarser screen fractions.

Staurolite occurs as angular grains somewhat similar in shape to epidote. At Grand Mesa, the grains are characterized by hacksaw or cockscomb terminations, similar to those described for augite. Because of various inclusions staurolite has a wide range of magnetic susceptibility, but the greatest part is extracted between 0.3 and 0.5 ampere.

Staurolite is pleochroic from orange to colorless. Inclusions are chiefly opaque and are probably carbonaceous material and magnetite. Some grains have trains of lenticular cavities and others contain numerous large transparent inclusions which give the grains a porous appearance.

Staurolite from the Sheep Mountain deposit has the following optical properties:

$$N_x = 1.739 \pm .003 \text{ colorless}$$
$$N_z = 1.750 \pm .003 \text{ orange}$$

Tourmaline

Tourmaline occurs in all the black sandstone deposits but, with the exception of associated low-grade sandstone, it is found in amounts less than 1 percent. Most of the tourmaline grains are markedly well rounded and many are almost perfect spheres. Prism faces are preserved on some grains, but terminal faces are rare. Many tourmaline grains are very dark to opaque in reflected light, and the remainder are some shade of brown or greenish blue. Two types of tourmaline are separated magnetically; dark to opaque tourmaline is usually extracted from 0.3 to 0.4 ampere, whereas transparent grains are extracted from 0.4 to 0.6 ampere. The two types are classed as schorlite and dravite, respectively.

The pleochroism of 170-mesh grains of schorlite is N_o = greenish blue to opaque and N_e = violet brown. Thin edges of these same grains show a pleochroism of N_o = greenish blue, N_e = colorless. Optical properties of schorlite from the Poison Spider deposit are as follows:

$$N_e = 1.630 \pm .003$$
$$N_o = 1.653 \pm .003$$

Dravite is lighter colored and separates magnetically at a higher amperage. Although this variety may have such strong absorption in the N_o position as to appear opaque, even thick grains are colorless in the N_e position. Optical properties of dravite from the Poison Spider deposit are as follows:

$N_e = 1.624 \pm .003$ colorless
$N_o = 1.645 \pm .003$ brown to green brown

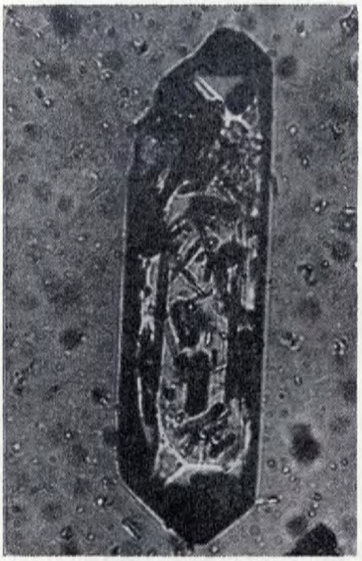
Zircon

Zircon is the most abundant nonopaque heavy mineral in the black sandstone. It is present in all deposits and commonly makes up 10 percent of the heavy-mineral fraction. At Grass Creek the average zircon content for ten samples is 17 percent of the total heavy-mineral fraction. It is an important contributor to the radioactivity of the black sandstone deposits. Some of the zircon emits a bright yellow-orange fluorescence when activated by short-wave ultraviolet light. Zircon is most abundant in screen sizes between 115 and 250 mesh (fig. 8) and is rare in coarse screen fractions. It is more abundant in high-grade samples than in low-grade samples because of its high specific gravity.

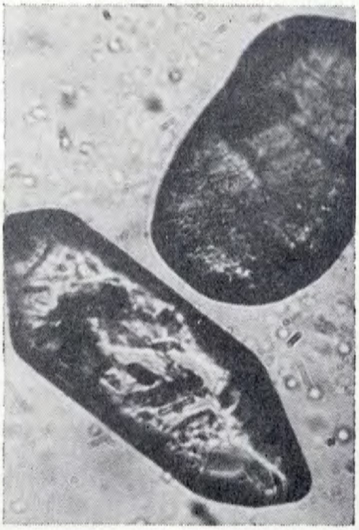
There are five common occurrences of zircon in the black sandstone: euhedral colorless, euhedral reddish-violet, well-rounded reddish violet, well-rounded colorless, and malacon.

Euhedral colorless.—The euhedral colorless is the common variety of zircon, as indicated by its index of refraction. It is present in all black sandstone deposits and is second in abundance to the well-rounded reddish violet type. Although generally euhedral, many grains have rather strongly abraded edges (pl. 8A and B). Most crystals are either doubly terminated or are fractured roughly parallel to 001. The most common forms of single crystals are 111, 311, 100, and 110.

PLATE 8



A. Photomicrograph of euhedral colorless zircon from the Black Butte Creek deposit. Ordinary light x 200.



B. Photomicrograph of euhedral colorless and well-rounded reddish-violet zircon from the Grass Creek deposit. Ordinary light x 200.

C. Photomicrograph of malacon zircon from the Sanostee, N. Mex., deposit, showing zoning and fracturing. Ordinary light x 155.

Many crystals are zoned and most contain inclusions that are usually aligned parallel to zonal directions. Typical inclusions are:

1. Magnetite grains, usually large.
2. Opaque dust commonly concentrated near the center of the crystal.
3. Elongate, rod-like cavities; on broken grains some of these cavities have outside openings and are filled with opaque material, probably hematite.
4. Dark needle-like grains, possibly rutile.
5. Large opaque grains with cracks radiating outward into the surrounding crystals. These may be radioactive opaque minerals.

Refractive indices of euhedral colorless grains from a number of Wyoming deposits, including Grass Creek, Cumberland Gap, Rock Springs, and Poison Spider, have been measured. The indices vary only slightly in spite of the wide distribution of the deposits; the range is as follows:

$$N_e = 1.980 - 1.983$$
$$N_o = 1.920 - 1.924$$

Semiquantitative spectrographic analyses of the euhedral colorless zircon are shown in table 7 and age determinations in table 8.

TABLE 7.—Semiquantitative spectrographic analysis of zircon varieties from the Grass Creek deposit.

[Analyst: R. Havens, U. S. Geological Survey.]

Percent	Euhedral colorless Lab No. 226386	Well-rounded reddish-violet Lab. No. 226387
10.0	Zr	Zr
0.215-0.464	Hf	Hf
0.10-0.215	Ti, Ca	Ti, Y
0.0464-0.10	Al, Y	Al, Ca
0.0215-0.0464	Yb, Fe	Yb, Fe
0.010-0.0215	Ba	Ba, Sc
0.00464-0.010	Sc	
0.00215-0.00464	Mg	Mg
0.001-0.00215	Cu	Cu
0.000215-0.000464	Mn	Mn

Looked for but not detected: P, K, As, Au, B, Be, Bi, Cd, Co, Dy, Er, Gd, Ge, Hg, In, Ir, Li, Mo, Nb, Ni, Os, Pd, Pt, Re, Rh, Rw, Sb, Sm, Ta, Th, Tl, Te, U, W, and Zn.

Table 8.—Lead-alpha age determinations of zircon.

[Analyst: H. W. Jaffe, U. S. Geological Survey.]

Locality and formation	Zircon type	α per mg per hr	Pb (ppm)	Pb/α (millions of years)
Grass Creek, Wyo.—Mesaverde formation	Euhedral colorless[1]	178	10	135
Red Creek, Wyo.—Rock Springs formation	Well-rounded reddish-violet	115	38	750
Cumberland Gap, Wyo.—Frontier formation	Euhedral colorless	218	8.5	94

[1] Sample included some well-rounded colorless and well-rounded reddish-violet zircon. For this reason, the age determined is probably too great for the pure euhedral colorless variety.

Well-rounded reddish-violet.—The well-rounded reddish-violet zircon (pl. 8B) is similar to a variety called hyacinth by a number of writers (Mackie, 1925; Tyler and others, 1940; Hutton, 1950). Hutton (1950, p. 689-690) has contrasted hyacinth zircon with colorless or normal zircon as follows:

1. The average grain size of hyacinth is larger.
2. Euhedra of hyacinth are rare; hyacinth is more commonly well rounded, often nearly spherical.
3. In crystals that show little or no abrasion, the crystal habit is simple.
4. Zonary structures are common.
5. Radiating or anastomosing cracks are present in some hyacinth crystals.
6. Overgrowths are common.
7. The grains are pink, purple, or reddish.
8. Hyacinth is more radioactive than normal zircon.

The reddish-violet zircon of the Wyoming black sandstone deposits fits the above description except that it is less radioactive than the normal zircon, as shown by table 8. Other characteristics of the well-rounded reddish-violet zircon which differ from those of the colorless zircon are as follows:

1. Refractive indices slightly lower.
2. Inclusions less common.
3. Much older (table 8).
4. Nonfluorescent.

Refractive-index data for the reddish-violet zircon are as follows:

$$N_e = 1.97$$
$$N_o = 1.917$$

A comparison of spectrographic analyses of reddish-violet and normal colorless zircon (table 7) indicates little difference in the minor elements present. In a survey of the literature, Hutton (1950, p. 700) found that the hyacinth variety described from Scotland, North America, Australia, and Madagascar was derived originally from rocks of Precambrian age. H. W. Jaffe, of the U. S. Geological Survey (personal communication, 1956), states that purplish zircon is almost invariably Precambrian in age. Some of the properties of hyacinth, such as color, slightly lower index, and perhaps lack of fluorescence, may be the result of aging.

Well-rounded colorless.—Well-rounded colorless zircon is not so abundant as the normal euhedral variety or the hyacinth variety, but it is present in minor amounts in all Wyoming deposits. Except for color, it is similar to the hyacinth zircon, and in making grain counts the two varieties were included together.

Euhedral reddish-violet.—Euhedral reddish-violet zircon is a rare constituent of the Wyoming deposits, but it is common in New Mexico deposits. Because of its rare occurrence in Wyoming, it was not studied petrographically, but it is believed to be related to the hyacinth variety.

Malacon.—The name malacon is used to designate a variety of slightly metamict zircon. It is rare in the Wyoming black sandstone deposits, but enough grains were obtained from a sample of the Red Creek deposit to make a petrographic study. Malacon is variable in appearance and probably in the degree to which it approaches the metamict state. It is characteristically simple in habit, and most crystals are doubly terminated with simple pyramid faces. It ranges from bluish brown to light brown to black in reflected light, and has a marked cloudy appearance. In transmitted light, the malacon is reddish brown to dark blue or opaque, and often has different colors within the same grain. Many of the crystals have a system of radiating cracks, and most of the crystals that will transmit light show pronounced zoning (pl. 8C). Like the well-rounded reddish-violet zircon, the malacon is nonfluorescent.

Malacon is characterized by relatively low refractive indices and low birefringence. The refractive indices show considerable variation. Determinations of N_o ranged from 1.783 to 1.90.

One of the most interesting properties of the malacon is its higher magnetic susceptibility as compared with colorless zircon and hyacinth. The malacon is extracted by the Frantz separator between 0.9 and 1.2 amperes, which is the same extraction amperage as thorite. A sample was analyzed for thorium, using the X-ray spectrograph, but none was detected. X-ray spectrometer patterns were made to compare the malacon with the euhedral colorless zircon. Well-defined diffraction lines in the forward $2\ \Theta$ region were found on both varieties, but the lines were slightly more diffuse for malacon. In the smaller interplanar spacing region (less than 90 degrees $2\ \Theta$), no lines were present for malacon. The X-ray data suggest that most of the malacon is not completely metamict, but it seems likely that some of the individual grains or zones of individual grains have been at least partly altered to a metamict state.

ORIGIN OF BLACK SANDSTONE DEPOSITS

The stratigraphy and mineralogy of the black sandstone deposits of Late Cretaceous age definitely indicate that they are fossil beach placer deposits. The source, mechanism of transport, and methods of sorting and final deposition are, however, still largely conjectural. There are many known deposits of black sand along present beaches, but the most notable are those of India, Brazil, Australia, and Florida. These and other recent deposits have been extensively studied by J. L. Gillson (1949, p. 1042-1073), who concluded that most of the commercial deposits have had similar geologic histories. The following is a summary of the steps in geologic history which Gillson lists as being common to all or most of these deposits:

1. A source area composed of crystalline rocks in which rutile, zircon, and opaque minerals are the accessory constituents.

2. A period of peneplanation during which a deep soil zone was formed in which magnetite was decomposed.

3. Uplift and rapid erosion followed by a quick dumping into the sea of the products of stream erosion, without intermediate deposition in stream channels which would result in dilution of heavy minerals into low-grade deposits.

4. Stage of deposition in coastal plain sediments which are later elevated and eroded, causing heavy minerals to be further concentrated.

5. Subsidence of the coast followed by shoreline straightening and the formation of longshore sand bars. Waves breaking over the bars carry minerals of lighter specific gravity into deep water on the landward side of the bar, leaving the heavy minerals on the bar itself.

6. Elevation of the coast permitting attack on the partly concentrated sand in bars or in coastal plain sediments by wave and wind actions. Particularly during storms, the waves attack previously deposited sediments and wash minerals of low specific gravity seaward.

Fossil black sand deposits probably originated in much the same manner, but in many respects they are more difficult to interpret than their recent counterparts because little is known about the location and environment of the source areas and the mineralogical changes of the fossil black sand deposits through geologic time. In other respects, however, certain long-range paleogeologic events associated with the formation of black sandstone are more clearly demonstrated in Upper Cretaceous deposits than in Pleistocene or Recent deposits. From studies of rocks associated with Upper Cretaceous black sandstone, geologic events following black sand deposition as well as events preceding it can be ascertained.

SOURCE

Stratigraphic and paleogeographic data indicate that the source area of Upper Cretaceous sedimentary rocks lay to the west of the present Rocky Mountains. Imlay (1956, pl. 8), shows a high land mass extending from eastern British Columbia to Lower California during the Jurassic period. Reeside (1957) shows that essentially the same land mass remained throughout the Cretaceous period. The eastern edge of this positive area trends in a north-south direction through westernmost Montana, central Idaho, along the western boundary of Utah, and through western Arizona. Directly east of the relatively permanent land mass, and lying parallel to it, was another belt several hundred miles in width which was periodically uplifted and eroded during the Cretaceous period. These Jurassic and Cretaceous positive areas undoubtedly provided most of the detritus for the Upper Cretaceous sediments and, more specifically, the black sand deposits.

Some information with regard to source rocks for the black sandstone can be obtained from the mineral suites themselves. Although this information may not be conclusive, it does permit speculation as to the lithologic character and age of the source rocks.

Zircon

According to the lead-alpha age determinations listed on table 8, well-rounded violet zircon is about 750 million years old, and euhedral colorless zircon is about 95 million years old, indicating that the former is Precambrian and the latter is Late Cretaceous in age.

Table 9 shows the regional distribution of the zircon varieties studied. If the lead-alpha age determinations of zircon are correct, then the distribution suggests a source in igneous or metamorphic rocks of Cretaceous age in Montana, a mixed source in Wyoming, and a source predominantly in Precambrian rocks or reworked from sedimentary or metamorphic rocks in Colorado and areas farther south. Intrusives emplaced during the Nevadian orogeny in Cretaceous time crop out closer to the known black sandstone deposits in Montana and Wyoming than they do in Colorado and New Mexico; and, therefore, the intrusive rocks could have supplied detritus including euhedral colorless zircon to the northern areas much more readily than to the southern areas. The euhedral colorless zircon has simplicity of crystal form, lack of color, and elongation between 2.0 and 3.0 that are generally common in zircon in granite (Poldervaart, 1956, p. 535).

The lead-alpha ages of 16 samples from the Idaho batholith range from 94 to 135 million years, and the mean age is 108 $\pm$ 12 million years (Larsen and others, 1958, p. 54). The main mass of Idaho batholith, accordingly, was probably intruded in early Late Cretaceous time, and it could have provided some of the heavy minerals now occurring in the black sandstone. The Boulder and Philipsburg batholiths of Montana, however, are dated as 68 ± 10 and 50 million years old, respectively (Chapman and others, 1955, p. 609), which indicates these rocks could not have contributed to the older Cretaceous strata.

Table 9.—Regional distribution of zircon varieties.

Localities	Euhedral colorless (percent)	Well-rounded violet (percent)	Euhedral violet (percent)
Montana	66	34	0
Northern Wyoming	49	51	0
Southern Wyoming	45	55	0
Northern Colorado	25	75	0
Southwestern Colorado and southeastern Utah	7	86	7
Northwestern New Mexico and northeastern Arizona	41	32	27

The well-rounded violet zircon has probably been reworked from older sedimentary rocks, but the relatively large amount of euhedral violet zircon suggests direct derivation from Precambrian rocks for at least part of the mineral suite in Colorado and New Mexico.

In Wyoming, well-rounded violet zircon is more abundant in the younger black sandstone deposits, and euhedral colorless zircon is more abundant in the older deposits (fig. 5). This suggests that igneous or metamorphic rocks of Cretaceous age were exposed to erosion very early in the Laramide orogeny and provided a major part of the detritus. As downcutting continued, older rocks, both sedimentary and crystalline, were eroded and provided increasing amounts of debris, including reworked violet zircon.

Sphene

David Gottfried (written communication, 1956) observed that sphene from various rock types of the Boulder Creek batholith, Colorado, varies in magnetic susceptibility over a wide range of amperage. Sphene from the more siliceous rocks shows the greatest variation in magnetic susceptibility, but most of it becomes magnetic at about 1.0 ampere. Sphene from more mafic rocks is less magnetic and is concentrated only at higher amperage. The sphene studied from Wyoming black sandstone deposits was separated between settings of 0.75 and 1.00 ampere in the Frantz magnetic separator, which may indicate that it was derived originally from a felsic igneous rock.

Opaque Minerals

The opaque minerals are, for the most part, iron-titanium oxides. As a group, the opaque minerals show distinct regional differences in chemical composition. The iron oxide to titanium oxide ratio is high in Montana, but becomes progressively lower in a southward direction. Furthermore, the ferromagnetic minerals are much more abundant in the northern deposits and gradually decrease in abundance southward. The regional difference can also be expressed mineralogically; essentially pure magnetite is present in Montana deposits, and essentially pure ilmenite is present in the New Mexico deposit which has been studied. In Wyoming, on the other hand, the so-called ferrian ilmenite is in great abundance.

This regional variation in the composition of the opaque minerals may reflect a change in the lithology of the source rocks from north to south. Iron-titanium oxides, such as intergrown ilmenite and magnetite and the ferrian ilmenite(?), found in abundance in the northern deposits, are commonly derived from high-temperature basic effusive rocks (Goldschmidt, 1954, p. 414). Titanium oxides, such as those found in the southern deposits, are relatively low in iron content and are derived from a wide variety of igneous rocks but especially from gabbros, norites, and basic nepheline rocks, such as ijolites (Goldschmidt, 1954, p. 414).

The difference in composition of the opaque minerals may also be due to other factors: 1) The source rocks of the northern deposits may have been richer in iron oxide, possibly reflecting an iron metallographic province. Conversely, the high percentage of TiO_2 of the southern deposits may reflect a titanium metallographic province. 2) Decomposition of magnetite and other iron-rich oxides in the source area may have been more complete in the southern region than in the northern region. 3) Postdepositional alteration, which seems to be more advanced in the southern deposits, could produce regional differences in the opaque mineral suite. Degree of alteration, however, has no bearing on the lithology of the source areas.

The niobium content of opaque minerals from different deposits, as determined by spectrographic analyses of magnetic fractions of high-grade samples separated at an amperage of 0.25 to 0.45, are compared on table 10. No specific niobium province is indicated, but the analyses do suggest a slightly higher niobium content in the opaque minerals of Wyoming and Colorado than in those of Montana and New Mexico. No systematic variation in niobium content with increasing age was noticed. X-ray fluorescence analyses for hafnium were made of the total zircon fraction extracted from each of seven samples representing seven different deposits, as shown in table 11, but no significant difference in the hafnium-zirconium ratios was determined.

Table 10.—Semiquantitative niobium analyses of magnetic fractions separated at 0.25 to 0.45 ampere.

[Analyst: H. M. Nakagawa, U. S. Geological Survey.]

Lab No.	Location	Percent Nb
1920	Big Nose Hill, Mont.	0.04
1921	Cut Bank Creek, Mont.	.07
	Montana average	0.06
1919	Sheep Mountain, Wyo.	0.12
1918	Black Butte Creek, Wyo.	.06
1917	Red Creek, Wyo.	.06
1916	Poison Spider, Wyo.	.02
1915	Grass Creek, Wyo.	.17
1914	Grass Creek, Wyo.	.11
	Wyoming average	0.09
1913	Grand Mesa, Colo.	0.11
1912	Standing Rock, N. Mex.	0.00
1911	Salt Creek Wash, N. Mex.	0.00
1910	Sanostee, N. Mex.	.09
1909	Tah Chee Wash, Ariz.	.04
	New Mexico-Arizona average	0.03

Table 11.—Hafnium-zirconium ratios of zircon concentrates determined by X-ray fluorescence analyses.

[Analyst: Michael Milton, U. S. Geological Survey.]

Lab No.	Deposit	Weight ratio Hf/zr*
256395	Red Creek, Wyo.	0.026
256396	Black Butte Creek, Wyo.	.031
256397	Grass Creek, Wyo.	.025
256398	Sheep Mountain, Wyo.	.023
256399	Mancos River, Colo.	.027
256400	Sanostee, N. Mex.	.031
256401	Tah Chee Wash, Ariz.	.029

*All ratios ± .001

TRANSPORTATION

There is little doubt that the clastic debris that makes up the Cretaceous sedimentary rocks in the Rocky Mountain region was eroded from high land areas and moved to the sea in eastward-flowing rivers. The distance transported, however, is known only approximately, and the amount of winnowing and reworking that took place before and after reaching the sea is unknown.

In an attempt to determine a possible relation between degree of abrasion of individual grains and the distance of transport, the median grain size of each black sandstone deposit was plotted in its geographical position. Theoretically, a decrease in grain size should have been apparent from west to east, transverse to the generally accepted north-south trend of the strand line of the Late Cretaceous sea in Wyoming. Figure 6 shows that no such decrease is apparent, and that there is no relation between size and geographic location.

Similar plots were made of the average sorting index of each deposit in an attempt to relate increase in sorting to distance from source, but no relation was noted.

In general, the degree of rounding of grains is probably not a valid index to distance of transport either, because most of the minerals in the black sandstone have probably been subjected to several cycles of erosion and deposition. Euhedral zircon, on the other hand, is a first-cycle mineral and should be better suited for roundness studies. However, euhedral zircon in the Sheep Mountain deposit (farthest east) appears to be no more abraded than euhedral zircon in the Cumberland Gap deposit (farthest west). Apparently zircon is too resistant to show significant abrasion.

Selective sorting studies were also made to determine whether the lighter heavy minerals (specific gravity less than 4.0) were generally moved farther from the source area than heavier heavy minerals (specific gravity more than 4.0). Zircon (sp.gr. 4.6-4.7) and garnet (sp.gr. 3.75-4.0) were chosen for this study because of their relatively high stability. The percentage of each mineral was plotted geographically, and a general increase in the lighter garnet was noted from west to east across Wyoming (fig. 6). To be certain that this increase in garnet away from the source was not effected by the degree of sorting at the site of deposition, a second comparison was made of samples from only the highly concentrated deposits. This comparison, plate 15, also showed an increase in garnet to the east, but it was not quite so marked. In addition, selective sorting may have been influenced to a degree by grain size, grain shape, and chemical stability, but the significance of these factors was ruled out in evaluating the results.

DEPOSITION

Common beach sands are composed largely of quartz grains; in some places more than 98 percent of the total sand is quartz. Heavy minerals, on the other hand, comprise less than 1 percent of the average beach sand. Through continuous agitation and sorting by wave and wind action under optimum beach conditions, however, the ratio of quartz to heavy minerals can become reversed in local areas. Where this occurs, or even where the heavy minerals have been concentrated to 4 or 5 percent of the total, a black sand deposit is formed. Many of the Upper Cretaceous black sandstone deposits were so thoroughly sorted that the heavy minerals comprise more than 90 percent of the total after removal of the acid-soluble cement (pl. 3).

Most studies of black sand deposits have shown that the final and most effective concentration of heavy minerals on recent beaches takes place during severe storms (Martens, 1928, p. 150; Fisher, 1948, p. 5; Gillson, 1949, p. 1054; Gardner, 1955, p. 42). The Beach Erosion Board (1938, p. 4) defines the beach as "the zone extending from the low-water mark to the . . . landward limit of effective wave action." Johnson (1919, p. 161) divides the beach into a foreshore, which is that part lying between ordinary high and low tides, and a backshore, which is that part covered by water during exceptional storms only. During periods of fair weather a platform or "berm" is built seaward across the backshore to the foreshore where it terminates in a low rounded scarp or "beach crest" cut by normal wave action. The berm is built by a combination of windblown sand, and sand thrown shoreward by the surf. The resulting beach profile during fair weather has a relatively horizontal backshore, and a comparatively steep foreshore descending to the water's edge at an angle of about eight degrees (see fig. 13).

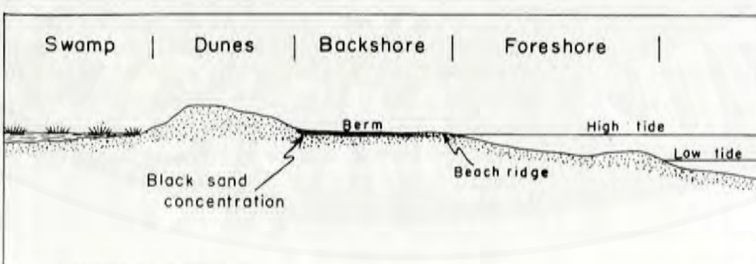


Figure 13. Idealized cross section of modern beach showing principal area of black sand concentration. Data taken from beach studies in Florida (Martens, 1928), Oregon (Pardee, 1934), and the eastern coast of Australia (Gardner, 1955).

Storm waves cause a great turbulence on both the foreshore and backshore parts of the beach. Large quantities of sand are churned into suspension and are moved shoreward by the surf. The velocity of the returning ebb-flow is considerably less than that of the incoming waves, and, as a result, only the lighter quartz sand and clay-size particles are carried back to sea. The heavy-mineral grains are left high on the backshore beyond the zone of turbulence. These storm waves attack the berms and beach ridges and continually reduce the beach slope until the amount of sand being moved seaward is balanced by the amount being moved landward. The resulting beach profile is a long uninterrupted gentle slope of about four degrees. Following the storm the beach-building process begins again. The lesser turbulence created by normal waves is sufficient to bring the quartz sand into suspension, and it is carried shoreward. This sand is accumulated at the edge of the breakers, where it builds a new beach ridge and aids in the resteepening of the foreshore slope. Additional sand is moved to the backshore area by wind action, and the heavy minerals left by the preceding storm waves are covered. After this cycle of aggradation and progradation has been repeated over long periods of time, the heavy minerals on the backshore become more concentrated, and the layer becomes thicker until a sizeable black sand deposit has formed.

Although most beach sands have similar textures and compositions and all coastlines are subjected to periodic storms, black sands are concentrated on relatively few beaches. Several excellent studies of recent black sand deposits along the eastern coast of Australia have related the positions of black sand concentrates to the configuration of the shoreline and natural obstructions found on it. N. H. Fisher (1948, p. 5) regards "a headland, rock outcrop or other natural bar, or a river or creek mouth" as being necessary to obstruct the longshore migration of the black sands during storms. These natural obstructions anchor the leading end of the deposit while further wave action continually winnows out the quartz sand and adds heavy minerals. A stretch of beach with a high dune at the back and an open sea in front is also considered necessary by Fisher.

The black sandstone concentrations of Late Cretaceous age were also deposited along beaches, possibly very much like those of the southeastern United States today. While it is clear that the sorting agent of the black sandstone was largely wave action, there is no evidence to indicate whether most of the concentration took place during storms. For the most part, the present-day deposits consist of laminae or thin beds of heavy minerals intercalated with thicker beds of very low grade or barren sand. In Australia the thickness of the heavy-mineral beds is greater than those reported from other localities, but even there the maximum thickness is only about 5 feet, and the average is usually only 1 or 2 feet (Fisher, 1948, p. 6). Most of the black sandstone deposits in Upper Cretaceous rocks are considerably thicker than those of recent origin; several are more than 15 feet thick and contain practically no interbedded barren sandstone. It is unlikely that such thicknesses could be accumulated during a single storm, but they may have been accumulated during successive storms. The shoreline and its associated beach features, such as bars, dunes, and headlands, probably maintained the same configuration over relatively long periods of time. The prevailing direction of storm winds and probably the intensity of storms would also have had to be constant over an extended period. The lack of interbedded barren sandstone in the Upper Cretaceous deposits also suggests either that no berms formed during intervening fair weather periods or that they were removed by succeeding storms without appreciably disturbing the underlying black sand. The grade of the Upper Cretaceous black sandstone suggests that a somewhat more selective and thorough winnowing process must have prevailed. The heavy-mineral content of the Australian deposits that have been worked ranges from 20 to 80 percent by volume (Fisher, 1948, p. 9). These are the highest grade recent deposits reported. On the other hand, many samples of the black sandstone of Late Cretaceous age contain more than 90 percent heavy minerals (pl. 3) after removal of the cement, which is largely secondary.

The width of Australian black sand deposits is generally not more than 50 feet, whereas the width of those of Late Cretaceous age is everywhere in excess of 50 feet and commonly exceeds 500 feet. The Dugout Creek deposit is at least 1,700 feet wide (fig. 17) and extends for an unknown additional distance beneath younger beds. This suggests that the Upper Cretaceous deposits have grown slowly and that their growth has been accompanied by a slow migration of the beach during regression of the sea. These anomalous widths compared to recent black sand deposits also suggest that the beaches, particularly the backshore parts, may have been much wider than the present-day beaches, and therefore the gradient of the ancient beaches may have been less, and the corresponding nearshore part of the adjacent sea somewhat shallower than along modern beaches.

The cross section of typical present-day heavy mineral deposits, as described by Fisher (1948, p. 6) and inferred by Martens (1928, p. 128), shows the thickest part to lie on the back of the beach, where it terminates abruptly. In a seaward direction, the heavy-mineral concentration thins gradually and terminates as the upper surface of the deposit merges with the slope of the beach surface. A cross section showing the shape has been observed in only one of the black sandstone deposits of Late Cretaceous age; namely, the Red Creek deposit (pl. 14). This deposit reaches a maximum thickness of 6.3 feet within a few feet of its western (landward) edge. In an easterly direction the deposit thins gradually for about 800 feet, beyond which it is absent or unrecognizable. Exposures are too poor to observe the entire cross section of other deposits.

Fisher (1948, p. 6) and Gardner (1955, p. 38) both note that the Australian deposits thicken gradually in a northward direction along their long axis, which is to be expected because of the prevailing southeasterly winds. The north half of the Dugout Creek deposit (fig. 17) has a pronounced thickening which, according to the criterion of Fisher and Gardner, would suggest that storm winds came from the southeast during deposition. Drilling and more detailed surface mapping may demonstrate that other deposits are thicker at one end than the other, thereby providing information on direction of prevailing wind in certain areas during Late Cretaceous time.

Gardner, 1955, p. 56, shows that in the Australian black sand deposits the proportions of heavy minerals vary systematically from one end of the deposit to the other. He concluded that, as the heavy minerals migrate along the beach in response to storm winds, minerals having higher specific gravities tend to lag behind, whereas the lighter minerals move ahead. Gardner (1955, p. 59) arranges the heavy minerals according to their relative rates of transport from slowest to fastest as follows: zircon, ilmenite, rutile. Rutile is relatively more abundant at the heading (downwind) end of the deposits and zircon is relatively more abundant at the trailing (upwind) end. The distribution of samples collected from most of the Upper Cretaceous deposits is not adequate to indicate the lateral distribution of minerals except at the Dugout Creek deposit, where as shown in

Table 12.—Progressive increase in relative proportion of zircon from north to south in the Dugout Creek deposit.

[Sample localities as shown on figure 17.]

Sample locality		Ratio of zircon to total opaque fractions
North	D-5	0.014
	D-4	.025
	D-6	.017
	D-3	.056
	D-8	.020
	D-9	.120
	D-10	.097
South	D-11	.096

table 12, the relative percentage of zircon decreases noticeably from the south end to the north end of the deposit. Rutile is virtually absent in this deposit. The heavy-mineral distribution suggests a northward movement of heavy minerals along the beach, which is the direction of movement suggested by the northward thickening of the deposit.

In Australia, successive deposits of heavy minerals occur in parallel bands which are usually covered, each in turn, by sand dunes formed successively as the beach migrated seaward. In cross section the heavy mineral bands appear to be arranged *en echelon*, with the landward edge of the younger layer overlapping the seaward edge of the older. The deposits of Late Cretaceous age, on the other hand, seem to be completely isolated from each other. Where exposures have permitted, thorough searches were made of the areas surrounding known deposits, but no additional concentrations were located. This may be somewhat anomalous, because the beaches of Late Cretaceous age were undoubtedly receiving an excessive amount of sand. Ancient sand dunes and the natural barriers or anchors referred to by Fisher as being important in the formation of a large deposit have not been identified in or near the Upper Cretaceous black sandstone concentrations. Such features were probably eroded and replaced by lagoonal and coastal plain deposits as the sea regressed eastward.

It is generally agreed that an emerging coast is necessary to form black sand deposits. Streams erode the recently emerged coastal plain and add partially sorted sand to the beach for reworking. Like the recent deposits, the black sandstone deposits of Late Cretaceous age were deposited along emerging coasts. The regressive sandstone beds, in which are found all of the Upper Cretaceous blackstone concentrations known in the Rocky Mountain region, were deposited as a direct result of an emergent coastal area.

POSTDEPOSITIONAL CHANGE

The abundance of highly stable heavy minerals and the paucity of unstable heavy minerals in the black sandstone mineral suite is considered evidence that intrastratal solution has played a part in the postdepositional changes. The ragged terminations of staurolite and augite (pl. 5C) suggest that these minerals have been altered after deposition, either by solution or perhaps through replacement by the matrix. Delicate terminations would not be preserved during transport. As described in previous chapters, ilmenite, magnetite, and ferrian-ilmenite(?) have been extensively altered to mixtures and aggregates of hydrated iron oxide, anatase, and rutile which form part of the matrix. These secondary aggregates are usually very fine grained, but extremely small authigenic crystals of anatase can be recognized in the more highly altered specimens.

Specimens rich in oxides are cemented largely by a hematite-anatase mixture, and those poor in oxides are cemented by carbonate. Apparently the cement of the samples rich in oxides is largely derived from the titanium-iron minerals of the sandstone, whereas the cement of the lower grade samples may have been introduced.

Partial or complete solution of minerals, accompanied in part by redeposition and crystallization of authigenic minerals, has also occurred in these rocks during the postdepositional period. Unweathered black sandstone is richer in ferromagnetic minerals than weathered black sandstone. A sample from the bottom of a shaft 17 feet deep at the Poison Spider deposit is much richer in ferromagnetic minerals than surface samples from the same deposit, and the same enrichment was found in a sample taken from a drill core at the Dugout Creek locality. These observations are not conclusive, but they suggest that a large part of the alteration of heavy minerals has taken place in the vadose zone.

ECONOMIC GEOLOGY

The black sandstone deposits have great tonnages of heavy minerals, containing one of the largest reserves of titanium-iron oxide and the largest known reserve of zircon in the Rocky Mountain region. The known deposits in Montana, Wyoming, Utah, Colorado, Arizona, and New Mexico probably represent only a small proportion of the deposits that may exist. Prospecting for black sandstone deposits would be relatively simple because they are radioactive and are confined to specific stratigraphic horizons.

The minerals of possible economic value are opaque minerals, containing principally titanium dioxide and iron oxide; rutile, containing titanium dioxide; zircon, containing zirconium, hafnium, and uranium; monazite, containing thorium and rare earth elements; and a radioactive opaque mineral containing niobium.

Titanium-iron-bearing opaque minerals are used mainly by the paint and ceramics industries. The opaque mineral used for this purpose is the titanium-iron oxide ilmenite containing 50 percent TiO_2 or altered ilmenite containing as much as 60 percent TiO_2. The titanium-bearing opaque minerals identified in the Wyoming deposits are ferrian ilmenite(?), containing about 35 percent TiO_2, and altered ilmenite containing about 65 percent TiO_2. The difference in the magnetic susceptibility of these two minerals suggests that it may be possible to make a magnetic separation between them. The lower grade (35 percent TiO_2) mineral, however, makes up the major part of most deposits, and this mineral has not been marketable. Therefore, the value of the black sandstone depends on the tonnage of altered ilmenite that could be recovered. Studies of the Grass Creek, Black Butte Creek, and Sheep Mountain deposits indicate that only one of these deposits, Grass Creek, has enough altered ilmenite to be of economic interest in the present market.

Many of the titanium-iron opaque minerals have been altered to extremely fine grained anatase, rutile, and iron oxide which form part of the cementing material. This fine-grained material would not be recovered if current gravity methods of recovery, such as those used on unconsolidated beach sands in Florida, were employed. In highly altered deposits as much as half of the total titanium-iron oxide might be lost as sludge.

Rutile is the main commercial source of titanium metal. In the Wyoming deposits it occurs as detrital grains and as a fine-grained constituent of the cement. The rutile in the cement would be lost as sludge, but the detrital rutile could be recovered. Detrital rutile, however, is only a minor constituent of the black sandstone, making up 1 percent of the heavy-mineral fraction or about 0.5 percent of the bulk sample, although it would make a valuable by-product of any mining operation.

Zircon is the main source of zirconium metal, which is in particular demand as a structural material in nuclear reactors. Zircon also contains hafnium, an element used in the field of atomic energy, and minor amounts of uranium and the rare earth elements yttrium and ytterbium. The zircon content of the black sandstone varies from one deposit to another, but concentrates from many deposits contain more than 10 percent.

According to an estimate by Wessel (1960, p. 995) domestic consumption of zircon was 50,000 tons in 1958 and may vary between 50,000 and 125,000 tons during the next 5 years. Wessel (1960, p. 1000-1001) also states that the domestic supply is ample in 1960, and he does not predict a greatly expanded market in the near future for zircon or zirconium metal. Therefore, it seems unlikely that under these market conditions the black sandstone could be mined solely as a source of zircon.

The small amount of uranium, yttrium, and ytterbium contained in the zircon of these deposits is probably not of economic value, but the hafnium may be. The market for such elements as hafnium is not well established, but continued expansion in the field of atomic energy may ultimately cause high demand for this element.

Monazite is the major source of thorium and many of the rare earth elements. Thorium is used in the manufacture of incandescent mantles and in the field of atomic energy. The rare earth elements are becoming increasingly important as alloying materials for steel and light metals. Monazite is a minor constituent of the sandstone, making up less than 0.5 percent of the heavy minerals, and is also erratic in distribution both locally and regionally. Like rutile, this mineral might be a valuable by-product of any black sandstone mining operation.

Niobium-bearing radioactive opaque minerals have not been isolated or specifically identified, but they are probably present in small amounts in nearly all deposits. They are a potential by-product of the black sandstone.

No attempt was made in the present investigation to estimate tonnage, but it is possible to make some general appraisals of the grade and extent of the various deposits, based on field examination and chemical analyses of the samples collected. These appraisals are discussed in the detailed descriptions of individual deposits in the following chapter. To cite an example, however, the high-grade Grass Creek deposit has an estimated average TiO_2 content of 16 percent and may average as much as 40 percent heavy minerals. In heavy-mineral content, the Grass Creek deposit is comparable to the rich black sand ore at Quilon, India, and is considerably richer than black sand deposits in Florida, where large tonnages of ore having 4 or 5 percent heavy minerals are mined. The black sandstone offers the most promise as a source of titanium dioxide and zircon, but the value depends on available tonnage. It should be emphasized that the black sandstone is a highly indurated sedimentary rock, and that the TiO_2 is not only present as opaque grains, as in most modern beach placer deposits, but it is also present in the matrix of the sandstone. This, coupled with the fact that two types of titanium-bearing oxides are present in the sandstones, makes recovery of the titanium from indurated rocks a more complex problem than that encountered in the exploitation of modern beach sands.

DESCRIPTION OF DEPOSITS

COWLEY DEPOSIT

The Cowley deposit is about 2 miles south-southwest of the town of Cowley, Wyo. (fig. 14), in sec. 1, T. 56 N., R. 97 W. It can be reached by driving south from Cowley on a graded dirt road to the top of the first prominent sandstone scarp. The deposit crops out about half a mile northwest of the road along this scarp. The black sandstone is within 1 mile of the Chicago, Burlington, and Quincy Railroad.

The Cowley deposit seems to be an erosional remnant of an originally larger concentration. It is exposed for a distance of about 900 feet in a northwest direction. The maximum thickness is 3.5 feet, but the average is about 1 foot. The strike of the bedding is N. 60° W., and the dip is 9° SW. The south end of the deposit is covered by alluvium, and thus its maximum extent in that direction is not known; thickness measured at various places on the exposed part indicates that the deposit thins to the south.

The strata surrounding this black sandstone are only partly exposed; but the deposit lies in and at the top of a littoral-type sandstone which is at least 50 feet thick. It is not known whether the host rock is the basal sandstone unit of the Mesaverde formation or a part of the marine sandstone sequence at the top of the underlying Cody shale. The host rock is separated from stratigraphically lower sandstone beds by marine shale, which is presumably a tongue of Cody shale deposited during a minor transgression of the sea. No exposed strata overlie the black sandstone or the host sandstone at the site of the deposit, but farther to the west the overlying rocks are poorly exposed nonmarine carbonaceous shale and lenticular sandstone beds of the Mesaverde formation.

Three samples from the Cowley deposit were analyzed petrographically. These samples contain an average of 40 percent acid-soluble matrix, 45 percent light minerals, and 15 percent heavy minerals, of which 2 percent is ferromagnetic. A histogram of a typical sample from the Cowley deposit shown on plate 3 illustrates graphically the size distribution of the heavy minerals and the high degree of sorting of the sandstone in general.

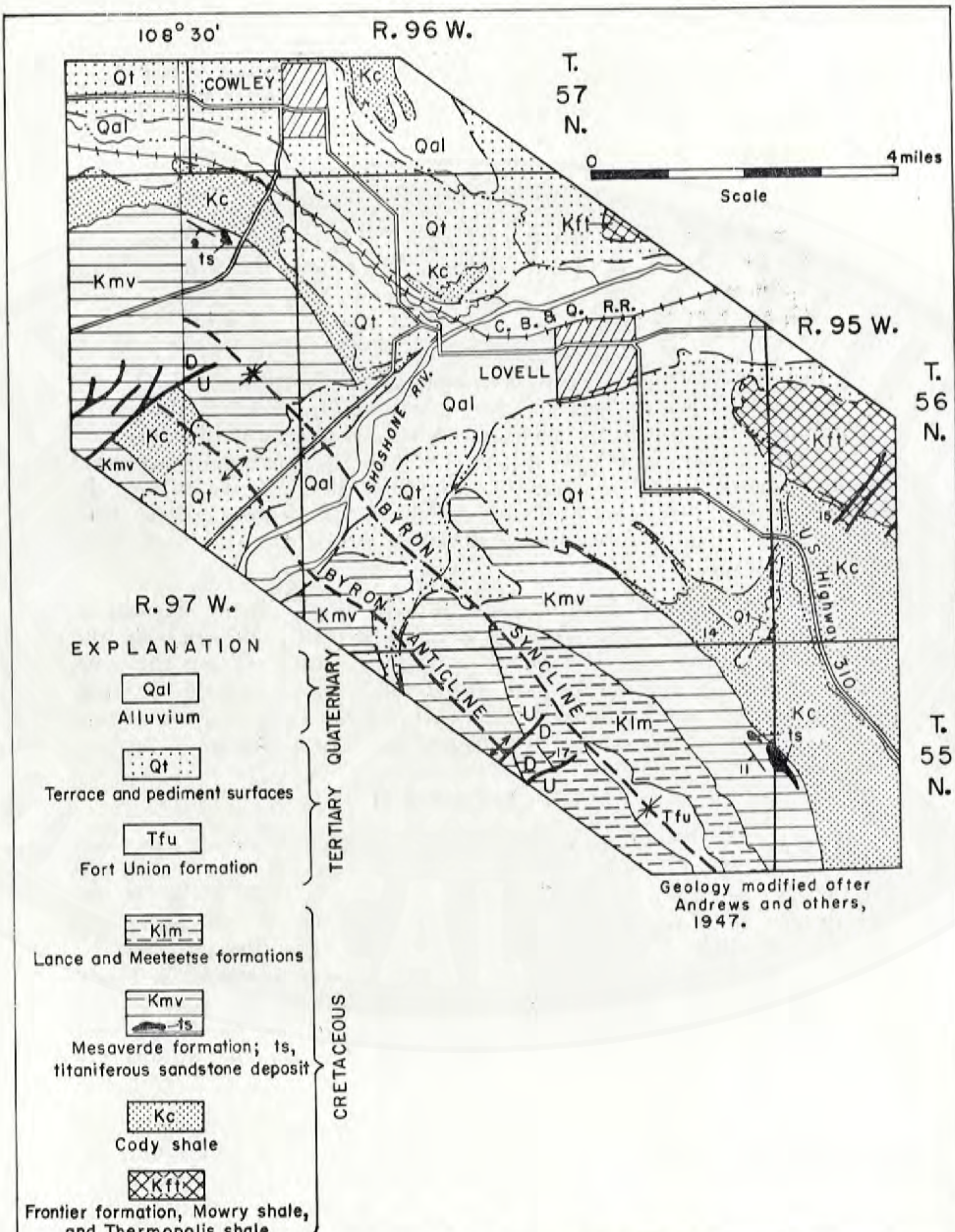


Fig. 14. Map showing geologic setting and location of Cowley and Lovell titaniferous sandstone deposits.

Heavy minerals in the Cowley deposit occur in the following relative percentages:

	Percent of total heavy fraction
Zircon	4.1
Garnet	5.5
Tourmaline	1.0
Rutile	1.0
Amphibole	1.0
Epidote	1.0
Sphene	1.0
Opaque minerals	89.0

Chemical analysis of a single sample shows 3.0 percent TiO_2 and 33.8 percent total iron oxides expressed as Fe_2O_3. Radiometric analysis of the same sample showed an equivalent uranium of 0.001 percent. The 11 to 1 ratio of Fe_2O_3 to TiO_2 in the chemically analyzed sample suggests that the ratio of magnetite to ilmenite in the deposit was originally high, but inasmuch as the ferromagnetic fraction is negligible, the original magnetite probably has been thoroughly oxidized.

The analytical determinations indicate the Cowley deposit is low grade. It apparently is also a small deposit, although if the southward thinning of the black sandstone observed on the outcrops is due to local irregularities, the deposit may continue for some distance to the south beneath the overburden. Down-dip extension of the concentration can be determined only by drilling.

LOVELL DEPOSIT

The Lovell deposit is about 6 miles south-southeast of the town of Lovell in Big Horn County, Wyo. (fig. 14). It crosses the township line between sec. 7, T. 55 N., R. 95 W. and sec. 12, T. 55 N., R. 96 W. The nearest railroad facilities are in Lovell, which is serviced by the Chicago, Burlington, and Quincy Railroad. The deposit can be reached by driving about 6.5 miles south from Lovell on U. S. Highway 310, and then about 1 mile southwestward on an unimproved dirt road. The black sandstone can be recognized by its dark color, which contrasts sharply with the light-buff color of the underlying host sandstone.

The Lovell deposit is made up of two erosional remnants separated by a dry wash. The northernmost remnant is small and inconspicuous, but the southern remnant is somewhat more than 3,000 feet long in a northwesterly direction; the combined length of the two remnants exceeds 5,000 feet. A maximum thickness of 4.0 feet was measured at the north end of the larger remnant, but the average is probably about 3.0 feet. The strike of the bedding is N. 34°

W., and the dip is 11° SW. For the most part, the deposit has been stripped of overburden, and its upper surface is exposed as a broad dip slope. The northwest edge of the deposit is well exposed and forms a scarp; the deposit presumably dips beneath younger strata to the southwest, but the contact with the younger rocks is obscured by alluvium.

The black sandstone occurs at the top of a littoral regressive sandstone which is at or near the base of the Mesaverde formation, and which is probably the same sandstone that contains the black sandstone at Cowley, 10 miles to the northwest. The host rock of the Lovell deposit is a light-buff fine-grained sandstone, but it is poorly exposed and bedding features are not discernible. Here, as at Cowley, the host sandstone is directly underlain by marine shale which in turn overlies still older littoral sandstone. Lenticular channel sandstone and carbonaceous shale of the Mesaverde formation crop out sporadically some distance stratigraphically above the black sandstone, but the beds directly overlying the black sandstone are covered by alluvium.

The long axis of the Lovell deposit, as presently exposed, trends N. 45°-50° W., but inasmuch as the original shape cannot be reconstructed, the present long axis may not be exactly parallel to the original strand line.

The three samples from the Lovell deposit that were analyzed petrographically contain from 2.0 percent to 53.9 percent heavy minerals, which includes a range of 0 to 73.5 percent ferromagnetic minerals. The average composition of the three samples is 19.0 percent acid-soluble matrix, 56.0 percent light minerals, and 25.0 percent heavy minerals, of which 51.0 percent is ferromagnetic. Heavy minerals that were identified and their relative abundance are listed below:

	Percent of total heavy fraction
Zircon (euhedral colorless and well-rounded violet)	5.6
Garnet (pyralspite and grossularite)	5.1
Tourmaline	1.0
Rutile	1.0
Amphibole	1.0
Epidote	1.0
Sphene	1.0
Chlorite	Trace
Biotite	Trace
Staurolite	Trace
Opaque minerals	87.0

Chemical analysis of one selected high-grade sample shows 15.10 percent TiO_2 and 71.09 percent total iron oxides expressed as Fe_2O_3. Equivalent uranium for the same sample was 0.003 percent.

Although the Cowley and Lovell deposits were not sampled and analyzed in detail, the available analyses indicate that the Lovell deposit is the higher grade. The considerable variation in the abundance of ferromagnetic material in different samples from the Lovell deposit is probably due to variation in degree of alteration.

DUGOUT CREEK DEPOSIT

The Dugout Creek deposit is the largest individual deposit in areal extent and tonnage reported to 1960 in Wyoming. It is located about 15 miles south of Tensleep, Wyo., in secs. 34 and 35, T. 45 N., R. 89 W., and secs. 2 and 11, T. 44 N., R. 89 W. (fig. 15). It can be reached by driving west from the center of Tensleep on U. S. Highway 16 for 3.2 miles, and then south on graded and unimproved dirt roads for 17.7 miles. The deposit is readily recognizable as it forms a broad dip slope much darker in color than the surrounding rocks (pl. 10B). The nearest railroad connection is at Worland, Wyoming, a distance of about 35 miles by paved and dirt roads.

The length of the deposit is about 2.7 miles in a north-northeast direction, and the maximum exposed width is about 1,500 feet. The present length of 2.7 miles is believed to be the maximum original length, but inasmuch as the deposit dips northwestward beneath younger rocks, the maximum width is greater than the exposed width of 1,500 feet. The deposit seems to be only slightly eroded except where it has been dissected by Dugout Creek and its tributaries. The maximum exposed thickness of the black sandstone is 25 feet (pl. 10A), and the average is probably between 10 and 15 feet. Information from private drilling on unexposed parts of the concentration indicates a maximum thickness of 40 feet, but this report has not been substantiated. The strike of the bedding and the trend of the long axis of the deposit are both N. 15° E., and the dip is 3° to 5° NW.

The deposit is in the upper part of the basal sandstone unit of the Mesaverde formation (fig. 16). Because of poor exposures, the thickness of this basal sandstone is not known, but along Dugout Creek at least 50 feet is exposed. Northward from the deposit, the basal part of the Mesaverde is difficult to trace. It either lenses out rapidly or becomes so shaly that it is nonresistant and rarely exposed. The contact with the underlying Cody shale is also impossible to identify, but sporadic outcrops of typical Cody shale are present in places within 50 feet stratigraphically below the lowest basal sandstone outcrops.

Overlying the black sandstone deposit is sandy shale 110 feet thick, which contains a sparse invertebrate fauna including *Ostrea* sp., *Nuculana* sp., and *Cymella* sp. These are typical of a shallow-

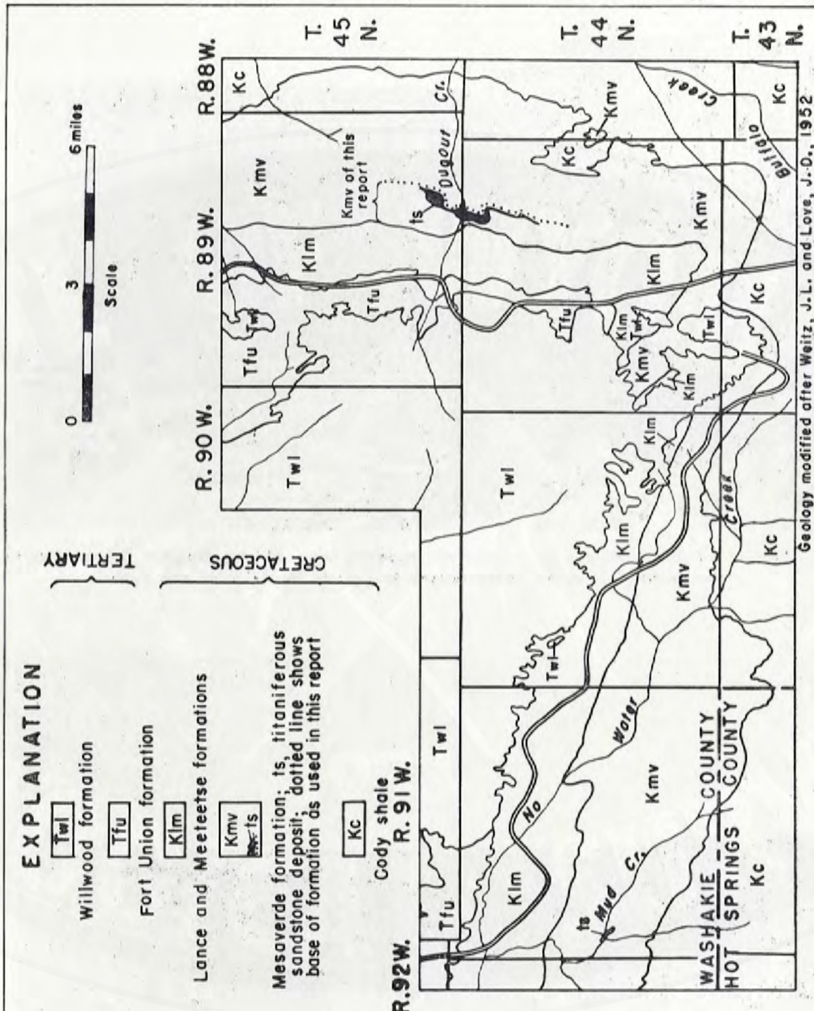


Fig. 15. Map showing geologic setting and location of Dugout Creek and Mud Creek titaniferious sandstone deposits.

PLATE 10

A. Section of black sandstone in the northcentral part of the Dugout Creek deposit. Conspicuous bedding characterizes low-grade deposits of this type.

B. View northward along eastern edge of Dugout Creek deposit. The poorly exposed beds underlying the deposits are Cody shale. Cedar-covered ridge in background is Teapot sandstone member of Mesaverde formation.

marine or brackish-water environment, and indicate either a minor readvance of the sea or a lagoonal area protected from wave action by beach dunes or bars. At the base of the sandy shale unit is a thin zone of carbonaceous shale that crops out discontinuously.

Above the sandy shale beds is 218 feet of interbedded sandstone and shale. The sandstone is buff to light rust brown, fine grained, lenticular, and forms many ledges. The shale is gray, weathers buff to light rust brown, soft, carbonaceous, and contains a few thin lignitic beds. This sequence probably was deposited in a coastal plain environment. The upper unit of the Mesaverde formation near the Dugout Creek deposit is made up of 90 feet of white fine-grained sandstone which is locally crossbedded and contains large concretions in the lower part. This unit probably is the correlative of the Teapot sandstone member of the Mesaverde formation in the Powder River Basin to the east and the Wind River Basin to the south.

Composite samples from eight of the localities shown on figure 17 were studied petrographically. The samples consist of equal mixtures of material taken at 2-foot intervals from the top to the bottom of the deposits. The samples average 39.5 percent matrix, 48.3 percent light minerals, and 12.2 percent heavy minerals, of which 20.0 percent is ferromagnetic. The heavy minerals found in the deposit, and their relative abundance are given below:

	Percent of total heavy fraction
Zircon (euhedral colorless and well-rounded violet)	5.0
Garnet (pralspite and grossularite)	3.0
Tourmaline	1.0
Rutile	1.0
Amphibole	1.0
Epidote	1.0
Sphene	1.0
Monazite	1.0
Spinel	Trace
Biotite	Trace
Opaque minerals	91.0

Thirteen samples were analyzed for TiO_2 and Fe. Nine were composite samples similar to those studied petrographically. The location of each of the composite samples and the TiO_2 and Fe content is given in table 13. The composite samples averaged 5.9 percent TiO_2 and 38.9 percent total iron oxides expressed as Fe_2O_3. Two selected samples of higher grade averaged 10.5 percent TiO_2 and 62.2 percent Fe_2O_3, and two samples of lower grade averaged 7.0 percent TiO_2 and 38.6 percent Fe_2O_3. Equivalent uranium in the Dugout

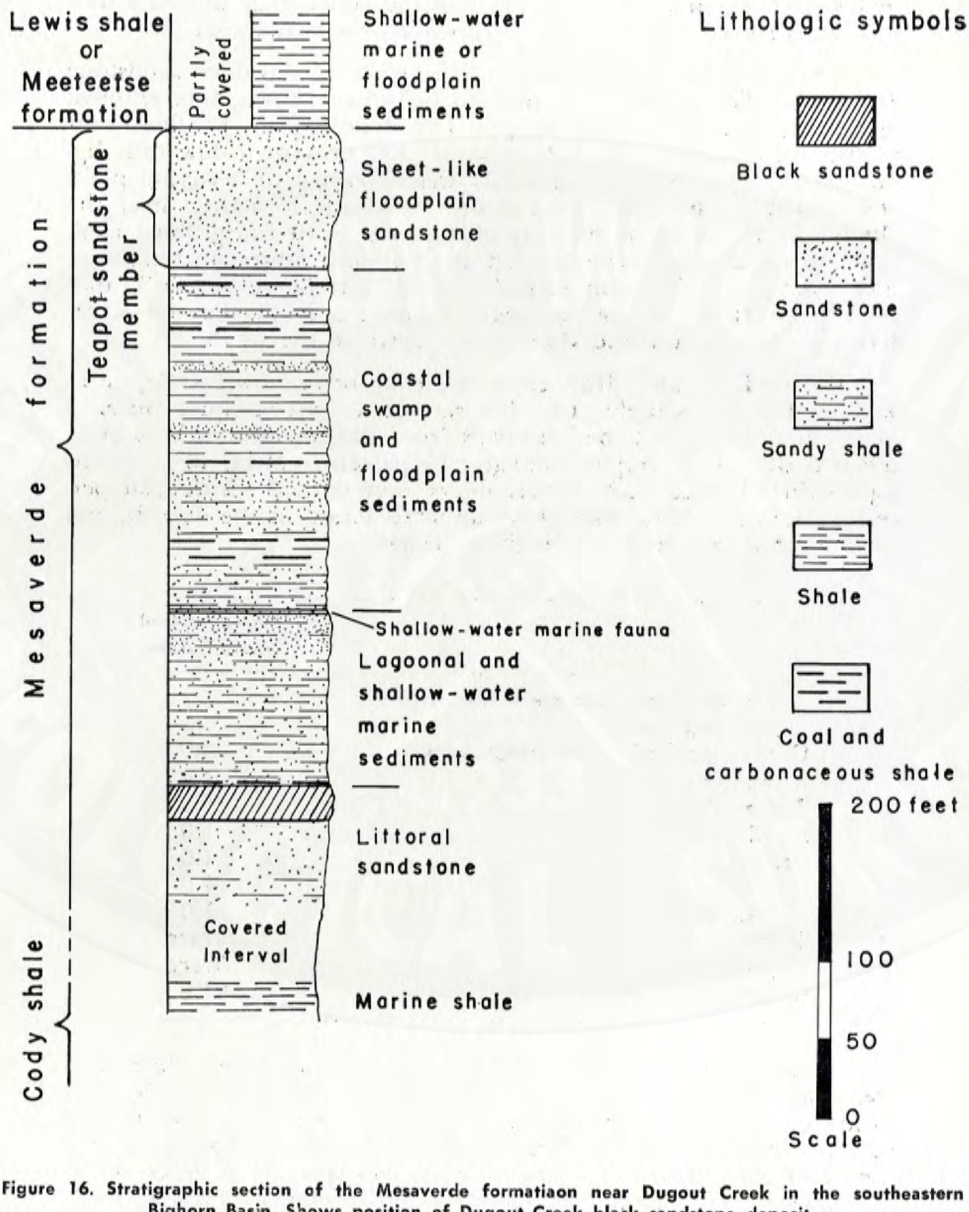


Figure 16. Stratigraphic section of the Mesaverde formatiaon near Dugout Creek in the southeastern Bighorn Basin. Shows position of Dugout Creek black sandstone deposit.

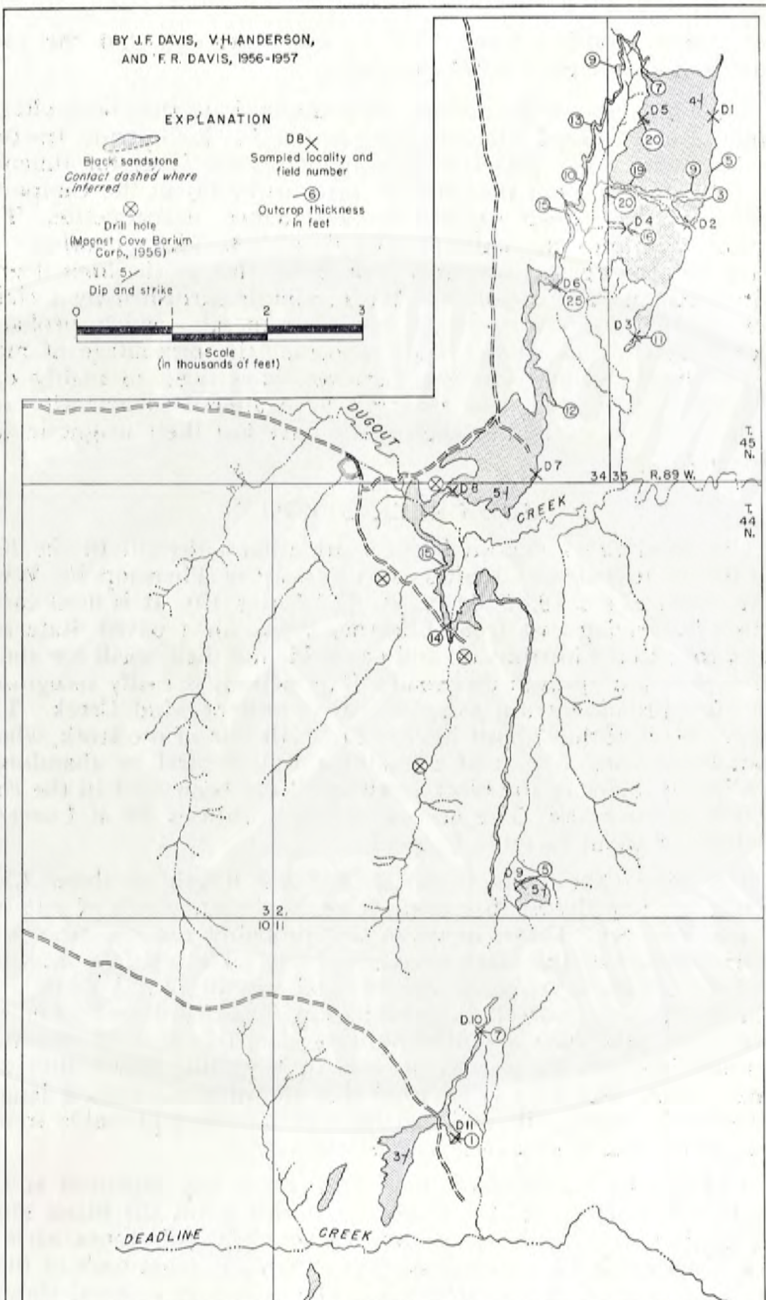


Figure 17. Plane-table map of Dugout Creek black sandstone deposit, Washakie County, Wyoming.

Creek samples ranged from 0.001 to 0.021 percent, and the composite samples averaged 0.004 percent.

X-ray analyses of the opaque minerals indicate that both altered magnetite and altered ilmenite are present in the opaque fraction (fig. 11). The X-ray patterns show more intense lines for ilmenite than for magnetite, but the ratio of TiO_2 to Fe_2O_3 in the composite samples is 1:6.6, which suggests an abundance of magnetite. The ratio of ilmenite to magnetite may be about 1:3. The somewhat conflicting data on opaque minerals is probably due to the high degree of alteration in surface samples. A core sample furnished by a claim owner is rich in ferromagnetic opaque minerals, which probably indicates that in less altered black sandstone the percentage of magnetite is high. Surface samples, however, have been so highly oxidized that the ferromagnetic minerals have altered to hematite and hydrous iron oxides, and in the process have lost their magnetic susceptibility.

MUD CREEK DEPOSIT

The Mud Creek deposit is the southernmost deposit in the Bighorn Basin. It is about 20 miles east-northeast of Thermopolis, Wyo., in the center of sec. 19, T. 44 N., R. 91 W. (fig. 15). It is most easily reached by driving east from Lucerne, Wyo., on a paved State secondary road to the Murphy oil and gas field, and then north for about 5 miles over unimproved dirt roads. The deposit is easily recognized on a high prominent dip slope directly south of Mud Creek. The northwest end of the deposit lies on the north side of the creek, where its outcrop is used as part of a retaining wall behind an abandoned ranch house. Slabs of the black sandstone have been used in the construction of the house. The nearest railroad facilities are at Lucerne, a distance of about 21 miles by road.

The Mud Creek deposit has an exposed length of about 1,500 feet in a west-northwest direction. The maximum width of outcrop is about 100 feet. These, however, are probably not the true original dimensions of the black sandstone body. The strata containing the black sandstone strike N. 70° W. and dip 10° N. All available stratigraphic data, as well as information obtained from better exposed black sandstone deposits, indicate that the general direction of strand lines of Late Cretaceous seas in Wyoming was within 20° of true north. Hence, it is believed that the present exposed length is actually the true width, and that the true long axis probably trends nearer north but is obscured by overlying strata.

The deposit was sampled and its thickness was measured at the eastern end, where it is best exposed. At this point the black sandstone appears to be made up of two distinct high-grade zones, each of which is underlain by a rust-brown zone. Samples from each of these zones were studied petrographically. The rust-brown zones, though resembling low-grade zones of other deposits, are actually barren, each containing much less than one percent heavy minerals. Appar-

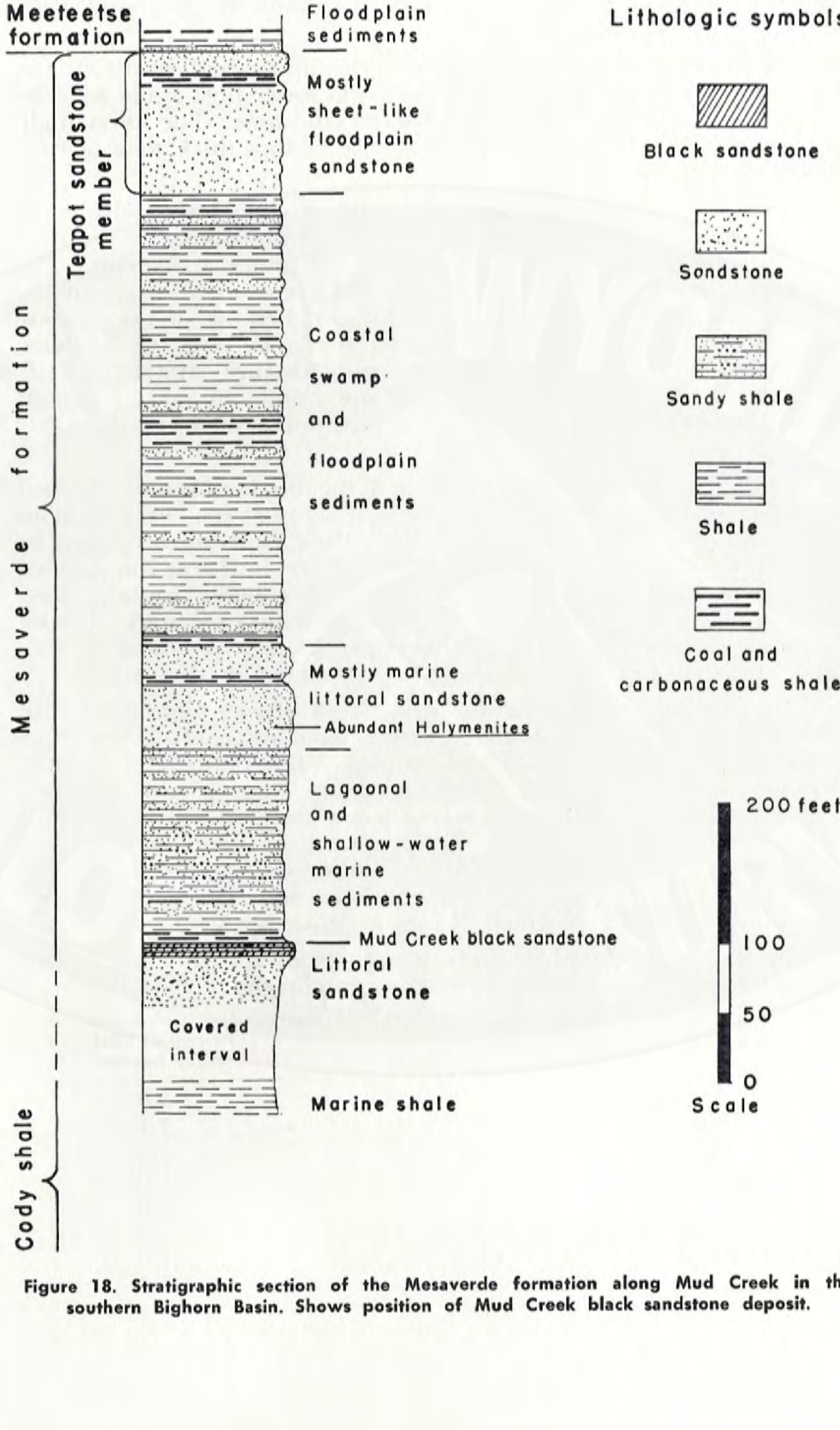


Figure 18. Stratigraphic section of the Mesaverde formation along Mud Creek in the southern Bighorn Basin. Shows position of Mud Creek black sandstone deposit.

ently the color is due to iron oxides derived from the overlying black sandstone by leaching.

At the eastern end of the deposit the upper high-grade zone is 4.5 feet thick, and it is separated from the lower high-grade zone by 3.4 feet of rust-brown fine-grained barren sandstone. The lower high-grade zone is 3.0 feet thick and overlies a 3.5-foot thick zone of rust-brown fine-grained barren sandstone.

These zones form the uppermost unit of the basal sandstone in the Mesaverde formation (fig. 18). The strata are similar to the beds in which the Dugout Creek deposit occurs 16 miles to the east. The thickness of the basal sandstone of the Mesaverde in the area of the Mud Creek deposit could not be determined because of poor exposures and the gradational contact with the underlying Cody shale. Other sandstone beds crop out at some distance stratigraphically below the basal sandstone, but these are clearly of marine origin; thus, they are assigned to the upper transitional phase of the Cody shale.

Overlying the basal sandstone and the black sandstone deposit is a nonmarine sequence 34 feet thick, consisting of coal, carbonaceous shale, and gray, fine-grained sandstone. These beds are succeeded by 150 feet of sandy shale which grades upward into buff-gray fine-grained sandstone. The lower part of this 150-foot sequence contains fragments of *Ostrea* sp. indicating probable deposition in a brackish-water lagoonal environment, whereas the upper 33 feet of sandstone contains abundant *Halymenites* and is of near-shore marine origin.

No chemical analyses of the Mud Creek deposit were made, but petrographic analyses of both the upper and lower black sandstone zones indicate that the mineral assemblage is like that found in other deposits. A sample analyzed from the upper zone contains 53.6 percent acid-soluble matrix, and 46.6 percent heavy minerals of which 66.8 percent is ferromagnetic. Only a trace of light minerals was detected. A sample analyzed from the lower zone contains 40.0 percent acid-soluble matrix, 32.8 percent light minerals, and 27.2 percent heavy minerals, of which 23.0 is ferromagnetic.

In the relatively high grade sample from the upper zone the heavy minerals occur in the following percentages:

	Percent of total heavy fraction
Zircon	5.0
Garnet	1.1
Rutile	1.0
Tourmaline	1.0
Amphibole	1.0
Sphene	1.0
Apatite	1.0
Opaque minerals	92.2

In the lower zone, 97.4 percent of the heavy fraction is opaque minerals, 1.7 percent is zircon, and less than 1 percent is garnet.

The economic potential of the Mud Creek deposit cannot be determined from existing data. The northern limit of the deposit is not known, but could be determined by drilling. The northward dip of 10° and the 200 to 300 feet of overburden overlying the deposit at several places would make strip mining expensive.

GRASS CREEK DEPOSITS

The Grass Creek deposits are the largest high-grade deposits known in Wyoming. They crop out in two isolated segments on the flanks of the Grass Creek anticline (pl. 15) in Hot Springs County, Wyo. The northern segment is located in secs. 8, 9, and 16, T. 46 N., R. 98 W., on the northeast flank of the anticline, and the southern segment is located in secs. 33 and 34, T. 46 N., R. 98 W., on the southeast flank. Both exposures are visible from the town of Grass Creek and are readily accessible by dirt roads. The nearest railroad facilities are at Thermopolis, a distance of about 35 miles.

Field relations suggest that the two segments originally formed a continuous black sand body (pl. 15) at least 4 miles long. If this interpretation is correct, the Grass Creek deposit was the largest known in rocks of Late Cretaceous age in the Rocky Mountain region. The northern segment (fig. 19) can be traced northward, from the edge of the rimrock on the northeast flank of the anticline, for a distance of about 5,600 feet. Farther north the black sandstone body is covered by overlying strata, and its extent is not known. A maximum width of 680 feet can be measured in the central part of the northern segment. The maximum thickness is about 16 feet, but the average is probably in the range of 10 to 12 feet. The trend of the long axis is N. 15° W., and the strata containing the black sandstone strike about N. 25° W. and dip about 15° NE.

The southern segment is poorly exposed and broken up by several north-trending small normal faults. Black sandstone crops out sporadically over a distance of more than 1,600 feet in an east-west direction, which is the width direction of the original deposit if the long axis of the original deposit was nearly north-south. The black sandstone has a maximum exposed thickness of 3.5 feet near its east edge. Near the western end of the outcrop, the black sandstone is at least 5 feet thick in a partial exposure; the upper part is concealed by talus. The strata strike N. 80° W. and dip 30° to 35° S.

The stratigraphic sequence containing the black sandstone at Grass Creek is much like that of the other localities already discussed. The major difference is that at Grass Creek no marine beds overlie the host rock of the deposit. The black sandstone occurs at the top of the basal sandstone of the Mesaverde formation (frontispiece). The sandstone, which is about 140 feet thick (Long, 1957),

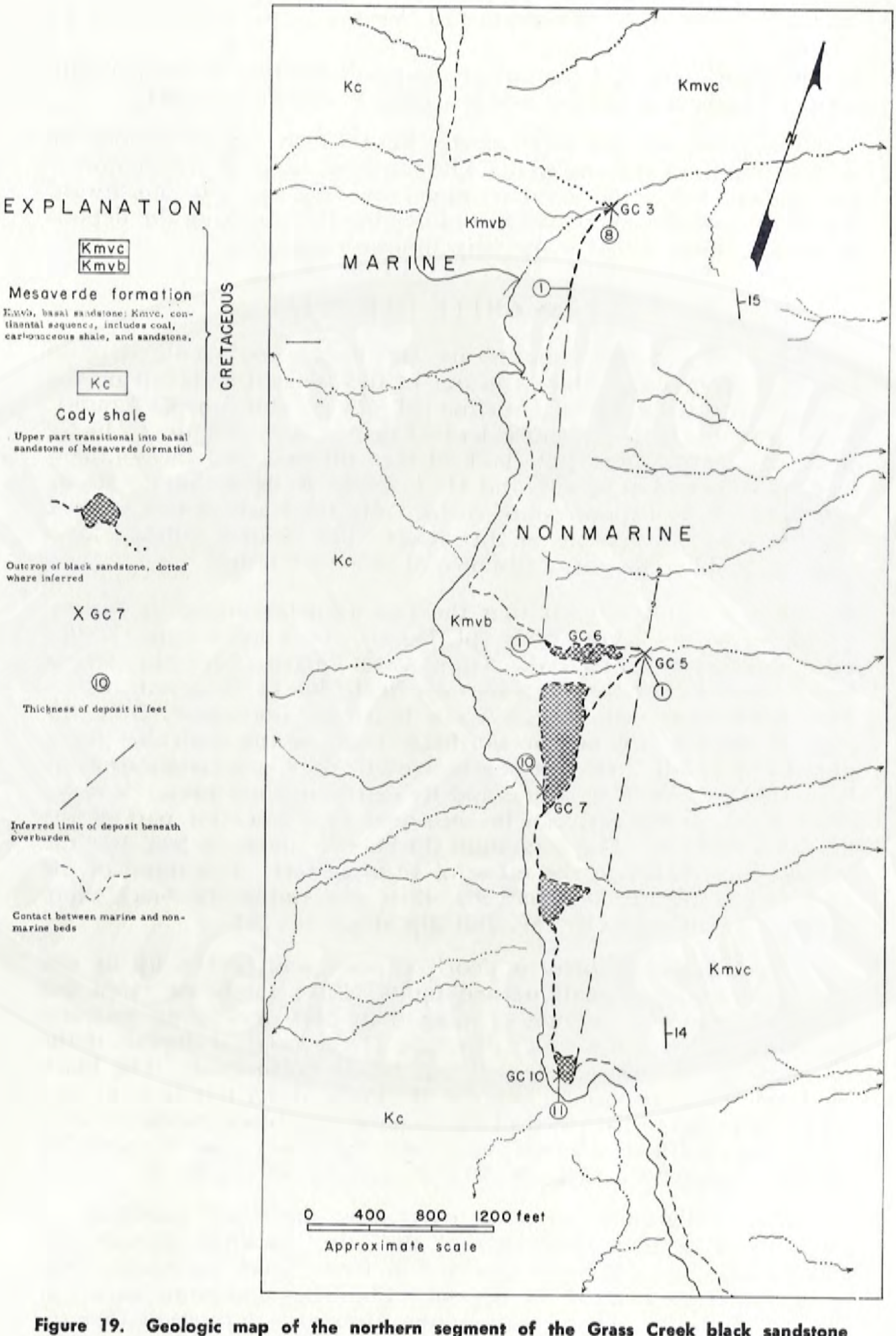


Figure 19. Geologic map of the northern segment of the Grass Creek black sandstone deposit. Location shown as inset on plate 15.

is buff, fine grained, massive, and locally has distinct crossbedding and a pitted surface. The upper part of this unit forms a precipitous cliff, and the lower part, where the sandstone is interbedded with Cody shale, forms a steep concave slope.

Overlying the basal sandstone is about 1,250 feet (Long, 1957), of lenticular sandstone, sandy shale, and carbonaceous shale. The lower one-third of this unit contains many lignite and coal beds which were deposited in coastal swamps and flood plains. The uppermost unit of the Mesaverde formation in this area consists of about 212 feet (Long, 1957) of white fine-grained sandstone that contains many small iron concretions and forms a low ridge. This sandstone may be the equivalent of the Teapot sandstone member to the east and the white sandstone member of the Mesaverde formation (Troyer and Keefer, 1955) to the south.

Twelve samples were analyzed petrographically. These average 44.0 percent acid-soluble matrix, 26.0 percent light minerals, and 30.0 percent heavy minerals of which 12.5 percent is ferromagnetic (table 13). Heavy minerals were identified as follows:

	Percent of total heavy fraction
Zircon (euhedral colorless and well-rounded violet)	18.0
Garnet (pyralspite)	2.0
Tourmaline	1.0
Rutile	1.0
Monazite	1.0
Opaque minerals	78.0

Chemical analyses of 25 samples show an average content of 16.0 percent TiO_2 and 23.0 percent total iron oxides expressed as Fe_2O_3. The average equivalent uranium content of these samples is 0.015 and the average chemical uranium content is 0.002 percent. Table 13 gives the location and results of analyses of each of these samples.

Semiquantitative spectrographic analyses of the two principal types of zircon indicate a hafnium content averaging between 0.215 and 0.464 percent. The zircon is also believed to contain the small amount of uranium detected by chemical analyses of the bulk samples.

Niobium-bearing radioactive opaque minerals and monazite are present in minor amounts and probably contain all of the rare earth elements identified by spectrographic analysis (table 14).

Overburden as much as 100 feet thick covers a large part of the northern segment. For the most part, it consists of soft carbonaceous shale and coal, but some thick indurated sandstone beds are present. The strata overlying the northern segment dip about 15° NE., but because the land surface also dips northeastward the overburden thickness does not increase greatly in a down-dip direction. Because the southern segment dips 30° to 35°, however, only small amounts of the deposit could be uncovered easily by strip mining. It is possible that the two black sandstone bodies extend much farther to the north or south than indicated by the outcrops, but this could be substantiated only by drilling.

COTTONWOOD CREEK DEPOSIT

The Cottonwood Creek deposit is in Hot Springs County near the junction of Cottonwood Creek and Wyoming State Highway 120 in SE¼, sec. 26, T. 45 N., R. 97 W. (pl. 15). It is 9.7 miles southeast of the southern edge of the Grass Creek deposit, on the northeast flank of Waugh anticline. The deposit is accessible by paved roads and is most easily reached by driving about 21 miles northwest from Thermopolis, Wyo., on State Highway 120 to the point where the highway crosses Cottonwood Creek. From the bridge crossing the creek, the deposit is 0.9 miles to the southeast and can be seen capping the first prominent hill in that direction. The nearest railroad facilities are at Thermopolis.

The Cottonwood Creek deposit appears to be an erosional remnant of an originally larger deposit. The remnant forms an irregular outcrop measuring about 150 feet in a northwest direction and 150 feet in a northeast direction. The black sandstone caps the backslope of a scarp formed by the basal sandstone of the Mesaverde formation. The maximum exposed thickness of the deposit is 9 feet. Strata containing the deposit strike N. 43° W. and dip 20° NE. At the base of the dip slope the black sandstone is poorly exposed, and drilling would be required to ascertain whether the deposit continues beneath the surface. There is no indication of the original trend of the long axis of the deposit, but it can probably be assumed that, like other deposits in Wyoming, the original trend did not deviate significantly from a north-south direction.

The rocks in which the Cottonwood Creek deposit is found are similar stratigraphically to those at Grass Creek, with one slight difference. At Cottonwood Creek, the deposit does not lie directly at the top of the basal sandstone of the Mesaverde Formation, but rather is separated from it by 5.4 feet of gray shale and thin coal partings. The shale and coal are lagoonal sediments probably buried during a minor transgression of the sea. After a relatively short time, the sea probably again withdrew and the black sand was deposited.

Four samples of the Cottonwood Creek deposit carry an average of 9.7 percent TiO_2 and 38.4 percent iron expressed as Fe_2O_3 (table 13). Three samples were collected from the lower 2 feet of the deposit, which is light buff to tan and appears superficially to be barren or very low grade. These samples average 7.4 percent TiO_2 and 35.4 percent iron as Fe_2O_3. The upper 7 feet of the deposit is a homogeneous dark color, and the fourth sample, which was collected 3 feet below the top of the high-grade rock, contains 16.8 percent TiO_2 and 47.2 percent iron as Fe_2O_3. The average equivalent uranium content of all samples is 0.006 percent, and the average chemical uranium is 0.001 percent.

Only the highest grade sample from the Cottonwood Creek deposit was analyzed petrographically. This sample contains 71.0 percent soluble matrix, which is anomalously high and probably indicates extensive alteration of insoluble ferrous iron to soluble ferric iron in much of the opaque fraction, or possibly a high percentage of carbonate in the cement. The sample contains 17.2 percent of heavy minerals, of which about 10 percent is ferromagnetic. A histogram of this sample on plate 3 illustrates the size distribution of both the heavy and light fractions.

Heavy-mineral percentages in the deposit are as follows:

	Percent of total heavy fraction
Zircon	18.5
Garnet	1.0
Tourmaline	1.0
Rutile	1.0
Amphibole	1.0
Monazite	1.0
Opaque minerals	79.0

COALBANK HILLS DEPOSIT

The Coalbank Hills deposit is near the northern end of the Rattlesnake Hills, Natrona County, in the center of sec. 5, T. 34 N., R. 88 W. (fig. 20). It can be reached by driving south from Waltman, Wyo., on a graded county road for about 14 miles, and then northwestward on ungraded roads for about 3 miles. From this point the deposit is readily visible less than half a mile to the northeast. It forms a dark rust-brown caprock on two prominent buttes. The nearest rail facilities are those of the Chicago, Burlington, and Quincy Railroad at Powder River, Wyo., 11 miles east of Waltman on U. S. Highways 20 and 26.

As shown in figure 20, the deposit is exposed in two large outcrops about 700 feet apart. Assuming the outcrops are connected, the deposit is longer than 1,400 feet. The trend of the original strand line is not known, so it is difficult to predict the orientation of the long dimension of the original deposit. The thickness of the deposit at its southeastern end is about 5 feet. The strike of the bedding is N. 40° W. and the dip is 23° NE.

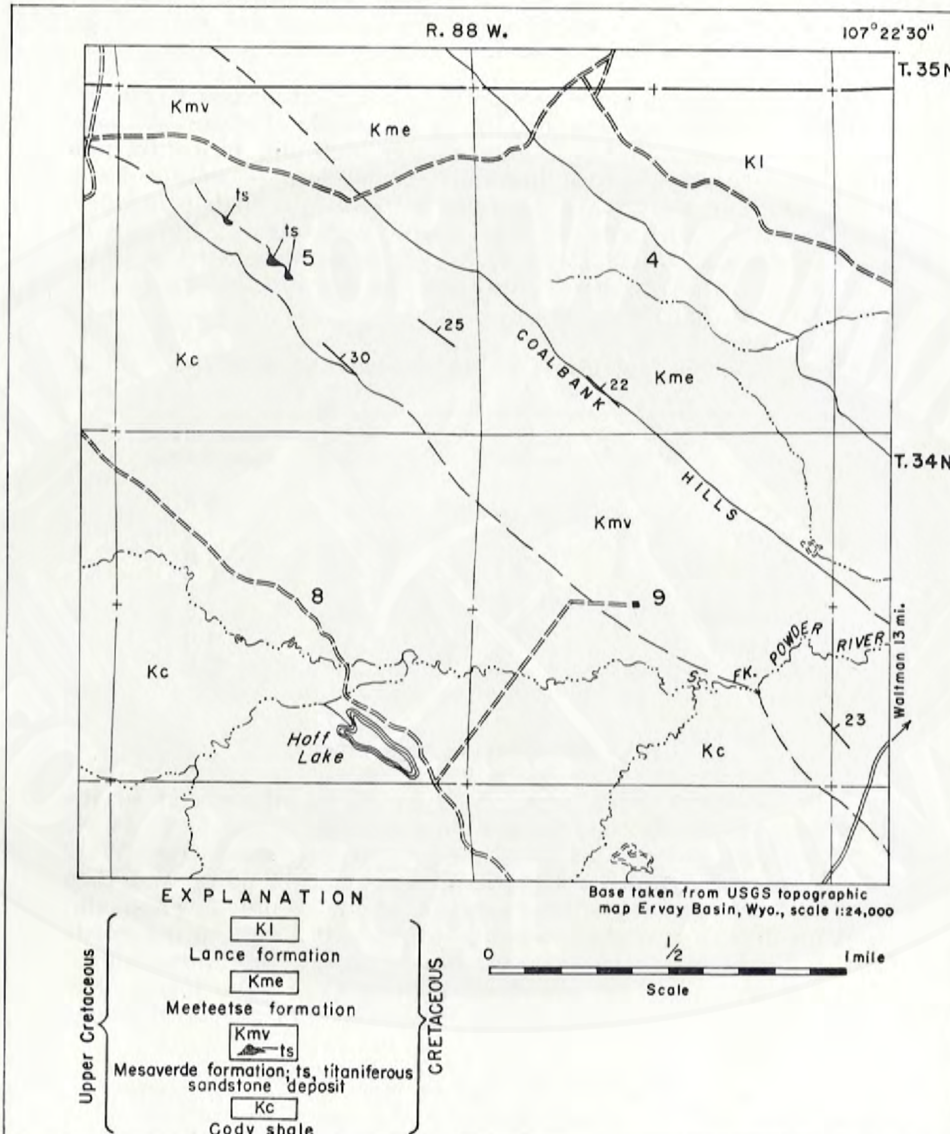


Fig. 20. Map showing geologic setting and location of Coalbank Hills titaniferous sandstone deposit.

The Coalbank Hills deposit is the uppermost part of the basal sandstone of the Mesaverde formation. According to J. R. Barwin (oral communication, 1958), 40 feet of the basal sandstone is exposed; the lower contact is covered. Nearby a normal gradational contact with the underlying Cody shale can be observed. The black sandstone is overlain by 80 to 100 feet of lagoonal-type sedimentary rock consisting of gray shale, thin platy sandstone beds, and some carbonaceous shale. No lignite beds overlie the deposit, but a short distance to the southeast about 15 feet of lignite is exposed in the lower part of the lagoonal beds. Thin beds of coquina composed of mollusk shells are common in these rocks. The lagoonal-type sedimentary rocks are overlain by about 180 feet of marine sandy shale with a *Halymenites*- bearing sandstone at the top (J. R. Barwin, oral communication, 1958). The remainder of the Mesaverde formation consists of typical fluviatile channel sandstone and carbonaceous shale, including at the top the Teapot sandstone member.

No chemical analyses of the Coalbank Hills deposit were made, but petrographic studies of a sample from the southeastern end indicates that the mineral suite is similar to that in other Wyoming deposits. The sample contains 43.6 percent acid-soluble matrix, 2.3 percent light minerals, and 54.1 percent heavy minerals of which 33.6 percent is ferromagnetic. The heavy minerals occur in the following percentages:

	Percent of total heavy fraction
Zircon	2.4
Garnet	1.0
Rutile	1.0
Amphibole	1.0
Apatite	1.0
Opaque minerals	96.7

A histogram of the analyzed sample suggests that the degree of sorting of this deposit is not so complete as in other similar deposits. As in most other deposits, a distinct peak was present between the 115- and 170-mesh fractions, but minor peaks were also present between the 250- and 326-mesh fractions and in the +60-mesh fraction. Heavy minerals including ferromagnetic minerals are abundant throughout the entire range of sieve sizes. No light minerals, however, were found on the sieves finer than 170 mesh.

Too little is known about this deposit to assess its economic potential. If the original long axis was in a general north-south direction, considerably more tonnage may be present than is indicated by the exposure.

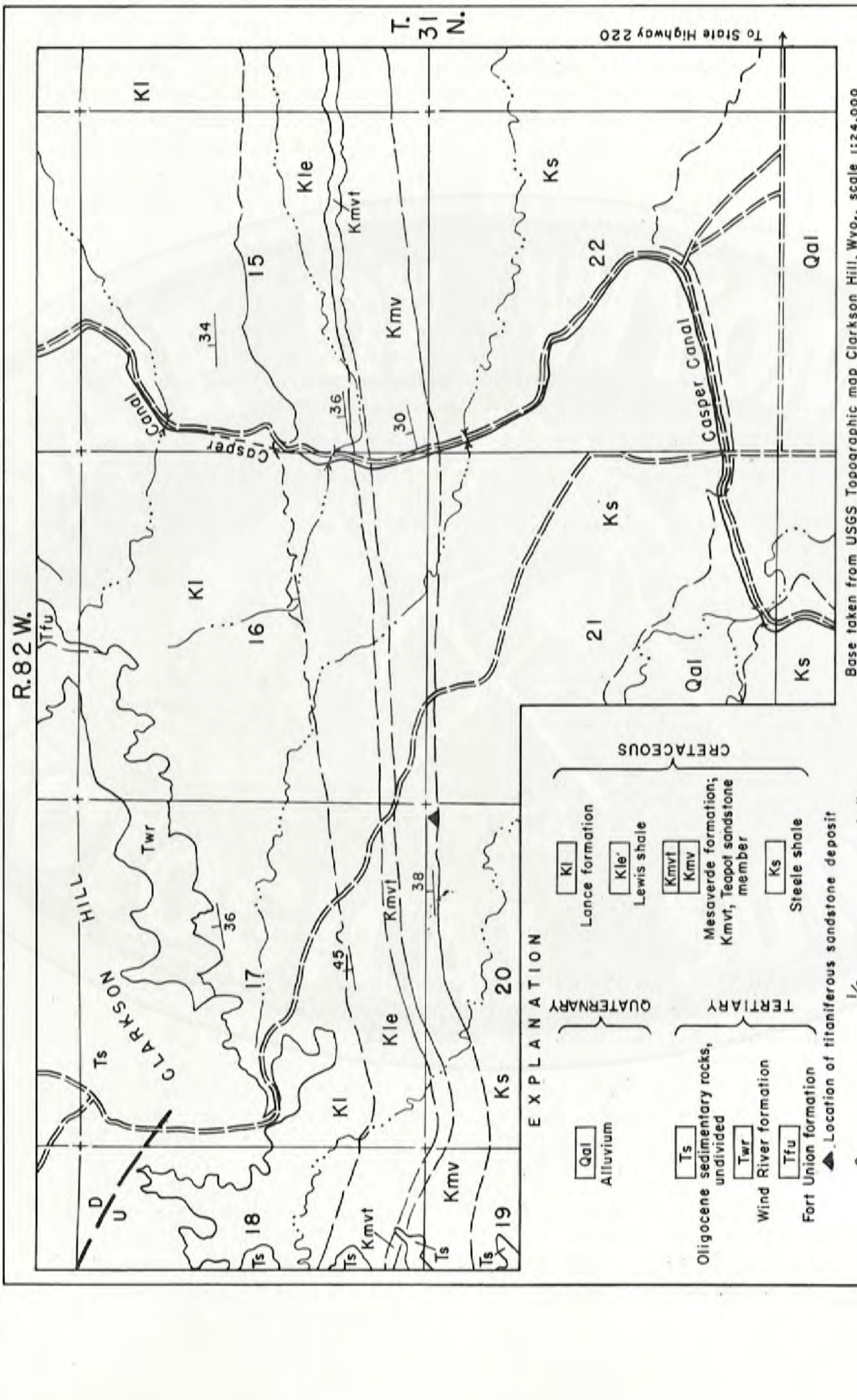


Figure 21. Map showing geologic setting and location of Clarkson Hill titaniferous sandstone deposit.

PLATE 11

A. Clarkson Hill deposit at top of Parkman sandstone member of Mesaverde formation. Teapot sandstone member of Mesaverde formation in left background. View looking north.

B. Cross section of Poison Spider deposit. Bedding characterizes low-grade deposits of this type. View looking southeast.

CLARKSON HILL DEPOSIT

The Clarkson Hill deposit is the only black sandstone occurrence known in the Parkman sandstone. It is near the southeastern end of the Wind River Basin in the NE¼ NE¼ NE¼ sec. 20, T. 31 N., R. 82 W. (fig. 21, pl. 11A). It is most easily reached by driving northeastward from the post office at Alcova, Wyo., on State Highway 220, for a distance of 7.4 miles. Turn westward on a graded dirt road and drive for 1.7 miles to a north-south cross road. Turn north, cross the bridge that spans the Casper Canal, and proceed north and west on an unimproved dirt road for about 1.6 miles. The deposit lies about 300 yards south of this point. The nearest rail facilities are located at Casper, Wyo., a distance of about 26 miles by road.

The Clarkson Hill deposit has an exposed length of about 150 feet in an east-west direction and an exposed width of about 20 feet. The strata containing the black sandstone strike about N. 80° E. and dip 38° N. The original strand-line direction in this area was probably generally north-south, and the original long axis of the deposit therefore was probably normal to the long dimension of the deposit as presently exposed. The maximum exposed thickness of the deposit is 5.6 feet.

The deposit forms the upper part of the Parkman sandstone member (basal unit) of the Mesaverde formation (pl. 11A). Rich (1958, p. 2430, section 5) describes the Parkman about 1¼ miles east of the deposit as consisting of about 100 feet of fine- to medium-grained yellowish-gray sandstone. The Parkman is overlain by about 450 feet of yellowish-gray lenticular sandstone, dark-gray to black carbonaceous siltstone and shale, and coal beds, all of which are assigned by Rich to "the nonmarine facies of the unnamed middle member of the Mesaverde formation." The upper member of the Mesaverde, the Teapot sandstone member, is about 60 feet thick in this area.

One sample was analyzed chemically and shows 4.8 percent TiO_2 and 26.1 percent total iron expressed as Fe_2O_3. The equivalent uranium content is 0.004 percent and the chemical uranium content is 0.001 percent.

One sample of the higher grade material, collected 4.0 feet below the top of the deposit, was studied petrographically. It contains 28.0 percent acid-soluble matrix, 36.7 percent light minerals, and 35.3 percent heavy minerals of which 1.1 percent is ferromagnetic. Opaque minerals, zircon, pyralspite garnet, tourmaline, rutile, augite, greenish-brown hornblende, oxyhornblende, biotite, chlorite, and sphene were identified in the heavy-mineral suite. Minerals having specific gravities greater than 4.0 include zircon which makes up 3.0 percent, and the opaque minerals which make up 65.0 percent of the suite. Minerals having specific gravities greater than 2.8 but less than 4.0 include amphibole, biotite, chlorite, sphene, garnet, augite, and tourmaline and comprise 32.0 percent of the heavy-mineral suite. Amphibole and augite make up 18.0 percent of these minerals. The Clarkson Hill deposit is unusual in that it contains an abundance of lighter heavy minerals; the average black sandstone of Late Cretaceous age contains only traces of lighter heavy minerals.

POISON SPIDER DEPOSIT

The Poison Spider deposit is in the NE¼ NE¼ NE¼, sec. 1, T. 33 N., R. 84 W., and the SE¼ SE¼ SE¼, sec. 36, T. 34 N. R. 84 W., Natrona County, Wyo. (fig. 22). It lies about 12 miles south of Natrona and about 25 miles west of Casper. The deposit can be reached by driving south from Powder River on the Powder River road to the South Casper Creek oil field and from there west along the Northern Utilities Pipe Line road for 2.7 miles. From this point, prospect pits adjacent to the deposit can be seen a few hundred yards north of the road. The nearest rail facilities are at Natrona, about 15 miles to the north by graded roads.

The Poison Spider deposit has a maximum thickness of 7 feet and is traceable along its outcrop for about 300 feet. The long dimension of the deposit and the strike of the bedding are N. 42° W. and the dip of the bedding is 70° SW. Owing to erosion and the steep inclination of the deposit (pl. 11B), no estimate can be made of the original size and extent of the concentration. Estimates of the size of the deposit are further complicated by a normal fault which truncates the deposit at the north end (fig. 22).

The Poison Spider deposit is the only one that has been reported to 1960 in the Lewis shale. In this general area, (Rich 1958) has subdivided the Lewis shale into lower and upper marine tongues, separated by a tongue of continental rocks of the Meeteetse formation. The top of the lower marine tongue, as shown by Rich and inferred by Dobbin and Reeside (1929, p. 21), is about 300 to 400 feet above the base of the Lewis shale. The Poison Spider deposit lies about 375 feet above the base of the Lewis, which places it at or near the top of the lower marine tongue, in a position which indicates that it was deposited during an early regression of the Lewis sea.

Five samples of the Poison Spider deposit contain an average of 40.3 percent soluble matrix, 25.6 percent light minerals, and 34.1 percent heavy minerals, of which 15.0 percent is ferromagnetic.

The heavy minerals are:

	Percent of total heavy fraction
Zircon	6.2
Garnet	8.2
Tourmaline	1.0
Epidote	1.0
Sphene	1.0
Staurolite	1.0
Rutile	1.0
Monazite	1.0
Opaque minerals	84.0

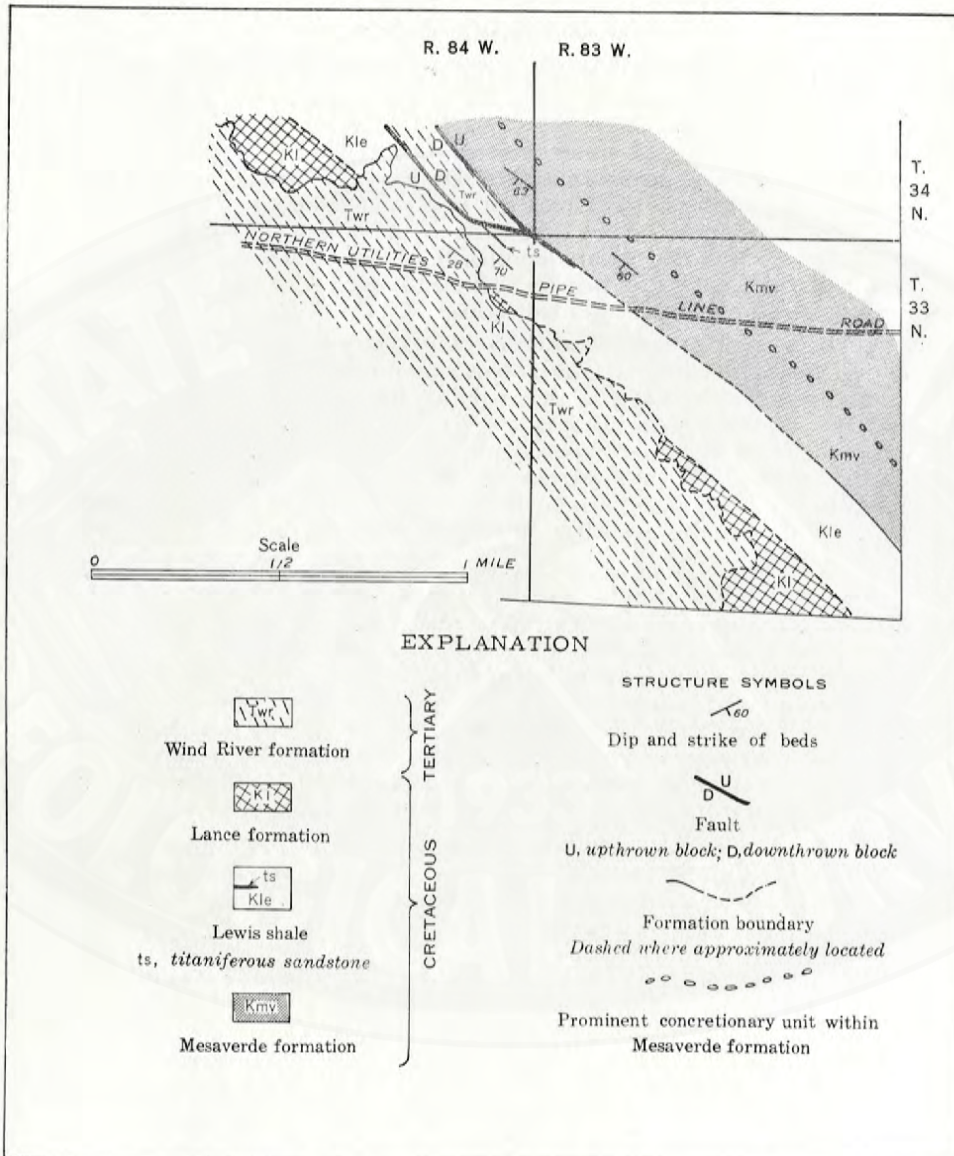


Figure 22. Map showing geologic setting and location of Poison Spider titaniferous sandstone deposit.

One sample taken from a depth of 17 feet in a prospect pit dug on the main outcrop is much richer in ferromagnetic minerals than surface samples. This sample may be more representative of the original black sand because it is less altered by weathering. It contains 7.9 percent TiO_2 and 63.7 percent total iron expressed as Fe_2O_3. An average of 13 samples of weathered rock from the Poison Spider deposit has 5.2 percent TiO_2 and 21.7 percent Fe_2O_3. Equivalent uranium content averages 0.003 percent and the chemical uranium content averages 0.0008 percent for the 13 samples analyzed. The 1:4 ratio of titanium dioxide to total iron oxides is about the same as in other lower grade deposits such as Dugout Creek, and probably indicates either a high magnetite to ilmenite ratio in the original sandstone or an abundance of low titanium-bearing minerals.

SHEEP MOUNTAIN DEPOSIT

The Sheep Mountain deposit is the easternmost deposit known in Wyoming. It lies at the north end of the Sheep Mountain Federal Game Refuge in Albany County, Wyo., in the SE½ sec. 10, T. 15 N., R. 77 W. (pl. 12). It is readily accessible by road and can be reached by driving west from Laramie on State Highway 130 for 23.5 miles and then due south about 0.8 mile on a graded dirt road to the fence bounding the game refuge. The deposit crops out about half a mile west of this point. It is readily visible as an isolated, dark outcrop, protruding through an alluvial slope. The Coalmont Branch of the Union Pacific Railroad passes within 1.5 miles north of the deposit.

The deposit is exposed sporadically for a distance of about 1,900 feet in northwest-southeast direction. The maximum width of outcrop is about 50 feet. The strata containing the black sandstone strike N. 30°-45° W. and dip 25° to 35° NE. A maximum thickness of 17.0 feet was measured in a prospect pit (pl. 13A), which cuts across the northwest end of the exposures. The thickness is considerably less toward the southeastern end, the minimum thickness measured being about 2 feet. Most of the exposures of the black sandstone are isolated outcrops completely surrounded by alluvium, and it is impossible to determine the original trend of the deposit from surface data alone. It is believed, however, that the exposed outcrop represents a section oblique to the original long axis, which probably trends generally north-south. It seems likely that the deposit may be encountered by drilling directly north of the northwesternmost black sandstone outcrops.

Because the black sandstone and the surrounding strata are poorly exposed, it is not possible to determine precisely where the deposit occurs in the Upper Cretaceous sequence. At the southeastern end of the deposit, many poorly perserved thin-shelled mollusks were found in association with the black sandstone. These were identified by W. A. Cobban of the U. S. Geological Survey as *Inoceramus sublaevus* Hall and Meek. This species is most common in cen-

PLATE 13

A. Prospect pit of Sheep Mountain deposit showing massive but fractured bed of black sandstone.

B. View looking northeastward at a ridge-forming titanium-bearing sandstone south of Kemmerer, Wyo. The sandstone is about 15 feet thick.

tral South Dakota, where it is restricted to the Gregory member of the Pierre shale. The Gregory fauna has been found at several other localities within the Laramie Basin in the upper part of the Steele shale and the basal part of the Mesaverde formation (Cobban and Reeside, 1952a). Inasmuch as the Sheep Mountain deposit originated as a beach placer, it probably lies in the basal part of the Mesaverde formation.

Six samples of the Sheep Mountain deposit were analyzed petrographically. These samples were collected from a cross-cutting prospect pit which affords an excellent exposure of the northwesternmost outcrop. They average 22.0 percent acid-soluble matrix, 15 percent light minerals, and 63.0 percent heavy minerals of which 28.0 percent is ferromagnetic. These samples contain a greater variety of heavy minerals than is found in the average deposit. They occur in the following percentages:

	Percent of total heavy fraction
Zircon	10.3
Garnet	3.0
Epidote	1.0
Tourmaline	1.0
Monazite	1.0
Staurolite	1.0
Amphibole	1.0
Sphene	1.0
Biotite	1.0
Spinel	1.0
Opaque minerals	84.2

Chemical analyses were made of seven samples, collected at 2-foot intervals in the same prospect pit. The average of these analyses shows 15.6 percent TiO_2 and 40.4 percent total iron expressed as Fe_2O_3. In TiO_2 content the samples range from 3.7 percent to 23.6 percent (table 13). The average equivalent uranium content is 0.007 percent, and the average chemical uranium content is 0.0015 percent.

A mineralogical analysis of a sample from the thin southeastern part of the deposit shows the same individual heavy minerals, but the total heavy-mineral fraction is only a very minor part of the bulk sample in contrast to the 63 percent heavy minerals present in the northern part of the deposit. Chemical analyses of two samples from the southern part of the deposit show an average TiO_2 content of 0.49 percent and an average Fe_2O_3 content of 11.2 percent. These analyses suggest that the southeasternmost outcrops may not be parts of the original black sand deposit, but rather are a part of the zone which has been permeated by iron-bearing solutions derived by leaching from the adjacent black sandstone concentration.

If the southeastern part of the Sheep Mountain deposit is entirely barren or of extremely low grade, then the exposed length of the deposit is reduced by about 50 percent and, hence, the deposit would be of less economic value than might be supposed. The deposit may continue for some distance north, but this could only be demonstrated by test drilling; however, the steep north dip reduces the economic potential of the deposit in that direction.

RED CREEK DEPOSIT

The Red Creek deposit is in the NE¼ sec. 22, T. 12 N., R. 105 W. in Sweetwater County, Wyoming, about half a mile northeast of the point where Red Creek crosses the Wyoming-Colorado State line (fig. 1). It lies on the north flank of the Uinta Mountains about 40 miles due south of Rock Springs, Wyo., and is easily accessible from Rock Springs on both paved and graded roads. At this locality, strata of the Mesaverde Group form a conspicuous rimrock around the northern half of Clay Basin, a topographic depression on the Wyoming-Colorado border. The deposit is visible directly east of the road as it passes through a gap in the rimrock. The nearest rail facilities are those of the Union Pacific Railroad at Rock Springs.

The Red Creek deposit is exposed for a maximum distance of about 800 feet in an east-west direction, but the dense concentration of heavy minerals is restricted to about 125 feet of this distance. The western end of the exposure, which consists of higher grade rock, averages about 6 feet in thickness, and the eastern end, which is lower in grade, tapers from 4 feet to a wedge-edge. The deposit caps part of a prominent dip slope, and the down-dip extension to the north is concealed by overlying strata. Rocks adjacent to the black sandstone strike essentially east-west and dip about 20° N. The deposit is an irregularly shaped lens which fills a channel cut into the underlying white sandstone. At the west end of the outcrop, where the black sandstone is thickest (pl. 14), the lens abuts sharply against the host sandstone, whereas to the east it thins gradually. Because of limited exposures, it is difficult to estimate the size or trend of the original deposit, but it is probable that the long axis was parallel to the Late Cretaceous shoreline which was essentially north. Hence, the long axis would be in the down-dip direction.

The black sandstone lens is at the top of a littoral marine sandstone tongue of the Rock Springs formation. This sandstone, which is about 60 feet thick, is white to pale buff, fine grained, well sorted, and massive. It is transitional downward into thin-bedded sandstone and shale which makes up the upper part of the underlying Blair formation or the Black Butte tongue of the mancos shale (Hale, 1950, p. 52 and 1955, p. 93). The sandstone was deposited in a littoral environment during a regression of the Late Cretaceous sea.

Overlying the sandstone tongue of the Rock Springs formation is a nonmarine sequence of carbonaceous shale, sandstone, and some

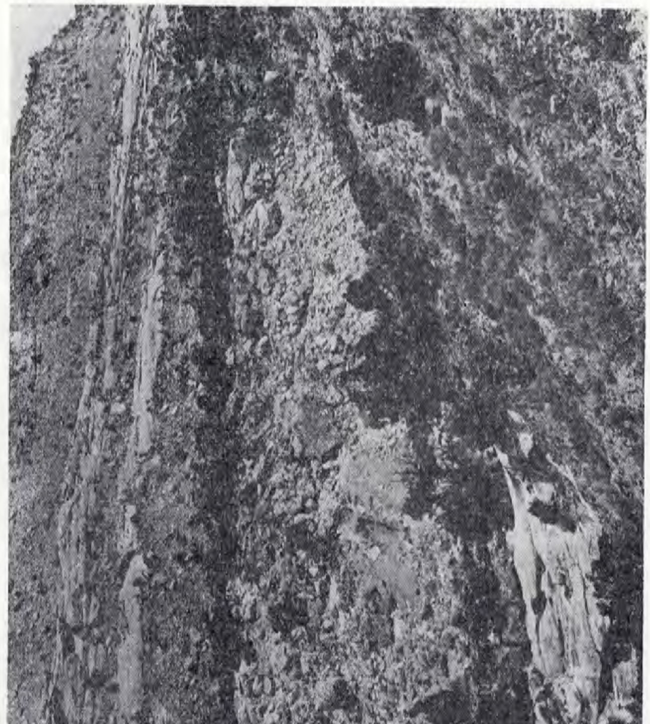


PLATE 14

Panorama looking northward at Red Creek black sandstone deposit. Note the abrupt termination at the left and the gradual tapering to the right. White sandstone is the uppermost unit of the Rock Springs formation.

lignite of the Ericson formation. This sequence is lithologically similar to sequences overlying the black sandstone in the previously described localities, but differs in that the sandstone beds are much thicker, more abundant, and seem to be more extensive. These sandstone beds, rather than being soft and easily eroded as is common in other places, are moderately well lithified and form steep slopes and cliffs.

Four samples of the Red Creek deposit were analyzed petrographically. They average 29.8 percent acid-soluble matrix, 44.7 percent light minerals, and 27.5 percent heavy minerals of which 28.0 percent is ferromagnetic. The heavy mineral suite includes:

	Percent of total heavy fraction
Zircon	13.7
Garnet	2.4
Tourmaline	1.0
Rutile	1.0
Biotite	Trace
Epidote	Trace
Chlorite	Trace
Staurolite	Trace
Monazite	Trace
Opaque minerals	82.8

The light-heavy minerals epidote, staurolite, biotite, and chlorite were found in very minor amounts in lower grade samples.

Eight samples from this deposit were analyzed chemically (table 13) and the average shows 14.3 percent TiO_2 and 19.0 percent total iron expressed as Fe_2O_3. The average equivalent uranium content is 0.011 percent, and the average chemical uranium content is 0.005 percent.

SALT WELLS CREEK DEPOSIT

The Salt Wells Creek deposit is near the southern end of the Rock Springs uplift in the SE¼ sec. 7, T. 14 N., R. 103 W., about 28 miles south-southeast of Rock Springs, Wyo. (fig. 1). It is easily accessible from Rock Springs on paved and graded roads. The deposit is clearly visible on a hillside directly east of the road at a point about half a mile north of the confluence of Bean Spring Creek and Salt Wells Creek. The nearest rail facilities are those of the Union Pacific Railroad at Rock Springs.

The black sand makes a lens-shaped outcrop that is about 250 feet long in a northeast-southwest direction, and has a maximum thickness of 3.0 feet in the central part. The limited exposure prevents any appraisal of the extent of the deposit beneath the overlying rocks. Bedding in strata adjacent to the black sandstone strikes N. 82° E. and dips 5° S.

The black sandstone fills a lenticular channel at the top of a massive white to buff littoral marine sandstone of the Rock Springs formation. The sandstone forms a persistent marker bed 60 feet in thickness at the base of a scarp which rims the southeastern part of the Rock Springs uplift. It is similar lithologically and stratigraphically to the host sandstone of the deposit at Red Creek about 17 miles to the southwest. Underlying this sandstone and separated from it by a thin shale zone, is a tan to dark-buff shaly sandstone which forms a conspicuous scarp in this area, but apparently grades into shale to the south. The lower sandstone probably is part of a transition zone from the Blair formation below to the littoral sandstone above. Stratigraphically beneath the transitional unit lies nonresistent valley-forming marine sandy shale of the Blair formation.

The beds overlying the black sandstone deposit are chiefly carbonaceous shale, sandstone, and some lignite. As in the Red Creek area to the south, this sequence of beds forms steep slopes and cliffs because the sandstones are thicker and apparently more extensive than those described in comparable stratigraphic positions at many other black sandstone localities.

Four samples of the Salt Wells Creek deposit were analyzed petrographically. They average 37.5 percent acid-soluble matrix, 7.0 percent light minerals, and 55.5 percent heavy minerals of which 14.5 percent is ferromagnetic.

Heavy minerals include:

	Percent of total heavy fraction
Zircon	12.4
Garnet	1.1
Tourmaline	1.0
Rutile	1.0
Monazite	1.0
Opaque minerals	85.0

Two samples were analyzed chemically (table 13). The average of these analyses shows 22.5 percent TiO_2 and 25.5 percent total iron expressed as Fe_2O_3. The average equivalent uranium content is 0.010 percent, and the average chemical uranium content is 0.003 percent.

BLACK BUTTE CREEK DEPOSIT

The Black Butte Creek deposit is in sec. 30, T. 18 N., R. 101 W. on the south side of a major draw which crosses that area. A minor occurrence of black sandstone is located nearby in sec. 1, T. 17 N., R. 102 W. and will be discussed here because of its proximity to the larger Black Butte Creek deposit. Both deposits are readily accessible on paved and graded roads from Rock Springs, Wyo., about 20 miles to the northwest (fig. 1). The nearest rail facilities are those of the Union Pacific Railroad at Rock Springs.

The larger black sandstone deposit is exposed sporadically in a ledge along a steep brush-covered slope. The only good exposures are in prospect pits at each end of the deposit. The length of the deposit is about 1,500 feet in an east-northeast direction. In the eastern pit the deposit is 3 to 4 feet thick, but the lower one foot is of very low grade. At the western pit, the deposit may be as much as 3 feet thick, but the rock is all low in grade and contacts with the host rock cannot be determined. Strata adjacent to the black sandstone strike about N. 40° E. and dip about 7° SE. The relation between the black sandstone and the host sandstone is obscured by soil cover and vegetation. Because of the limited exposures it is impossible to reconstruct the original shape of the deposit.

The smaller deposit lies on the east side of an ungraded road about 2 miles south-southwest of the larger deposit. It is a poorly exposed deposit which dips gently to the southeast. It is about 1 foot thick and caps a low ridge.

The stratigraphic position of the Black Butte Creek deposits is uncertain. They are in the littoral sandstone sequence of the Rock Springs formation and are overlain by sandstone and carbonaceous shale, as are deposits at Red Creek and Salt Wells Creek. However, the marine shale sequence that underlies the littoral sandstone beds of the Rock Springs formation in the Black Butte Creek area is very sandy and contains many ledges which rise above the general level of the shale valley. Hale (1950) suggests that the shaly sandstone beds are off-shore marine deposits laid down during a period when coal-swamp deposition took place to the northwest.

Four samples of the Black Butte Creek deposit were analyzed petrographically. Three of the samples came from the larger deposit and one from the smaller deposit. The samples from the larger deposit average 34.5 percent acid-soluble matrix, 41.5 percent light minerals, and 24.0 percent heavy minerals of which 4.0 percent is ferromagnetic. The sample from the smaller deposit contains 37.0 percent acid-soluble matrix and 59.0 percent heavy minerals of which 13.0 percent is ferromagnetic. The remainder comprises the light fraction.

The heavy-mineral suite from all four samples includes the following:

	Percent of total heavy fraction
Zircon	11.1
Garnet	2.3
Tourmaline	1.0
Rutile	1.0
Monazite	Trace
Amphibole	Trace
Staurolite	Trace
Chlorite	Trace
Opaque minerals	84.0

Three samples from the large deposit were analyzed chemically (table 13). The average shows 14.0 percent TiO_2 and 15.0 percent total iron expressed as Fe_2O_3. The average equivalent uranium content is 0.014 percent, and the average chemical uranium content is 0.002 percent. Chemical analysis of one sample from the small deposit shows 28.0 percent TiO_2 and 35.8 percent total iron as Fe_2O_3. The equivalent uranium content is 0.015 percent and the chemical uranium content is 0.003 percent.

CUMBERLAND GAP AREA

The deposits of the Cumberland Gap area are in the W½ sec. 25, T. 18 N., R. 117 W. and in secs. 18, 19, and 30, T. 18 N., R. 116 W. in Uinta County, Wyoming (fig. 1). The area can be reached by driving south from Kemmerer, Wyo., on U. S. Highway 189 for about 23 miles to a dirt road which bears east through Scully Gap. Turn east on this road and continue for about 1 mile through the gap to an unimproved road which bears north. The area of the deposits is marked by numerous prospect pits about 2 miles north along this unimproved road. The black sandstone deposits of the Cumberland Gap area do not stand out in marked color contrast with surrounding rocks as do most of the other deposits previously described, but they can be readily identified with radiation-detection instruments. A spur line of the Union Pacific Railroad extends from Kemmerer to a point about 4 miles north of the black sandstone area.

The deposits in the Cumberland Gap area have been examined only briefly in the field, and very little is known concerning their extent and geologic setting. Radiometric anomalies of about five times background were obtained over an area 2.5 miles long and several hundred feet wide. These anomalies were localized in two main sandstone ledges and several minor ones which were sampled and later proved to contain heavy-mineral concentrations. The longest continuous exposure of any of these radio-active ledge-forming sandstones (pl. 13B) is about 600 feet in a direction parallel to the strike of the bedding which is N. 42° E. The general dip of the strata is 15° NW.

The deposits are located in the lower part of the Frontier formation of Late Cretaceous age (pl. 1). The tops of the two major heavy-mineral-bearing sandstone beds lie about 120 feet and 355 feet, respectively, above the base of the formation. Shale, siltstone, and minor amounts of bentonite and coal are interbedded with the black sandstone beds. About 4 miles to the north, in secs. 31 and 32, T. 19 N., R. 116 W., a detailed stratigraphic section was measured by Cobban and Reeside (1952b, p. 1923) who describe the formation as consisting of 1,955 feet of marine and nonmarine sandstone, shale, and siltstone with some coal, carbonaceous shale, and bentonite. The two major heavy-mineral-bearing sandstone beds are believed to correlate with the sandstone beds described by Cobban and Reeside in units 3 and 19 (1952b, p. 1928-1929), the tops of which occur 149.5 and 339.3 feet, respectively, above the base of the Frontier formation. The interval from 235 to 335 feet (units 13-19) above the base of the formation contains oysters, *Brachydontes,* and shark teeth, which suggests shallow-marine origin. The upper sandstone of this sequence (unit 19) seems to be a regressive sandstone deposited during a minor retreat of the sea.

The origin of the lower of the two major black sandstone beds has no ready explanation. The top of this sandstone lies essentially in the middle of the basal sequence which Cobban and Reeside refer to as nonmarine and largely of fluviatile origin. Many occurrences of fluviatile heavy-mineral concentrations are known, but for the most part they are much lower in grade than this deposit, which contains almost 80 percent heavy minerals after removal of the matrix. The authors believe that this occurrence is a marine beach placer, and that the enclosing sandstone is a previously unrecognized regressive littoral sandstone. The section described by Cobban and Reeside (1952b) is 4 miles from the black sandstone deposits and facies changes could account for the presence of a regressive littoral sandstone in one place and not in the other.

Five samples of the Cumberland Gap area were analyzed petrographically. Three of these samples came from the lower black sandstone and two from the upper. They average 41.4 percent acid-soluble matrix, 49.4 percent light minerals, and 9.2 percent heavy minerals of which 4.3 percent is ferromagnetic. The heavy fraction includes the following percentages of heavy minerals:

	Percent of total heavy fraction
Zircon	10.6
Chlorite	* 7.2
Anatase	1.6
Garnet	1.0
Rutile	1.0
Tourmaline	1.0
Apatite	1.0
Monazite	1.0
Epidote	1.0
Sphene	1.0
Opaque minerals	78.4

*Includes all micaceous minerals.

Four samples were analyzed chemically, two from the lower and two from the upper black sandstone (table 13). The lower sandstone samples average 7.1 percent TiO_2 and 27.0 percent total iron expressed as Fe_2O_3. The average equivalent uranium content is 0.014 percent, and the average chemical uranium is 0.0015 percent. The upper sandstone samples average 9.5 percent TiO_2 and 20.0 percent total iron expressed as Fe_2O_3. The average equivalent uranium content is 0.002 percent and the average chemical uranium content is 0.001 percent.

The opaque minerals are highly altered, and X-ray patterns reveal anatase and possibly goethite pseudomorphic after the original opaque minerals. The original opaque minerals may once have been similar to those studied at Grass Creek, but now are more highly altered. Chemical analyses were not made of the opaque fraction, but X-ray spectrometer patterns indicate titanium and iron as major constituents. The peak intensities of titanium lines in the Cumberland Gap patterns are comparable to those of Grass Creek opaque minerals.

The Cumberland Gap deposits are the only ones known in which anatase occurs in discrete grains; it is probably authigenic. The large size of the anatase crystals in these deposits, in contrast to those found in the deposits of younger Late Cretaceous age, may be due in part to the difference in age, although other unknown factors are undoubtedly involved.

Another feature of the Cumberland Gap black sandstone that sets it apart from younger deposits is that four samples average 8.3 percent TiO_2, yet contain only 10.5 percent heavy minerals. Apparently the matrix contains a major part of the titanium in these deposits.

The Cumberland Gap deposits are the only ones in which large quantities of chlorite or altered biotite are found in the heavy-mineral suite. As mentioned previously, the biotite is thought to have a volcanic origin. In one sample containing abundant chlorite in the matrix, a deep reddish-brown fibrous mineral with parallel extinction, which may be a secondary iron-titanium mica, was observed.

CLIFF CREEK DEPOSIT

The Cliff Creek deposit is at the center of the south line of sec. 33, T. 38 N., R. 114 W. in Sublette County, Wyo. (fig. 1). It can be reached by traveling southeast from Jackson, Wyo., on U. S. Highways 187 and 189 for a distance of about 28 miles to the bridge crossing Cliff Creek. Turn south on the Forest Service graded road along Cliff Creek and continue for about 4 miles to a Forest Service timber road that bears west along Gibbs Creek. The deposit is located about three-fourths of a mile along this road on an east-facing cliff on the north side of Gibbs Creek. The railroad facilities which best serve this area are at Kemmerer, about 135 miles by road to the south.

The writers have not examined this deposit in the field, but in 1955, J. D. Love of the U. S. Geological Survey sampled the deposit, and Houston and Love (1956, p. 72-74) have described the mineral and chemical content and the stratigraphic setting of the deposit.

The Cliff Creek deposit differs from those previously discussed in that it occurs in the Stump sandstone of Late Jurassic age and therefore is significantly older. The environment of deposition of this deposit is not as clearly understood as for those of Late Cretaceous age, but it is reasonable to assume that the deposit is a beach placer. According to Imlay (1956), the part of the Late Jurassic represented by the Stump sandstone (Oxfordian) "marks the greatest marine transgression on North America during the Jurassic." If the entire Stump sandstone is a transgressive littoral deposit, then the black sandstone is the only ancient beach placer known to have been laid down under transgressive conditions. The writers are inclined to the opinion that the Jurassic sea may have oscillated during its advance and that the Cliff Creek deposit was deposited during a short-lived regression.

The black sandstone zone is 3.7 feet thick and lies 19.8 feet below the top of the Stump sandstone. The upper 0.6 foot of the black sandstone is high-grade rock, the lower 0.4 foot is medium grade, and the central 2.7 feet is very low grade and may be considered barren. The host rocks both above and below the deposit are sandstones which are generally dark greenish, medium to coarse grained, hard, limy, oolitic and glauconitic. These sandstone beds are thin to massive and contain some hematitic partings. Below the deposit the sandstone is conglomeratic, and contains sandstone and chert pebbles as much as 2 inches in diameter.

A complete petrographic analysis was made of only one high-grade sample from the Cliff Creek deposit, but heavy-mineral grain counts were made of two other samples. The single sample contains 26.7 percent matrix and 71.0 percent heavy minerals of which 0.9 percent is ferromagnetic. The equivalent uranium content of this sample is 0.002 percent.

Heavy minerals identified in all three samples are chiefly altered opaque minerals with minor amounts of euhedral zircon, well-rounded violet zircon, garnet, rutile, tourmaline, chlorite, epidote, anatase, and amphibole. These samples contain a larger percentage of heavy minerals than is usually found in low-grade deposits; the mineral suite, however, is not so complex as that found in low-grade deposits.

Four samples were analyzed for titanium and iron. These samples varied considerably in tenor and are therefore listed according to the type of sandstone that was analyzed.

Lithologic type	TiO^2	Fe as Fe_2O_3	eU
Dark-red sandstone rich in heavy minerals	20.15	54.93	0.003
Ferruginous sandstone	0.70	5.70	0.001
Greenish-brown oolitic sandstone	0.74	7.06	0.001
Ferruginous oolitic sandstone	7.66	13.40	0.002

This occurrence is similar to Cumberland Gap in that it contains much larger anatase crystals than found in younger deposits. The mineralogy is not significantly different from the deposits of Cretaceous age, except for the presence of abundant iron-stained calcareous oolites and green to brown casts that are probably glauconitic. The oolites and glauconitic (?) casts are in barren sandstone and high-grade black sandstone alike. The oolites were not affected by the acid treatment used to clean the heavy minerals.

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BULLETIN 49

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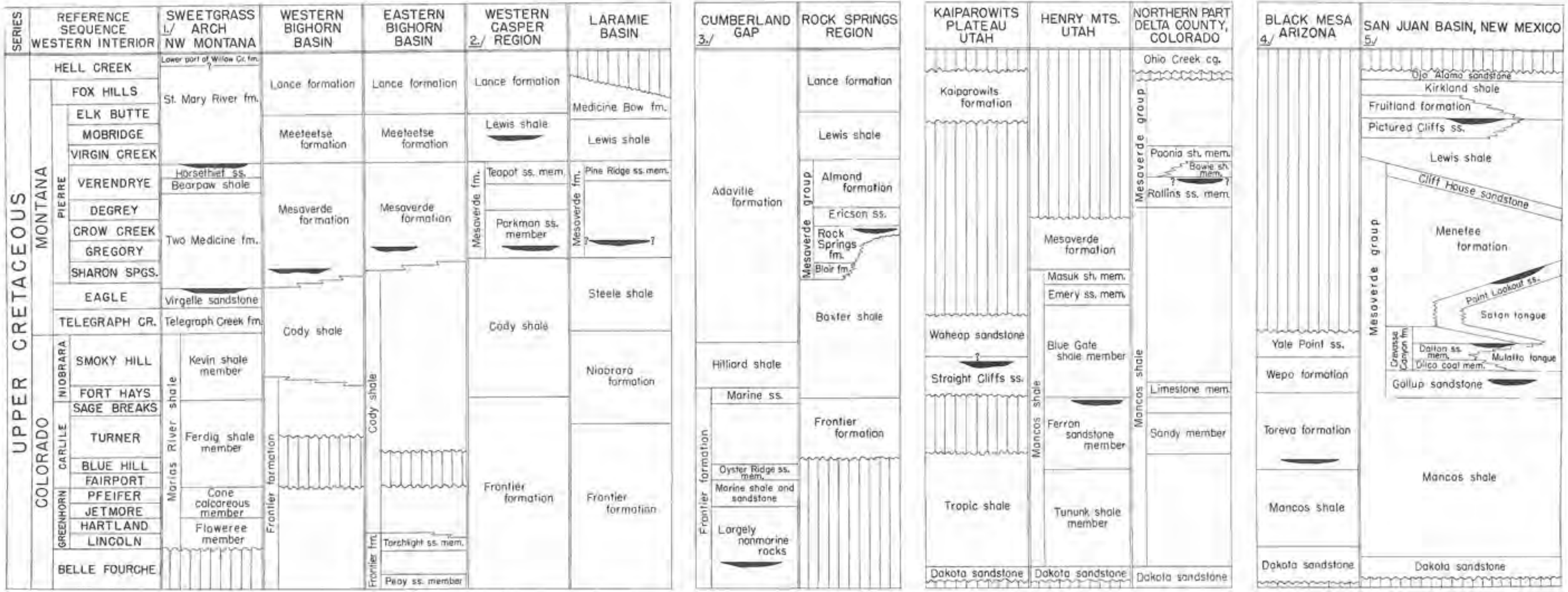


Except where source is referenced, all correlations are from Cobban and Reeside, 1952a, and are essentially unmodified.

1./ Modified after Cobban and others, 1959.

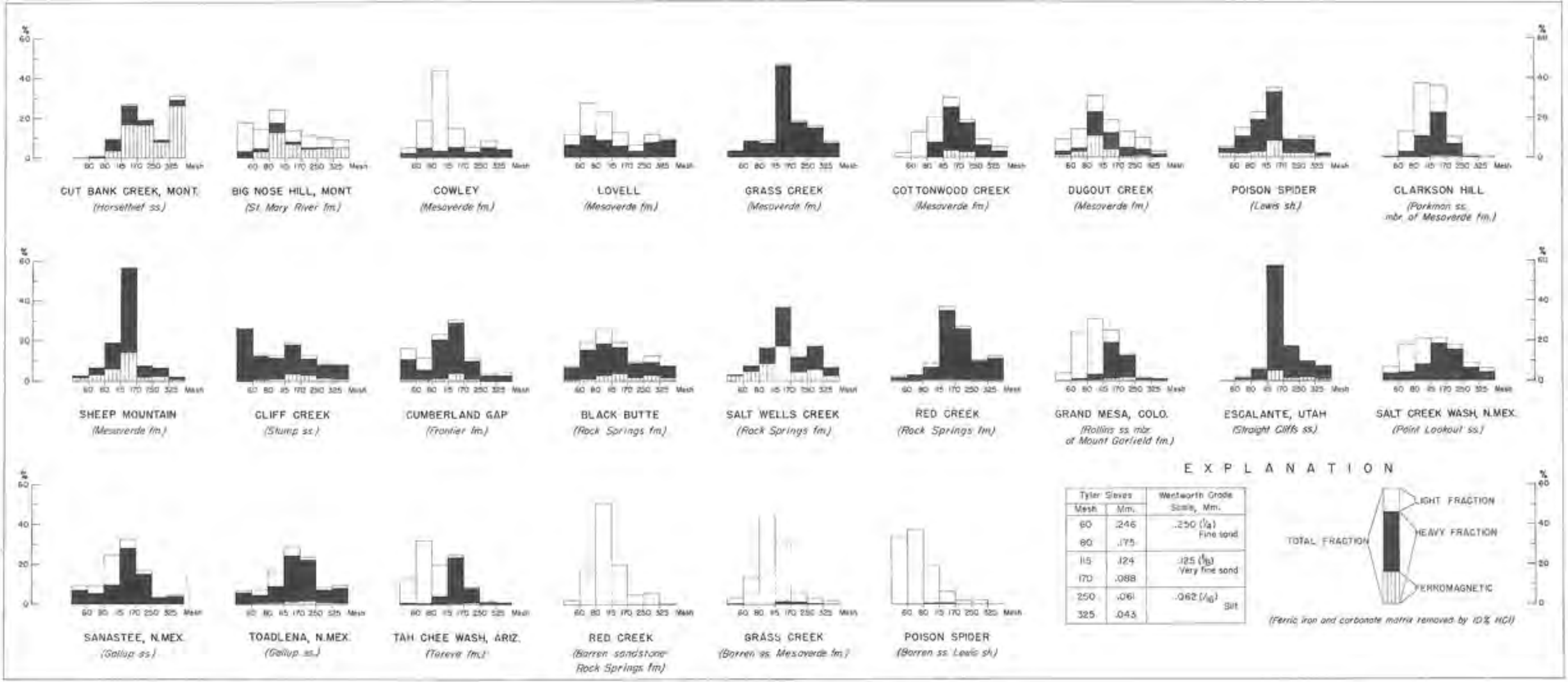
2./ Modified after Cobban and Reeside, 1952a, and Snow and McGrew, 1954.

3./ After Cobban and Reeside, 1952b, p. 1958, and Dorf, 1955, p. 97.

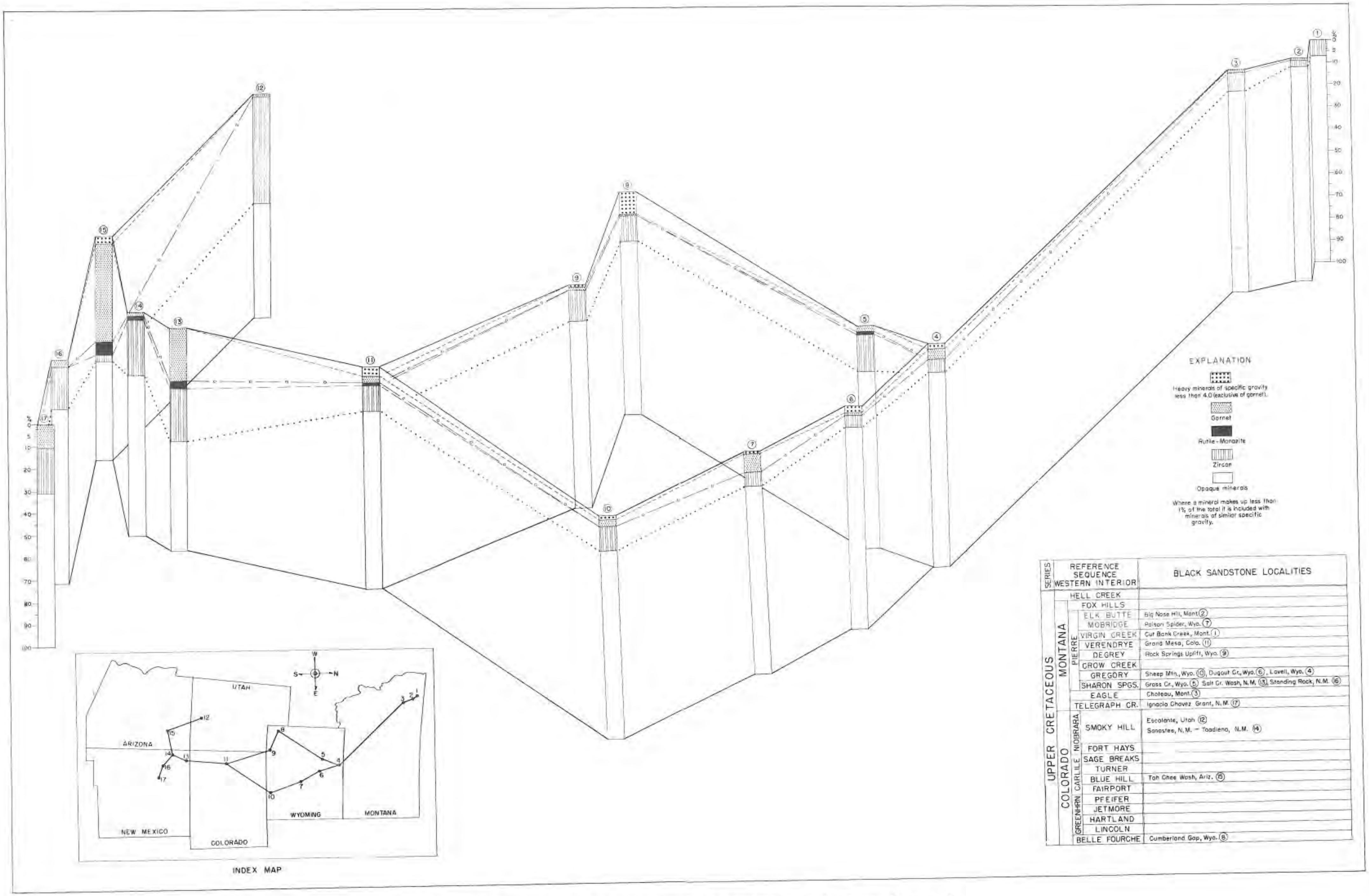
4./ After Repenning and Page, 1956, p. 266.

5./ Terminology modified after Beaumont, Dane, and Sears, 1956.

Correlation chart showing approximate stratigraphic positions of Cretaceous black sandstone deposits (in solid black).

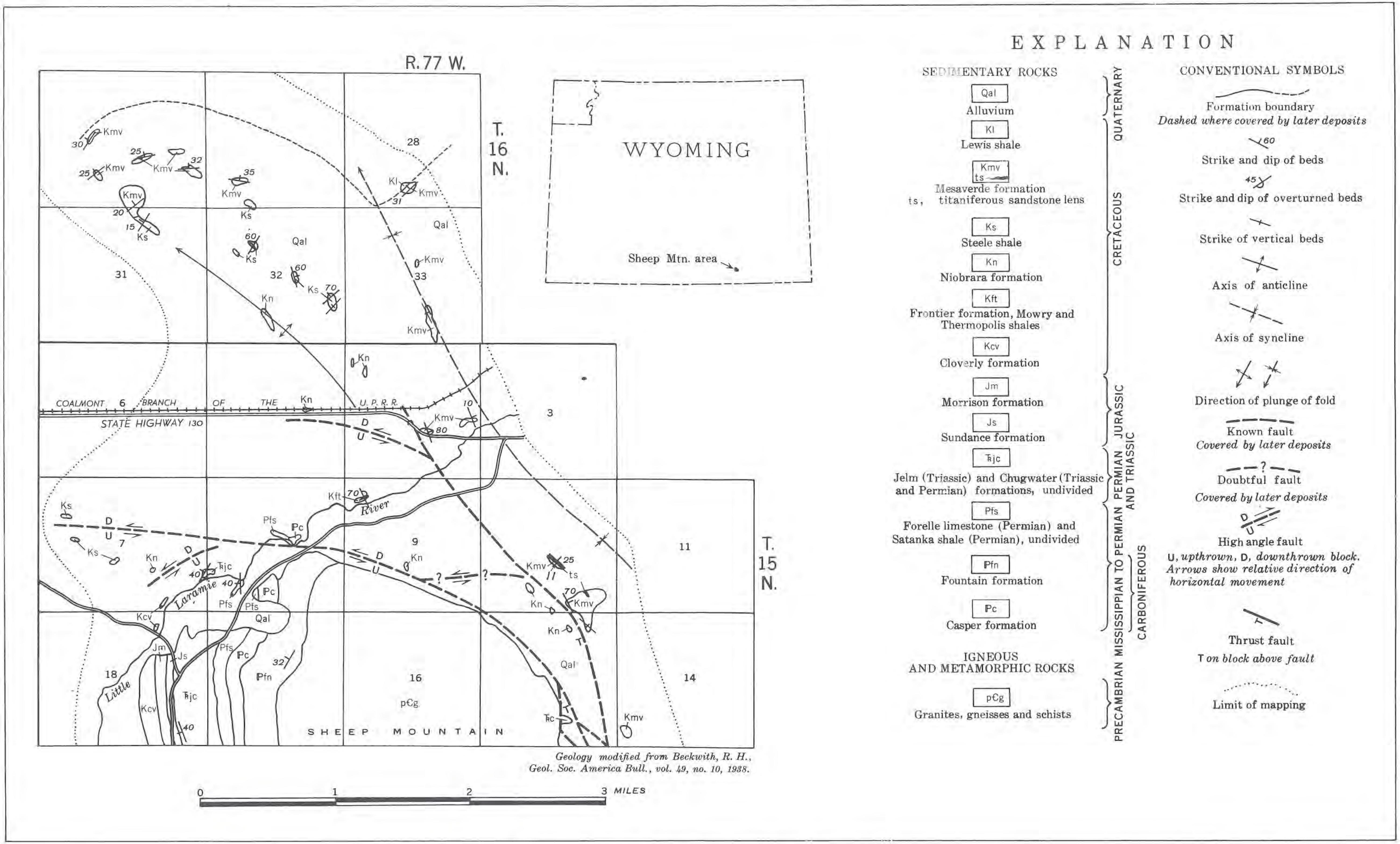


Typical histograms of black sandstone and barren host sandstone, showing percentage of ferromagnetic, heavy and light fractions.

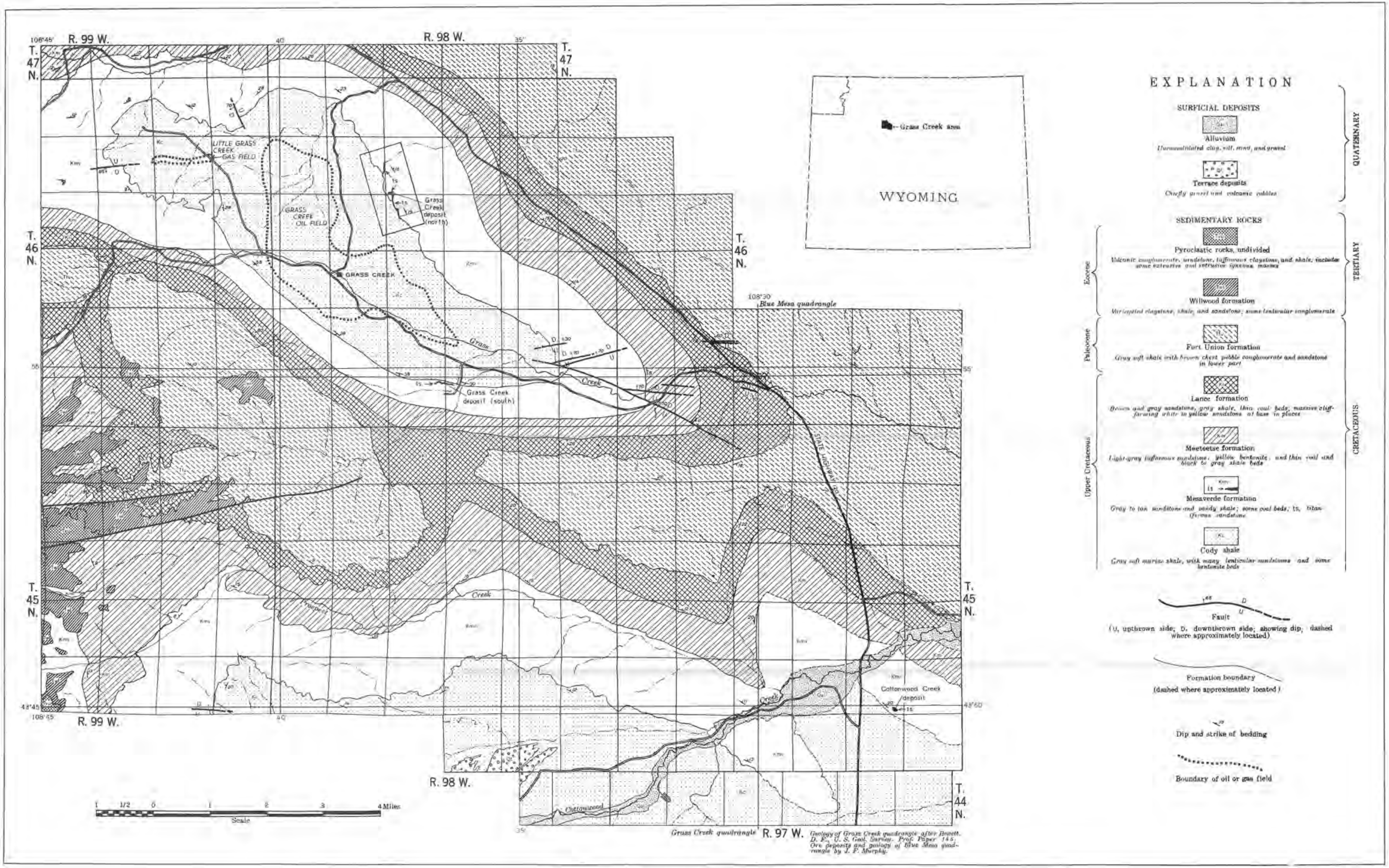


SERIES				REFERENCE SEQUENCE WESTERN INTERIOR	BLACK SANDSTONE LOCALITIES
UPPER CRETACEOUS				HELL CREEK	
	MONTANA			FOX HILLS	
		PIERRE		ELK BUTTE	Big Nose Hill, Mont. (2)
				MOBRIDGE	Poison Spider, Wyo. (7)
				VIRGIN CREEK	Cut Bank Creek, Mont. (1)
				VERENDRYE	Grand Mesa, Colo. (11)
				DEGREY	Rock Springs Uplift, Wyo. (9)
				CROW CREEK	
				GREGORY	Sheep Mtn., Wyo. (10), Dugout Cr., Wyo. (6), Lovell, Wyo. (4)
				SHARON SPGS.	Grass Cr., Wyo. (5) Salt Cr. Wash, N.M. (13) Standing Rock, N.M. (16)
				EAGLE	Choteau, Mont. (3)
				TELEGRAPH CR.	Ignacio Chavez Grant, N.M. (17)
	COLORADO	NIOBRARA		SMOKY HILL	Escalante, Utah (12) Sanostee, N.M. – Toadlena, N.M. (14)
				FORT HAYS	
		CARLILE		SAGE BREAKS	
				TURNER	
				BLUE HILL	Toh Chee Wash, Ariz. (15)
				FAIRPORT	
		GREENHRN		PFEIFER	
				JETMORE	
				HARTLAND	
				LINCOLN	
				BELLE FOURCHE	Cumberland Gap, Wyo. (8)

Regional variation of heavy-mineral frequencies in high-grade samples.



Geologic map of Sheep Mountain area showing location of titaniferous sandstone deposits.



Map showing geologic setting and location of Grass Creek and Cottonwood Creek titaniferous sandstone deposits.

TABLE 13.—ANALYSIS OF BLACK SANDSTONE IN WYOMING
(Results reported in percent)

Laboratory No.	Field No.	Chemical analyses: TiO_2	Chemical analyses: Iron as Fe_2O_3	Chemical analyses: Uranium	Equivalent uranium eU	Cement	Light minerals	Heavy minerals: Total	Heavy minerals: 1/ Ferro-magnetic	Sample location and remarks
Cowtey deposit, Mesaverde formation, sec. 1, T. 56 N., R. 97 W., Big Horn County										
252187	COW-1	3.0	33.85	-	0.001	37.0	52.5	10.5	7.0	Grab sample of high grade rock; south end of deposit.
Lovell deposit, Mesaverde formation, sec. 7, T. 55 N., R. 95 W., and sec. 12, T. 55 N., R. 96 W., Big Horn County										
252188	LOV-4	15.1	71.09	-	0.003	39.0	7.2	53.9	73.5	Grab sample of high grade rock near south end.
Grass Creek deposit (north), Mesaverde formation, secs. 8, 9, and 16, T. 46 N., R. 98 W., Hot Springs County										
204391	GC3-2	32.37	46.20	0.002	0.020	51.0	1.8	47.2	42.2	Base of black sandstone at locality GC3 (fig.19).
204392	GC3-4	14.01	24.73	.002	.013	-	-	-	-	4.0 ft. above base at locality GC3.
204393	GC3-6	16.67	23.37	<.001	.013	-	-	-	-	7.5 ft. above base at locality GC3.
204394	GC3-7	7.77	12.81	<.001	.007	35.6	60.2	4.2	.0	1.0 ft. above top of deposit at locality GC3.
204395	GC3-1A	8.84	10.69	<.001	.011	-	-	-	-	Grab sample about 400 ft. south of locality GC3 (fig. 19).
204396	GC5	.37	4.70	-	.001	-	-	-	-	Eastern wedge-edge of deposit (fig. 19).
204397	GC6-A	32.37	53.18	.020	.056	26.7	1.9	71.4	44.8	Depth of 4.0 ft. at locality GC6 (fig. 19).
204398	GC6-B	8.34	16.76	.001	.010	-	-	-	-	Surface sample at locality GC6 (fig. 19).
204399	GC7-2	6.30	13.96	<.001	.007	30.0	67.2	2.8	.0	1.5 ft. below base of deposit at locality GC7 (fig. 19).
204400	GC7-4	23.17	26.64	.002	.018	-	-	-	-	1.0 ft. above base of deposit at locality GC7 (fig. 19).
204401	GC7-5	0.40	3.63	-	.002	-	-	-	-	1.4 ft. above base at locality GC7.
204402	GC7-6	18.34	25.58	.001	.015	-	-	-	-	2.8 ft. above base at locality GC7.
204403	GC7-8	33.36	45.81	.004	.021	56.2	1.6	42.2	20.7	6.5 ft. above base at locality GC7.
204404	GC7-9	17.02	28.61	.002	.011	47.7	26.7	25.6	.0	8.5 ft. above base at locality GC7.
204405	GC7-10	2.64	7.72	<.001	.005	-	-	-	-	0.5 ft. above top of black sandstone.
204406	GC10-1	21.01	32.94	.001	.013	-	-	-	-	Middle of lower 3.2 foot black sandstone zone (fig. 19).
204407	GC10-2	8.31	8.66	<.001	.005	-	-	-	-	Middle of intermediate 5.0 foot black sandstone zone.
204408	GC10-3	32.51	32.43	.002	.026	66.9	4.3	28.8	.4	Middle of upper 2.5 foot black sandstone zone.
Grass Creek deposit (south), Mesaverde formation, secs. 33 and 34, T. 46 N., R. 98 W., Hot Springs County										
204384	GC1-2	15.68	20.87	0.001	0.024	54.4	11.1	34.5	3.1	East end of deposit, sec. 34; base of black sandstone.
204385	GC1-5	15.01	15.31	.001	.012	33.7	49.8	16.5	12.8	East end of deposit, sec. 34; 3.0 above base (GC1-2).
204386	GC1-6	1.40	3.94	-	.001	-	-	-	-	East end of deposit, sec. 34; 4.0 above base (GC1-2).
204409	GC13-1	5.75	5.52	<.001	.005	25.4	73.6	1.0	.0	Top of hill, sec. 33 (pl. 23); 3.5 below visible base of black sandstone.
204410	GC13-3	19.35	24.47	.002	.014	-	-	-	-	Top of hill, sec. 33 (pl. 23); base of black sandstone.
204411	GC13-4	28.20	39.32	.005	.024	48.6	11.0	40.4	19.2	Top of hill, sec. 33 (pl. 23); 1.3 ft. above base of black sandstone.
204416	GC13-5	-	-	.009	.032	51.2	2.2	46.6	6.0	Top of hill, sec. 33 (pl. 23); grab sample of high grade rock.
204412	GC13-6	30.52	49.20	.005	.023	-	-	-	-	Top of hill, sec. 33 (pl. 23); grab sample from top of deposit.
Cottonwood Creek deposit, Mesaverde formation, sec. 26, T. 45 N., R. 97 W., Hot Springs County										
204387	WB2-5	7.27	45.30	<0.001	0.005	-	-	-	-	Base of black sandstone deposit.
204388	WB2-6	6.77	29.39	<.001	.004	-	-	-	-	1.0 ft. above base of deposit.
204389	WB2-7	8.10	31.59	<.001	.005	-	-	-	-	2.0 ft. above base of deposit.
204390	WB2-9	16.84	47.16	<.001	.011	71.0	11.9	17.1	8.0	6.7 ft. above base of deposit (WB2-5).
Dugout Creek deposit, Mesaverde formation, secs. 34 and 35, T. 45 N., R. 89 W., and secs. 2 and 11, T. 44 N., R. 89 W., Washakie County										
252177	D-5	5.40	40.81	-	0.003	46.9	35.1	18.0	21.5	2/ Average of 7 samples from locality D5 (fig. 17).
252176	D-4	2.50	37.29	-	.003	44.7	44.2	11.1	16.2	2/ Average of 8 samples from locality D4 (fig. 17).
252179	D-6	4.00	40.37	-	.005	32.2	58.6	9.2	66.1	2/ Average of 12 samples from locality D6 (fig. 17).
252175	D-3	10.00	48.19	-	.008	58.4	27.0	14.6	35.8	2/ Average of 6 samples from locality D3 (fig. 17).
252181	D-7	5.00	35.57	-	.004	32.3	53.2	14.5	10.6	2/ Average of 9 samples from locality D7 (fig. 17).
252182	D-8	1.70	29.31	-	.001	40.0	53.0	7.0	7.3	2/ Average of 11 samples from locality D8 (fig. 17).
252183	D-9	6.00	34.66	-	.003	35.3	55.0	9.7	62.9	2/ Average of 3 samples from locality D9 (fig. 17).
252185	D-10	4.00	29.31	-	.003	47.0	49.6	3.4	36.0	2/ Average of 3 samples from locality D10 (fig. 17).
252186	D-11	14.80	55.39	-	.009	30.0	26.4	43.6	39.0	Grab samples of zone 1 ft. thick; locality D11 (fig. 17).
Poison Spider deposit, Lewis shale, sec. 1, T. 33 N., R. 84 W., and sec. 36, T. 34 N., R. 84 W., Natrona County										
207006	GH2-1	0.30	10.63	-	0.001	-	-	-	-	Prospect pit, sec. 36; 1.0 ft. above base of black sandstone.
207005	GH2-2	1.03	30.22	-	.001	-	-	-	-	Prospect pit, sec. 36; 2.8 ft. above base of black sandstone.
207004	GH2-3	7.76	31.83	0.001	.002	37.0	48.5	14.5	1.0	Prospect pit, sec. 36; base of upper zone of black sandstone.
207007	GH2-4	9.50	53.84	<.001	.004	17.9	8.6	73.5	22.8	Prospect pit, sec. 36; 2 ft. above sample GH2-3.
206982	GH1-1	0.42	1.66	-	.001	-	-	-	-	Prospect pit, sec. 1; 2 ft. below black sandstone.
206983	GH1-2	2.54	6.45	-	.002	-	-	-	-	Prospect pit, sec. 1; base of black sandstone.
206984	GH1-4	9.42	37.87	.003	.004	39.2	17.5	43.3	4.8	Prospect pit, sec. 1; 1.0 ft. above base of black sandstone.
206985	GH1-7	6.00	26.10	<.001	.004	-	-	-	-	Prospect pit, sec. 1; 2.3 ft. above base of black sandstone.
206986	GH1-8	1.33	7.97	-	.001	-	-	-	-	Prospect pit, sec. 1; 3.7 ft. above base of black sandstone.
206987	GH1-11	10.99	13.78	<.001	.009	-	-	-	-	Prospect pit, sec. 1; 5.4 ft. above base of black sandstone.
206988	GH1-14	2.72	28.88	-	.001	-	-	-	-	Prospect pit, sec. 1; 7.1 ft. above base of black sandstone.
206989	GH1-16	7.93	8.88	<.001	.004	-	-	-	-	Prospect pit, sec. 1; 8.0 ft. above base of black sandstone.
206981	GH3	7.93	63.72	<.001	.003	75.3	5.9	18.8	21.2	Prospect shaft in sec. 1; 1.5 ft. below top of black sandstone at a depth of 17 ft.
Clarkson Hill deposit, Parkman sandstone member, Mesaverde formation, sec. 20, T. 31 N., R. 82 W., Natrona County										
236157	CH3-1	4.80	26.1	.001	.004	28.0	36.7	35.3	3.0	4 ft. above base; thickest part of exposed deposit.
Sheep Mountain deposit, Mesaverde formation, sec. 10, T. 15 N., R. 77 W., Albany County										
206994	SM-1-1	3.77	13.53	<0.001	0.004	-	-	-	-	Prospect pit in center of exposed deposit; 13 ft. below top.
206995	SM-1-3	14.18	28.32	<.001	.008	-	-	-	-	Prospect pit in center of exposed deposit; 11 ft. below top.
206996	SM-1-5	3.94	16.27	-	.002	-	-	-	-	Prospect pit in center of exposed deposit; 9 ft. below top.
206997	SM-1-7	23.68	45.64	<.001	.007	40.0	17.6	42.4	26.0	Prospect pit in center of exposed deposit; 7 ft. below top.
206998	SM-1-10	22.86	59.19	<.001	.011	30.2	5.4	64.4	23.6	Prospect pit in center of exposed deposit; 4 ft. below top.
206999	SM-1-12	20.85	58.22	<.001	.010	-	-	-	-	Prospect pit in center of exposed deposit; 2 ft. below top.
207000	SM-1-14	19.18	61.27	.006	.016	22.5	.1	77.4	44.6	Prospect pit in center of exposed deposit; Top of black sandstone.
207001	SM-2-1	0.70	9.01	-	.001	-	-	-	-	Southeast end of main exposed deposit; selected sample.
207002	SM-3-1	0.26	13.32	-	.001	-	-	-	-	Low grade deposit about 1500 ft. southeast of main deposit; selected sample.
Black Butte Creek deposit, Rock Springs formation, sec. 30, T. 18 N., R. 101 W., Sweetwater County										
236153	RSBB-1	33.0	37.6	0.002	0.017	58.8	2.1	39.1	15.4	Top of deposit in eastern prospect pit.
236154	RSBB-4	7.50	4.00	.002	.008	-	-	-	-	Lower one foot of eastern prospect pit.
236155	RSBB-6	1.34	1.99	<.001	.003	34.0	-	-	-	Select grab sample from western prospect pit.
236156	RSBBS-1	28.00	35.80	.003	.015	37.2	4.0	58.8	12.8	Grab sample of high grade rock from small deposit south of main deposit in sec. 1, T. 17 N., R. 102 W.
Salt Wells Creek deposit, Rock Springs formation, sec. 7, T. 14 N., R. 103 W., Sweetwater County										
229362	SW-1-2	9.75	10.35	0.003	0.009	-	-	-	-	Base of black sandstone in central part of deposit.
229363	SW-1-4	35.50	40.67	.003	.011	33.9	1.9	64.2	18.6	1.0 ft. above base of black sandstone (SW-1-4).
Red Creek deposit, Rock Springs formation, sec. 22, T. 12 N., R. 105 W., Sweetwater County										
228401	RS-1	34.50	42.34	0.012	0.017	55.8	0.	44.7	1.5	West end of deposit; selected high grade sample.
229355	RS-3-2	.33	7.06	.008	.023	-	-	-	-	West end of deposit; base of black sandstone.
229356	RS-3-4	36.50	37.27	.008	.021	32.0	2.0	66.0	38.6	West end of deposit; 2.0 ft. above base.
229357	RS-3-7	36.00	42.14	.005	.019	-	-	-	-	West end of deposit; 5.0 ft. above base.
229358	RS-3-9	2.75	7.97	.001	.003	-	-	-	-	West end of deposit; 7.0 ft. above base, top of black sandstone.
229359	RS-4	.73	6.80	.001	.002	-	-	-	-	East end and top of black sandstone deposit.
229360	RS-2-3	.16	2.65	<.001	.001	-	-	-	-	Central part of black sandstone deposit; 1.0 ft. above base.
229361	RS-2-6	3.43	6.52	.001	.002	26.0	69.2	4.8	15.6	Central part of black sandstone deposit; 4.0 ft. above base.
Cumberland Gap area, Frontier formation, sec. 25, T. 18 N., R. 117 W., and secs. 18, 19, and 30, T. 18 N., R. 116 W., Uinta County										
225149	CG-1	4.39	21.50	0.002	0.003	60.0	39.4	.06	-	Selected sample submitted by prospector from general area.
236150	CGB-1	12.00	41.50	.001	.013	68.5	4.7	26.8	7.5	Sandstone sample about 115 ft. above Aspen shale.
236151	CGB-3	2.36	12.30	.002	.015	42.8	54.7	2.5	11.6	About 325 ft. northeast of sample CGB-1; same zone.
236152	CGB-1	14.50	18.60	-	.002	32.2	57.6	10.2	2.5	Selected sample about 330 ft. above Aspen shale.
Cliff Creek deposit, 'Stump sandstone, sec. 33, T. 38 N., R. 114 W., Sublette County										
236158	CC-3-1	7.66	13.40	-	0.002	26.7	2.3	71.0	0.9	Base of black sandstone; 23.1 ft. below top of Stump sandstone.
236159	CC-4-1	.74	7.06	-	.001	-	-	-	-	Low grade zone 2.7 ft. thick; 21.4 ft. below top of Stump sandstone.
236160	CC-5-1	.70	5.70	-	.001	-	-	-	-	Low grade zone 0.6 ft. thick; 19.8 ft. below top of Stump sandstone.

1/ Percent of total heavy minerals separated by an electromagnet designed to separate magnetite from ilmenite.

2/ Samples collected at roughly equal vertical intervals; usually 2 ft.

TABLE 14.—SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSIS OF WYOMING BLACK SANDSTONE

Explanation of code figures used in table

Percent	Code	Percent	Code	Percent	Code	Percent	Code
>10	XX.	0.5 - 1	.X+	0.02 - 0.05	.OX	0.001 - 0.002	.OOX-
5 - 10	X.+	.2 - .5	.X	.01 - .02	.OX-	.0005 - .001	.OOOX+
2 - 5	X.	.1 - .2	.X-	.005 - .01	.OOX+	.0002 - .0005	.OOOX
1 - 2	X.-	.05 - .1	.OX+	.002 - .005	.OOX	.0001 - .0002	.OOOX-

Zero (0), indicates element looked for but not detected. Trace (Tr), near threshold (below limit of sensitivity); Dash(—), not looked for.

[Analysts: N. M. Conklin, G. W. Boyles, R. G. Havens, J. D. Hamilton, U. S. Geological Survey]

Laboratory No.	Field No.	Si	Al	Fe	Ti	Mn	Ca	Mg	Na	K	B	Ba	Ce	Co	Cr	Cu	Ga	La	Nb	Nd	Ni	Sc	Sn	Sr	V	Y	Yb	Zn	Zr	Laboratory No.
204391	OC3-2	X.-	.X+	XX.	XX.	.X+	X.+	.X+	0	0	0	.X-	.X	0	.OX+	.OOX+	0	.X	.OX+	.X-	0	.OX-	0	0	.OX+	.OX+	.OOX+	0	X.+	204391
204392	OC3-4	XX.	X.	XX.	XX.	.X+	X.-	.X	0	0	0	.OX+	.X+	0	.OX-	.OOX+	0	.X+	.OX+	.X	0	0	0	0	.OX	.OX	.OOX+	0	X.-	204392
204393	OC3-6	XX.	X.-	XX.	X.+	.X	X.-	.X	0	0	0	.OX+	.X+	0	.OX	.OOX	0	.X+	.OX+	.X	0	0	0	0	.OX	.OX	.OOX+	0	X.-	204393
204394	OC3-7	XX.	X.-	X.+	X.	.X	X.	.X	0	0	0	.OX	.X	0	.OX-	.OOX	0	.X	.OX	.X-	0	0	0	.OOX	.OX-	.OX	.OOX	0	.X+	204394
204395	OC3-1A	XX.	X.-	X.+	X.	.X	.X+	.X-	0	0	0	.OX+	.X+	0	.OX-	.OOX	0	.X	.OX	.X-	0	0	0	0	.OX-	.OX	.OOX	0	X.-	204395
204396	OC5	XX.	X.	X.-	.X-	.OX+	.X-	.X-	.OX+	.X+	.OX	.OX	.OX	Tr	.OOX-	.OOX+	0	.OX-	Tr	.OX-	.OX-	0	0	.OOX	.OOX	.OOX	.OOOX	0	.OX-	204396
204397	OC6-4	X.-	.X+	XX.	XX.	.X+	.X+	.X+	0	0	0	.OX+	.X	0	.OX+	.OOX	0	.X	.X-	.X-	0	.OOX+	0	0	.OX+	.X-	.OX-	0	X.	204397
204398	OC6-8	XX.	X.-	XX.	X.	.X	X.-	.X	0	0	0	.OX+	.X+	0	.OX-	.OX-	0	.X	.OX+	.X-	0	0	0	0	.OX-	.OX	.OOX	0	.X+	204398
204399	OC7-2	XX.	X.-	X.+	X.-	.X	X.-	.X+	0	0	0	.OX+	.X	0	.OX-	.OOX+	0	.X-	.OX-	0	0	0	0	0	.OX-	.OX-	.OOX	0	.X+	204399
204400	OC7-4	X.+	X.-	XX.	XX.	.X+	X.	.X+	0	0	0	.X-	.X+	0	.OX	.OOX+	0	.X	.OX+	.X	0	0	0	0	.OX	.OX	.OOX+	0	X.+	204400
204414		X.+	.X+	XX.	X.+	.X	X.	X.-	0	0	0	.OX+	.X	.OOX	.OX	.OX-	0	.X	.OX-	.X-	.OX	.OOX+	0	.OOOX+	.OX	.OX	.OOX	0	X.-	204414
204401	OC7-5	XX.	X.-	X.	.X-	.X-	X.+	X.	0	0	0	.OX	0	0	.OOX-	.OOX+	0	0	0	0	0	0	0	0	.OOX	0	0	0	.OX+	204401
204402	OC7-6	X.+	X.-	XX.	X.+	.X+	X.-	.X+	0	0	0	.OX+	.X+	0	.OX	.OOX+	0	.X+	.OX+	.X	0	0	0	0	.OX	.OX	.OOX+	0	X.	204402
204403	OC7-8	X.-	.X+	XX.	XX.	.X+	.X+	.X+	0	0	0	.X-	.X+	0	.OX+	.OOX+	0	.X+	.OX+	.X	0	.OX-	0	0	.OX+	.OX+	.OOX+	0	XX.	204403
204413		X.-	.X+	XX.	X.	.X+	.X+	.X+	0	0	0	.OX+	.X+	.OOX	.OX	.OOX+	0	.X	.OX-	.X-	.OX	.OOX+	0	0	.OX+	.OX+	.OOX+	0	X.	204413
204404	OC7-9	X.+	.X+	XX.	X.+	.X+	X.	.X+	0	0	0	.OX+	.X	0	.OX	.OOX+	0	.X	.OX+	.X-	0	0	0	0	.OX	.OX	.OOX+	0	X.+	204404
204405	OC7-10	XX.	X.	X.+	X.-	.X-	.X+	.X	0	0	0	.OX+	0	0	.OX-	.OOX	0	.OX+	.OX-	0	0	0	0	0	.OOX+	.OX-	.OOX-	0	.X+	204405
204406	OC10-1	X.+	X.-	XX.	XX.	.X+	.X+	.X	0	0	0	.X-	.X+	0	.OX+	.OOX+	0	.X	.OX+	.X	0	0	0	0	.OX	.OX	.OOX+	0	X.	204406
204407	OC10-2	XX.	X.-	X.+	X.	.X-	X.-	.X	0	0	0	.OX+	.X	0	.OX-	.OOX+	0	.X	.OX	.X-	0	0	0	0	.OOX+	.OX	.OOX	0	.X	204407
204408	OC10-3	X.-	X.-	XX.	XX.	.X+	X.-	.X	0	0	0	.X-	X.-	0	.OX+	.OOX+	0	.X+	.X-	.X+	0	0	0	0	.OX	.X-	.OX-	0	XX.	204408
204384	OC1-2	X.+	X.-	XX.	X.+	.X+	X.+	.X	0	0	0	.X-	X.-	0	.OX+	.OOX	0	.X+	.OX+	.X+	0	0	0	.OOX+	.OX	.X-	.OX-	0	.OX-	204384
204385	OC1-5	XX.	X.-	X.+	X.+	.X	X.-	.X	0	0	.OX	.OX+	.X+	0	.OX	.OX-	0	.X+	.OX+	.X	0	0	0	0	.OX-	.OX+	.OOX+	0	X.-	204385
204386	OC1-6	XX.	X.-	X.-	.X+	.OX	.X	.X-	.OX+	0	.OX-	.OX	.OX+	.OOOX+	.OOX	.OOX	0	.OX	.OOX+	.OX	.OOX+	0	0	.OOX	.OOX	.OX-	.OOX-	0	.OX+	204386
204409	OG13-2	XX.	X.	X.	X.	.OX+	.OX+	.X	0	0	0	.OX+	0	0	.OOX+	.OOX+	0	.OX+	.OX	0	0	0	0	0	.OOX+	.OX-	.OOX-	0	.X+	204409
204410	OG13-3	XX.	X.-	XX.	XX.	.OX+	X.	.X	0	0	0	.X-	.X+	0	.OX	.OOX+	0	.X+	.OX+	.X	0	0	0	.OOX	.OX	.OX	.OOX+	0	X.	204410
204411	OG13-4	X.	.X+	XX.	XX.	.OX+	X.-	.X	0	0	0	.OX+	.X+	0	.OX+	.OOX+	0	.X+	.OX+	.X	0	.OX-	0	0	.OX	.OX+	.OOX+	0	X.+	204411
204416	OG13-5	X.-	.X+	XX.	X.+	.X+	X.	.X	0	0	0	.OX+	.X	.OOX	.OX+	.OOX	0	.X	.OX-	.X-	.OX	.OOX+	0	.OOOX+	.OX+	.OX+	.OOX+	0	X.	204416
204412	OG13-6	X.-	.X+	XX.	XX.	.OX+	X.	.X	0	0	0	.OX+	.X+	0	.OX+	.OOX+	0	.X+	.OX+	.X	0	.OX-	0	0	.OX+	.OX+	.OOX+	0	X.+	204412
204387	WR2-5	X.+	X.	XX.	X.	.X+	X.-	.X	0	0	.OX	.OX+	.X	0	.OOX+	.OOX	0	.X-	.OX-	.X-	.OOX+	0	0	0	.OX	.OX	.OOX+	0	.X+	204387
204388	WR2-6	X.+	X.-	XX.	X.	.X	X.	.X+	0	0	.OX	.OX+	.X	0	.OX-	.OOX+	0	.X-	.OOX+	.X-	.OX-	0	0	0	.OX	.OX	.OOX	0	.X	204388
204389	WR2-7	X.+	X.-	XX.	X.	.X+	X.+	.X+	0	0	.OX	.OX	.X	0	.OOX+	.OOX+	0	.X-	.OOX+	.X-	0	0	0	.OOX	.OX	.OX	.OOX	0	.X+	204389
204390	WR2-9	X.+	X.-	XX.	XX.	.X+	X.-	.X	0	0	.OX-	.OX+	.X+	0	.OX-	.OOX+	0	.X	.OX	.X	0	.OOX+	0	0	.OX+	.OX	.OOX+	0	X.	204390
204415		X.	X.-	XX.	X.+	.X+	X.	.X	0	0	0	.OX+	.X	.OOX	.OX-	.OOX	0	.X	.OOX+	.X-	.OX-	.OOX+	0	.OOOX+	.OX+	.OX	.OOX	0	X.-	204415
207006	GR2-1	XX.	X.+	X.	.X-	.OX+	.X+	.X+	.X+	X.-	0	.OX+	0	.OOOX+	.OOX	.OOOX	Tr	0	0	0	.OOOX+	.OOOX+	0	.OX-	.OOX+	.OOX-	.OOOX-	0	.OX-	207006
207005	GR2-2	XX.	X.-	X.+	.X	.X-	.X	.X+	.X	.X+	0	.OX	.OX	.OOX-	.OOX	.OOOX+	Tr	.OX-	.OOX-	0	.OOOX+	.OOOX+	0	.OOX+	.OX-	.OOX-	.OOOX-	0	.OX-	207005
207004	GR2-3	XX.	X.-	X.+	X.-	.X-	X.-	.X+	.X	0	0	.OX	.OX+	.OOX	.OX-	.OOX	0	.OX+	.OOX	.OX	—	.OOX-	0	.OOX+	.OX	.OOX+	.OOX-	0	.X-	207004
207007	GR2-4	.X+	X.-	XX.	X.-	.X	X.	X.-	0	0	0	.OX	.X-	.OOX+	.OX	.OOX	0	.X-	.OOX+	.OX	—	.OOX	0	.OOX-	.OX+	.OX-	.OOX-	0	.X	207007
206982	GH1-1	XX.	X.+	X.-	.X	.OX	.X+	.X+	.X+	.X+	0	.OX+	.OX	.OOOX+	.OOX	.OOOX+	.OOOX+	.OX-	.OOX-	.OOX+	.OOX-	.OOOX+	0	[illegible]	.OX-	.OOX-	.OOOX	0	.OOX+	206982
206983	GH1-2	XX.	X.+	X.	X.-	.X-	.X+	.X+	.X+	X.-	0	.OX+	.OX+	.OOX-	.OX	.OOX-	0	.OX	.OOX+	.OX-	—	.OOX-	0	.OX	.OX-	.OOX+	.OOX-	0	.OX+	206983
206984	GH1-4	X.+	X.	XX.	X.	.X	X.-	X.-	0	0	0	.OX+	.X	.OOX+	.OX+	.OOX	0	.X-	.OX-	.X-	—	.OOX	0	.OX-	.OX+	.OX-	.OOX	0	.X	206984
206985	GH1-7	XX.	X.	XX.	X.	.X	X.-	X.-	0	0	0	.OX+	.X-	.OOX	.OX	.OOX	0	.X-	.OOX+	.OX+	—	.OOX	0	.OOX+	.OX	.OX-	.OOX-	0	.X-	206985
206986	GH1-8	XX.	X.+	X.	.X+	.X-	X.-	.X+	.X+	X.-	0	.OX+	.OX+	.OOX-	.OX-	.OOX+	0	.OX	.OOX	.OX-	.OOX-	.OOX	0	.OX-	.OOX+	.OOX	.OOOX+	0	.OX	206986
206987	GH1-11	XX.	X.+	X.+	X.	.X	X.-	X.-	.X	0	0	.OX+	.X	.OOX+	.OX	.OOX	0	.X	.OX	.X-	—	.OOX+	0	.OOX+	.OX	.OX	.OOX	0	.X+	206987
206988	GH1-14	XX.	X.+	XX.	.X+	.X-	.X+	X.-	.X+	X.-	0	.OX+	.OX+	.OOX	.OX-	.OOX-	0	.OX+	.OOX	.OX	—	.OOX	0	.OX-	.OX	.OOX+	.OOX-	0	.OX+	206988
206989	GH1-16	XX.	X.+	X.+	X.	.X	X.-	X.-	.X	0	0	.OX+	.X-	.OOX	.OX	.OOX	0	.X-	.OX-	.OX+	—	.OOX	0	.OOX+	.OX	.OX-	.OOX	0	.X	206989
206991	GH3	.X+	.X	XX.	X.+	.X	X.	X.-	0	0	0	.OX-	Tr	.OOX+	.OX	.OOX+	.OOX	.OX-	.OOX+	0	—	.OOX-	0	.OOX	.X-	.OOX	—	0	.X+	206991
206981		.X+	.X+	XX.	X.-	.X	X.	X.-	0	0	0	.OX-	0	.OOX+	.OX	.OOX+	0	0	.OOX+	0	—	0	0	0	.OX	.OOX	.OOX-	0	.X-	206981
236157	GH3-1	XX.	X.	XX.	X.	.X-	X.+	X.-	.X	X.-	.OOX+	.OX-	.OX+	.OOX	.X-	.OOX	0	.OX	.OOX+	.OX	.OX	.OX-	0	.OX-	.OX+	.OX-	.OOX-	0	.OX+	236157
206994	SH-1-1	XX.	X.	X.+	X.-	.X-	.X+	.X+	.X-	0	0	.OX	.OX+	0	.OX	.OOX-	0	.OX	.OOX+	0	0	0	0	0	.OX-	.OOX+	.OOX-	0	.X-	206994
206995	SH-1-3	XX.	X.	XX.	X.+	.X	.X+	.X+	0	0	0	.OX-	.X	.OOX+	.X-	.OOX	0	.X-	.OX	.X-	—	.OOX+	0	0	.OX	.OX-	.OOX	0	.X	206995
206996	SH-1-5	XX.	X.	X.+	X.-	.X-	X.-	.X+	.X-	0	0	.OX	.OX+	0	.OX	.OOX-	0	.OX+	.OOX+	0	0	0	0	0	.OX-	.OOX+	.OOX-	0	.X	206996
206997	SH-1-7	X.+	X.-	XX.	X.+	.X+	X.-	.X+	0	0	0	.OX-	.X	.OOX+	.X	.OOX	0	.X-	.OX+	.OX+	—	.OOX+	0	0	.OX+	.OX	.OOX	0	.X+	206997
206998	SH-1-10	.X+	.X+	XX.	X.+	.X+	X.-	.X+	0	0	0	.OOX+	.X	.OOX+	.X-	.OOX+	0	.X-	.OX	.OX+	0	.OOX+	0	0	.OX+	.OX	.OOX	0	X.-	206998
206999	SH-1-12	X.-	.X+	XX.	X.+	.X+	X.	.X+	0	0	0	.OOX+	.X	.OOX+	.X-	.OOX	0	.X-	.OX	.OX+	0	.OOX+	0	0	.OX+	.OX	.OOX	0	X.-	206999
206992	SH-1-14	X.-	.X	XX.	XX.	.X+	.X+	.X+	0	0	0	.OOX+	.OX+	.OOX+	.X	.OOX+	.OOX-	.OX+	.OX	.OX+	—	.OOX+		.OOOX+	.X-	.OX-	—	0	X.	206992
207000		.X+	.X+	XX.	X.+	.X+	X.	.X+	0	0	0	.OX-	.X	.OOX+	.OX+	.OOX	0	.X	.OX	.X-	0	.OOX+	.OX+	0	.OX+	.OX	.OOX+	0	X.-	207000
207001	SH-3-1	XX.	X.	X.	.X-	.OX	.X	.X	.X	.X-	0	.OX	0	Tr	.OOX+	.OOOX+	Tr	.OOX	0	0	.OOOX+	0	0	.OOX+	.OOX	.OOX-	.OOOX	0	.OX-	207001
207002	SH-3-1	XX.	X.	X.	.OX+	.OX	.X	.X	.X	X.-	0	.OX	0	0	.OOX	.OOOX+	Tr	0	0	0	.OOOX	0	0	.OOX+	.OOX	.OOOX+	.OOOX-	0	.OOX+	207002
236153	RSBB-1	X.	X.	XX.	XX.	X.-	X.-	X.	0	.X+	0	.OX+	.X+	.OOX+	.OX	.OOX+	0	.X+	.OX	.X	.OX	.OX	.OOX	.OX-	.OX+	.OX+	.OX-	0	.X+	236153
236154	RSBB-4	XX.	X.+	X.	X.+	.X-	X.	.X	.X+	X.	.OX+	.OX	.X-	0	.OX-	.OOX-	0	.X-	.OX	.OX	.OOOX+	.OX-	.OOX-	.OOX+	.OX	.OX+	.OOX-	0	.OX+	236154
236155	RSBB-6	XX.	X.	X.-	.X	.OOX+	.X	.X	.X+	X.	.OOX+	.OX	.OX-	0	.OOX	.OOOX+	0	.OX	0	0	.OOOX+	.OOX	0	.OOX	.OOX	.OOX-	.OOOX	0	.OX-	236155
236156	RSBBB-1	XX.	X.	XX.	XX.	.X	X.-	.X+	.X	0	.OOX+	.X-	.X+	.OOX+	.OX+	.OOX+	0	.X	.OX	.X-	.OX+	.OX	.OOX-	.OX	.OX+	.OX+	.OX-	0	X.-	236156
229362	SH-1-2	XX.	X.	X.+	X.+	.X	X.	X.-	.X	X.-	.OX-	.OX	.X	0	.OOX+	.OOX+	0	.X-	.OX	.OX+	0	.OOX+	0	.OX-	.OX-	.OX	.OOX	0	X.-	229362
229363	SH-1-4	.X+	.X+	XX.	XX.	.X+	X.-	.X+	0	0	0	.OX+	.X-	0	.OX-	.OOX+	0	.X-	.OX+	.OX+	0	.OX-	0	.OOX+	.OX+	.OX	.OOX+	0	X.	229363
228401	RS-1	.X+	.X+	XX.	XX.	.X+	.X+	X.-	0	0	0	.OX	.OX+	.OOX	.OX	.OOX	0	.OX+	.OX	.OX+	0	.OX-	.OOX+	.OOX	.OX+	.OX	.OOX	0	X.	228401
229355	RS-3-2	XX.	X.-	X.	.X	.OX+	.OX+	.X-	.X-	.X+	.OOX+	.OX-	0	.OOX-	.OOX	.X-	Tr	.OOX+	.OOX-	0	.OOX	.OOX-	0	.OOX-	.OOX	.OOX	.OOOX	0	.OX-	229355
229356	RS-3-4	X.-	.X+	XX.	XX.	.X+	X.-	.X+	0	0	0	.OX+	.X	0	.OX	.OX	0	.X-	.OX+	.X-	0	.OX-	0	.OOX+	.OX+	.OX+	.OOX+	0	X.+	229356
229357	RS-3-7	X.-	.X+	XX.	XX.	.X+	X.-	.X+	0	0	0	.OX	.X-	0	.OX	.OX	0	.OX+	.OX+	.OX+	0	.OX-	0	.OOX	.OX+	.OX	.OOX+	0	X.-	229357
229358	RS-3-9	XX.	X.-	X.	X.-	.X-	.X-	.X-	.X-	X.-	.OOX	.OX	.OX	.OOX	.OOX	.OOX+	Tr	.OX	.OOX	.OX-	.OOX	.OOX-	0	.OOX-	.OOX+	.OOX+	.OOOX+	.OX	.OX+	229358
229359	RS-4	XX.	X.-	X.	.X+	.OX	.OX+	.OX+	.X	X.-	.OOX	.OX	0	0	.OOX-	.OOX+	Tr	.OOX	.OOX-	0	0	.OOOX+	0	.OOX-	.OOX	.OOX	.OOOX	0	.OX+	229359
229360	RS-3-3	XX.	X.	X.-	.X-	.OOX+	.OX-	.X-	.X	X.-	.OOX	.OX	0	0	.OOX-	.OOX	Tr	Tr	0	0	0	.OOOX+	0	.OOX-	.OOX	.OOX-	.OOOX-	0	.OX-	229360
229361	RS-3-5	XX.	X.	X.	X.-	.OX+	.X	.X-	.X	X.-	.OOX	.X-	Tr	0	.OOX	.OOX	Tr	.OX-	.OOX+	.OX-	.OOX-	.OOX	0	.OOX	.OX-	.OOX+	.OOOX+	0	.X-	229361
225149	OO-1	XX.	XX.	XX.	.X+	.X	X.+	.X+	X.	X.-	Tr	.OX	0	.OOX	.OOX+	.OOX	.OOX+	.OX-	.OOX+	.OX+	0	.OOX+	0	.OOX-	.OX-	.OX-	.OOX-	0	.OX	225149
236150	OOB-1	X.	X.	XX.	XX.	X.	XX.	X.-	.OX+	.X+	0	.OX-	.X+	.OX-	.OOX+	.OOX	0	.X+	.OX-	.X	.OOX	.OX	.OOX-	.OX-	.X-	.OX-	.OOX	.X-	.X	236150
236151	OOB-3	XX.	X.+	X.+	X.-	.X+	XX.	X.-	X.	0	0	.OX+	.OX	0	.OOX+	.OOX-	0	.OX-	0	.OX-	.OOOX+	.OOX	0	.OX-	.OX-	.OOX	.OOOX+	0	.OX-	236151
236152	OOB-1	XX.	X.+	X.+	XX.	.OX+	.X+	.X+	.X+	0	0	.OX-	.X-	.OOOX+	.OX-	.OOX	0	.X-	.OX-	.OX+	.OOX+	.OOX+	0	.OOX	.OX+	.OX-	.OOX	0	.X	236152
236158	[illegible]	X.	X.-	X.+	X.-	.X+	XX.	X.	.X	X.-	0	.OOOX+	—	.OOX-	.OX-	.OOX-	0	.OOX+	0		.OOX+	.OOX-	0	.OX	.OX	.OOX+	.OOOX+	0	.OX+	236158
236159	[illegible]	X.	X.	X.	.X	.X-	XX.	X.-	.X	0	0	.OOOX+	—	.OOX-	.OOX+	.OOOX+	0	.OOX-	0		.OOX	.OOX-	0	.OX	.OOX+	.OX-	.OOX-	0	.OX-	236159
236160	[illegible]	X.	X.	X.	.X	.X-	XX.	X.-	.X	0	0	.OOOX+	—	.OOX-	.OOX+	.OOX-	0	.OX-	0		.OOX+	.OOX	0	.OX+	.OX-	.OX-	.OOX-	0	.OX	236160