Nonopaque Heavy Minerals in Sandstone of Jurassic and Cretaceous Age in the Black Hills Wyoming and South Dakota

GEOLOGICAL SURVEY BULLETIN 1161-C

Prepared on behalf of the U.S. Atomic Energy Commission

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By W. J. MAPEL, W. A. CHISHOLM, *and* R. E. BERGENBACK

CONTRIBUTIONS TO GENERAL GEOLOGY

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By W. J. Mapel, W. A. Chisholm, and R. E. Bergenback

ABSTRACT

Sandstone beds in the Fall River and Lakota Formations of Early Cretaceous age, and in the underlying Unkpapa and Morrison Formations of Late Jurassic age were sampled at 24 measured sections and 1 drill hole along the northern and western sides of the Black Hills for study of the nonopaque heavy minerals. Grain-size analyses were made of most of the samples, and thin sections were examined for about one-fourth to aid in classifying the samples and interpreting the heavy-mineral data.

The sandstone in all formations studied is predominantly fine grained; however, samples from the Fall River and Lakota Formations included some medium-grained sandstone, and those from the Lakota Formation included some coarse-grained to conglomeratic sandstone. Individual and composite quartz grains generally make up 80 to 95 percent of the sandstone. Schist fragments and muscovite occur fairly consistently in small amounts in the Fall River Formation, and chert fragments are abundant in coarse-grained and conglomeratic sandstone in the Lakota Formation.

Consistent differences in the nonopaque heavy-mineral suites in the very fine grained sand fraction of the formations studied permit separation into three zones. The lower zone includes the lower calcareous part of the Morrison Formation and the underlying Sundance Formation. It is characterized by a high proportion of garnet and by dominantly rounded zircon and tourmaline grains. The middle zone includes the Unkpapa Sandstone, the upper noncalcareous part of the Morrison Formation, and most of the Lakota Formation. It also has dominantly rounded zircon and tourmaline grains, but rarely has garnet. The upper zone includes the upper part of the Lakota Formation at some localities, the Fall River Formation, and the Newcastle Sandstone. It has little garnet, dominantly angular zircon and tourmaline grains, and at some places, abundant chloritoid and hornblende. The change from rounded to angular zircon and tourmaline grains, and the local appearance of chloritoid are abrupt at most places and are useful in identifying and correlating the Lakota and Fall River Formations.

Sedimentary materials of all the formations examined probably were derived mainly from preexisting sedimentary rocks, and subordinately from metamorphic and igneous rocks during deposition of the Fall River Formation. Several lines

of evidence point to a western source for a large part of the Lakota Formation: however, a source to the east seems likely for some of the sedimentary material in the Lakota Formation and for most or all of the material in the Fall River Formation in the Black Hills.

INTRODUCTION

PURPOSE AND SCOPE OF THE REPORT

The Fall River and Lakota Formations, which make up the Inyan Kara Group of Early Cretaceous age, and the underlying Morrison Formation and Unkpapa Sandstone of Late Jurassic age, comprise a sequence from 350 to 800 feet thick of sandstone, siltstone, claystone, limestone, and intermediate rock types that crops out on the flanks of the Black Hills in northeastern Wyoming and western South Dakota. The nonopaque heavy minerals in sandstone from these formations were examined to determine if differences in the shapes of the grains and proportions of minerals are sufficiently distinctive to be used in subdividing and correlating the formations. An attempt was made to gather enough data for simple statistical treatment. In addition, most of the grains were analysed for grain size, and thin sections of about one-fourth were examined to aid in classifying the samples and in interpreting the heavy-mineral data.

About 375 samples of sandstone were taken at outcrops from 24 measured sections and from the cores of 1 drill hole along the northern and western sides of the Black Hills in an arc extending from Sturgis, S. Dak., northwestward to the north end of the Black Hills in Wyoming, and from there southeastward to Hot Springs, S. Dak.—a maximum airline distance of about 140 miles (fig. 1). A few samples were collected from some older and younger deposits in the area for comparitive analyses of the heavy-mineral suites, but no systematic study was made of the older or younger rocks.

All the samples from the measured sections are grab samples taken from near the middle of beds less than 6 feet thick and at intervals of 5 to 15 feet in thicker beds. Lenses of texturally different sandstone within thick, otherwise homogeneous beds were sampled separately. In the measured sections, nearly all the sandstone units more than 1 to 2 feet thick were sampled. With a few exceptions, siltstone and claystone, which occur commonly in the Inyan Kara Group and in the associated rocks, were excluded from the sampling.

Plates 1 and 2 show measured sections at the sample localities and the stratigraphic positions of the samples.

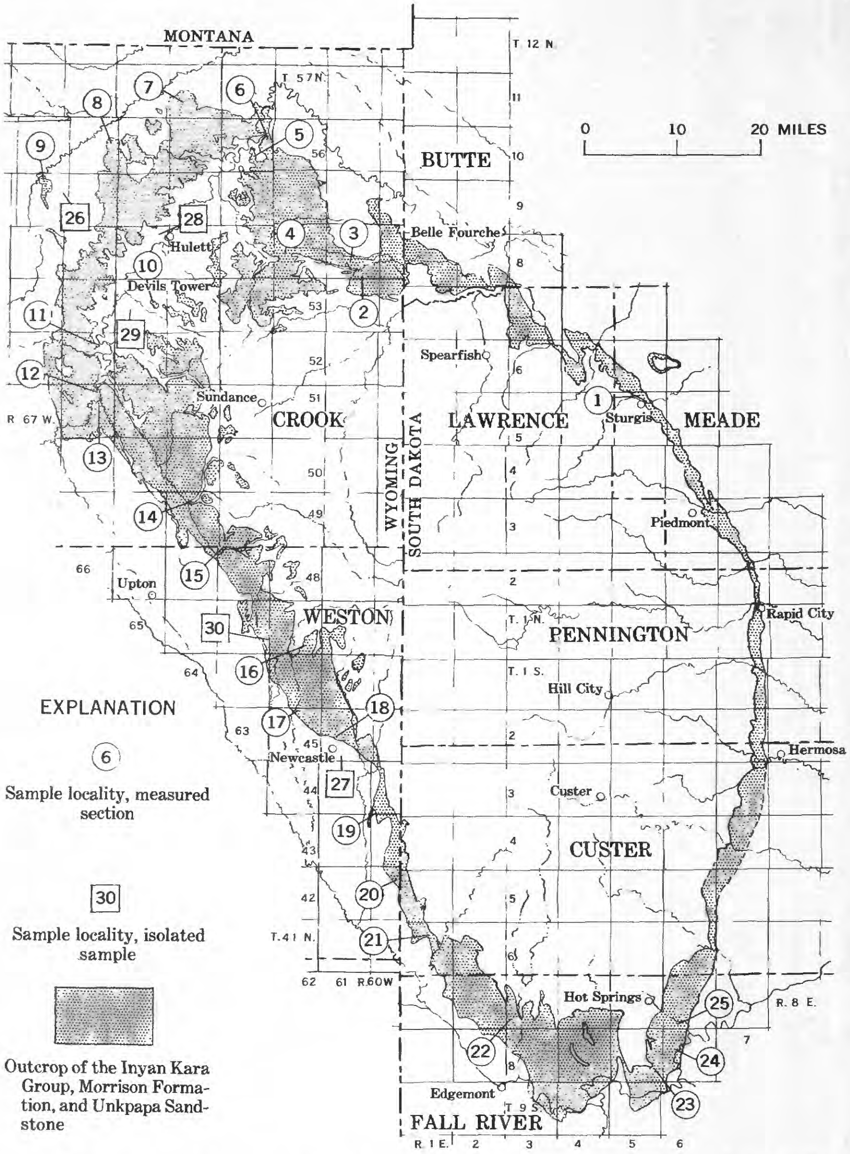

Figure 1.—Index map showing sample localities, Inyan Kara Group and associated rocks, Black Hills. Measured sections are shown on plates 1 and (or) 2.

FIELDWORK AND ACKNOWLEDGMENTS

Most of the stratigraphic sections from which samples were collected were measured by K. M. Waagé and Copeland MacClintock in 1955 and by W. J. Mapel and C. L. Pillmore in 1956 and 1957. Most of the sampling was done by Mapel and R. E. Bergenback in 1956 and by Pillmore and Mapel in 1957. G. B. Gott and E. V. Post measured the section at Red Canyon, and G. A. Izett measured and sampled the section at Jolley dome. Bergenback examined the thin sections, and W. A. Chisholm made most of the heavy-mineral analyses. J. A. Thomas, Bergenback, and Mapel made the grain-size analyses. M. H. Bergendahl furnished grain-size analyses of samples collected from the Inyan Kara Group by him and his associates in and near T. 51 N., Rs. 66 and 67 W., Crook County, Wyo., and G. A. Izett made available the results of his heavy-mineral analyses of samples from the same area. Their work has been reported separately (Bergendahl, Davis, and Izett, 1961, p. 660–667).

The work was done by the U.S. Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

PREVIOUS WORK

The geology of areas on the northern and western sides of the Black Hills is described in many reports. Among the most comprehensive are reports by Darton (1909), Darton and Paige (1925), and Robinson, Mapel, and Bergendahl (1963), which summarize information on large regions in the Black Hills. Waagé (1959) described the Inyan Kara Group and underlying rocks in the Black Hills, reviewed earlier work, and proposed the nomenclature followed in the present report. Mapel and Gott (1959) and Post and Bell (1961) have summarized intraformational correlations in the Fall River, Lakota, and Morrison Formations on the western side of the Black Hills, and Post and Bell (1961) named the Chilson Member of the Lakota Formation in the southern Black Hills. References to other papers dealing with local areas can be found in the publications mentioned above.

Except for an earlier summary report that presented the conclusions of this report (Bergenback, Chisholm, and Mapel, 1957), no systematic study has been published previously of the petrography of sandstone in the Inyan Kara Group and associated rocks for any large area in the Black Hills, although several reports give information about selected samples in local areas. Petrographic work similar to that reported here has been published for two nearby parts of Wyoming. Hooper (1961) has described the petrology of sandstone in the Lower Cretaceous Cloverly Formation on the Casper Arch in east-central Wyoming, and Mirsky (1961) has examined the heavy minerals and grain-size distribution of the Cloverly and Morrison Formations in the southern Bighorn Mountains in north-central Wyoming. More recently, MacKenzie and Poole (1962) described the mineralogy of sandstone of Early Cretaceous age, including sandstone in the Lakota and Fall River Formations, for a large area in Colorado, Nebraska, and some adjacent States.

Information on the grain-size distribution and mineralogy of sandstone in the Unkpapa and Sundance Formations in the Black Hills is given by Graham,[1] Ruede,[2] and Sacrison.[3] Their descriptions agree in general with those given in this report.

The clay mineralogy of about 100 samples from the Fall River and Lakota Formations has been described by Schultz and Mapel (1961). Tank (1956) gave information on the clay mineralogy of the Morrison Formation.

STRATIGRAPHY

The characteristic lithology of the formations examined in this report is summarized in table 1 and is briefly described below. Stratigraphic sections at the sample localities are shown graphically on plates 1 and 2. Detailed descriptions of the rocks at most of these localities have been published elsewhere (Waagé, 1959; Robinson, Mapel, and Bergendahl, 1963) and are not repeated here.

The Sundance Formation is a marine deposit characterized in the top part (Redwater Shale Member) by greenish-gray shale, gray siltstone and sandstone, thin fossiliferous limestone beds, and glauconite. The Sundance passes gradationally upward into the nonmarine Morrison Formation in most parts of the northern and western Black Hills, and abruptly upward into the Unkpapa Sandstone near Hot Springs, S. Dak., at the southern end of the Black Hills.

The Morrison Formation consists mostly of claystone, limestone, and marl that contain abundant ostracodes and charophytes, some nonmarine mollusks, and a few dinosaur bones. The rocks apparently were deposited in shallow lakes and ponds on a land surface that was nearly flat.

The Unkpapa is well-sorted friable to locally crossbedded sandstone that probably is nonmarine, but whose depositional environment otherwise is uncertain.

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[1] Graham, G. E., 1950, Petrographic study of the heavy minerals of certain sandstones of the Sundance Formation of western South Dakota and Wyoming: Nebraska Univ. M.S. thesis, 56 p.

[2] Ruede, G. M., 1951, A mapping and field study of the Unkpapa Sandstone in the Black Hills, South Dakota: Nebraska Univ. M.S. thesis, 91 p.

[3] Sacrison, W. R., 1958, A study of the Jurassic Unkpapa Sandstone of the Black Hills region, western South Dakota and eastern Wyoming: Wyoming Univ. M.A. thesis, 78 p.

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TABLE 1.—*Generalized section of Upper Jurassic and Lower Cretaceous rocks exposed along the western side of the Black Hills*

Series	Group	Formation	Thickness (feet)	Lithology
Lower Cretaceous		Mowry Shale	130–220; thickens northward.	Mostly hard siliceous shale that weathers light gray and contains numerous thin beds of bentonite; commonly grades to soft black shale in the basal few feet; marine fossils.
		Newcastle Sandstone	0–75; commonly about 40 ft.	Discontinuous beds of sandstone, sandy shale, impure coal, bentonite, and (where thin) phosphatic nodules; marine and nonmarine fossils.
		Skull Creek Shale	200–260; thickens northward.	Fissile black shale and a few ferruginous concretions; thin silty seams in the lower part and a few lenses of sandstone locally; marine fossils.
	Inyan Kara	Fall River Formation	125–160; thickens southward.	Interbedded and interlaminated brown-weathering sandstone, light- to dark-gray siltstone, and dark-gray shale; local seams of impure coal; nonmarine pelecypods locally at the base.
		Lakota Formation	100–550; mostly 100 to 250 ft in Wyoming; thickens southward.	Variable seqnence of light-gray, locally conglomeratic sandstone, and variegated claystone and sandy claystone; local seams of coal and carbonaceous shale at the base. A bed of light-gray limestone as much as 35 ft thick (Minnewaste Limestone Member) crops out about 100 ft below the top in about 4 townships near Hot Springs, S. Dak., where it divides the formation into an upper part (Fuson Member) and a lower part (Chilson Member); nonmarine fossils.
Upper Jurassic		Morrison Formation / Unkpapa Sandstone	0–240; commonly about 100 ft.	Morrison Formation: lower 60 to 80 ft greenish-gray and dull red calcareous claystone, light-gray limestone, and light-gray calcareous sandstone; remainder is greenish-gray to dark-gray noncalcareous claystone; nonmarine fossils. Unkpapa Sandstone: massive sandstone commonly mottled shades of gray, red, and purple; present at the southern end of the Black Hills.
		Sundance Formation	325–375	Divided into five members as follows from youngest to oldest: Redwater Shale Member: greenish-gray shale, some interbedded light-gray calcareous sandstone and siltstone and light-gray limestone; glauconitic; a persistent bed of yellow-weathering sandstone at the top; 140–180 ft thick. Lak Member: friable red and yellow sandstone and siltstone; 40 to 60 ft thick. Hulett Sandstone Member: cliff-forming grayish-yellow sandstone; 50 to 75 ft thick. Stockade Beaver Shale Member: greenish-gray shale and some interbedded sandstone; 60 to 80 ft thick. Canyon Springs Sandstone Member: light-gray to pale-red sandstone; 0 to 40 ft thick. Marine fossils in all but the Lak Member, which is unfossiliferous.

The Lakota Formation in much of the Black Hills can be divided into a lower part consisting characteristically of more or less evenly bedded paludal and fluviatile sandstone interbedded with locally carbonaceous siltstone, claystone, and shale, and an overlying upper unit consisting characteristically of conglomeratic crossbedded fluviatile sandstone and variegated claystone. The lower part appears to be conformable with the Morrison Formation at most places; the upper part truncates the lower part in the northwestern part of the Black Hills, and in the vicinity of Devils Tower equivalents of the upper part rest unconformably on the Morrison Formation. Local relief of the land surface during deposition of the Lakota Formation was slight.

The Fall River Formation, which is unconformable on the Lakota Formation, is fairly uniform in its lithology. Its bedding features, and the persistence of thin stratigraphic units within the formation, suggest deposition in a shallow marine or marginal marine environment (Waagé, 1959, p. 63–64). The Fall River grades upward into marine black shale of the Skull Creek Shale.

The outcrop area of the Inyan Kara Group, Morrison Formation, and Unkpapa Sandstone in the Black Hills is a small fraction of the total area in the western interior region underlain by rocks of the same age and similar lithology. Some lithogenetic equivalents of the Inyan Kara Group and associated rocks are shown in figure 2.

Black Hills		Bighorn Basin, Wyoming	Wind River Basin, Wyoming	Sweetgrass Arch, Montana		Western Kansas
Skull Creek Shale		Thermopolis Shale (part)	Thermopolis Shale (part)	Blackleaf Formation (part)	Taft Hill Glauconitic Member	Kiowa Shale
Inyan Kara Group	Fall River Formation	Rusty beds	Rusty beds		Flood Member	Cheyenne Sandstone
	Lakota Formation	Cloverly Formation	Cloverly and Morrison Formations, undifferentiated	Kootenai Formation		
Morrison Formation / Unkpapa Sandstone		Morrison Formation		Morrison Formation		Morrison Formation
Sundance Formation		Sundance Formation	Sundance Formation	Ellis Group (part)		Lower unit of the Morrison Formation

FIGURE 2.—Some lithogenetic equivalents of the Inyan Kara Group and associated rocks.

SAMPLES

GRAIN SIZE

Size analyses were made of about 275 of the 375 samples from the Inyan Kara Group, Morrison Formation, and Unkpapa Sandstone to determine the sandsize distribution and sorting (pls. 1, 2). No study was made of the frequency distribution of silt- or clay-sized particles of most of the samples. The samples are classified according to the well-known Wentworth grain-size scale (Wentworth, 1922). The phi scale, which is a logarithmic transformation of the Wentworth scale

(Krumbein, 1934), is used also for convenience in reporting the results of the analyses. The two scales are given below:

Grain-size classification

Class	Size range	
	Wentworth scale (mm)	Phi scale (ϕ)
Pebbles	64 to 4	−6 to −2
Granules	4 to 2	−2 to −1
Very coarse sand	2 to 1	−1 to 0
Coarse sand	1 to 0.50	0 to 1
Medium sand	0.50 to 0.250	1 to 2
Fine sand	0.250 to 0.125	2 to 3
Very fine sand	0.125 to 0.062	3 to 4
Silt and clay	<0.062	>4

Sieves having openings that correspond to the Wentworth size-limits given above were used in the analyses of most samples; additional sieves having openings intermediate in size were used for some samples. Cumulative curves showing the size distribution of particles were drawn on graphs on which the grain-size coordinate was plotted on a logarithmic scale and the cumulative-percent coordinate was plotted on a probability scale. On such a graph, cumulative curves of sediments that follow a symmetrical probability distribution are straight lines. Statistical parameters of grain size used to describe and compare the samples were determined from these curves and include the graphic mean, the graphic standard deviation, and the graphic skewness, as defined by Folk (1957, p. H–2).[4] Histograms showing the grain-size distribution of the samples are shown on plates 1 and 2.

Sandstone in the Inyan Kara Group and the Unkpapa Sandstone is predominantly fine grained, as shown by the diagrams on figure 3. Nineteen samples from a thick sandstone bed that makes up the Morrison Formation at Oil Creek (loc. 16, pl. 2) are also mostly fine grained; however, thinner sandstone beds more typical of the Morrison Formation at other localities are generally very fine grained.

For the most part, grains coarser than medium are rare in the Fall River Formation and none was found in the samples examined; how-

[4] Graphic mean is $\phi16+\phi50+\phi84$ (grain sizes at the 16, 50, and 84 percentiles) divided by 3. Graphic standard deviation is

$$\frac{\phi84-\phi16}{2}.$$

Graphic skewness is

$$\frac{\phi16+\phi84-2\phi50}{\phi84-\phi16}.$$

The graphic standard deviation and the graphic skewness as thus defined are the same as the "phi deviation measure" and the "phi skewness measure," respectively, of Inman (1952).

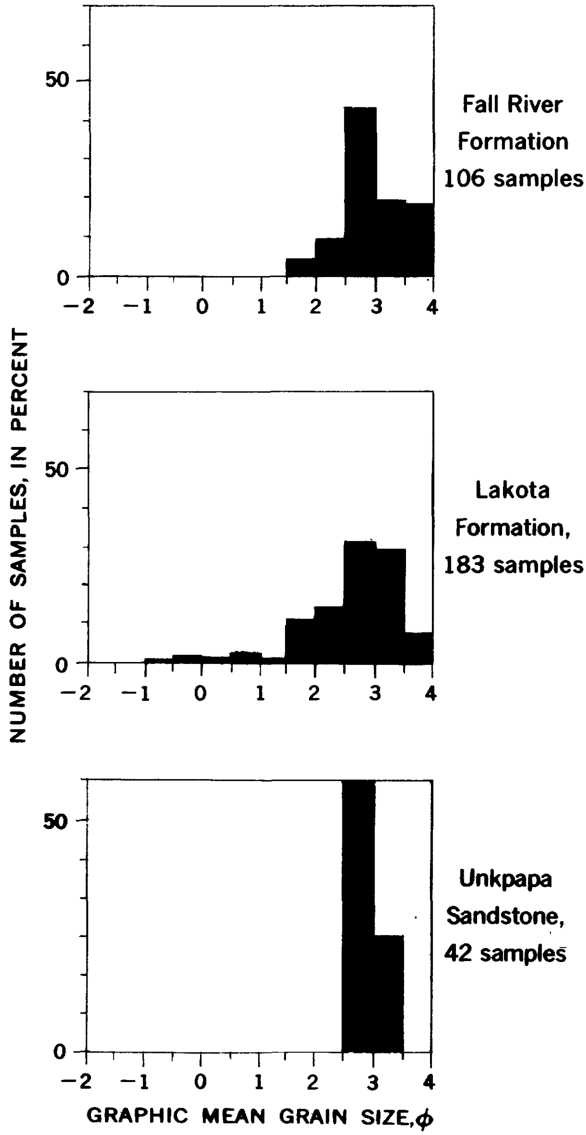

FIGURE 3.—Mean grain size of samples from the Fall River, Lakota, and Unkpapa Formations.

ever, a few fragments of brown chert and gray quartzite as coarse as granules are locally present in a few thin seams in the lower part of the formation, especially along Oil and Plum Creeks near localities 16, 17, and 18 (fig. 1), about 2 to 10 miles north of Newcastle (Mapel and Pillmore, 1963). The Lakota Formation has the greatest range in grain size; all sizes from clay to granule are represented. Locally abundant pebbles and cobbles were noted in the Lakota Formation at several places, but no fragments of these sizes were collected in the samples studied. The Unkpapa Sandstone has the least range in grain size; in the samples studied, about 95 percent of the grains are in the fine and very fine sand sizes and the remainder are in the silt and clay size.

The sorting of the samples can be expressed by the graphic standard deviation, which in phi units has the following qualitative meaning according to Folk (1957, p. H–3): less than 0.35, very well sorted; 0.35 to 0.50, well sorted; 0.50 to 1.00, moderately sorted; 1.00 to 2.00, poorly sorted; greater than 2.00, very poorly sorted. Not enough samples were collected from the Morrison Formation for meaningful averages; samples from the other formations have the following average values:

Formation	Average graphic standard deviation	Samples
Fall River	0.50	86
Lakota	.64	167
Unkpapa	.38	42

Fairly wide ranges in sorting were found in both the Fall River and Lakota Formations, as shown in figure 4, but on the average, sorting is appreciably better in the Fall River Formation than in the Lakota Formation in all size ranges (fig. 5). In both formations, the fine-grained sandstone tends to be the best sorted.

The graphic skewness, or asymmetry of the grain-size frequency distribution, for some Fall River and Lakota samples is shown in figure 6. Nearly all the samples analyzed from both formations are positively skewed or, in other words, nearly all the samples analyzed have an excess of grains finer than the mean size. Friedman (1961, p. 523–524) points out that skewness is generally positive in medium to very fine grained dune and river sands and is generally negative in beach sands.

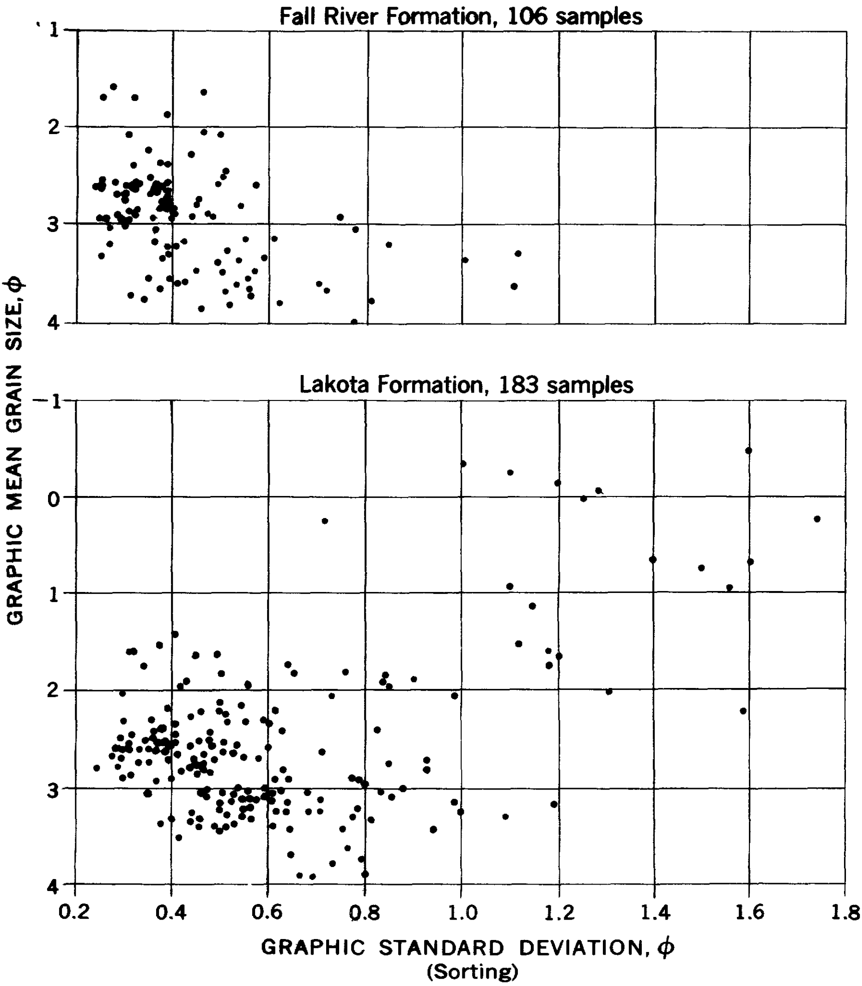

FIGURE 4.—Sorting of sandstone from the Fall River and Lakota Formations.

ROCK-FORMING MATERIALS

COMPOSITION

Microscopic examination in thin section of the sandstones in the Inyan Kara Group and Morrison and Unkpapa Formations shows them to be quartz-rich clastic rocks containing several varieties of quartz grains and a small percentage of other mineral and rock fragments.

Three varieties of individual quartz grains were differentiated by the extinction characteristics of the grains under crossed nicols, and four varieties of composite grains were differentiated by the shapes and interrelations of the particles that make up the grains. The grain varieties were determined by following a modification of a procedure outlined by Folk (1957, p. M–7).

For the purposes of the investigation, individual quartz grains are classified as having straight or slightly undulose extinction if extinction occurs relatively abruptly when the microscope stage is rotated less than about 8°. Grains of moderately undulose extinction are those in which the extinction shadow sweeps smoothly across the grain when the stage is rotated about 8° to 20°. Grains of strongly undulose extinction are those in which the extinction shadow moves irregularly across the grain when the stage is rotated more than about 20°.

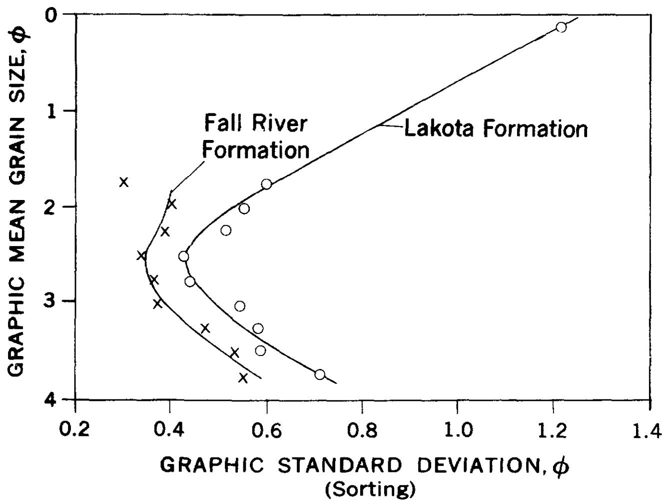

FIGURE 5.—Comparison of mean grain size to sorting, Fall River and Lakota Formations. Points show mean sorting for groups of samples having ranges of ½ϕ in mean grain size.

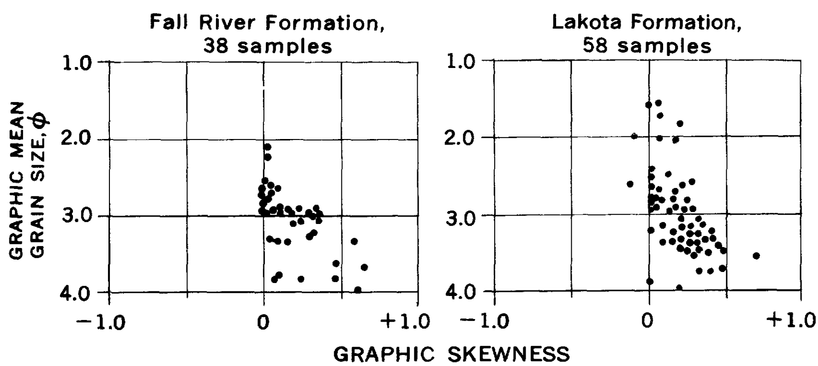

FIGURE 6.—Comparison of skewness to mean grain size of samples of sandstone from the Fall River and Lakota Formations.

Composite quartz grains are classified according to whether the constituent particles are in parallel or in random optical orientation. Composite grains having particles in parallel to semiparallel optical orientation are subdivided into (a) grains composed of particles that have nearly straight borders such as characterize fragments of vein quartz or deformation lamellae in metaquartzite, and (b) grains that have smoothly curving borders such as characterize fragments of schist. Composite grains having particles in random optical orientation are subdivided into (a) grains composed of particles that have crenulated borders such as characterize fragments of metaquartzite, and (b) grains composed of particles that have smooth borders and are held together by silica cement, such as characterize fragments of orthoquartzite.

Blatt and Christie (1960) pointed out that the apparent degree of undulatory extinction of quartz grains varies according to the orientation of the crystal axes of the grain with respect to the microscope, and that the maximum value is the only one having significance in indicating the type of rock from which the grains were derived. Correct orientation of the grains is achieved by using a universal rather than a flat microscope stage. Measurements given here were made on unoriented grains on a flat stage. In any one formation, no great significance can be attached to the proportions of grains determined as having slight, moderate, or strong undulatory extinction. Nonetheless, for formations that are alike in proportions of grains, the maximum and observed values of undulatory extinction differ by the same factors for corresponding groups of grains; thus, variations in the proportions of grains in the three categories of extinction are valuable in showing differences among the formations.

Common minor constituents include grains of potassium feldspar (including some microcline), plagioclase, granular and fibrous chert, schist, claystone, calcilutite, sandstone, and siltstone.

The matrix and cementing materials are generally clay paste, calcilutite, granular chalcedony in small irregular patches, opal, and silica as overgrowths on quartz grains. In addition, a light-brown, partly fibrous, partly isotropic substance tentatively identified as chalcedony cements some samples from the Lakota Formation. Chemical analysis shows that this substance is not phosphate.

Iron oxides are common in the Fall River Formation as grain coatings, and in concretions and thin seams. Drill cores lack iron oxides but contain locally abundant pyrite, which suggests that most of the iron oxides are weathering products of pyrite.

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PROPORTIONS OF CONSTITUENTS

Table 2 shows the average percentages of rock-forming grains in 129 thin sections of samples mostly from the Fall River and Lakota Formations. The samples are fairly evenly distributed geographically and stratigraphically; they were collected from 17 of the 25 sections shown on plates 1 and 2.

Detrital chert is most abundant in the Lakota Formation; it makes up an average of 4 percent of the fragments in sandstone that is medium grained and finer, and 49 percent of the fragments in sandstone coarser than medium grained. Muscovite flakes and schist fragments are slightly more abundant in the Fall River Formation than in the other formations studied. Quartz grains having straight or slightly undulose extinction and composite quartz grains having parallel or semiparallel orientation and straight borders are considerably more abundant in the Unkpapa Sandstone than in the other formations. Feldspar, in general, is most abundant in the lower part of the Morrison Formation and decreases in abundance in the younger rocks. Many of the feldspar grains in the Lakota and Fall River Formations are partly altered to clay. Chalcedony and opal are somewhat more common cementing materials in the Lakota Formation than in the Fall River or Morrison Formations.

Six samples of limestone from the Morrison Formation consist largely of calcilutite containing varying amounts of very fine or silt-sized angular quartz grains, and in some samples fragments of pelecypods and ostracodes. Some of the calcilutite consists of dark angular apparently reworked fragments of calcilutite set in a matrix of lighter colored calcilutite and crystalline carbonate cement.

SHAPE AND ROUNDNESS OF THE GRAINS

Casual inspection of thin sections of sandstone from the Lakota and Fall River Formations suggests that sand grains in the Lakota tend to be rounder than those in the Fall River. Measurements were made of the shape and roundness of the quartz grains in two samples, one each from the Fall River and Lakota Formations, to assess the differences in these properties. The sample from the Fall River Formation was collected by C. S. Robinson; it is a channel sample of a bed 23 feet thick of light yellowish-gray friable medium-bedded sandstone about 65 feet above the base of the formation in sec. 10, T. 55 N., R. 66 W., Crook County, Wyo. (near loc. 8, fig. 1). This sample is considered representative of the more massive parts of the Fall River Formation in the northern Black Hills. The sample from the Lakota Formation is a grab sample from the lower part of a bed 57 feet thick of grayish-white friable, inconspicuously crossbedded sandstone near

TABLE 2.—*Average percentages of mineral and rock fragments in thin sections of sandstone*

[X, less than 1 percent]

Formation	Samples examined	Quartz								Feldspar	Muscovite	Chert	Schist [1]	Claystone	Glauconite	Other [2]
		Individual grains			Composite grains				Total quartz							
		Straight or slightly undulose extinction	Moderately undulose extinction	Strongly undulose extinction	Parallel orientation, straight borders	Semiparallel orientation, smooth borders	Random orientation, smooth borders	Random orientation, crenulated borders								
Fall River	56	33	28	20	1	1	X	8	92	1	3	1	3	X	0	X
Lakota:																
Medium grained and finer	48	37	28	20	1	X	X	7	94	1	X	4	X	X	0	X
Coarse grained to conglomeratic	11	18	13	9	X	X	X	5	46	0	0	49	0	0	0	5
Unkpapa	8	52	18	8	11	X	X	7	96	4	0	X	0	0	0	0
Morrison:																
Upper part (loc. 16, fig. 1)	2	36	21	29	X	0	0	7	94	5	0	X	X	0	0	X
Lower part	3	34	26	16	1	X	0	8	86	7	X	2	X	3	0	0
Sundance (loc. 16)	1	32	17	23	0	0	0	2	74	3	0	0	0	0	22	0

[1] Mostly muscovite and quartz.
[2] Mostly fragments of sandstone and siltstone.

the base of the formation at locality 15 (horizon of sample 2, loc. 15, pl. 2). This sample is considered representative of sandstone in the lower part of the Lakota Formation in the northwestern part of the Black Hills.

The roundness of the grains (sharpness of the edges) was determined by comparing the grain outlines, as projected on a screen, with standard pebble images given by Krumbein (1941, pl. 1). By Krumbein's system, the degree of roundness is classified from 0.1 (most angular) to 0.9 (most round). The shape (sphericity) of the grains was determined from the grain outlines according to the method described by Wadell (1935, p. 264–265) and Krumbein and Pettijohn (1938, p. 295–298). In this system, the sphericity is expressed as a ratio that for a perfect sphere equals one.

The two samples are compared below:

Formation	Mean grain size of sample (ϕ)	Size fraction examined (ϕ)	Average roundness	Average sphericity
Fall River	3. 5	1.5 to 2.0	0. 39	0. 81
		2.5 to 3.0	. 37	. 78
Lakota	2. 7	1.5 to 2.0	. 50	. 85
		2.5 to 3.0	. 51	. 82

The samples show no significant differences in the average sphericity. In both size ranges examined, however, the samples show differences of about 1 roundness class in the average grain roundness, the Lakota grains being the rounder.

PEBBLES IN THE LAKOTA FORMATION

Beds of claystone and the tops of some beds of sandstone in the upper part of the Lakota Formation locally contain polished pebbles and cobbles concentrated in thin discontinuous layers. The pebbles and cobbles commonly are 1 to 3 inches long, but locally are as much as 6 inches long. Quartzite and chert make up nearly all the pebbles in the proportion of about 60 percent quartzite to 40 percent chert. Similar pebbles and cobbles are mentioned in most descriptions of equivalent rocks in other parts of Wyoming and Montana.

Pebbles were collected at two places on the western side of the Black Hills: at locality 7 (fig. 1), the pebbles are at the top of a sandstone bed 60 feet below the top of the Lakota Formation, and at locality 30 the pebbles are in the basal part of a sandy claystone bed, an estimated 150 feet below the top of the Lakota Formation. The table below lists the pebble varieties and their relative abundance at each locality.

Rock type	Description	Percent in sample from—	
		Locality 7	Locality 30
Total pebbles in sample		173	100
Quartzite	Red, red purple, and pink; fine to coarse grained.	26	17
	Gray and brown; fine to medium grained.	27	35
	Light gray to white; vitreous; fine to coarse grained.	7	5
Chert	Mottled red, gray, and brown	16	13
	Gray and brown	23	20
	White	0	2
	Black	0	2
All other	Conglomerate: angular fragments of pink and purple quartzite and gray and red chert in a matrix of finer grained quartzite.	1	5
	Schist: dark-gray	0	1
Total		100	100

The shapes of pebbles vary from spheroidal to irregular, the chert pebbles being the most irregular. Most of the pebbles have fairly well rounded edges and corners. From the sample collected at locality 7, 43 quartzite pebbles and 42 chert pebbles 1 to 4 inches long were selected at random and the pebbles were classified, according to their roundness and shape, by the methods described by Krumbein (1941). The results are given on figures 7 and 8. Measurements made by G. A. Izett (oral communication, 1962) of 100 pebbles collected by him from the Lakota Formation a few miles northwest of Devils Tower showed an average sphericity of 0.70 and an average roundness of 0.67 compared to 0.70 and 0.59, respectively, for pebbles from locality 7.

About 50 of the pebbles from localities 7 and 30 were examined in thin sections. Several of the mottled red, gray, and brown chert pebbles consist of microcrystalline granular aggregates of chalcedony with scattered very fine angular grains of quartz. Some gray and brown chert pebbles are microcrystalline granular and contain silicified fossil fragments including pieces of bryozoans and fusulinids. This variety suggests chert replacement of calcarenite. A few mottled red chert pebbles consist almost wholly of microcrystalline fibrous spherulites of chalcedony.

Some of the gray, pink, and vitreous quartzite pebbles are metaquartzite consisting of moderately to strongly strained quartz grains with crenulated and granulated borders. Other gray, pink, and gray-

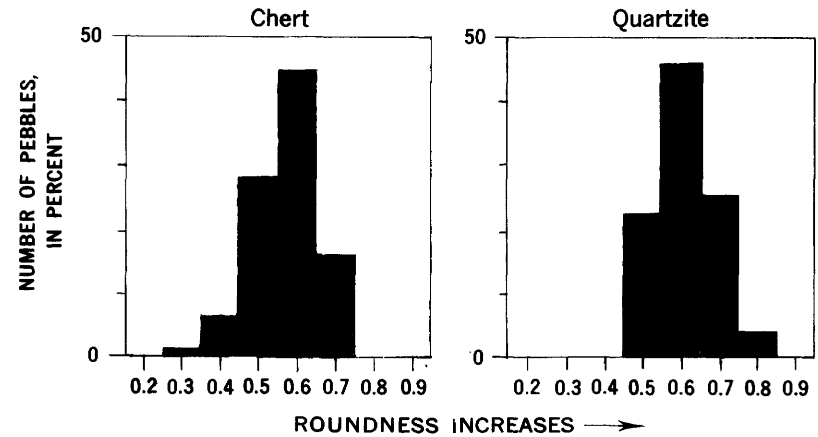

FIGURE 7.—Roundness of pebbles in the Lakota Formation, locality 7. Roundness scale from Krumbein (1941, pl. 1).

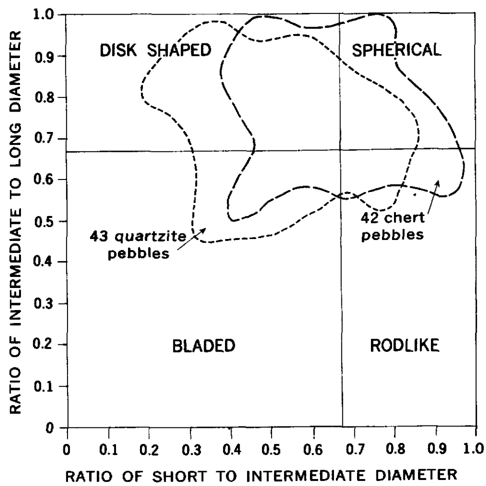

FIGURE 8.—Shape of pebbles in the Lakota Formation, locality 7. Shape designations are those of Zingg (*in* Krumbein, 1941. p. 67).

ish-white quartzite pebbles are orthoquartzite composed of rounded fine to coarse grains of quartz, metaquartzite, orthoquartzite, and chert. In some pebbles, well-rounded medium-sized quartz grains are set in a background of finer, more angular quartz grains and are cemented by silica or chert. The remaining quartzite pebbles are intermediate rock types that have some of the textural features of orthoquartzite, but have incipient crenulated grain boundaries and moderate to strong straining of grains characteristic of metaquartzites. Bergendahl, Davis, and Izett (1961, p. 665) described many of the same varieties of pebbles from the upper part of the Lakota Formation in and near T. 51 N., Rs. 66 and 67 W., Crook County, Wyo.

NONOPAQUE HEAVY MINERALS

METHOD OF ANALYSIS

Heavy minerals were concentrated in bromoform (specific gravity 2.87 at 20° C.) from the very fine grained sand fraction of 381 samples from the Newcastle Sandstone, Inyan Kara Group, and Morrison, Unkpapa, and Sundance Formations; in addition, nonopaque heavy minerals were concentrated from the fine grained sand fraction of 42 samples from the Fall River and Lakota Formations for comparison of the heavy-mineral suites in the two size grades. Table 3 shows the proportions of nonopaque heavy-mineral grains from the very fine grained sand fraction, and table 4 compares the average proportions of grains from the two size grades. The amount of heavy minerals concentrated by bromoform in the very fine grained fraction ranges from 0.1 to 1 percent of the total weight of grains of this size.

Some of the heavy-mineral concentrates were coated with hematite or limonite, and some contained authigenic pyrite. These samples were warmed in dilute (3:1) hydrochloric acid or dilute (10:1) nitric acid from 5 to 45 minutes to remove the coatings and facilitate mineral identification.

Grain roundness was noted for the tourmaline and zircon grains, which commonly make up 80 to 90 percent of the nonopaque heavy-mineral concentrates in the very fine grained fraction. Classification of grains as round or angular was done rapidly by inspection. The classification was done mostly by one person and the results are believed to be consistent; however, different observers might have assigned somewhat different proportions of grains to the two categories.

No detailed study was made of the opaque heavy minerals. They consist largely of hematite and limonite aggregates, authigenic pyrite, ill-defined clay aggregates, and leucoxene, and make up as much as 50 percent of the concentrates in some samples. Muscovite appears in both the light and heavy fractions, and authigenic barite appears locally in the heavy fraction of some samples. Neither of these minerals were included in computing the percentages of heavy minerals.

About 140 nonopaque grains were counted for each sample, and percentages based on a count of that many grains are believed to be accurate to within 5 percent. Accuracy of this order is considered sufficient to show significant differences in the heavy-mineral assemblages.

TABLE 3.—*Average percentages of very fine nonopaque heavy-mineral grains in the formations studied, Black Hills*

[×, less than 1 percent or small amounts in most samples; R, rare]

Formation	Zircon			Tourmaline			Zircon-tourmaline, combined			Garnet	Rutile	Staurolite	Apatite	Hornblende	Actinolite	Epidote	Diaspore	Brookite	Anatase	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Other [1]	Samples examined
	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total																	
Newcastle	16	13	29	33	6	39	49	19	68	2	7	4	0	0	0	0	0	R	R	0	0	18	0	R	0	3
Fall River	22	22	44	25	8	33	47	30	77	3	7	5	×	R	0	R	R	×	×	R	×	6	R	R	R	122
Lakota	12	48	60	7	24	31	19	72	91	2	3	4	R	R	0	R	R	R	R	R	R	R	R	R	R	200
Unkpapa	2	86	88	R	9	9	2	95	97	2	R	×	0	0	0	0	0	0	R	0	0	0	R	0	0	14
Morrison:																										
Upper part (loc. 16, pl. 2)	4	64	68	1	24	25	5	88	93	5	×	2	0	0	0	0	0	0	0	0	0	0	0	0	0	7
Lower part	7	25	32	14	16	30	21	41	62	28	3	3	3	0	0	R	R	R	R	0	R	0	R	×	R	14
Sundance:																										
Redwater Shale Member	4	31	35	7	19	26	11	50	61	32	1	2	3	0	0	0	R	0	R	0	0	R	R	1	R	17
Hulett Sandstone Member	5	54	59	2	5	7	7	59	66	24	5	3	2	0	0	0	0	×	×	0	0	0	0	0	0	2
Precambrian rocks, central Black Hills [2]	R	0	R	8	0	8	8	0	8	31	×	×	2	40	8	2	×	0	R	1	R	0	0	6	R	10

[1] Kyanite, sphene, corundum, monazite, or diopside.
[2] Samples from deposits of streams draining Precambrian igneous and metamorphic rocks, central Black Hills.

TABLE 4.—*Comparisons of average percentages of nonopaque heavy-mineral grains in the very fine (0.062 to 0.125 mm) and the fine (0.125 to 0.250 mm) size fractions, Fall River and Lakota Formations, Black Hills*

[×, less than 1 percent or small amounts in most samples; R, rare]

Formation	Size fraction (mm)	Zircon			Tourmaline			Zircon-tourmaline, combined			Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Samples examined
		Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total															
Fall River	0.062 to 0.125	17	15	32	27	6	33	44	21	65	6	6	18	R	R	R	×	×	0	R	×	2	0	R	14
	.125 to .250	R	4	4	57	10	67	57	14	71	3	3	19	R	R	0	1	R	0	R	2	×	0	R	
Lakota	.062 to .125	13	58	71	5	16	21	18	74	92	1	2	5	R	R	0	0	R	R	0	R	0	R	0	28
	.125 to .250	6	14	20	24	33	57	30	47	77	1	1	21	0	0	R	R	0	R	0	0	0	R	0	

The very fine grained sand fraction was chosen for comparisons between samples because it is the modal size or the next size smaller of most samples, and it is a size that consistently contains a relatively large amount and variety of nonopaque heavy minerals. It should be emphasized, however, that because the proportions of heavy minerals of one grain size do not necessarily reflect the proportions of heavy minerals in all sizes taken together, the study of one grain size gives somewhat limited information in evaluating the relative importance of various sources for the deposits.

The tendency of minerals of different specific gravity to segregate in different size fractions has been discussed by several investigators, including Rubey (1933), Rittenhouse (1943), and Van Andel (1950). The magnitude of the differences to be expected in the proportions of nonopaque heavy minerals in different size fractions in the Inyan Kara Group is shown in table 4 where a comparison is made between the very fine and the fine sand fractions of 42 samples. These differences are brought out in more detail on figure 9 where the proportions of five varieties of heavy minerals in three samples are compared for several sizes ranging from coarse silt to fine sand. In the coarser sizes, a marked decrease occurs in the proportion of zircon, and a slight decrease occurs in the proportion of rutile. Compensating increases occur in the relative amounts of tourmaline and staurolite. Garnet shows no consistent trend.

Systematic changes also can be noted in the proportion of heavy minerals in the very fine sand size if the samples are grouped according to their mean grain size. As shown in figure 10, the proportions of zircon, garnet, and staurolite increase, and the proportions of tourmaline, rutile, and chloritoid decrease in the very fine sand fraction as average grain size of the samples increases. If allowances are made for these shifts in proportion, then consistent differences in the heavy mineral suites in the very fine sand size should be useful in correlations.

HEAVY-MINERAL ZONES

The nonopaque heavy-mineral suites in the very fine grained sand fraction of samples from all the formations studied are generally similar. Most of the samples contain zircon and tourmaline as the major constituents. Nevertheless, three fairly consistent zones can be recognized by the proportions of minerals, by a few distinctive minerals, and by shapes of the tourmaline and zircon grains.

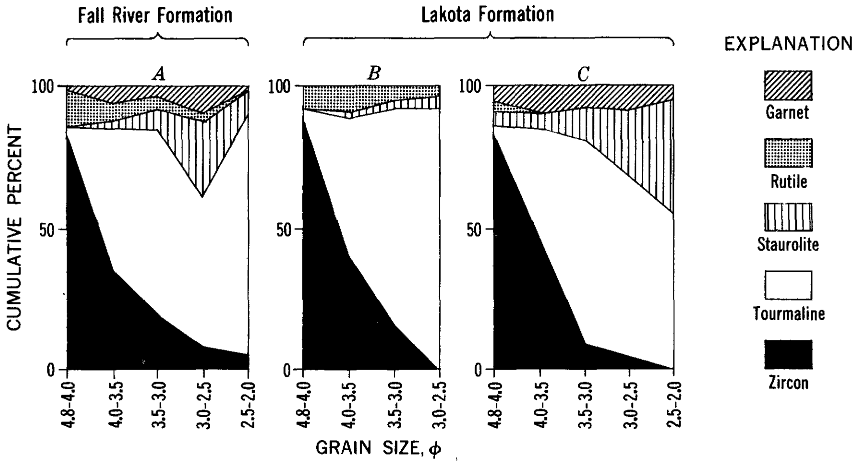

FIGURE 9.—Proportions of nonopaque heavy minerals of different grain size in three samples from the Fall River and Lakota Formations. *A*, Channel sample from 23-foot bed near middle of the Fall River Formation near locality 8. *B*, Sample 7, locality 15. *C*, Sample 4, locality 15.

LOWER ZONE

The lowest of the three zones includes the Hulett Sandstone and Redwater Shale Members of the Sundance Formation and the lower calcareous part of the Morrison Formation. Relatively large amounts of garnet characterize the nonopaque heavy-mineral suite from these rocks, the average garnet content in the suites from 33 samples being 30 percent. The garnet is mostly light violet and light pink but includes some red grains in samples from the lower part of the Morrison Formation at localities 14 and 16. The garnet grains are both rounded and angular, and some are etched (fig. 11*A*). Garnet is fairly abundant in the basal 20 feet of the Unkpapa Sandstone at Sheps Canyon (loc. 23), and in this respect the basal part of the Unkpapa resembles the lower calcareous part of the Morrison Formation.

Zircon and tourmaline generally make up about 60 percent of the nonopaque heavy-mineral suite in the lowest zone. Tourmaline tends to be slightly more abundant than zircon, and rounded zircon and tourmaline grains are about twice as abundant as angular ones.

Apatite is locally abundant, usually as rounded grains, but angular grains, including a few broken euhedral crystals, were observed in some samples. The nonopaque concentrate of one sample from the Redwater Shale Member of the Sundance Formation at locality 16 contains 30 percent apatite, and several other samples from sandstone beds in the lower zone contain from 1 to 10 percent apatite in the concentrate. Biotite is in two samples: one sample from the Redwater Shale Member of the Sundance Formation at locality 16 contains 21 percent biotite, and one from the lower part of the Morrison Formation at locality 21 contains 6 percent biotite in the nonopaque suite. About 3 percent each of rutile and staurolite occur in the nonopaque suite from the lowest zone. Other nonopaque heavy minerals found in a few samples in trace amounts include diaspore, brookite, anatase, sphene, chlorite, chloritoid, spinel, epidote, and monazite(?).

MIDDLE ZONE

The next higher heavy-mineral zone includes the upper noncalcareous part of the Morrison Formation, most of the Unkpapa Sandstone, and most or all of the Lakota Formation at most localities. Zircon and tourmaline make up 75 to 100 percent of the nonopaque heavy-mineral suite in this zone, and the two minerals together average 92 percent of the suite in the samples examined. Zircon is about 2½ times as abundant as tourmaline. The characteristic feature of the heavy minerals is the rounding of the zircon and tourmaline grains. The average ratio of rounded to angular grains is about 7 to 2 in samples of the Lakota Formation, and about 45 to 1 and 18 to 1 in samples from the Unkpapa Sandstone and upper part of the Morrison Formation, respectively.

Garnet occurs erratically in the middle zone in amounts rarely exceeding 5 percent of the nonopaque heavy minerals; in many samples it is absent. An exception is the lower part of the Lakota Formation at locality 20 where a conglomeratic sandstone 95 feet thick at the base of the Lakota Formation rests within 5 feet of the top of the Sundance Formation. Garnet makes up 10 to 15 percent of the nonopaque heavy-mineral suite in several samples from various stratigraphic levels in this sandstone. The garnet colors are the same as in the lower zone, and both rounded and angular grains were noted. This garnet may have been derived by local reworking of the Morrison Formation.

Rutile and staurolite are generally present but somewhat erratically distributed in the middle zone. Each of the two minerals averages about 3 percent of the nonopaque heavy-mineral suite in the very fine grained fraction, and in individual samples rutile rarely exceeds 10 percent and staurolite 15 percent.

Formation (fig. 10)	Samples examined (fig. 10) having mean grain size shown			
	Very fine	Fine	Medium	Coarse to conglomeratic
Fall River	26	35	5	0
Lakota	27	46	12	6
Morrison	6	15	0	0

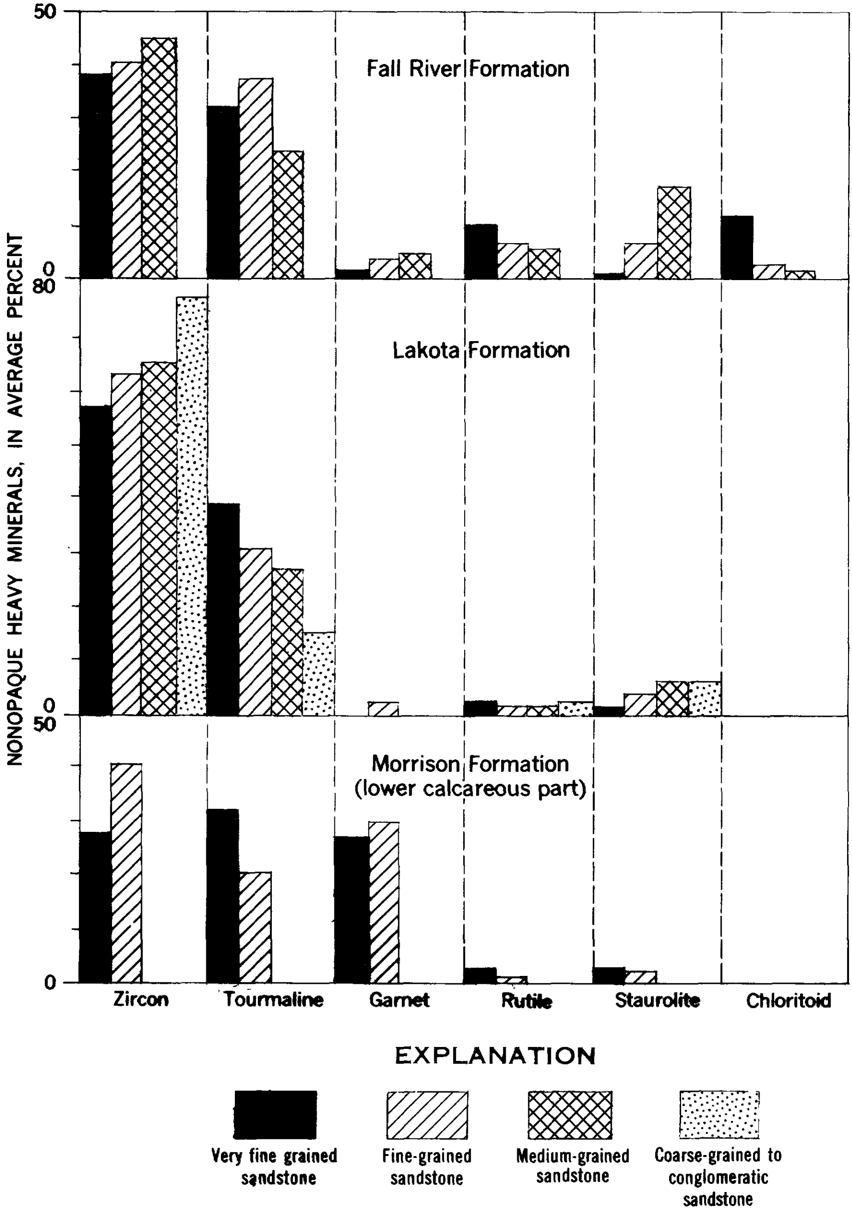

FIGURE 10.—Changes in proportion of some heavy minerals in the very fine grained sand fraction of samples having different mean grain sizes, Fall River, Lakota, and Morrison Formations. See table on opposite page for mean grain size of samples examined.

Other minerals rarely found in the middle zone include apatite, hornblende, epidote, diaspore, brookite, anatase, kyanite, sillimanite, chlorite, spinel, biotite, corundum, and monazite.

UPPER ZONE

Rocks comprising the upper heavy-mineral zone include the upper part of the Lakota Formation in the vicinity of Aladdin and Mona Butte at the northern end of the Black Hills (locs. 3, 5), the Fall River Formation, and the Newcastle Sandstone. As in the two lower zones, zircon and tourmaline predominate; they range from 40 to more than 90 percent and average about 75 percent of the nonopaque heavy minerals. Zircon tends to be more abundant than tourmaline; the average ratio is about 4 zircon grains to 3 tourmaline grains, but tourmaline greatly exceeds zircon in some samples.

The grains in the upper zone tend to be predominantly angular at the ratio of about 5 angular grains to 3 rounded ones. As shown on figure 12, the boundary between the middle and upper zones in 10 of 19 localities is marked by a fairly abrupt change in grain roundness at the Fall River-Lakota contact. At six other localities (locs. 4, 7, 9, 13, 18, and 19) the principal change in grain roundness is very near the contact. At two localities (locs. 3 and 5) the change from rounded to angular grains is sharp but is within the Lakota Formation about 80 to 100 feet below the top. At locality 17, zircon and tourmaline grains in the Fall River Formation tend to be more rounded than average, and the two zones overlap in the lower part of the Fall River Formation. Figure 13 illustrates the differences in grain roundness across the Fall River-Lakota contact at locality 25. On the whole, differences in grain roundness are consistent enough to be useful in separating the Fall River from the Lakota Formation along much of the west flank of the Black Hills.

Chloritoid occurs somewhat erratically in the very fine grained sand fraction but is locally abundant in samples from the Fall River and Newcastle Formations. No chloritoid was found in the Lakota Formation except for a single grain in a sample from the upper part of this sequence at locality 3. In general, chloritoid appears to be somewhat more common in the northern part of the Black Hills than in the southern part in the size fractions examined.

Garnet is more consistently present in the upper zone than in the middle zone. Rutile and staurolite are present in about the same proportions as in the lower two zones. Brown and green-brown hornblende was fairly abundant in a few samples, notably at locality 9, where hornblende makes up 26 percent of the suite in a sample from the middle part of the Fall River Formation, and at locality 3, where hornblende makes up 18 percent of the suite in a sample from

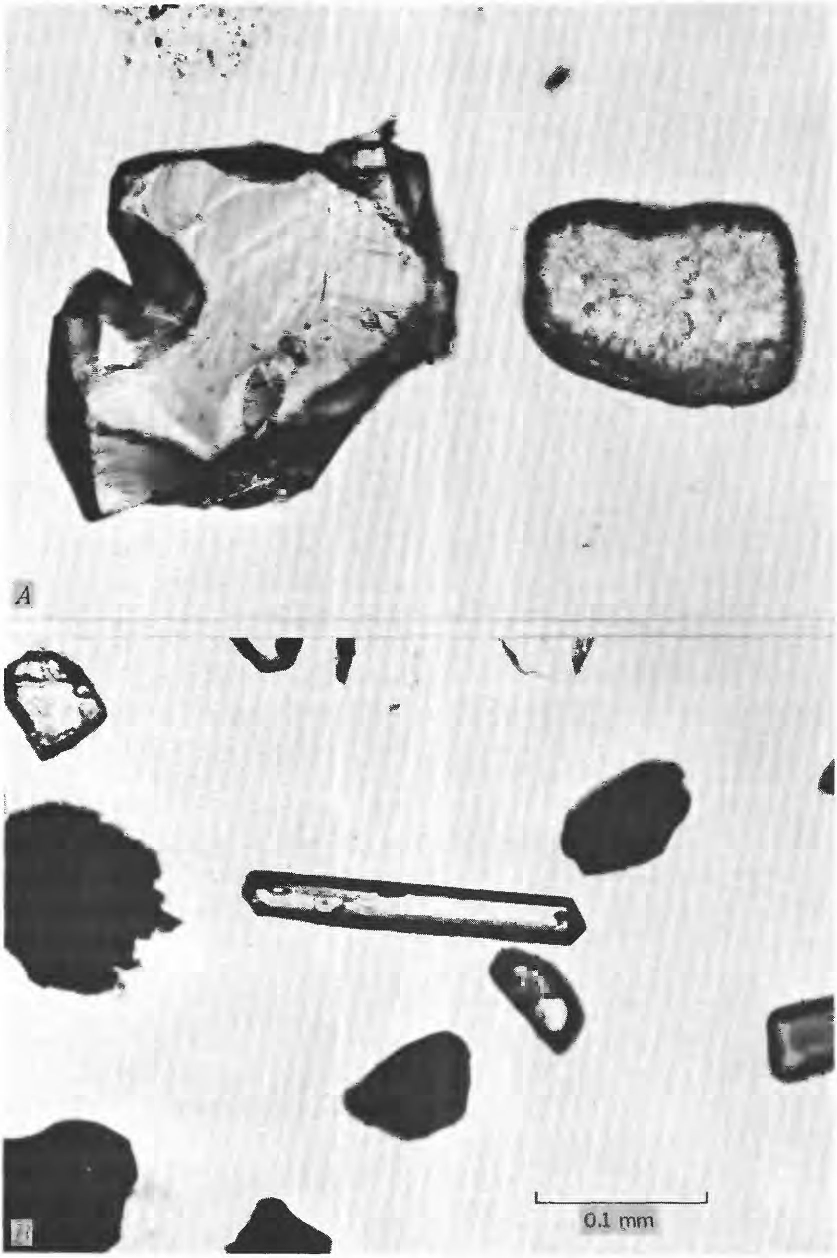

FIGURE 11.—Some varieties of heavy minerals in the Morrison and Fall River Formations. *A*, Angular and rounded garnet grains from the lower part of the Morrison Formation, locality 14. *B*, Euhedral apatite crystal from the lower part of the Fall River Formation, locality 13.

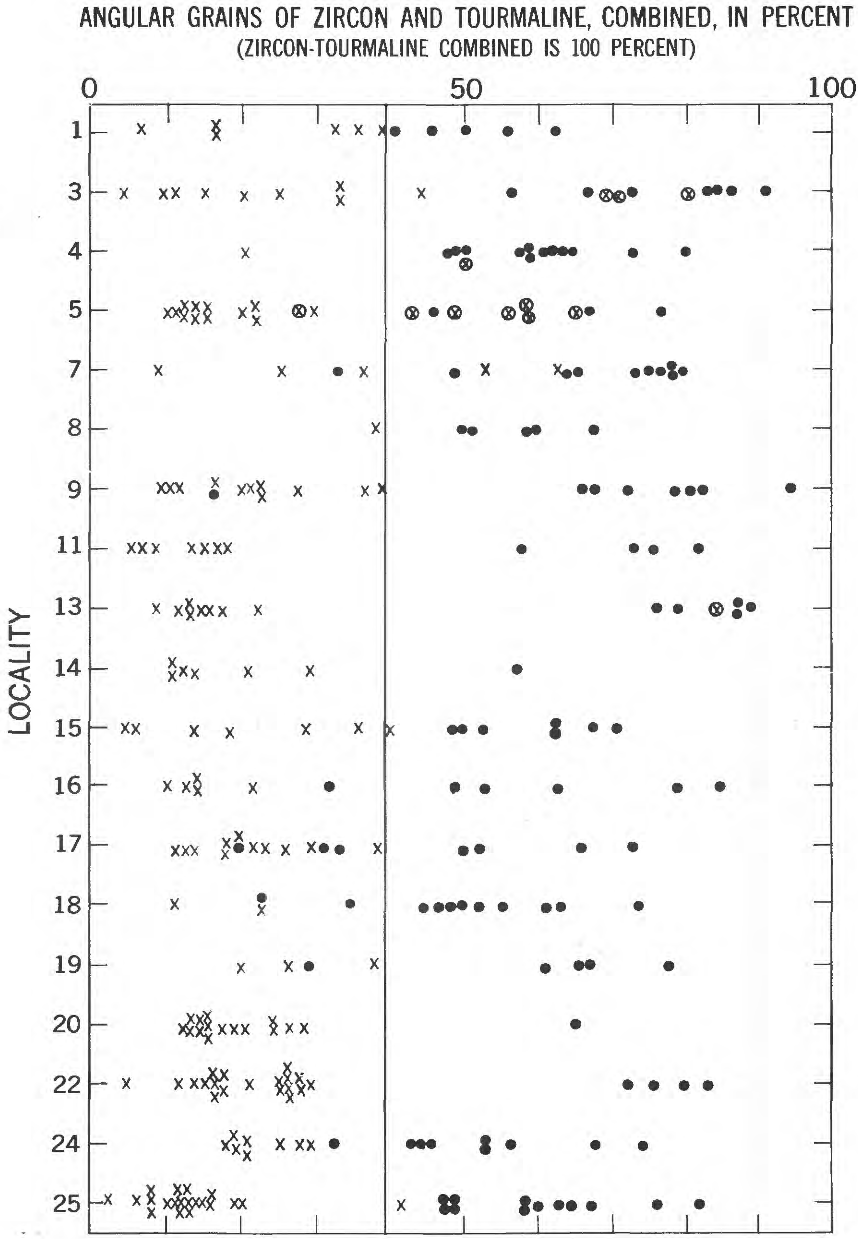

FIGURE 12.—Comparison of angularity of zircon and tourmaline grains in samples from the Fall River and Lakota Formations (0.062 to 0.125 mm size fraction). Samples from Fall River Formation indicated by dot; samples from Lakota Formation indicated by ×; and samples from top of Lakota Formation (localities 3, 4, 5, and 13) indicated by × in circle. The line drawn at 40-percent angular grains separates 92 percent of the Fall River samples from 91 percent of the Lakota samples.

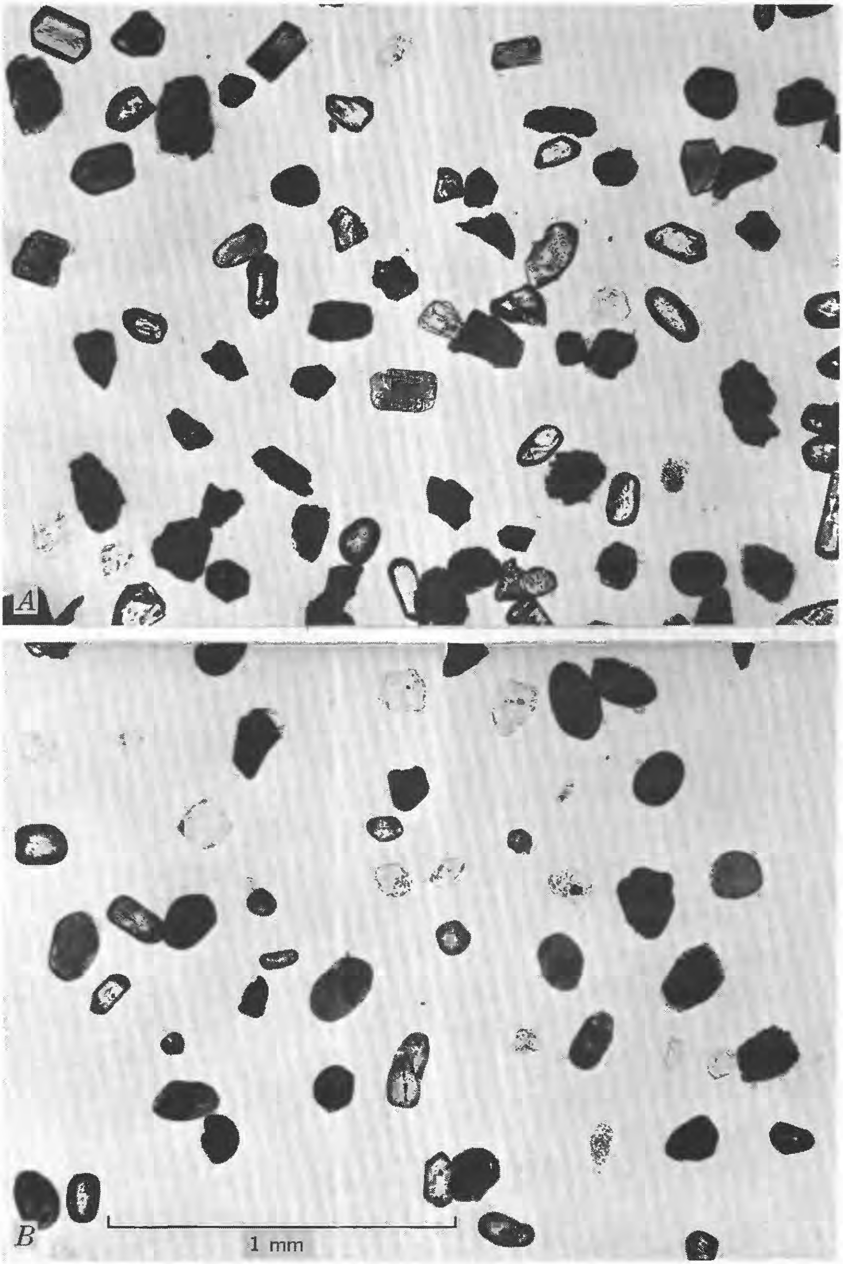

FIGURE 13.—Differences in proportion of angular and rounded grains in heavy-mineral concentrates from locality 25. *A*, Fall River Formation 20 feet above the base, grains predominantly angular. *B*, Lakota Formation 4 feet below the top, grains predominantly rounded.

the lower part of the formation. Apatite occurs both as rounded grains and euhedral crystals (fig. 11*B*), and it is fairly common in small amounts. Apatite was noted particularly at locality 13 where as much as 17 percent apatite is in the suite of a sample from near the base of the Fall River.

Several other minerals are found from place to place, mostly in trace amounts; but, except for chloritoid and hornblende, the suite is almost the same as for the middle zone.

VARIETIES OF TOURMALINE, BY COLOR OF GRAINS

The angular and rounded tourmaline grains in the very fine grained sand fractions of samples from the Fall River and the Lakota Formations are classified by color in table 5. Brown and green-brown tourmaline predominate; no appreciable difference was noted in the proportions of the different colors in the two varieties of grains.

SOURCE OF THE SEDIMENTS

The few varieties of nonopaque heavy minerals and the large proportion of quartz grains found in all formations studied suggest that the sediments comprising the sandstones were derived principally from preexisting sedimentary rocks. Much of the clastic material has probably undergone several cycles of sedimentation as shown by the high proportion of rounded zircon and tourmaline grains, particularly in the Lakota, Unkpapa, and upper part of the Morrison. The large amount of chert fragments in the coarse-grained sandstone and conglomerate indicates that chert or cherty limestone was extensively exposed in the source area or areas during deposition of the Lakota Formation. During deposition of the Fall River Formation, some of the streams in the source areas may have either cut through the sedimentary cover and exposed metamorphic rocks or shifted to a metamorphic terrane, as shown by the rather consistent presence of schist fragments in small amounts, the increase in muscovite, the local abundance of chloritoid, and the local presence of brown hornblende in the Fall River Formation. The increase in angular tourmaline and zircon grains in the Fall River Formation suggests an increased contribution of first-cycle sedimentary material, perhaps from metamorphic or igneous rocks.

A stripping away of sedimentary rocks in the source area or areas to expose increasingly greater areas of metamorphic rocks might be expected to produce a gradational rather than an abrupt change in the heavy-mineral suites at the site of deposition. The abruptness of the change in angularity of zircon and tourmaline grains at or near the Lakota-Fall River contact, and other changes in the detrital mineral suite at about the same horizon, seem more easily explained if sediments above and below the contact came from different source areas. MacKenzie and Poole (1962) conclude from an analysis of the mineralogy of sandstone of Early Cretaceous age in the western interior region that nonopaque heavy minerals characteristic of the Lakota Formation came from source areas mostly west or southwest of the Black Hills, and that nonopaque heavy minerals characteristic of the Fall River Formation came from source areas east or northeast of the Black Hills.

Except in the Aladdin and Mona Butte areas (loc. 3 and 5), the change upward from predominantly rounded to predominantly angular heavy-mineral grains is fairly sharp at the top of the Lakota Formation. If this change was practically simultaneous for all the Black Hills area, then presumably the upper 80 to 100 feet of the Lakota Formation at Aladdin and Mona Butte, which contains predominantly angular zircon and tourmaline grains, is younger than the upper part of the formation at most sections sampled elsewhere.

The locally abundant biotite and the euhedral needlelike apatite crystals in the Redwater Shale Member of the Sundance Formation and in the Fall River Formation suggest the possibility of some pyroclastic material in these formations.

Crowley (1951) suggested, on the basis of spectrographic analyses of detrital gold from the Newcastle Sandstone and the presence of cassiterite in opaque heavy-mineral suites from the Newcastle and Fall River Formations, that Precambrian rocks in the Black Hills furnished some sediment to the Inyan Kara Group and Newcastle Sandstone. Waagé (1959, p. 49) maintained that, on the contrary, the regional stratigraphic relations, pebble varieties, and current directions as shown by crossbedding in the Inyan Kara Group give no evidence for such uplift and deep erosion of the central part of the Black Hills as would be necessary to expose Precambrian rocks during deposition of the Lakota and Fall River Formations.

To gain information on this question, nonopaque heavy minerals were collected during this investigation from the fine and very fine sand fractions of 10 samples of Recent stream deposits derived from the Precambrian core of the Black Hills. The collecting localities are shown on figure 14 and the results of the heavy-mineral analyses are given in tables 3 and 6. Nonopaque heavy-mineral suites in these samples differ strikingly from those in the Inyan Kara Group and Newcastle Sandstone by having no zircon, relatively little tourmaline, no chloritoid, and relatively large amounts of garnet, hornblende, and biotite. These large differences seem to outweigh the similarities in the opaque minerals noted by Crowley and to rule out the likelihood of any contribution of sediment to the Inyan Kara Group from the Precambrian core of the Black Hills.

TABLE 5.—*Tourmaline grains in 0.062- to 0.125-mm fractions, in percent by color, Fall River and Lakota Formations, Black Hills*

[X, less than 1 percent]

Formation	Locality (fig. 1)	Angular grains											Rounded grains										
		Brown	Green brown	Green	Blue and gray blue	Gray	Pink to opaque	Orange and yellow	Red brown	Colorless	Bicolor, brown and blue	Grains counted	Brown	Green brown	Green	Blue and gray blue	Gray	Pink to opaque	Orange and yellow	Red brown	Colorless	Bicolor, brown and blue	Grains counted
Fall River	3	59	23	1	3	0	7	5	1	X	0	300	62	22	3	5	0	0	6	0	2	0	64
	9	55	17	3	7	X	6	9	2	0	X	490	57	14	3	3	X	5	13	4	0	0	84
	13	55	9	10	5	X	2	18	1	X	0	349	57	7	2	4	4	0	24	0	0	2	49
	19	44	36	3	5	0	3	9	0	0	0	244	43	27	4	7	0	3	15	0	0	0	67
	24	51	32	2	5	X	4	5	0	X	0	237	46	38	3	7	0	1	4	1	0	0	76
Weighted average[1]	------	54	21	4	5	X	5	10	X	X	X	1620	53	22	3	5	1	2	12	1	X	X	340
Lakota	2	49	25	4	6	0	7	8	0	0	0	80	54	27	X	6	0	1	11	0	0	0	324
	3	48	30	2	5	0	9	5	X	0	X	303	50	25	1	6	0	3	11	3	X	0	200
	9	41	15	3	10	0	0	28	3	0	0	39	50	24	3	6	X	2	15	X	0	0	240
	13	67	7	11	4	3	X	8	X	0	0	160	65	15	3	3	0	X	14	0	0	0	360
	20	50	21	7	8	X	2	8	4	0	0	131	53	27	1	5	0	3	9	2	0	X	555
	24	34	37	0	14	0	6	9	0	0	0	35	58	22	2	5	0	3	9	1	0	0	201
Weighted average[1]	------	51	22	5	6	2	5	7	X	0	X	748	55	24	2	5	X	2	11	1	X	X	1880

[1] Weighted according to number of grains counted.

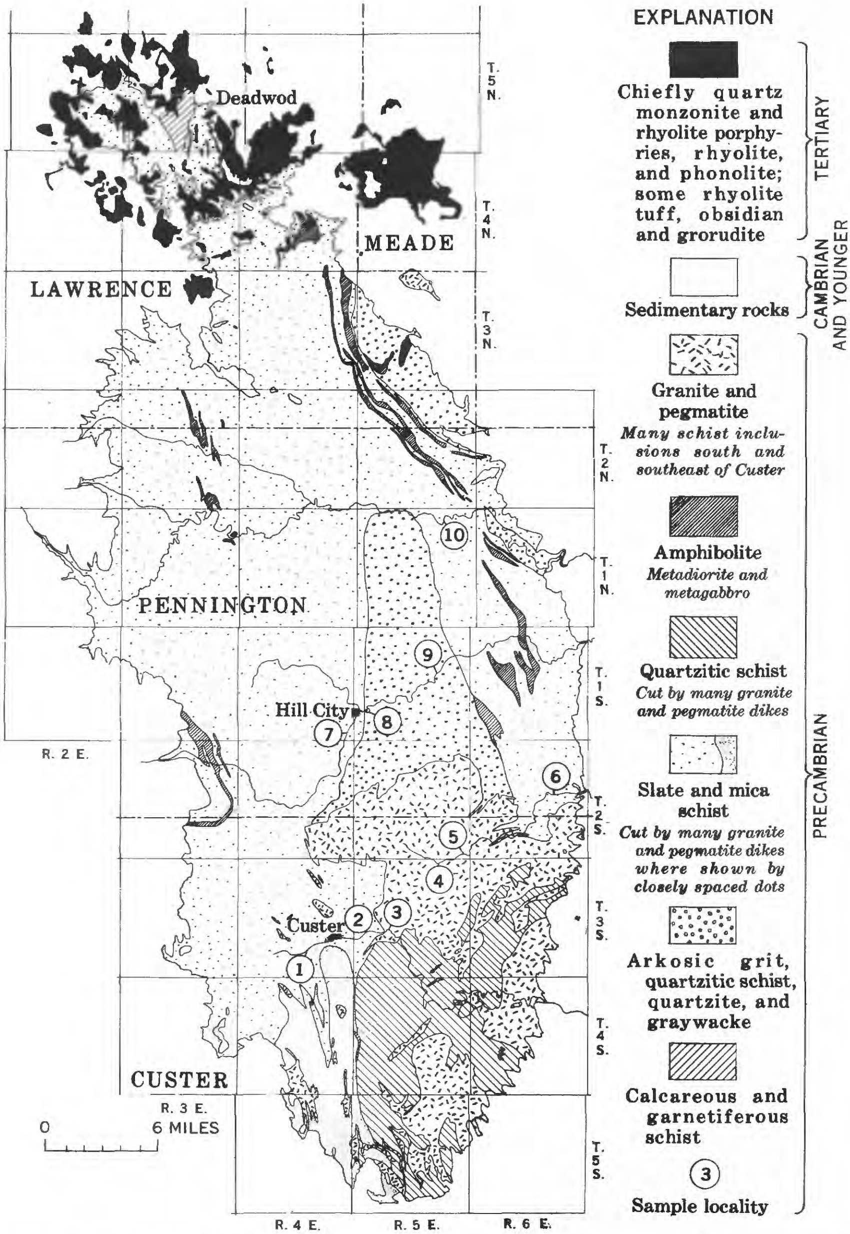

FIGURE 14.—Geologic map and location of Recent stream deposits sampled for heavy minerals, central Black Hills, South Dakota. Map generalized from Darton and Paige (1925).

TABLE 6.—*Percentages of nonopaque heavy-mineral grains in samples from Recent stream deposits, central Black Hills*

[×, less than 1 percent]

Sample	Tourmaline					Hornblende																
	Brown	Green brown	Blue	Other	Total	Green or blue green	Green brown	Brown	Total	Garnet [1]	Actinolite	Rutile	Staurolite	Apatite	Epidote	Diaspore	Sillimanite	Chlorite	Biotite	Diopside	Other [2]	Grains counted
0.062 to 0.125-mm fraction																						
1	×	2	0	0	2	52	0	0	52	34	5	0	1	0	4	2	0	0	0	0	0	100
2	18	4	0	0	22	36	4	0	40	28	9	0	0	0	1	0	0	0	0	0	0	100
3	19	6	0	0	25	35	0	1	36	17	1	0	0	12	2	0	0	×	5	×	0	177
4	1	0	1	0	2	42	22	0	64	9	14	1	0	1	5	0	2	0	×	0	2	100
5	0	0	0	0	0	45	7	1	53	25	17	×	0	0	0	2	3	0	0	0	0	100
6	10	4	0	0	14	35	6	0	41	23	16	0	0	0	2	0	3	0	1	0	×	100
7	×	×	0	×	1	24	×	1	25	31	×	0	1	2	1	1	×	0	36	0	0	254
8	4	0	×	×	5	24	0	3	27	50	5	×	1	1	2	×	0	0	6	0	×	300
9	4	5	1	0	10	45	1	2	48	29	1	0	1	0	0	2	0	0	9	0	0	100
10	2	0	0	×	2	14	3	0	17	64	9	×	1	0	3	0	3	1	0	0	0	100
Average	6	2	×	×	8	35	4	1	40	31	8	×	×	2	2	×	1	×	6	×	×	------
0.125 to 0.250-mm fraction																						
1	2	2	0	1	5	44	0	0	44	42	2	0	2	0	3	1	×	1	0	0	0	100
2	8	0	×	0	8	7	2	0	9	76	4	0	1	0	1	0	1	0	0	0	0	100
3	15	1	1	×	17	34	0	0	34	30	1	0	2	5	3	1	1	0	6	0	0	146
4	5	1	0	0	6	54	0	2	56	17	13	0	0	0	2	1	5	0	0	0	0	100
5	1	0	0	0	1	29	34	4	67	16	10	0	0	0	2	0	4	0	0	×	0	100
6	4	1	0	0	5	37	6	0	43	32	15	0	0	0	3	1	1	0	0	0	0	100
7	2	0	0	0	2	23	0	1	24	59	2	0	3	×	×	×	0	0	8	0	×	200
8	4	0	0	0	4	9	1	1	11	78	5	×	×	×	×	0	0	0	1	0	0	272
9	5	1	0	×	7	31	4	1	36	39	4	0	2	0	0	1	0	1	9	1	0	100
10	0	0	0	0	0	10	0	0	10	76	3	0	0	0	1	0	0	10	0	0	0	100
Average	5	×	×	×	6	28	5	1	34	47	6	×	1	×	2	×	1	1	2	×	×	------

[1] Mostly light violet, small amount light pink.
[2] Brookite and zoisite, sample 4; zircon, sample 6; kyanite, sample 7; and anatase, sample 8.

Clues to the direction of transport of sediment in the Inyan Kara Group are given by evidence other than the composition of the nonopaque heavy-mineral suites. The average mean grain size of sandstone in samples from the Fall River Formation shows a small but consistent increase from northwest to southeast: samples of sandstone from Crook County, Wyo., average 3.10ϕ in mean grain size; those from Lawrence County, S. Dak., and Weston County, Wyo., average 2.88 and 2.87ϕ, respectively; and those from Fall River County, S. Dak., average 2.70ϕ. Field observations indicate a somewhat irregular increase in the amount of sandstone in the formation in the same direction. In addition, Brobst (1956) has described a major channel system in the basal part of the Fall River Formation in the southwestern part of the Black Hills in which the streamflow was from the southeast. All these relations suggest a source for the Fall River Formation to the east or southeast.

During Early Cretaceous time, limestone, sandstone, and shale of Cambrian to Permian age were exposed in much of Kansas, Nebraska, and nearby areas south and east of the Black Hills, and metamorphic rocks of Precambrian age were exposed in the Great Lakes region farther northeast (fig. 15). The paleogeologic and paleogeographic relations harmonize with an eastward or southeastward source for sandstone in the Fall River Formation.

Several geologists have presented evidence for a western source for sediment in the Lakota Formation in the Black Hills. Waagé (1959, p. 48–49) pointed out the similarity of black chert pebbles in the Lakota Formation in the northern Black Hills to black chert pebbles in the Pryor Conglomerate Member of the Cloverly Formation on the east side of the Bighorn Mountains in Montana. He suggested that beds containing the polished chert and quartzite pebbles had a western source, although he stated (1959, p. 49) that older parts of the formation had a southeastern source. G. A. Izett (oral communication, 1961) noted a close similarity of red and pink quartzite pebbles in the Lakota to the Cambrian Brigham Quartzite in northeastern Utah and to the Precambrian Swauger Quartzite in Idaho; he favors a western source for the pebbles.

Crossbeds in the Lakota Formation in the northern Black Hills indicate a dominant direction of streamflow from the west or southwest and a secondary direction of streamflow from the southeast (Mapel and Pillmore, 1962, fig. 13.2). Two channel systems have been identified in the Lakota Formation in the southern Black Hills (Brobst, 1956); in both systems the streamflow was from the southeast.

The Black Hills lie about halfway between possible source areas to the west and those to the east (fig. 15), and although the weight of

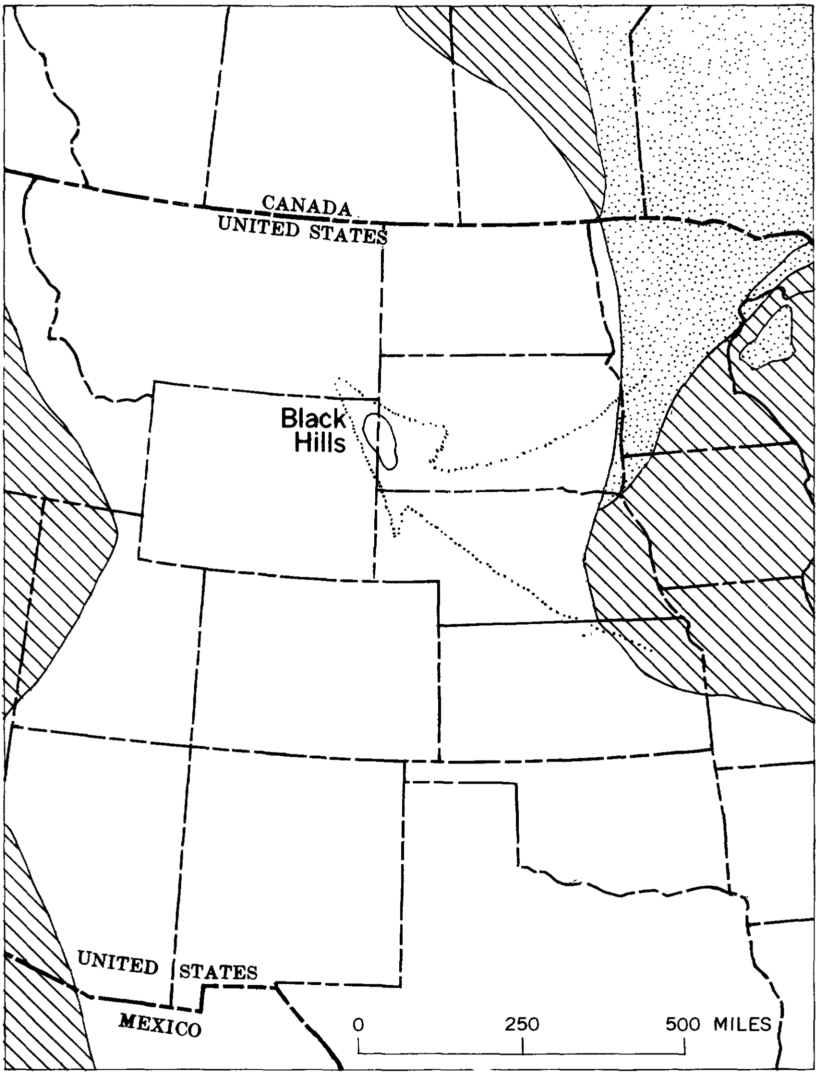

FIGURE 15.—Paleogeologic map at the end of the Jurassic Period showing source areas for Lower Cretaceous rocks, western interior region. Unpatterned area, depositional area of Lower Cretaceous rocks, boundaries approximately located; diagonal lines, outcropping sedimentary rocks Triassic to Cambrian in age; stippled pattern, outcropping metamorphic and igneous rocks Precambrian in age. Arrow shows likely direction of transport for sandstone in the Fall River Formation and for some sandstone in the Lakota Formation, Black Hills. Map adapted from Eardley (1949, p. 679–680).

evidence seems to favor a western source for most of the sandstone in the Lakota, sediment from each direction may be mingled in the formation in the Black Hills.

Hooper (1961, p. 1540) and Mirsky (1961, p. 583) cited petrographic evidence showing that in other parts of Wyoming preexisting sedimentary rocks furnished most of the sedimentary material in the Lakota (or Cloverly) Formation and that crystalline rocks were probably minor contributors. Both writers believed that the source for most of the sediment in the areas they studied was to the west.

HEAVY-MINERAL DATA FROM NEARBY AREAS IN WYOMING

Heavy-mineral suites found in the Inyan Kara Group and Morrison Formation in the Black Hills have some close similarities with suites in the formation or its equivalents as reported by Hooper (1961) on the Casper Arch in east-central Wyoming and by Mirsky (1961) in the southern Bighorn Mountains in north-central Wyoming. Hooper's data are based on samples of heavy minerals that were not segregated according to size. In the Lakota Formation (Lakota Conglomerate of his report) he found (1961, p. 1536) about 80 percent rounded and about 20 percent angular grains. According to Hooper (1961, p. 1537), the nonopaque heavy-mineral fraction has the following average proportion of minerals (total nonopaque fraction taken as 100 percent): zircon, 74 percent; tourmaline, 20 percent; staurolite, 3 percent; rutile, 3 percent; hornblende, small amounts near the base of the Lakota Formation in two sections. Hooper found that green tourmaline exceeds brown tourmaline by about 2 to 1, which is the reverse of the relation in the Black Hills.

Mirsky (1961) reported on only the very fine grained heavy minerals, and his results, therefore, are directly comparable with those of this report. Mirsky (1961, p. 580) stated that garnet is either absent or nearly absent in the Lakota Formation, but that it is a noteworthy constituent of the Morrison Formation—an observation that holds also for the Black Hills.

SUMMARY

Some similarities and differences in sandstone in the four formations most intensively studied are summarized in table 7. Grain-size and thin-section analyses show slight differences among these formations that probably reflect differences both in the environment of deposition and in the rocks exposed in the source areas; however, the differences are not consistent enough to be useful in stratigraphic correlations.

Fairly consistent differences in the very fine grained nonopaque heavy minerals permit differentiation of three heavy-mineral zones. Abundant garnet characterizes the lower zone and chloritoid characterizes the upper zone. Both minerals are virtually absent in the middle zone. A change from predominantly rounded to predominantly angular zircon and tourmaline grains in the very fine grained sand fraction of the sandstone beds in the Inyan Kara Group is sharp enough to be useful in subdividing the group within the Black Hills.

Sediment composing the sandstone of the formations examined probably were derived mainly from preexisting sedimentary rocks. The Fall River received as well some additions of material from metamorphic rocks, and perhaps minor additions from volcanic sources. The evidence points to a western source for a large part of the Lakota Formation; however, a source to the east seems likely for some of the sedimentary material in the Lakota Formation and for most or all of the material in the Fall River Formation in the Black Hills.

TABLE 7.—*Some characteristics of the sandstones from the formations studied*

Formation	Sorting	Grain size	Light minerals	Nonopaque heavy minerals (0.062 to 0.125 mm)
Fall River	Well sorted	Mostly fine to very fine.	Feldspar, muscovite, and schist fragments fairly consistent in small amounts.	Predominantly angular zircon and tourmaline grains; locally abundant chloritoid, hornblende, and apatite; small amounts of garnet.
Lakota	Well to poorly sorted.	Mostly fine, but some medium to very coarse grains.	Abundant chert in coarser grained beds; feldspar locally present in small amounts; muscovite and schist fragments rare.	Predominantly rounded zircon and tourmaline grains; virtually no chloritoid, hornblende, or apatite; almost no garnet except in lower part at one locality (loc. 20).
Unkpapa	Well sorted	Mostly fine	High proportion of quartz grains having straight or slightly undulose extinction, and composite quartz grains having particles in parallel optical orientation and smooth particle boundaries; some feldspar; rare muscovite and schist fragments.	Predominantly rounded zircon and tourmaline grains; very little garnet except in bottom few feet; no chloritoid, hornblende, or apatite.
Morrison	do	Fine to very fine	More feldspar than in overlying rocks; rare muscovite and schist fragments.	Predominantly rounded zircon and tourmaline grains; garnet abundant; apatite fairly abundant locally; virtually no chloritoid or hornblende.

TABULATION OF DATA

The proportions of nonopaque heavy mineral grains of the 0.062 to 0.125-mm fractions and the mean grain sizes of most of the samples examined are shown in table 8 by locality number and by stratigraphic position (pls. 1, 2; fig. 1).

TABLE 8.—*Percentages of nonopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*

[Localities are shown on pls. 1 and 2. ×, less than 1 percent (or small number of grains in most samples); R, rare (or small number of grains in at least one sample)]

Formation	Sample	Grain size of sample,[1] (ϕ)		Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2]																									
				Zircon			Tourmaline			Zircon-tourmaline, combined																			
		Graphic mean	Graphic standard deviation	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 1																													
Fall River	1	2.9	0.3	12	19	31	29	20	49	41	39	80	6	5	9	0	0	0	0	0	0	0	0	×	0	0	0	0	122
	2	2.9	.3	8	8	16	33	24	57	41	32	73	8	5	14	×	0	0	0	0	0	0	0	0	0	×	0	0	107
	3	2.8	.3	7	16	23	29	27	56	36	43	79	5	5	12	0	0	0	0	0	0	0	0	0	0	0	0	0	109
	4	2.9	.5	21	45	66	11	2	13	32	47	79	4	9	10	0	0	0	0	0	0	0	0	0	0	0	0	0	138
	5	4.3	1.2	7	7	14	26	12	38	33	19	52	1	4	4	0	0	0	0	0	0	0	0	×	0	38	0	0	103
Lakota	6	2.8	.5	4	21	25	25	38	63	29	59	88	0	7	5	0	0	0	0	0	0	0	0	0	0	0	0	0	120
	8	2.4	.4	6	60	66	9	14	23	15	74	89	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0	0	116
	10	1.6	.3	7	29	36	19	17	36	26	46	72	3	3	20	0	0	0	0	0	1	1	0	0	0	0	0	0	103
	12	1.7	.3	9	23	32	22	24	46	31	47	78	4	8	9	0	0	0	0	×	0	0	0	0	0	0	0	0	117
	14	3.5	.9	8	31	39	7	43	50	15	74	89	0	1	10	0	0	0	0	0	0	0	0	0	0	0	0	0	110
	16	3.4	.8	5	68	73	2	19	21	7	87	94	0	2	4	0	0	0	0	0	0	0	0	0	0	0	0	0	185
Average, Fall River	------	3.2	0.5	11	19	30	25	17	42	36	36	72	5	5	10	×	0	0	0	0	0	0	0	×	0	8	0	0	
Lakota	------	2.6	.5	6	39	45	14	26	40	20	65	85	1	5	8	0	0	0	0	R	R	R	0	0	0	0	0	0	

See footnotes at end of table.

TABLE 8.—*Percentages of nonopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*—Continued

Formation	Sample	Grain size of sample,[1] (φ): Graphic mean	Grain size of sample,[1] (φ): Graphic standard deviation	Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2] — Zircon: Angular grains	Zircon: Rounded grains	Zircon: Total	Tourmaline: Angular grains	Tourmaline: Rounded grains	Tourmaline: Total	Zircon-tourmaline, combined: Angular grains	Zircon-tourmaline, combined: Rounded grains	Zircon-tourmaline, combined: Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 2																													
Lakota	11	2.8	0.4	24	55	79	7	2	9	31	57	88	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	130
	10	2.6	.4	20	53	73	7	7	14	27	60	87	0	10	3	0	0	0	0	0	0	0	0	0	0	0	0	0	142
	9	2.5	.4	29	51	80	6	4	10	35	55	90	0	7	3	0	0	0	0	0	0	0	0	0	0	0	0	0	133
	8	.8	2.2	18	63	81	4	6	10	22	69	91	×	4	5	0	0	0	0	0	0	0	0	0	0	0	0	0	154
	7	2.3	.4	15	70	85	3	2	5	18	72	90	3	2	5	0	0	0	0	0	0	0	0	0	0	0	0	0	147
	6	2.3	.6	9	43	52	5	20	25	14	63	77	0	1	21	0	0	0	0	0	0	0	0	0	0	0	0	0	206
	5	2.6	.3	5	39	44	4	38	42	9	77	86	×	×	13	0	0	0	0	0	0	0	0	0	0	0	0	0	144
	4	2.6	.5	14	77	91	0	2	2	14	79	93	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	189
	3	2.7	.6	12	38	50	3	34	37	15	72	87	0	4	9	0	0	0	0	0	×	0	0	0	0	0	0	0	151
	2	2.8	.9	2	16	18	4	50	54	6	66	72	×	0	28	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	1	3.1	.7	2	2	4	15	80	95	17	82	99	0	×	×	0	0	0	0	0	0	0	0	0	0	0	0	0	119
Sundance	1a	0	0	18	18	36	9	22	31	27	40	67	25	3	4	0	0	0	0	×	0	×	0	0	0	0	0	0	162
Average, Lakota	------	2.5	0.7	14	46	60	5	22	27	19	68	87	×	4	8	0	0	0	0	0	R	0	0	0	0	0	0	0	

Locality 3																													
Fall River	18	2.6	0.3	14	7	21	47	15	62	61	22	83	0	7	10	0	0	0	0	0	0	0	0	0	0	0	0	0	182
	17	2.8	.4	3	1	4	46	7	53	49	8	57	3	5	5	0	0	0	×	0	×	0	0	0	0	29	0	0	192
	16	3.6	.4	5	2	7	29	4	33	34	6	40	0	10	×	0	0	0	×(?)	0	0	0	0	0	0	48	0	0	141
	15	3.5	.5	12	3	15	25	4	29	37	7	44	11	18	1	0	×	0	0	0	×	0	0	0	0	25	0	0	144
	14	3.6	.4	4	0	4	40	4	44	44	4	48	0	0	0	0	4	0	0	0	0	0	0	0	0	48	0	0	23
	13	0	0	2	4	6	14	4	18	16	8	24	2	7	0	0	18	0	0	0	0	0	0	0	1	48	0	0	62
	12a	0	0	31	34	65	20	4	24	51	38	89	×	8	2	0	0	0	0	×	0	0	0	0	0	0	0	0	168
Lakota	12	3.2	.6	8	8	16	60	9	69	68	17	85	×	6	6	0	0	0	0	2	×	0	0	0	0	0	0	0	128
	11	3.1	.6	19	10	29	41	14	55	60	24	84	×	8	7	0	0	0	0	0	0	0	0	0	0	0	0	0	139
	10	3.4	.6	27	19	46	31	5	36	58	24	82	0	14	3	0	×	0	0	0	0	0	0	0	0	×	×	0	193
	9	1.6	.5	15	31	46	24	17	41	39	48	87	0	7	5	0	0	0	0	0	0	0	0	0	0	0	0	0	239
	8	2.2	.5	19	75	94	×	×	1	20	75	95	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	130
	7	2.6	.4	18	54	72	12	6	18	30	60	90	0	7	3	0	0	0	0	0	0	0	0	0	0	0	0	0	134
	6	2.4	.5	19	59	78	4	6	10	23	65	88	0	2	10	0	0	0	0	0	0	0	0	0	0	0	0	0	143
	5	2.2	.5	10	42	52	16	11	27	26	53	79	0	4	16	0	0	0	0	0	0	0	0	0	0	0	0	0	147
	4	1.2	1.2	11	88	99	0	×	×	11	88	99	0	×	0	0	0	0	0	0	0	0	0	0	0	0	0	0	136
	3	2.7	.4	4	65	69	1	28	29	5	93	98	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	156
	2	2.6	.3	9	58	67	×	28	29	10	86	96	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	129
	1	3.2	.6	14	79	93	1	4	5	15	83	98	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	178
Average, Fall River	------	3.2	0.4	10	7	17	32	6	38	42	13	55	2	8	3	0	3	0	R(?)	R	R	0	0	0	R	28	0	0	
Lakota	------	2.5	.7	14	46	60	18	11	29	32	57	89	R	4	6	0	R	0	0	R	R	0	0	0	0	R	R	0	
Locality 4																													
Fall River	1	0	0	23	12	35	36	10	46	59	22	81	×	10	9	0	×	0	0	0	0	0	0	0	0	0	0	0	162
	2	0	0	27	25	52	22	9	31	49	34	83	0	6	10	0	×	0	0	×	0	0	0	0	0	0	0	0	163
	3	0	0	38	27	65	6	3	9	44	30	74	4	9	13	0	0	0	0	0	0	0	0	0	0	0	0	0	149
	4	0	0	16	8	24	40	6	46	56	14	70	0	5	24	0	0	0	1	0	0	×	0	×	0	0	0	0	156
	5	0	0	26	25	51	27	4	31	53	29	82	0	8	9	0	0	0	0	1	0	0	0	0	0	0	0	0	157
	6	0	0	31	40	71	12	3	15	43	43	86	2	6	6	0	0	0	0	×	0	0	0	0	0	0	0	0	150
	7	0	0	50	29	79	8	4	12	58	33	91	1	7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	8	0	0	37	32	69	19	4	23	56	36	92	0	4	3	0	0	0	0	×	1	0	0	0	0	0	0	0	141
	9	0	0	44	36	80	8	2	10	52	38	90	1	6	3	0	0	0	0	0	0	0	0	0	0	0	0	0	96
	10	0	0	32	32	64	9	10	19	41	42	83	×	5	12	0	0	0	0	0	0	0	0	0	0	0	0	0	147
	11	0	0	31	27	58	16	7	23	57	34	91	0	8	0	0	0	0	0	0	1	0	0	0	0	0	0	0	143
	12	0	0	40	46	86	4	2	6	44	48	92	0	7	×	0	0	0	0	0	0	0	0	0	0	×	0	0	134
Lakota	13	2.9	0.4	10	13	23	30	26	56	40	39	79	0	5	16	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	14	2.8	.3	16	67	83	3	6	9	19	73	92	0	3	5	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Average, Fall River	--------	0	0	33	28	61	18	5	23	51	33	84	×	7	7	0	R	0	R	R	R	R	0	R	0	R	0	0	
Lakota	--------	2.9	0.4	14	40	54	16	16	32	30	56	86	0	4	10	0	0	0	0	0	0	0	0	0	0	0	0	0	

See footnotes at end of table.

TABLE 8.—*Percentages of nonopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*—Continued

Formation	Sample	Grain size of sample,[1] (φ): Graphic mean	Graphic standard deviation	Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2]: Zircon: Angular grains	Zircon: Rounded grains	Zircon: Total	Tourmaline: Angular grains	Tourmaline: Rounded grains	Tourmaline: Total	Zircon-tourmaline, combined: Angular grains	Zircon-tourmaline, combined: Rounded grains	Zircon-tourmaline, combined: Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 5																													
Fall River	1	3.0	0.5	36	21	57	22	7	29	58	28	86	2	6	6	0	0	0	0	1	1	0	0	0	0	0	0	0	166
	2	2.6	.3	21	30	51	12	9	21	33	39	72	4	10	14	0	0	0	0	0	0	X	0	0	0	0	0	0	129
	3	2.2	.5	11	11	22	30	1	31	41	12	53	2	5	37	0	0	0	2(?)	0	0	X	0	0	0	0	0	0	143
Lakota	4	3.3	.7	28	18	46	26	11	37	54	29	83	0	10	7	0	0	0	0	X	X	0	0	0	0	0	0	0	163
	5	2.6	.3	20	26	46	20	3	23	40	29	69	0	10	21	0	0	0	0	0	X	0	0	0	0	0	0	0	151
	6	2.4	.4	18	27	45	26	7	33	44	34	78	0	5	17	0	0	0	0	0	0	0	0	0	0	0	0	0	152
	7	1.5	.4	26	65	91	2	5	7	28	70	98	0	X	1	0	0	X	0	0	0	X	0	0	0	0	0	0	158
	8	2.5	.6	25	29	54	12	9	21	37	38	75	0	6	19	0	0	0	X	0	0	0	0	0	0	0	0	0	159
	9	.3	.7	11	28	39	43	9	52	54	37	91	0	3	6	0	X	0	0	0	0	0	0	0	0	0	0	0	144
	10	−.7	1.6	28	46	74	8	2	10	36	48	84	0	5	11	0	0	0	0	0	0	0	0	0	0	0	0	0	89
	11	2.7	.7	12	68	80	3	8	11	15	76	91	0	X	8	0	0	X	0	0	0	0	0	0	0	0	0	0	143
	12	2.6	.5	15	54	69	5	15	20	20	69	89	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	173
	13	2.7	.6	7	39	46	4	36	40	11	75	86	0	2	11	0	0	0	0	X	0	0	0	0	0	0	0	0	135
	14	2.9	.8	12	82	94	0	5	5	12	87	99	0	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	155
	15	2.0	1.3	11	61	72	1	17	18	12	78	90	0	2	8	0	0	0	0	0	0	0	0	0	0	0	X	0	139
	16	2.5	.4	12	79	91	X	5	6	13	84	97	0	X	3	0	0	0	0	0	0	0	0	0	0	0	0	0	182
	17	2.4	.8	8	42	50	4	42	46	12	84	96	0	X	3	0	0	0	0	0	0	0	0	0	0	0	0	0	135
	18	.6	1.4	9	62	71	4	20	24	13	82	95	0	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	134
	19	2.0	1.0	10	75	85	X	12	13	11	87	98	0	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	136
	20	1.9	.8	9	44	53	10	34	44	19	78	97	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	160
	21	1.6	1.2	25	53	78	2	10	12	27	63	90	0	3	6	0	0	0	0	0	0	0	0	0	0	0	0	0	144
	22	2.3	.5	12	35	47	9	40	49	21	75	96	0	X	3	0	0	0	0	0	0	0	0		0	0	0	0	148
Average, Fall River	------	2.6	0.4	22	21	43	21	6	27	43	27	70	2	7	19	0	0	0	X(?)	X	X	X	0	0	0	0	0	0	
Lakota	------	2.0	.8	16	47	63	10	15	25	26	62	88	0	3	8	0	R	R	R	R	R	R	0	0	0	0	R	0	

Locality 6																													
Lakota	8	0	0	21	39	60	5	28	33	26	67	93	0	6	0	0	0	0	0	×	×	0	0	0	0	0	×	0	139
	7	0	0	16	56	72	0	24	24	16	80	96	×	2	×	0	0	0	0	0	0	0	0	0	0	0	0	0	133
	6	0	0	10	37	47	4	32	36	14	69	83	15	2	0	0	0	0	0	0	×	0	0	0	0	0	0	0	153
	5	0	0	23	16	39	17	16	33	40	32	72	14	5	5	2	0	0	0	0	0	0	0	0	0	0	0	2	89
Morrison	4	0	0	9	9	18	36	15	51	45	24	69	18	6	6	0	0	0	0	×	0	0	0	0	0	0	0	0	122
	3	0	0	×	32	33	4	13	17	5	45	50	31	2	15	2	0	0	×	0	0	0	0	0	0	0	0	0	129
	2	0	0	5	48	53	2	6	8	7	54	61	28	×	8	0	0	×	2	0	×	0	0	0	0	0	0	0	140
Sundance	1	0	0	8	21	29	11	20	31	19	41	60	32	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	104
Average, Lakota	------	0	0	17	37	54	6	25	31	23	62	85	7	4	1	×	0	0	0	R	R	0	0	0	0	0	R	×	
Morrison	------	0	0	5	30	35	14	11	25	19	41	60	26	3	10	×	0	R	1	R	R	0	0	0	0	0	0	0	
Locality 7																													
Fall River	15	2.9	0.4	12	6	18	49	16	65	61	22	83	6	8	0	0	0	×	×	×	0	0	0	0	0	0	0	0	115
	14	2.1	.4	21	29	50	9	2	11	30	31	61	6	6	27	0	0	0	0	0	0	0	0	0	0	0	0	0	167
	13	3.7	.4	58	18	76	12	×	13	70	19	89	4	6	0	0	0	0	×	0	0	0	0	0	0	0	0	0	144
	12	3.8	0	32	21	53	18	7	25	50	28	78	8	13	0	0	0	0	0	1	×	0	0	0	0	0	0	0	88
	[3] 11	4.5	0	8	10	18	21	0	21	29	10	39	3	8	5	0	5	0	0	3	0	0	0	0	0	32	0	0	38
	10	3.8	.6	32	12	44	27	5	32	59	17	76	2	13	3	0	0	×(?)	0	1	0	0	0	0	0	4	0	0	174
	9	2.4	.3	23	53	76	5	2	7	28	55	83	6	4	6	0	0	0	0	0	×	0	0	0	0	0	0	0	157
	8	3.4	.5	19	13	32	42	5	47	61	18	79	5	9	2	0	0	0	0	×	×	0	0	0	4	0	0	0	169
	7	2.7	.3	6	9	15	53	8	61	59	17	76	3	3	6	0	2	0	0	0	0	0	0	0	10	0	0	0	110
	6	3.7	.6	12	13	25	40	15	55	52	28	80	0	8	4	0	×	0	0	0	0	0	0	0	0	7	0	×	108
Lakota	5	3.2	1.2	21	43	64	8	8	16	29	51	80	×	15	4	0	0	0	0	0	×	0	0	0	0	0	0	0	141
	4	3.1	.4	26	23	49	22	5	27	48	28	76	0	22	2	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	3	2.6	.4	32	31	63	10	6	16	42	37	79	0	13	8	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	2	3.2	1.0	8	78	86	1	11	12	9	88	97	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	200
	1	0	0	22	55	77	2	12	14	24	67	91	×	8	1	0	0	0	0	0	×	0	0	0	0	0	0	0	171
Average, Fall River	------	3.3	0.4	23	18	41	28	6	34	51	24	75	4	8	5	0	×	R	R	×	R	0	0	0	1	4	0	R	
Lakota	------	3.0	.8	22	46	68	9	8	17	31	54	85	R	12	3	0	0	0	0	0	R	0	0	0	0	0	0	0	
Locality 8																													
Fall River	1	3.0	0.3	17	23	40	22	15	37	39	38	77	2	10	8	0	0	0	0	0	0	0	0	0	0	3	0	0	114
	2	2.2	.4	16	29	45	17	5	22	33	34	67	5	5	23	0	0	0	0	0	0	0	0	0	0	0	0	0	133
	3	2.9	.4	12	10	22	39	25	64	51	35	86	4	5	3	0	0	0	0	×	0	0	0	×	0	×	0	0	138
	4	3.8	.8	8	8	16	48	18	66	56	26	82	4	8	2	0	0	0	0	2	0	0	0	0	0	2	0	0	105
	5	3.3	.4	11	8	19	39	25	64	50	33	83	0	7	4	0	0	0	0	×	0	0	0	0	0	5	0	0	100
Lakota	6	1.9	.4	4	28	32	25	18	43	29	46	75	0	2	23	0	0	0	0	0	0	0	0	0	0	0	0	0	116
Average, Fall River	------	3.4	0.5	13	16	29	33	18	51	46	34	80	2	7	8	0	0	0	0	×	0	0	0	R	0	2	0	0	

See footnotes at end of table.

TABLE 8.—*Percentages of nonopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*—Continued

Formation	Sample	Grain size of sample,[1] (φ): Graphic mean	Graphic standard deviation	Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2]: Zircon: Angular grains	Zircon: Rounded grains	Zircon: Total	Tourmaline: Angular grains	Tourmaline: Rounded grains	Tourmaline: Total	Zircon-tourmaline, combined: Angular grains	Zircon-tourmaline, combined: Rounded grains	Zircon-tourmaline, combined: Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 9 (AEC drill hole HC 202)																													
Fall River	[4] 1	3.3	0.5	14	12	26	50	5	55	64	17	81	3	6	×	0	0	×(?)	0	0	0	0	0	0	0	8	0	0	149
	[5] 2	2.5	.5	22	9	31	33	4	37	55	13	68	9	2	19	0	0	0	0	×	0	0	0	0	0	2	0	0	175
	3	2.8	.5	28	25	53	27	3	30	55	28	83	7	3	4	0	0	0	0	0	0	0	0	0	0	3	0	0	164
	4	3.6	.4	7	3	10	58	1	59	65	4	69	2	20	2	3	0	0	0	2	1	0	0	0	1	0	0	0	115
	5	3.1	0	23	18	41	23	4	27	46	22	68	×	5	0	0	26	0	×	0	×	0	0	0	0	0	0	0	181
	6	2.8	.4	13	7	20	61	9	70	74	16	90	6	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	194
	7	2.6	.3	12	10	22	44	12	56	56	22	78	2	3	16	×	0	×(?)	0	0	×	0	0	0	0	0	0	0	196
	8	3.2	.8	15	70	85	×	11	11	15	81	96	×	2	×	0	0	0	0	0	0	0	0	0	0	0	0	0	149
Lakota	9	3.0	.8	39	56	95	×	4	4	39	60	99	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200
	10	3.4	.5	26	68	94	1	5	6	27	73	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	195
	11	3.2	.8	31	57	88	×	10	11	32	67	99	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	74
	12	2.2	.6	19	57	76	3	21	24	22	78	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	185
	13	0	0	14	74	88	2	9	11	16	83	99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	139
	14	3.0	.9	11	85	96	0	4	4	11	89	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	137
	15	3.3	.4	20	70	90	0	10	10	20	80	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	171
	16	3.1	.5	10	77	87	0	10	10	10	87	97	0	0	2	×	0	0	0	0	0	0	0	0	0	0	0	0	136
	17	2.2	1.6	7	72	79	2	19	21	9	91	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	156
	18	3.7	.8	9	27	36	11	43	54	20	70	90	7	2	1	0	0	×	0	0	0	0	0	0	0	0	0	0	89
	19	3.2	1.0	12	45	57	8	29	37	20	74	94	1	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	203
Average, Fall River	------	3.0	0.5	17	19	36	37	6	43	54	25	79	4	5	5	×	3	R	R	×	×	0	0	0	R	2	0	0	
Lakota	------	3.0	.8	17	63	80	3	15	18	20	78	98	1	×	1	R	0	0	0	0	0	0	0	0	0	0	0	0	

Locality 10																													
Lakota	6	2.2	0.4	15	70	85	0	7	7	15	77	92	0	6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	5	2.3	.3	12	21	33	16	38	54	28	59	87	1	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	4	0	0	12	63	75	3	12	15	15	75	90	8	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	154
Morrison	3	0	0	×	5	5	32	49	81	32	54	86	10	3	0	0	0	0	0	0	×	0	0	0	0	0	0	0	118
	2	0	0	7	41	48	4	15	19	11	56	67	27	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	54
Sundance	1	0	0	0	38	38	2	26	28	2	64	66	30	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	127
Average, Lakota	------	2.3	0.4	13	51	64	6	19	25	19	70	89	3	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	
Morrison	------	0	0	4	23	27	18	32	50	22	55	77	19	3	1	0	0	0	0	0	R	0	0	0	0	0	0	0	
Locality 11																													
Fall River	11	3.4	0.4	5	5	10	35	4	39	40	9	49	2	9	0	0	0	0	0	×	0	0	0	0	×	39	0	0	142
	10	2.8	.4	20	10	30	24	6	30	44	16	60	9	5	1	0	0	×(?)	0	×	0	0	0	0	×	24	0	0	157
	9	3.7	.4	9	5	14	33	8	41	42	13	55	3	5	0	0	0	0	0	0	×	0	0	0	×	36	0	0	148
	8	3.7	.4	30	28	58	15	5	20	45	33	78	0	12	1	0	0	0	0	4	0	0	0	0	0	5	0	0	81
Lakota	7	2.9	.4	4	6	10	8	78	86	12	84	96	0	2	2	0	0	0	0	0	×	0	0	0	0	0	0	0	135
	6	2.7	.3	17	73	90	1	7	8	18	80	98	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	213
	5	1.7	1.2	8	86	94	0	3	3	8	89	97	0	3	×	0	0	0	0	0	0	0	0	0	0	0	0	0	155
	4	1.0	1.6	13	69	82	2	6	8	15	75	90	0	×	10	0	0	0	0	0	0	0	0	0	0	0	0	0	133
	3	2.8	.9	5	91	96	0	2	2	5	93	98	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	171
	2	2.9	.8	6	86	92	1	5	6	7	91	98	0	×	×	0	0	0	0	0	0	0	0	0	0	0	×	0	160
	1	1.7	1.2	13	71	84	1	10	11	14	81	95	0	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	188
Morrison	1a	3.5	.5	30	21	51	13	18	31	43	39	82	1	6	4	0	2	0	1	4	0	0	0	0	0	0	0	0	100
Average, Fall River	------	3.4	0.4	16	12	28	27	6	33	43	18	61	4	8	×	0	0	R(?)	0	1	R	0	0	0	×	26	0	0	
Lakota	------	2.2	.9	9	69	78	2	16	18	11	85	96	0	2	2	0	0	0	0	0	R	0	0	0	0	0	R	0	
Locality 12																													
Lakota	7	0	0	1	17	18	10	69	79	11	86	97	0	2	0	0	0	0	0	0	0	0	0	0	0	0	×	0	153
	6	0	0	5	50	55	4	38	42	9	88	97	0	1	×	0	0	0	0	0	0	0	0	0	0	0	×	0	132
	5	0	0	12	84	96	0	3	3	12	87	99	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	147
	4	0	0	21	51	72	2	13	15	23	64	87	4	1	8	0	0	0	0	0	0	0	0	0	0	0	0	0	292
	3	0	0	13	43	56	3	38	41	16	81	97	2	0	×	0	0	0	0	0	0	0	0	0	0	0	0	0	146
Sundance	2	0	0	0	8	8	4	67	71	4	75	79	18	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	103
	1	0	0	0	42	42	1	17	18	1	59	60	37	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	155
Average, Lakota	------	0	0	10	49	59	4	32	36	14	81	95	1	1	2	0	0	0	0	0	0	0	0	0	0	0	R	0	
Sundance	------	0	0	0	25	25	2	42	44	2	67	69	28	×	2	0	0	0	0	0	0	0	0	0	0	0	0	0	

See footnotes at end of table.

TABLE 8.—*Percentages of nonopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*—Continued

Formation	Sample	Grain size of sample,[1] (ϕ)		Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2]																											
				Zircon			Tourmaline			Zircon-tourmaline, combined																					
		Graphic mean	Graphic standard deviation	Angular grais	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 13																															
Fall River	14	2.5	0.3	2	×	3	46	12	58	48	13	61	×	4	19	0	×	×	0	0	0	0	0	×	0	12	0	×	234
	13	3.7	.6	19	5	24	20	×	20	39	5	44	1	7	0	10	1	0	0	0	0	0	0	0	13	21	0	3	241
	12	3.4	1.0	25	7	42	20	×	21	55	8	63	2	11	1	1	0	2	0	1	0	0	0	0	1	17	0	×	170
	11	3.5	.5	37	14	51	10	1	11	47	15	62	×	9	8	17	0	×	0	0	×	0	0	0	0	3	0	0	251
	10	2.8	.4	3	2	5	59	7	66	62	9	71	1	3	6	0	×	0	0	0	0	0	0	×	×	18	0	0	214
Lakota	9	3.4	.8	8	5	13	69	10	79	77	15	92	0	5	0	0	0	0	2	0	0	0	0	0	1	0	0	0	124
	8	1.5	1.1	10	79	89	1	7	8	11	86	97	0	2	1	0	0	0	×	0	0	0	0	0	0	0	0	0	223
	7	.1	1.3	4	78	82	5	11	16	9	89	98	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	177
	6	2.9	.5	12	83	95	1	2	3	13	85	98	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	207
	5	2.8	.5	15	77	92	2	3	5	17	80	97	0	3	×	0	0	0	0	0	0	0	0	0	0	0	0	0	238
	4	2.8	.5	12	25	37	10	50	60	22	75	97	0	1	×	0	0	0	0	0	0	0	0	0	×	0	0	0	154
	3	−0.3	1.0	9	62	71	7	20	27	16	82	98	1	×	×	0	0	0	0	0	0	0	0	0	0	0	0	0	222
	2	1.7	.5	4	1	5	7	75	82	11	76	87	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	173
	1	−0.1	1.2	10	52	62	6	24	30	16	76	92	4	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	218
Average, Fall River	------	3.2	0.6	19	6	25	31	4	35	50	10	60	1	7	7	6	×	×	0	R	R	0	0	R	3	14	0	×	
Lakota	------	1.6	.8	9	52	61	12	22	34	21	74	95	×	2	2	R	0	0	×	0	0	0	0	0	R	0	0	0	

Locality 14

Fall River	8	3.7	0.5	41	31	72	10	7	17	51	38	89	×	7	1	0	0	0	0	1	1	0	0	0	0	0	0	0	166
Lakota	7	3.0	.6	8	80	88	1	5	6	9	85	94	0	5	×	0	0	0	0	×	0	0	0	0	0	0	0	0	137
	6	1.0	1.1	12	72	84	×	9	9	12	81	93	×	1	5	0	0	0	0	0	×	0	0	0	0	0	0	0	162
	5	2.6	.4	11	84	95	0	3	3	11	87	98	0	2	×	0	0	0	0	0	0	0	0	0	0	0	0	0	255
	4	2.5	.4	18	66	84	×	7	7	18	73	91	0	2	7	0	0	0	0	0	0	0	0	0	0	0	0	0	137
	3	2.6	.3	23	42	65	×	14	14	23	56	79	1	2	15	0	0	0	0	0	0	0	0	0	0	0	2	0	166
	2	2.5	.3	9	65	74	0	18	18	9	83	92	1	×	7	0	0	0	0	0	0	0	0	0	0	0	0	×	170
Morrison	1a	0	0	5	15	20	1	2	3	6	17	23	72	2	2	0	0	0	0	×	0	0	0	0	0	0	0	0	157
	1	3.2	.7	8	16	24	14	21	35	22	37	59	21	7	1	12	0	0	0	0	×	0	0	0	0	0	0	0	190
Average, Lakota	------	2.4	0.5	13	68	81	×	10	10	13	78	91	×	2	6	0	0	0	0	R	R	0	0	0	0	0	R	R	
Morrison	------	0	0	6	16	22	8	12	20	14	28	42	47	4	1	6	0	0	0	R	×	0	0	0	0	0	0	0	

See footnotes at end of table.

TABLE 8.—*Percentages of nonopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*—Continued

Formation	Sample	Grain size of sample,[1] (φ)		Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2]																								
				Zircon			Tourmaline			Zircon-tourmaline, combined																		
		Graphic mean	Graphic standard deviation	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 15																												
Fall River	14	5.8	2.5	15	20	35	7	1	8	22	21	43	14	7	2	1	0	0	0	2	0	0	0	0	0	36	0	0	115
	13	2.6	.3	5	3	8	56	22	78	61	25	86	0	2	7	0	0	0	0	0	0	0	0	0	0	5	0	0	120
	12	3.7	.7	17	17	34	29	5	34	46	22	68	1	11	2	0	0	0	0	4	0	0	0	1	0	13	0	0	102
	11	3.2	.4	14	12	26	28	13	41	42	25	67	0	11	1	0	×	0	0	0	0	0	0	0	0	21	0	0	140
	10	0	0	16	14	30	14	4	18	30	18	48	2	8	2	0	0	0	0	2	0	0	0	0	0	38	0	0	50
	9	0	0	12	21	33	33	26	59	45	47	92	2	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	108
	8	3.8	.5	16	25	41	29	15	44	45	40	85	0	8	5	0	0	0	0	2	0	0	0	0	0	0	0	0	110
Lakota	7	3.3	.6	7	21	28	30	32	62	37	53	90	0	7	3	0	0	0	0	0	0	0	0	0	0	0	0	0	130
	6	2.7	.3	6	23	29	23	28	51	29	51	80	0	5	15	0	0	0	0	0	0	0	0	0	0	0	0	0	122
	5	2.7	.4	13	48	61	10	9	19	23	57	80	0	11	7	0	0	0	0	1	0	1(?)	0	0	0	0	0	0	100
	4	2.6	.5	4	55	59	0	23	23	4	78	82	12	×	6	0	0	0	0	0	0	0	0	0	0	0	0	0	109
	3	0	0	12	22	34	×	35	36	13	57	70	13	2	15	0	0	0	0	0	0	0	0	0	0	0	0	0	111
	2	2.7	.4	3	24	27	2	54	56	5	78	83	9	×	8	0	0	0	0	0	0	0	0	0	0	0	0	0	190
	1	0	0	7	27	34	3	37	40	10	64	74	14	2	10	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Average, Fall River	------	3.8	0.9	14	16	30	28	12	40	42	28	70	3	7	3	×	×	0	0	1	0	0	0	×	0	16	0	0	
Lakota	------	2.8	.4	8	31	39	10	31	41	18	62	80	7	4	9	0	0	0	0	×	0	×(?)	0	0	0	0	0	0	

Locality 16

Fall River	31	3.7	1.1	4	4	8	48	26	74	52	30	82	0	3	2	0	0	0	0	0	0	0	0	2	0	11	0	0	114
	30	4.3	0	24	24	48	18	13	31	42	37	79	3	12	4	0	0	0	0	1	0	0	0	0	0	1	0	0	104
	29	5.5	0	5	5	10	40	7	47	45	12	57	4	2	2	0	0	0	0	0	0	0	0	0	0	35	0	0	43
	28	2.9	.3	36	42	78	8	4	12	44	46	90	0	4	6	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	27	3.8	.3	3	2	5	72	11	83	75	13	88	0	5	0	0	0	0	0	3	1	0	0	0	0	3	0	0	101
	26	4.5	0	22	43	65	6	18	24	28	61	89	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0	0	200
Lakota	25	3.2	.6	8	84	92	2	4	6	10	88	98	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	24	3.1	.5	14	82	96	X	2	2	14	84	98	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	186
	23	−0.3	1.1	10	75	85	3	9	12	13	84	97	0	X	2	0	0	0	0	0	0	0	0	0	0	0	0	0	149
	22	2.8	.3	13	78	91	X	6	7	14	84	98	0	X	X	0	0	X	0	0	0	0	0	0	0	0	0	0	171
	21	3.2	.6	21	69	90	X	7	8	22	76	98	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	135
Morrison, upper part	20	2.8	.4	X	50	50	1	34	35	1	84	85	13	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	147
	19	3.1	.5	1	67	68	1	21	22	2	88	90	8	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	146
	18	3.1	.5	1	69	70	3	19	22	4	88	92	3	1	4	0	0	X	0	0	0	0	0	0	0	0	0	0	165
	17	3.4	.6	11	73	84	1	10	11	12	83	95	4	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	140
	16	2.9	.4	1	33	34	2	56	58	3	89	92	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	193
	15	3.1	.5	4	75	79	X	16	17	5	91	96	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	149
	14	3.2	.5	7	78	85	0	10	10	7	88	95	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	165
lower part	13	2.8	.4	3	38	41	X	9	9	3	47	50	49	X	X	X	0	0	0	0	0	0	0	0	0	0	0	0	159
	[5] 12	2.9	.4	1	43	44	X	15	16	2	58	60	38	0	X	X	0	0	0	0	0	0	0	0	0	0	0	0	151
	11	2.8	.4	X	38	39	0	17	17	X	55	56	38	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	170
	10	2.9	.5	3	32	35	0	14	14	3	46	49	47	0	3	1	0	0	0	0	0	0	0	0	0	0	X	0	153
Sundance	9	3.0	.6	3	46	49	X	4	4	3	50	53	43	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	141
	8	3.1	.7	1	23	24	0	15	15	1	38	39	57	0	3	0	0	X	0	0	0	0	0	0	0	0	0	0	155
	7	3.1	.7	1	55	56	0	4	4	1	59	60	37	X	X	X	0	0	0	0	0	0	0	0	0	0	0	0	140
	6	3.1	.7	5	46	51	0	6	6	5	52	57	42	0	X	X	0	0	0	0	0	0	0	0	0	0	0	0	171
	5	3.1	.7	3	38	41	2	15	17	5	53	58	39	0	2	X	0	0	0	0	0	0	0	0	0	0	0	0	179
	4	3.2	.7	7	46	53	1	5	6	8	51	59	39	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	180
	3	2.9	.5	3	35	38	4	12	16	7	47	54	44	X	2	X	0	0	0	0	0	0	0	0	0	0	0	0	168
	2	3.1	.7	6	33	39	10	24	34	16	57	73	22	0	X	4	0	0	0	0	0	0	0	0	0	0	0	0	160
	1	3.6	.6	8	2	10	13	1	14	21	3	24	12	10	X	30	0	0	X	0	X	0	X	0	0	X	0	21	164
Average, Fall River	------	4.1	0.6	16	20	36	32	13	45	48	33	81	1	6	3	0	0	0	0	X	X	0	0	X	0	8	0	0	
Lakota	------	2.4	.6	15	76	91	1	6	7	16	82	98	R	1	X	0	0	R	0	0	0	0	0	0	0	0	0	0	
Morrison	------	3.0	.5	3	54	57	1	21	22	4	75	79	19	X	2	X	0	R	0	0	0	0	0	0	0	0	R	0	
Sundance	------	3.1	.7	4	36	40	3	11	14	7	47	54	38	1	1	4	0	R	R	0	R	0	R	0	0	R	0	2	

See footnotes at end of table.

TABLE 8.—*Percentages of nonopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*—Continued

Formation	Sample	Grain size of sample,[1] (ϕ)		Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2]																									
				Zircon			Tourmaline			Zircon-tourmaline, combined																			
		Graphic mean	Graphic standard deviation	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 17																													
Fall River	18	0	0	49	28	77	12	3	15	61	31	92	0	7	0	0	0	0	0	0	X	0	0	0	0	0	0	0	146
	17	0	0	36	44	80	12	X	13	48	45	93	0	7	0	0	0	0	0	X	X	0	0	0	0	0	0	0	119
	16	0	0	24	54	78	6	6	12	30	60	90	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	139
	15	0	0	22	60	82	7	5	12	29	65	94	X	5	X	0	0	0	0	0	0	0	0	0	0	X	0	0	193
	14	0	0	63	24	87	5	X	6	68	25	93	0	6	0	0	0	0	0	0	1	0	0	0	0	0	0	0	148
	13	0	0	15	55	70	X	7	8	16	62	78	0	2	0	19	0	0	0	X	0	0	0	0	0	X	0	0	138
	12	0	0	26	34	60	19	11	30	45	45	90	0	6	1	0	0	0	0	0	0	0	0	0	0	3	0	0	165
Lakota	11	0	0	24	55	79	5	12	17	29	67	96	0	3	X	0	0	0	0	0	0	0	0	0	0	0	0	0	190
	10	0	0	34	53	87	2	6	8	36	59	95	0	5	0	0	0	0	0	0	0	0	0	0	0	0	X	0	116
	9	0	0	20	54	74	2	16	18	22	70	92	0	3	5	0	0	0	0	0	0	0	0	0	0	0	0	0	152
	8	0	0	16	78	94	2	3	5	18	81	99	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113
	7	0	0	11	84	95	0	3	3	11	87	98	0	2	X	0	0	0	0	0	0	0	0	0	0	0	0	0	158
	6	0	0	11	84	95	1	1	2	12	85	97	0	2	0	0	0	0	0	0	0	0	0	0	0	0	X	0	166
	5	0	0	14	57	71	4	24	28	18	81	99	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	130
	4	0	0	4	5	9	18	72	90	22	77	99	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	133
	3	0	0	19	51	70	1	15	16	20	66	86	1	2	11	0	X	0	0	0	X	0	0	0	0	0	0	0	156
	2	0	0	15	51	66	4	26	30	19	77	96	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	140
	1	0	0	10	61	71	3	23	26	13	84	97	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	155
Average, Fall River	------	0	0	34	43	77	9	5	14	43	48	91	R	6	R	3	0	0	0	R	R	0	0	0	0	X	0	0	
Lakota	------	0	0	16	58	74	4	18	22	20	76	96	R	2	2	0	X	0	0	0	R	0	0	0	0	0	R	0	

Locality 18

Fall River	13	2.9	0.4	13	21	34	34	7	41	47	28	75	3	7	X	0	0	0	0	2	X	0	0	0	X	12	0	0	174
	12	2.7	.4	12	21	33	35	17	52	47	38	85	X	9	X	0	0	0	0	X	0	0	0	0	0	5	0	0	160
	11	2.8	.5	24	40	64	17	11	28	41	51	92	0	7	0	0	0	0	0	X	0	0	0	0	0	X	0	0	139
	10	3.3	.6	13	9	22	22	3	25	35	12	47	0	4	0	0	0	0	0	2	0	0	0	0	15	32	0	0	150
	9	2.6	.6	28	41	69	14	7	21	42	48	90	0	9	0	0	0	0	0	0	X	0	0	0	0	1	0	0	146
	8	2.6	.5	32	39	71	11	7	18	43	46	89	1	9	X	0	0	0	0	0	0	0	0	0	0	X	0	X	169
	7	2.5	.5	13	44	57	18	15	33	31	59	90	X	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	167
	6	0	0	41	43	84	4	2	6	45	45	90	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	144
	5	2.4	.4	18	33	51	28	10	38	46	43	89	0	10	X	0	0	0	0	X	X	0	0	0	0	0	0	0	191
	4	1.7	.5	13	30	43	40	4	44	53	34	87	0	5	7	0	0	0	X	0	X	0	0	0	0	0	0	0	151
	3	1.8	.9	13	71	84	9	1	10	22	72	94	0	5	2	0	0	0	0	0	1	0	0	0	0	0	0	0	191
Lakota	[6] 2	3.6	.6	5	48	53	5	38	43	10	86	96	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200
	1	2.0	.4	9	13	22	3	18	21	12	31	43	0	0	56	0	0	1	0	0	0	0	0	0	0	0	0	0	100
Average, Fall River	------	2.5	0.5	20	36	56	21	8	29	41	44	85	X	8	1	0	0	0	R	X	X	0	0	0	1	5	0	R	
Lakota	------	2.8	.5	7	30	37	4	28	32	11	58	69	0	4	27	0	0	X	0	0	0	0	0	0	0	0	0	0	

Locality 19

Fall River	1	0	0	40	28	68	9	3	12	49	31	80	0	17	0	0	X	0	0	1	X	0	0	0	0	1	0	0	166
	2	0	0	28	13	41	32	4	36	60	17	77	0	12	X	0	0	0	0	3	2	0	0	0	0	6	0	0	205
	3	0	0	21	18	39	41	11	52	62	29	91	X	7	X	0	0	0	X	X	0	0	0	0	0	0	0	0	185
	4	0	0	9	18	27	50	11	61	59	29	88	3	3	5	0	0	0	0	0	0	0	0	0	0	X	X	0	150
	5	0	0	9	28	37	7	10	17	16	38	54	26	0	2	0	10	0	0	0	2	0	2	0	0	2	0	2	43
Lakota	6	0	0	19	59	78	7	9	16	26	68	94	X	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	139
	7	0	0	19	68	87	0	6	6	19	74	93	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	188
	8	0	0	16	34	50	19	24	43	35	58	93	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	111
Average, Fall River	------	0	0	21	21	42	28	8	36	49	29	78	6	8	1	0	2	0	R	1	1	0	R	0	0	2	R	X	
Lakota	------	0	0	16	54	70	10	13	23	26	67	93	R	6	X	0	0	0	0	0	0	0	0	0	0	0	0	0	

See footnotes at end of table.

TABLE 8.—*Percentages of nonopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*—Continued

Formation	Sample	Grain size of sample,[1] (φ): Graphic mean	Grain size of sample,[1] (φ): Graphic standard deviation	Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2]: Zircon: Angular grains	Zircon: Rounded grains	Zircon: Total	Tourmaline: Angular grains	Tourmaline: Rounded grains	Tourmaline: Total	Zircon-tourmaline, combined: Angular grains	Zircon-tourmaline, combined: Rounded grains	Zircon-tourmaline, combined: Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 20																													
Fall River	17	0	0	10	7	17	52	30	82	62	37	99	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	99
Lakota	16	3.4	0.7	10	75	85	1	6	7	11	81	92	0	6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	117
	15	3.3	.4	16	44	60	3	32	35	19	76	95	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	178
	14	3.4	.5	11	50	61	8	30	38	19	80	99	0	1	0	0	0	0	0	0	×	0	0	0	0	0	0	0	135
	13	2.7	.3	9	23	32	12	38	50	21	61	82	12	2	4	0	0	0	×	0	0	0	0	0	0	0	×	0	135
	12	2.3	.5	10	61	71	3	10	13	13	71	84	12	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	179
	11	2.0	.9	7	58	65	4	18	22	11	76	87	10	×	3	0	0	0	0	0	0	0	0	0	0	0	0	0	156
	10	2.3	.6	9	61	70	3	18	21	12	79	91	×	0	×	0	0	0	0	0	0	0	0	0	0	0	0	0	156
	9	2.4	.4	7	58	65	3	19	22	10	77	87	7	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	150
	8a	0	0	8	35	43	9	46	55	17	81	98	0	1	0	0	0	0	0	×	0	0	0	0	0	0	0	0	129
	8	2.8	.5	11	50	61	4	33	37	15	83	98	×	×	0	0	0	0	0	0	0	0	0	0	0	0	×	0	133
	7	2.7	.4	17	56	73	4	19	23	21	75	96	3	×	0	0	0	0	0	0	×	0	0	0	0	0	0	0	150
	6	1.5	.4	9	38	47	11	16	27	20	54	74	15	5	6	0	0	0	0	0	0	0	0	0	0	0	0	0	147
	5	0.7	1.6	13	53	66	8	12	20	21	65	86	10	×	3	0	0	0	0	0	0	0	0	0	0	0	0	0	152
	4	1.9	.8	10	66	76	3	14	17	13	80	93	5	1	×	0	0	0	0	0	0	0	0	0	0	0	0	0	172
	[5] 3	.1	1.3	5	30	35	8	44	52	13	74	87	10	×	3	0	×	0	0	0	0	0	0	0	0	0	×	0	149
	2	2.0	.6	6	48	54	6	24	30	12	72	84	14	0	2	0	0	0	0	0	×	0	0	0	0	0	0	0	167
Average, Lakota	------	2.2	0.7	10	50	60	6	24	30	16	74	90	6	2	2	0	R	0	R	R	R	0	0	0	0	0	R	0	

Locality 21

Lakota	9	0	0	10	72	82	1	17	18	11	89	100	×	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	168
	8	0	0	13	55	68	10	15	25	23	70	93	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	149
	7	0	0	10	77	87	1	10	11	11	87	98	×	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	149
	6	0	0	9	41	50	8	40	48	17	81	98	×	×	0	0	0	0	0	0	0	0	0	0	0	0	0	0	138
Morrison	5	0	0	15	9	24	36	7	43	51	16	67	4	4	0	14	0	0	0	0	1	0	0	0	4	0	0	6	104
	4	0	0	10	3	13	53	15	68	63	18	81	11	4	×	1	0	0	0	0	2	0	0	0	0	0	0	0	131
Sundance	3	0	0	×	43	44	0	19	19	×	62	63	30	0	5	2	0	0	0	0	0	0	0	0	0	0	0	0	149
	2	0	0	0	23	23	3	43	46	3	66	69	26	0	3	2	0	0	0	0	0	0	0	0	0	0	×	0	121
	1	0	0	3	13	16	59	16	75	62	29	91	6	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	78
Average, Lakota	------	0	0	10	62	72	5	20	25	15	82	97	×	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Morrison	------	0	0	13	6	19	45	11	56	58	17	75	7	4	×	7	0	0	0	0	1	0	0	0	2	0	0	3	
Sundance	------	0	0	1	26	27	21	26	47	22	52	74	21	×	3	1	0	0	0	0	0	0	0	0	0	0	R	0	

Locality 22

Fall River	1	2.7	0.4	34	18	52	25	4	29	59	22	81	9	9	0	0	0	0	×	×	0	0	0	0	0	0	0	0	151
	2	2.6	.4	25	9	34	39	7	46	64	16	80	10	9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	190
	3	2.6	.4	25	10	35	32	2	34	57	12	69	11	9	3	2	0	×	1	1	0	0	0	0	3	0	0	0	150
	4[7]	2.4	.4	32	13	45	26	4	30	58	17	75	14	6	4	0	×	0	×	×	0	0	0	0	×	0	0	0	228
Lakota	5	3.2	.6	11	77	88	×	8	8	12	85	97	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	211
	6	3.2	.6	11	76	87	2	7	9	13	83	96	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	154
	7	3.1	.5	22	59	81	3	12	15	25	71	96	0	4	0	0	0	0	0	0	×	0	0	0	0	0	0	0	144
	8	3.2	.6	11	31	42	15	40	55	26	71	97	0	1	×	0	0	×	0	0	0	0	0	0	0	0	0	0	179
	9	2.8	.6	7	16	23	20	51	71	27	67	94	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	145
	10	3.0	.5	10	9	19	14	61	75	24	70	94	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	152
	11	2.5	.5	12	33	45	12	36	48	24	69	93	5	×	2	0	0	0	0	0	0	0	0	0	0	0	0	0	181
	12	2.9	.6	7	3	10	20	65	85	27	68	95	2	×	0	0	0	0	2	0	0	0	0	0	×	0	0	0	124
	13	3.4	.6	16	38	54	12	29	41	28	67	95	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	181
	14	3.1	.9	10	24	34	16	48	64	26	72	98	×	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	176
	15	2.7	.9	12	40	52	3	40	43	15	80	95	3	×	1	0	0	0	0	0	0	0	0	0	0	0	0	0	145
	16	2.3	.6	11	16	27	3	56	59	14	72	86	3	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	156
	17	2.1	.5	2	8	10	2	56	58	4	64	68	6	0	24	2	0	2	0	0	0	0	0	0	0	0	0	0	177
	18	3.3	.6	0	7	7	15	71	86	15	78	93	2	1	0	2	0	×	0	0	0	0	0	×	0	0	0	0	140
	19	3.1	.5	0	0	0	17	82	99	17	82	99	0	×	0	0	0	0	0	0	0	0	0	0	0	0	0	0	141
	20	3.1	.6	×	8	8	17	74	91	17	82	99	0	0	×	0	0	0	×	0	0	0	0	×	0	0	0	0	134
	21	3.4	.5	7	9	16	15	68	83	22	77	99	0	×	0	0	0	0	0	0	0	0	0	0	0	0	0	0	181
	22	2.8	.5	11	18	29	13	52	65	24	70	94	1	3	2	0	×	0	0	0	0	0	0	0	0	0	0	0	182
	23[8]	3.0	.5	×	1	2	15	82	97	16	83	99	0	×	0	0	0	0	0	0	0	0	0	0	0	0	0	0	161
	24	2.6	.9	8	18	26	6	64	70	14	82	96	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	100
	25	2.9	.3	6	7	13	16	71	87	22	78	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	26	4.0	.7	12	32	44	7	43	50	19	75	94	0	3	2	0	0	0	0	0	1	0	0	0	0	0	0	0	200
Average, Fall River	------	2.6	0.4	29	12	41	31	4	35	60	16	76	11	8	2	×	R	R	×	×	0	0	0	0	×	0	0	0	
Lakota	------	3.0	.6	9	24	33	11	51	62	20	75	95	1	1	2	R	R	R	R	0	R	0	0	R	R	0	0	0	

See footnotes at end of table.

TABLE 8.—*Percentages of nonopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*—Continued

Formation	Sample	Grain size of sample,[1] (φ)		Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2]																									
				Zircon			Tourmaline			Zircon-tourmaline, combined																			
		Graphic mean	Graphic standard deviation	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 23																													
Lakota	43	2.4	0.4	20	59	79	X	9	10	21	68	89	8	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	141
Unkpapa	41	2.6	.3	1	82	83	X	14	15	2	96	98	0	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	142
	37	2.7	.4	4	89	93	0	7	7	4	96	100	0	0	X	0	0	0	0	0	0	0	0	0	0	0	X	0	136
	34	2.6	.3	1	96	97	0	2	2	1	98	99	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0	0	140
	30	2.7	.3	3	89	92	0	7	7	3	96	99	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	150
	26	2.8	.4	3	80	83	X	15	16	4	95	99	0	0	X	0	0	0	0	0	0	0	0	0	0	0	X	0	146
	22	2.8	.3	5	82	87	0	7	7	5	89	94	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	145
	18	2.8	.5	2	73	75	0	24	24	2	97	99	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	133
	14	3.0	.5	3	90	93	X	5	6	4	95	99	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	116
	12	3.3	.5	4	84	88	0	12	12	4	96	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	129
	9	3.0	.4	3	84	87	0	12	12	3	96	99	0	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	154
	5	3.0	.5	2	94	96	0	4	4	2	98	100	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	134
	4	3.0	.5	0	85	85	0	5	5	0	90	90	9	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	153
	1	2.8	.3	1	88	89	0	1	1	1	89	90	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113
Average, Unkpapa	------	2.9	0.4	2	86	88	X	9	9	2	95	97	2	R	X	0	0	0	0	0	R	0	0	0	0	0	R	0	

Locality 24

Fall River	20	3.1	0.6	20	18	38	27	8	35	57	26	83	0	13	X	0	0	X	0	X	2	0	0	0	0	X	0	0	134
	19	3.5	.5	19	15	34	31	3	34	50	18	68	0	9	X	0	0	X(?)	0	1	1	0	0	0	0	20	0	0	193
	18	2.6	.4	28	42	70	10	4	14	38	46	84	X	9	7	0	0	0	0	0	0	0	0	0	0	0	0	0	126
	17	2.5	.3	25	59	84	4	0	4	29	59	88	0	4	8	0	0	0	0	0	0	0	0	0	0	0	0	0	147
	16	2.5	.3	19	27	46	20	2	22	39	29	68	4	4	24	0	0	0	0	0	X	0	0	0	0	0	0	0	135
	15	2.0	.5	22	25	47	6	X	6	28	25	53	9	6	32	0	0	0	0	0	0	0	0	0	0	0	0	0	163
	14	1.7	.3	14	34	48	16	2	18	30	36	66	7	7	20	0	0	0	X(?)	0	0	0	0	0	0	0	0	0	137
	12	3.5	.6	14	17	31	25	30	55	39	47	86	X	2	2	0	0	0	0	0	X	0	0	0	0	X	0	0	134
	10	3.6	.5	20	29	49	29	12	41	49	41	90	0	8	0	0	0	0	0	1	1	0	0	0	0	0	0	0	64
Lakota	8	3.3	.8	19	33	52	9	32	41	28	65	93	2	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	165
	7	2.6	.6	25	68	93	2	1	3	27	69	96	0	X	3	0	0	0	0	0	0	0	0	0	0	0	0	0	125
	6	2.6	.4	18	51	69	2	28	30	20	79	99	0	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	173
	5	2.2	.5	20	74	94	0	4	4	20	78	98	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	173
	4	2.6	.5	19	66	85	X	13	14	19	79	98	0	X	X	0	0	0	0	X	0	0	0	0	0	0	X	0	153
	3	1.7	.6	24	64	88	0	4	4	24	68	92	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	132
	2	.7	1.5	18	73	91	0	5	5	18	78	96	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	225
	1	3.0	.6	14	41	55	3	34	37	17	75	92	0	3	5	0	0	0	0	0	0	0	0	0	0	0	0	0	162
Average, Fall River	------	2.8	0.4	19	30	49	20	7	27	39	27	66	2	7	10	0	0	R	R(?)	R	X	0	0	0	0	3	0	0	
Lakota	------	2.3	.7	19	59	78	2	15	17	21	74	95	R	X	3	0	0	0	0	R	0	0	0	0	0	0	R	0	

Locality 25

Fall River	1	3.2	0.5	22	30	52	25	4	29	47	34	81	2	15	X	0	0	0	0	1	X	0	0	0	0	0	0	0	140
	2	3.8	.4	14	14	28	39	21	60	53	35	88	0	8	4	0	0	0	0	0	0	0	0	0	0	0	0	0	119
	3	2.8	.5	23	19	42	22	12	34	45	31	76	3	12	8	0	0	0	0	0	0	0	0	0	0	X	0	0	149
	4	3.6	.7	42	17	59	19	2	21	61	19	80	1	17	0	0	0	0	0	X	2	0	0	0	0	0	0	0	132
	5	1.6	.3	30	27	57	21	3	24	51	30	81	4	7	6	0	0	0	X(?)	X	X	0	0	0	0	0	0	0	149
	6	1.7	.3	18	8	26	36	6	42	64	14	78	2	6	9	0	X	0	X(?)	0	0	0	0	0	0	0	0	0	143
	7	3.4	.5	42	26	68	11	0	11	53	26	79	4	14	0	0	0	0	0	2	X	0	0	0	0	0	0	0	140
	8	3.1	.8	24	18	42	26	11	37	50	29	79	4	17	0	0	0	0	0	0	X	0	0	0	0	0	0	0	157
	9	1.9	.4	18	32	50	16	3	19	34	35	69	5	6	18	0	0	0	X	X	X	0	0	0	0	0	0	0	136
	10	2.4	.4	31	41	72	8	3	11	39	44	83	1	11	4	0	0	0	0	X	0	0	0	0	0	0	0	0	145
	11	2 6	.4	23	35	58	18	10	28	41	45	86	3	10	1	0	0	0	0	X	0	0	0	0	0	0	0	0	175
	12	2.3	.4	18	31	49	15	6	21	33	37	70	14	5	9	0	0	X	1	X	0	0	0	0	0	0	0	0	174
Lakota	13	1.8	.8	13	76	89	X	9	9	13	85	98	0	X	1	0	0	0	0	0	0	0	0	0	0	0	0	0	139
	14	1.8	.7	15	68	83	1	14	15	16	82	98	0	0	2	0	0	0	0	0	X	0	0	0	0	0	0	0	157
	15	1.8	.5	15	60	75	3	13	16	18	73	91	0	2	6	0	X	0	0	0	0	0	0	0	0	0	0	0	176
	16	2.9	.4	5	18	23	34	35	69	39	53	92	0	5	2	0	0	0	0	1	0	0	0	0	0	0	0	0	100
	17	3.2	.5	11	39	50	2	42	44	13	81	94	0	2	4	0	0	0	0	0	0	0	0	0	0	0	0	0	114
	18	3.0	.8	4	51	55	3	34	37	7	85	92	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	108
	19	3.3	.7	10	46	56	1	32	33	11	78	89	0	1	10	0	0	0	0	0	0	0	0	0	0	0	0	0	116
	20	2.8	.3	2	35	37	0	45	45	2	80	82	0	1	17	0	0	0	0	0	0	0	0	0	0	0	0	0	223
	21	2.8	.5	3	33	36	4	44	48	7	77	84	11	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	174
	22	3.3	.6	7	53	60	2	27	29	9	80	89	6	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	150

See footnotes at end of table.

TABLE 8—*Percentages of monopaque heavy minerals in 0.062- to 0.125-mm fraction and grain sizes of samples from the Inyan Kara Group and associated rocks, Black Hills*—Continued

Formation	Sample	Grain size of sample,[1] (φ)		Nonopaque heavy minerals, 0.062- to 0.125-mm size fraction[2]																									
				Zircon			Tourmaline			Zircon-tourmaline, combined																	
		Graphic mean	Graphic standard deviation	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Garnet	Rutile	Staurolite	Apatite	Hornblende	Epidote	Diaspore	Brookite	Anatase	Kyanite	Sphene	Sillimanite	Chlorite	Chloritoid	Spinel	Biotite	Grains counted
Locality 25—Continued																													
	23	2.8	0.2	4	18	22	13	55	68	17	73	90	6	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	103
	24	3.9	.7	1	10	11	14	70	84	15	80	95	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	102
	25	3.5	.5	4	25	29	6	49	55	10	74	84	12	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	133
	26	3.2	.6	9	41	50	4	34	38	13	75	88	9	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	140
	27	2.8	.4	2	41	43	5	41	46	7	82	89	6	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	180
	28	3.8	.7	4	45	49	7	32	39	11	77	88	6	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	110
	29	3.4	.4	5	25	30	6	55	61	11	80	91	5	4	0	0	0	0	0	0	X	0	0	0	0	0	0	0	107
	30	3.7	.8	7	33	40	4	43	47	11	76	87	7	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	127
	31	3.3	.5	3	25	28	3	63	66	6	88	94	4	2	X	0	0	0	0	0	0	0	0	0	0	0	0	0	154
	32	3.0	.5	3	41	44	6	34	40	9	75	84	13	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	181
Unkpapa	33	3.0	.3	1	84	85	0	13	13	1	97	98	0	X	2	0	0	0	0	0	0	0	0	0	0	0	0	0	147
Average, Fall River		2.7	0.4	25	25	50	22	7	29	47	32	79	4	10	5	0	R	R	X	X	X	0	0	0	0	R	0	0	
Lakota		3.0	.6	6	39	45	6	39	45	12	78	90	5	2	3	0	R	0	0	R	R	0	0	0	0	0	0	0	

Locality 26 (SE¼ sec. 11, T. 55 N., R. 67 W., Crook County, Wyo.)																												
Newcastle, lower part	0	0	9	11	20	25	4	29	34	15	49	4	6	7	0	0	0	0	0	0	0	0	0	0	33	0	×	135
Locality 27 (NW¼ sec. 28, T. 45 N., R. 61 W., Weston County, Wyo.)																												
Newcastle:																												
Upper part	0	0	14	5	19	57	10	67	71	15	86	×	9	0	0	0	0	0	0	×	0	0	0	0	4	0	0	139
Lower part	0	0	31	27	58	28	4	32	59	31	90	1	7	×	0	0	0	0	×	×	0	1	0	0	×	0	0	151
Average, Newcastle	0	0	22	16	38	43	7	50	65	23	88	×	8	×	0	0	0	0	×	×	0	0	0	0	2	0	0	
Locality 28 (NW¼ sec. 12, T. 54 N., R. 65 W., Crook County, Wyo.)																												
Sundance, Hulett Sandstone Member, middle part	0	0	8	45	53	5	8	13	13	53	66	20	8	4	4	0	0	0	×	×	0	0	0	0	0	0	0	119
Locality 29 (NW¼ sec. 20, T. 53 N., R. 65, W., Crook County, Wyo.)																												
Sundance, Hulett Sandstone Member, middle part	0	0	2	63	65	0	3	3	2	66	68	28	2	2	0	0	0	0	×	×	0	0	0	0	0	0	0	130

[1] Zero indicates value not determined.
[2] Zero indicates mineral not found.
[3] Five percent unidentified blue mineral, uniaxial positive.
[4] One grain of corundum(?).
[5] One grain of monazite(?).
[6] One grain of augite.
[7] One grain of corundum.
[8] One grain of monazite.

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