Stratigraphy of the Inyan Kara Group and Localization of Uranium Deposits, Southern Black Hills, South Dakota and Wyoming

GEOLOGICAL SURVEY PROFESSIONAL PAPER 763

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

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By GARLAND B. GOTT, DON E. WOLCOTT, and C. GILBERT BOWLES

ABSTRACT

The Inyan Kara Group in the southern Black Hills consists of the Lakota and Fall River Formations of Early Cretaceous age. The Lakota Formation constitutes approximately the lower two-thirds of the Inyan Kara Group, and the Fall River Formation constitutes approximately the upper one-third. The rocks are of continental origin and were deposited under variable depositional environments, resulting in a sequence of many rock units, each composed of several facies.

The Lakota Formation is composed of the Chilson, Minnewaste Limestone, and Fuson Members and ranges in thickness from 200 to 500 feet. The Chilson Member is composed largely of fluvial deposits that can be divided into two major units, which have been designated fluvial units 1 and 2.

The Minnewaste Limestone Member locally overlies the Chilson Member in the southern Black Hills but is not known to exist elsewhere.

From east to west the Fuson Member successively overlaps the Minnewaste Limestone Member and both units of the Chilson Member. At places this overlap brings the Fuson Member in contact with the Morrison Formation. The member is composed of red, green, and gray siltstone and mudstone that locally interfingers with a sandstone designated as fluvial unit 3. After deposition of the fine-grained siltstone and mudstone, deep channels were eroded and then filled with a fluvial sandstone, designated fluvial unit 4.

The Fall River Formation is composed of a heterogeneous group of rocks that ranges in thickness from 100 to 160 feet. Laminated carbonaceous siltstones and fine-grained sandstones are abundant in the lower part of the formation. These siltstones and sandstones are truncated by a thick crossbedded fluvial sandstone, designated fluvial unit 5. Fluvial unit 5 grades laterally into a fine-grained facies composed of tabular beds of alternating sandstone, siltstone, and mudstone. The upper part of the Fall River Formation is composed of a variegated mudstone 20–25 feet thick overlain by a sandstone similar to that in fluvial unit 5. This sandstone also grades laterally into a fine-grained facies.

Petrographic studies indicate that the Unkpapa Sandstone of Jurassic age and sandstones in the overlying Inyan Kara Group are orthoquartzites and feldspathic orthoquartzites derived mainly from preexisting sedimentary rocks. Sandstones of each fluvial unit of the Inyan Kara are identifiable by a characteristic mineral assemblage. Mineral assemblages of fluvial units 1 and 2 of the Chilson Member of the Lakota Formation are derived primarily from older sedimentary rocks and contain relatively little angular detrital material from igneous and metamorphic rocks which cropped out east and southeast, whereas the mineral assemblage of fluvial unit 5 of the Fall River Formation contains a significantly larger proportion of this material. Mineral assemblages of fluvial units 3 and 4 of the Fuson Member represent transitional assemblages having a smaller proportion of rounded grains from sedimentary rocks than the Chilson Member but a larger proportion than the Fall River Formation. The shape and orientation of the fluvial units and the direction of dip of the crossbeds within the sandstones indicate that the sandstones were deposited principally by streams flowing northwestward. It seems likely that most of the detritus that composes the Inyan Kara rocks was derived from areas southeast and southwest of the Black Hills.

The Black Hills uplift of Laramide age is an elongate northwest-trending dome about 125 miles long and 60 miles wide. Precambrian igneous and metamorphic rocks are exposed in the central part of the uplift, and outward-dipping Paleozoic and Mesozoic rocks form cuestas and hogbacks around the central core. Folds constitute the major structural features, and faults, which generally have less than 100 feet of displacement, are secondary features. In Early Cretaceous time minor deformation along concealed northeast-trending structures of Precambrian age affected the courses of the northwest-flowing consequent streams and their tributaries, thereby influencing the location of the fluvial sandstone deposits of the Inyan Kara Group. The recurrent deformation along the northeast-trending structures, both during and after the Early Cretaceous, also fractured the Paleozoic and Mesozoic rocks and indirectly contributed to the formation of collapse structures and breccia pipes of Tertiary to Holocene age.

The Laramide uplift of the Black Hills caused the dome to be breached by erosion, resulting in ground-water recharge of the Englewood, Pahasapa, and Minnelusa Formations of Devonian to Permian age and ground-water movement down the flanks of the dome. Artesian water ascended along fractures in these aquifers and dissolved evaporites in the Minnelusa Formation. Collapse of beds overlying the evaporite zone resulted in subsidence breccias and breccia pipes that extend upward to the Inyan Kara Group. This same process continues today at the margin of the Black Hills. The breccia pipes constitute part of a "plumbing" system through which artesian waters transported low concentrations of uranium into formations of the Inyan Kara where sandstone-uranium deposits were formed.

Uranium is introduced into the Inyan Kara with the artesian recharge of calcium sulfate type water from the Minnelusa. As this water migrates downdip, it is modified by ion exchange and sulfate reduction to either a sodium sulfate or a sodium bicarbonate type water, causing an increase in

pH values and a decrease in Eh values. Reduction of sulfate ions in the ground water was a major factor in creating a favorable environment for the precipitation of uranium.

Other factors that affect localization of the uranium deposits pertain to the concentration of metals in the ground water and to the rate of ground-water flow. Oxidation of uranium deposits near the Inyan Kara outcrop may locally increase the concentration of uranium in the ground water and thereby increase the volume of uranium transported to the site of deposition. The distribution of the fluvial sandstones directly affects the rate of ground-water flow and, therefore, the volume of transported uranium.

INTRODUCTION

In 1951 uranium was discovered in the southern Black Hills by Jerry G. Brennan of Rapid City, S. Dak. (Page and Redden, 1952). This discovery caused an influx of prospectors and mining companies into the area, resulting in the rapid discovery of many small carnotite-type uranium deposits.

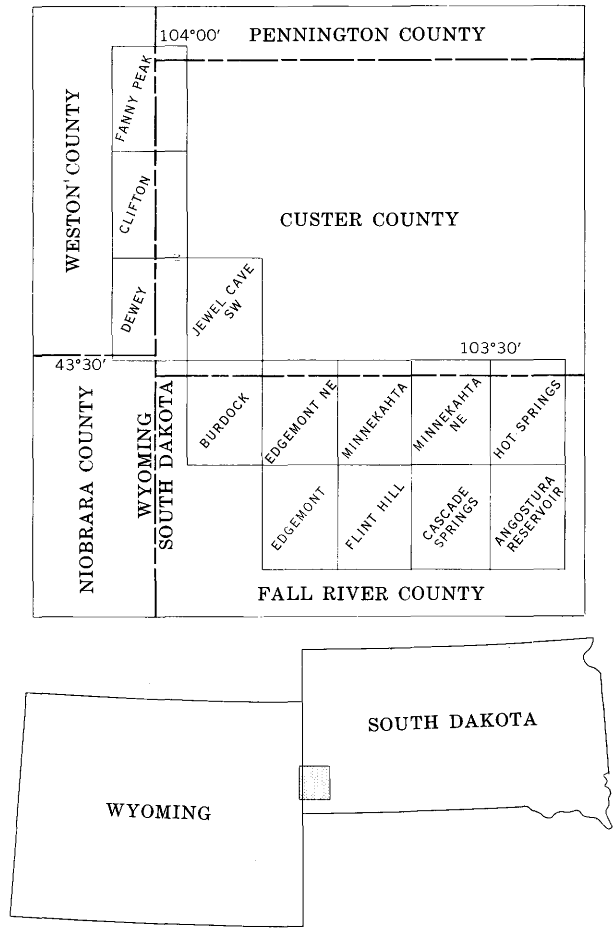
Although the reconnaissance geology had been mapped by N. H. Darton and published in several reports during the first decade of this century, more detailed geology was needed as an aid in prospecting for the uranium deposits. For this reason a program of detailed geologic investigations was carried out from 1954 through 1958 by the U.S. Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission. The principal objectives of the investigations were to determine the relation of the deposits to their geologic and geochemical environments and to determine criteria that would be useful in the exploration for concealed deposits.

As a result of these investigations thirteen 7½-minute quadrangles, as shown in figure 1, were mapped and described in detail by Wilmarth and Smith (1957a–d), Brobst (1961), Wolcott, Bowles, Brobst, and Post (1962), Brobst and Epstein (1963), Connor (1963), Gott and Schnabel (1963), Schnabel (1963), Braddock (1963), Cuppels (1963), Ryan (1964), Wolcott (1967), Post (1967), and Bell and Post (1971).

This report summarizes information about the stratigraphy, petrography, and factors affecting localization of ore deposits in the formations of the Inyan Kara Group discussed in detail in the reports listed in the preceding paragraph. In addition, unpublished information about the stratigraphy of the Minnekahta quadrangle and unpublished maps of the Runge mine by V. R. Wilmarth, formerly with the U.S. Geological Survey, were utilized.

The quadrangle geologic maps have been recompiled at a reduced scale on plate 1, which represents an area extending from Hot Springs, S. Dak., northwestward around the periphery of the Black Hills nearly to Newcastle, Wyo. A restored cross section (pl. 1, north half), constructed from the detailed maps and from many measured sections in the 13 quadrangles, summarizes the stratigraphic relations published elsewhere.

The Inyan Kara rocks of Early Cretaceous age are the ore-bearing formations. These rocks were



Quadrangle	*Reference*
Fanny Peak	Brobst and Epstein (1963).
Clifton	Cuppels (1963).
Dewey	Brobst (1961).
Jewel Cave SW	Braddock (1963).
Burdock	Schnabel (1963).
Edgemont NE	Gott and Schnabel (1963).
Minnekahta:	
West-central part	Wilmarth and Smith (1957a).
East-central part	Wilmarth and Smith (1957b).
Southeast part	Wilmarth and Smith (1957c).
Southwest part	Wilmarth and Smith (1957d).
Minnekahta NE	Wolcott, Bowles, Brobst, and Post (1962).
Hot Springs	Wolcott (1967).
Edgemont	Ryan (1964).
Flint Hill	Bell and Post (1971).
Cascade Springs	Post (1967).
Angostura Reservoir	Connor (1963).

FIGURE 1. — Index map showing 7½-minute quadrangles mapped that contain rocks of the Inyan Kara Group in the southern Black Hills.

deposited in varying continental environments, resulting in a sequence of diverse rock units, each composed of several facies. The stratigraphic complexities are such that it was necessary to map the beds in considerable detail before the sedimentary history could be determined. Other detailed studies were required to evaluate the effects of the Inyan Kara stratigraphy and structure on the problems of ore localization.

STRATIGRAPHY OF THE INYAN KARA GROUP

The Inyan Kara Group of Early Cretaceous age is composed of the Lakota and Fall River Formations. The Lakota Formation is 200–500 feet thick and makes up about the lower two-thirds of the group. The formation is composed of a diverse sequence of deposits laid down in streams, flood plains, lakes, and swamps. The Fall River Formation is 100–160 feet thick and makes up the upper one-third of the group. It is largely composed of a heterogeneous sequence of fluvial sandstones, siltstones, and mudstones. In the western part of the mapped area the Lakota Formation is underlain by the Morrison Formation of Jurassic age, but in the eastern part of the area it is underlain by the Unkpapa Sandstone, a formation thought to be equivalent in age to the Morrison (Imlay, 1947). The Fall River Formation is overlain by the Lower Cretaceous Skull Creek Shale.

Darton (1901) established, in ascending order, the names Lakota Formation, Minnewaste Limestone, Fuson Shale, and Dakota Sandstone for the sequence of rocks here referred to as the Inyan Kara Group. Later, Russell (1928) discovered that Darton's Dakota Sandstone was older than the type Dakota, and he changed the name from Dakota Sandstone to Fall River Formation. Rubey (1931) later assigned the Lakota Formation, the Fuson Shale, and the Fall River Formation to the Inyan Kara Group. As a result of a recent study of the Inyan Kara stratigraphy in the Black Hills, Waagé (1959) proposed that a twofold division of the Inyan Kara Group be established, with the lower part called the Lakota Formation and the upper part called the Fall River Formation. He further proposed that the boundary between the Fall River and the Lakota Formations be placed at a transgressive disconformity that can be recognized throughout the Black Hills region. He reduced the Fuson Shale and the Minnewaste Limestone to member status within the Lakota.

Detailed mapping subsequent to Waagé's (1959) regional stratigraphic studies has indicated that the pre-Fuson Lakota rocks, or the pre-Minnewaste rocks where the Minnewaste is present, are composed of two complex fluvial units, each predominantly composed of channel and flood-plain facies. These two units were called the Chilson Member by Post and Bell (1961). In some places in the Elk Mountains in the Clifton quadrangle, the Chilson Member is absent, and rocks of Fuson age apparently rest on the Morrison Formation (pl. 1, north half). Thus the Fuson Member rests on progressively older rocks from east to west, and its lower contact must locally represent a major hiatus.

While mapping in the southern Black Hills, we found the following informal terminology for the major fluvial units within the Inyan Kara Group to be useful. This terminology includes fluvial units 1 and 2 in the Chilson Member, 3 and 4 in the Fuson Member, and 5 and 6 in the Fall River Formation. Because of the interest in the uranium deposits in the area, many of the maps were published in preliminary form soon after their completion. Later it was found that some of the numbered units on these maps were of no regional significance and that the implied age relations of others were incorrect. These discrepancies and the current designation of the various numbered units are shown in table 1.

LAKOTA FORMATION

The lower part of the Lakota Formation is composed largely of fluvial deposits. These can be divided into two major units, designated fluvial units 1 and 2 (pl. 1, north half), which together are equivalent to the Lakota Sandstone of Darton and Paige (1925) and which Post and Bell (1961) included within the redefined Lakota Formation as the Chilson Member. Unit 1, the oldest, is present throughout most of the area between lower Chilson Canyon and the Elk Mountains (pl. 1). Unit 2, which overlaps unit 1, is present in the area between Hot Springs and Craven Canyon and in the southern part of the mapped area. It is thickest in the vicinity of Cascade Springs.

In the vicinity of Hot Springs and Cascade Springs, the Minnewaste Limestone Member, of lacustrine origin, overlies the Chilson Member (pl. 1). Between the Cascade Springs area and the northern part of the Burdock quadrangle, the limestone is present as small isolated patches, but it has not been found farther to the northwest.

Three units within the Fuson Member are shown on the geologic map (pl. 1). The most widespread unit is composed of red, green, and gray siltstone and mudstone, probably of lacustrine origin. Highly polished chert and quartzite pebbles, some of which contain Paleozoic fossils, are sparsely distributed throughout this unit. In the Pass Creek and Elk

TABLE 1. — *Unit designations*

[Lithologies of units are described on map explanations of previously published
unit designations does not necessarily imply correlation between

AREA		FANNY PEAK QUADRANGLE		CLIFTON QUADRANGLE	DEWEY QUADRANGLE			JEWEL CAVE SW QUADRANGLE	BURDOCK QUADRANGLE			EDGEMONT NE QUADRANGLE			EDGEMONT QUADRANGLE	MINNEKAHTA QUADRANGLE	
Source of data		1		2	3		4	5	6		7	8		9	10	11	
Fall River Formation	Upper unit	Kfums		Kfums	Kfr	ms	Kfums	Kfums	Kfr	sm m$_6$	Kfusm Kfum	Kfr	sm s$_6$,s m$_5$	Kfusm Kfus Kfum	Kfusm Kfus$_6$ Kfum		
	Middle unit	Kfml	Kfms$_5$	Kfms$_5$ Kfmsm Kfmm	Kfr	s$_5$	Kfms$_5$	Kfms$_5$ Kfmsm Kfmm	Kfr	s$_5$ sm	Kfms$_5$ Kfmsm	Kfr	s,s$_6$ sm ss	Kfms$_5$ Kfmsm Kfmss	Kfms$_5$ Kfmsm	Kfr	sm s$_5$,s
	Lower unit	Kfml	Kflss	Kflss	Kfr	st	Kflst	Kflst	Kfr	ss s	Kflss Kfls	Kfr	ss	Kflss	Kflss	Kfr	m
Lakota Formation	Fuson Member	Klfm Klfs$_3$		Klfm Klfs Klfs$_3$	Kfl	s ms s,sm s$_1$	Klfs$_4$ Klfm Klfs Klfs$_3$	Klfs4 Klfm Klfs Klfd Klfs$_3$	Kfml	m s$_4$ m s$_3$ 2a	Klfm$_4$ Klfs$_4$ Klfm Klfs Klfs$_3$	Kfml	m s$_4$ m s$_3$	Klfm$_4$ Klfs$_4$ Klfm Klfs	Klfs$_4$ Klfm Klfs	Kfml	s$_4$ ss,s
	Minnewaste Limestone Member				Kfl				Kfml	l	Klm	Kfml	l	Klm		Kfml	
	Chilson Member	Klcs$_1$ Klcst		Klcs$_1$ Klcst	Kfl	s$_1$ m	Klcs$_1$ Klcm	Klcsm$_1$ Klcms$_1$ Klcs$_1$ Klcst$_1$	Kfml	s$_1$ sm	Klcs$_1$ Klcsm$_1$	Kfml	m s m s$_1$ sm,m sm	Klcs$_2$ Klcm$_2$ Klcm Klcs$_1$ Klcsm$_1$ Klcsh	Klcs$_2$ Klcm Not exposed	Kfml	s,s$_1$ m,sm,ss sm,m s$_1$,s sm

SOURCE OF DATA

1. Brobst and Epstein (1963, pl. 25).
2. Cuppels (1963, pl. 23).
3. Brobst (1958a, b).
4. Brobst (1961, pl. 5).
5. Braddock (1963, pl. 20).
6. Schnabel (1958); Schnabel and Charlesworth (1958 a, b, c, d).
7. Schnabel (1963, pl. 17).
8. Gott and Schnabel (1956a, b, c, d, e, f).
9. Gott and Schnabel (1963, pl. 12).
10. Ryan (1964, pl. 27).
11. Wilmarth and Smith (1957a, b, c, d).
12. Bell and Post (1957a, b, c, d, e, f).
13. Bell and Post (1971, pl. 32)
14. Wolcott, Bowles, Brobst, and Post (1962).
15. Post and Cuppels (1959a, b); Post and Lane (1959a, b); Post (1959a, b).
16. Post (1967, pl. 29).
17. Connor (1963, pl. 11).
18. Wolcott (1967, pl. 28).
19. Mapel and Gott (1959).

Mountains area a conglomeratic sandstone designated as fluvial unit 3 interfingers with the basal Fuson mudstones, and is included within the Fuson Member. This sandstone rests successively on fluvial unit 1, on the Morrison Formation, and locally on the Redwater Shale Member of the Sundance Formation. After the variegated mudstones of the Fuson were deposited, they were locally dissected by pre-Fall River erosion, and the channels were filled with a medium- to coarse-grained sandstone. This sandstone has been included within the Fuson Member and designated as fluvial unit 4.

In addition to the three units just mentioned, other sandstones occur locally. The scale of the geologic map is so small that these units cannot be shown; their presence is indicated only on the cross section (pl. 1).

Several erosional unconformities extend throughout the southern Black Hills. (1) The sandstone facies of fluvial unit 1 seems to be unconformable with the underlying black fissile Lakota shale, mapped as part of fluvial unit 1, or with the underlying Morrison Formation. (2) The contact between fluvial units 1 and 2 is almost everywhere within the *of the Inyan Kara Group*

U.S. Geol. Survey reports and on plate 1 of the present report. Position of quadrangles. Crosshatch pattern indicates rock unit is absent]

FLINT HILL QUADRANGLE			MINNEKAHTA NE QUADRANGLE	CASCADE SPRINGS QUADRANGLE			ANGOSTURA RESERVOIR QUADRANGLE		HOT SPRINGS QUADRANGLE	SOUTHERN BLACK HILLS	SOUTHERN BLACK HILLS			
12		13	14	15		16	17		18	19	Present report (pl. 1)			
Kfr	sm	Kfust		Kfr		Kfuss	Kfsm		Kfus	Siltstone, sandstone, mudstone, and shale	Kfus$_6$	Fluvial unit 6	Upper unit	Fall River Formation
	s$_6$	Kfus$_6$			s$_5$,s	Kfus$_6$			Kfusm	Sandstone	Kfusm			
	m	Kfum			m,st,sst	Kfum			Kfum	Red and gray mudstone	Kfum			
	sm	Kfmsm Kfmm Kfmst Kfms$_5$	Kf middle and lower undivided		m	Kfmm Kfmss Kfms$_5$		Kfs$_5$	Kfms$_5$	s$_5$ Thin-bedded sandstone and siltstone	Kfms$_5$	Fluvial unit 5	Middle unit	
	s$_6$				s$_5$,s									
	m				m	Kfmsm			Kfmsm		Kfmsm			
	st	Kflst			sst	Kflss Kflst	Kfss		Kflss	Carbonaceous shale, siltstone, mudstone, or sandstone	Kflss		Lower unit	
Kfml	st	Klfm$_4$		Klf	s$_4$	Klfs$_4$	Klfm		Klfs$_4$	s$_4$ Variegated mudstone, siltstone, sandstone	Klfm$_4$	Fluvial unit 4	Fuson Member	Minnewaste Limestone Member
	s$_4$,s	Klfs$_4$									Klfs$_4$			
	m	Klfm	Klf		m	Klf			Klf		Klfm			
		Klfs						Klfs			Kflss			
										s$_2$,s$_3$(?)	Klfs$_3$	Fluvial unit 3		
	l	Klm		Klm		Klm	Klm		Klm	Minnewaste Limestone Member	Klm			
	m									s$_3$ Siltstone, claystone, mudstone, some interbedded sandstone			Chilson Member	Lakota Formation
	s$_2$	Klcs$_2$	Klcs$_2$	Klu	s$_2$	Klcs$_2$	Klcs$_2$		Klcs$_2$		Klcs$_2$	Fluvial unit 2		
	sm,m,s	Klcsm$_2$			m,sm	Klcm$_2$ Klcsm$_2$	Klcm$_2$			Interbedded mudstone, siltstone, and sandstone	Klcu$_2$			
	sm,st													
	s$_1$	Klcs$_1$ Klcm Klcst								s$_1$ Carbonaceous shale, siltstone, mudstone, or sandstone	Klcs$_1$ Klcu$_1$	Fluvial unit 1		

fine-grained poorly exposed flood-plain facies of the two units. The contact relations, therefore, can rarely be observed. The regional relations, however, suggest that unit 1 originally may have extended farther eastward than it now does. Black fissile carbonaceous shale similar to that which occurs below the sandstone facies of fluvial unit 1 is present several miles east of the main body of sandstone in this unit. One such area is near the mouth of Fall River canyon (W½ sec. 30, T. 7 S., R. 6 E.), where the carbonaceous shale underlies fluvial unit 2. We observed similar shale in the Angostura Reservoir quadrangle. Inasmuch as the carbonaceous shale is known to occur only as part of, or underneath, unit 1, these isolated patches of shale are probably erosional remnants of unit 1. If they are, an unconformity must exist between units 1 and 2. (3) The Fuson Member overlaps successively the Minnewaste Limestone Member and both units of the Chilson Member. At places this overlap brings the Fuson Member in contact with the Morrison Formation and indicates an unconformity of regional magnitude. (4) Fluvial unit 4, at the top of the Fuson Member, fills deep erosional irregularities in the Fuson variegated mudstones, particularly in the Cascade Springs, Flint Hill, Edgemont, and Edgemont NE quadrangles.

CHILSON MEMBER

FLUVIAL UNIT 1

Fluvial unit 1 is present in the region northwest of the eastern part of the Flint Hill quadrangle and is composed of sandstone, shale, siltstone, and mudstone. Locally, black fissile shale has been mapped as the basal part of this unit. The unit consists of a complex of channel sandstone deposits and their fine-grained equivalents and apparently was deposited under predominantly fluvial conditions. The unit is an elongate body whose long axis is oriented northwestward (pl. 1). Generally, the central part of the unit is a series of light-brownish-gray fine to very fine grained channel sandstones. The sandstones grade laterally into other fine-grained deposits composed of thin alternating fine-grained sandstones, siltstones, and mudstones. This unit is one of the four uranium-producing units in the Inyan Kara Group of the southern Black Hills.

The channel-type sandstone facies of unit 1 has been described by Bell and Post (1971), Braddock (1963), Brobst (1961), Brobst and Epstein (1963), Cuppels (1963), Gott and Schnabel (1963), and Schnabel (1963). The sandstone is exposed throughout much of the area between the Cheyenne River canyon in the southern part of the Flint Hill quadrangle and the south end of the Elk Mountains in the Dewey quadrangle. It is best exposed in Cheyenne, Chilson, and Craven Canyons, where it forms massive nearly vertical cliffs 75–100 feet high. It is composed of numerous discrete filled channels resulting in a complex sequence of scour and fill structures.

The sandstone is light brownish gray or yellowish gray and is fine to very fine grained, except for a few medium- to coarse-grained lenses. The sand grains are well sorted and consist mostly of quartz, but on an average include about 5 percent feldspar, a few percent each of detrital chert and white detrital clay grains, and less than 1 percent heavy minerals. Carbonized plant remains are randomly distributed throughout the sandstone. As discussed more fully later, the sandstone is, in places, cemented tightly by carbonate.

Along and marginal to an axial line, the sandstone is thickest and rests unconformably on the Morrison Formation; but in some places laterally from the axial line, the sandstone rests on black carbonaceous fissile shales of the Lakota. This black fissile shale is the oldest known Cretaceous rock in the southern Black Hills and appears to have been laid down as a blanket-type deposit and to have been subsequently dissected during early unit 1 time. The shale is exposed in only a few places throughout the area in which the basal Lakota rocks crop out. For this reason it has been mapped as part of unit 1. It is best exposed in several places along each side of Red Canyon in the vicinity of the Fay Ranch, along Pass Creek, and along the east side of the Elk Mountains, in sec. 16, T. 5 S., R. 1 E. In these areas it is 10–50 feet thick, but where it has been penetrated by drill holes in and adjacent to sec. 1, T. 8 S., R. 2 E., it is as much as 75 feet thick.

The direction of dip of crossbeds indicates that the sand was deposited in streams flowing northwestward. The sandstone thins in the downstream direction along the channel axes from a maximum of 300 feet in Chilson Canyon to 250 feet in Craven Canyon, and it further thins to 200 feet in the vicinity of the south end of the Elk Mountains. The sandstone also thins rapidly and grades into fine-grained deposits to the northeast at right angles to the direction of streamflow. Little is known of its extent southwest of the main channel, but presumably it likewise grades into fine-grained deposits in that direction.

The fine-grained flood-plain facies of unit 1 is composed of thin alternating beds of very fine grained sandstone, siltstone, and mudstone in variable proportions. Limestone beds as much as 1 foot thick occur locally. A few thin coal beds are present. Streaks, pods, and fragments of carbonaceous material are sparse to abundant. The thickness of the flood-plain facies of unit 1 is greatest, as much as 150 feet, northeast of the margin of the sandstone facies in the eastern part of the Edgemont NE quadrangle, in the southern part of the Minnekahta quadrangle, and in the north-central part of the Flint Hill quadrangle.

A varied assemblage of fossils was found in moderate abundance during this investigation. In some places the siltstone and mudstone beds contain abundant ostracodes. Estella Leopold and Helen Penn of the U.S. Geological Survey have recognized spores related to the tropical fern genus *Anemia*. Numerous cycads also indicative of a tropical to subtropical climate have been collected from this unit. The abundant carbonaceous material, including coal beds, indicates a humid, warm climate that supported a luxurious growth of vegetation.

FLUVIAL UNIT 2

Throughout a considerable part of the southeastern Black Hills, unit 1 is overlain unconformably by a sequence of younger rocks that has been designated as fluvial unit 2. This unit extends from the Inyan Kara hogback in the vicinity of Hot Springs and Cascade Springs westward to the central part of the Edgemont NE quadrangle. The thickness of the unit averages about 250 feet east of the central part of the Flint Hill quadrangle; it gradually thins to zero west of the central part of the Flint Hill quadrangle. The unit, like fluvial unit 1, is a fluvial complex composed of stream and flood-plain deposits designated as sandstone and mudstone facies, and it locally includes rocks of possible lacustrine origin.

The unit is lens shaped and elongate to the northwest. Structural depression of the Cascade Springs area caused the axial line of unit 2 to shift to that area, about 6 miles east of the axial line of unit 1 (pl. 1, north half, restored cross section). Sandstone, which predominates near the axial line, grades laterally into interbedded claystone, siltstone, and silty very fine grained sandstone. The sandstone facies generally is light yellowish gray and is fine to very fine grained. It is composed predominantly of quartz but contains a small amount of feldspar and clay. In general, the sand is well sorted.

Several subtle differences are useful in distinguishing unit 1 from unit 2. Unit 2 is more oxidized, probably as a result of climatic changes after the deposition of unit 1, as shown by its lack of carbon and its greater abundance of red, brown, and yellow colors in contrast to the presence of carbon and the less vivid colors in unit 1. The mudstones of unit 2 are shades of red, green, and gray; those in unit 1 are predominantly gray, although a few are green and red. Fissile shales are absent from unit 2 but are commonly present in the basal part of unit 1. Many of the sandstones in unit 2 contain abundant pink calcite cement, whereas those in unit 1 contain less abundant and characteristically gray calcite cement.

The contact relations between the two units are variable. Throughout most of the area northwest of Craven Canyon where unit 2 is absent, unit 1 rocks are directly overlain by the Fuson Member. Unit 1 is absent eastward from the northeastern part of the Flint Hill quadrangle, and there, unit 2 lies directly on the Unkpapa Sandstone of Jurassic age. Where the two units are present in the same area, the fine-grained flood-plain deposits of each are generally in contact. This distribution of rock types occurs near the northeastern boundary of unit 1 in the south-central part of the Minnekahta quadrangle and throughout the east-central part of the Flint Hill quadrangle. Farther west, in the eastern part of the Edgemont NE quadrangle, the sandstone facies of unit 2 apparently rests on the fine-grained facies of unit 1, although unit 2 fine-grained facies may be present in some places in this area.

Where the boundary between the two units is within nonresistant fine-grained rocks, it is rarely exposed, and the contact relations cannot be observed in detail. In the S½ sec. 18, T. 9 S., R. 4 E., and at other places along the Cheyenne River, the sandstone facies of the two units are in contact. The magnitude of the hiatus cannot be determined from the exposures in this area, but sufficient time may have elapsed to allow the removal of 300–400 feet of rock before the deposition of unit 2.

MINNEWASTE LIMESTONE MEMBER

The Minnewaste Limestone Member is restricted to the southern part of the Black Hills. It is continuous east, northeast, and southeast of Cascade Springs and is discontinuous from Cascade Springs west to the northeastern part of the Burdock quadrangle (pl. 1). It has not been recognized in the western, the northern, and much of the eastern part of the Black Hills.

The Minnewaste Member in its thickest part is almost pure limestone, but it grades outward to sandy limestone and, toward the margins, to calcareous sandstone. It ranges in thickness from a few inches to 80 feet. East of Cascade Springs it has an average thickness of about 20 feet, but where it occurs in the Flint Hill, Edgemont NE, and Burdock quadrangles, it generally has a thickness of less than 10 feet. The limestone generally is structureless and weathers to a hackly surface. It strongly resists weathering and forms a vertical cliff where it is exposed in the canyons. In some places, notably in the eastern part of the Angostura Reservoir quadrangle, the limestone contains thin lenses of carbonaceous siltstone and structureless sandstone.

Commonly the limestone is highly brecciated and recemented with calcite. Baker (1947) reported that in the Amerada Petroleum Corp., South Dakota Agricultural College well 1, SW¼SE¼ sec. 27, T. 8 S., R. 7 E., just east of the mapped area, the Minnewaste includes 30 feet of anhydrite interbedded with limestone, dolomite, sandstone, and shale. Solution of the soluble calcium sulfate and subsequent collapse of the overlying beds, therefore, seem to be the most reasonable causes of brecciation.

In the Flint Hill quadrangle and eastward, the limestone commonly rests on red sandstone at the top of fluvial unit 2. Locally, however, gray mudstone separates the red sandstone from the limestone, and in places where fluvial unit 2 is represented by fine-grained flood-plain facies, the limestone also rests on mudstones. Westward the Minnewaste overlaps fluvial unit 2 and occurs as isolated patches resting on sandstones and mudstones of fluvial unit 1 (pl. 1, south half).

Fresh-water sponge spicules have been found in a few places within the limestone. These fossils, together with the limited distribution of the limestone, suggest that the limestone is lacustrine in origin.

FUSON MEMBER

The Fuson Member was evidently deposited in most of the southern Black Hills as gray to variegated mudstone containing variable amounts of fine-grained sandstone. In the vicinity of Pass Creek and the Elk Mountains, however, the lower part of the mudstone interfingers with conglomeratic sandstone that has been designated as fluvial unit 3 (pl. 1). In numerous places between the Elk Mountains and Hot Springs, particularly in the Edgemont area, the top of the Fuson mudstone has been channeled during pre-Fall River erosion. The sandstone that fills these erosional irregularities has been designated as fluvial unit 4 (pl. 1). The Fuson member, therefore, is composed of a variety of rock types including fluvial unit 3, the variegated mudstone, which locally contains fine-grained sandstones, and fluvial unit 4.

After the nomenclature of the formations now included within the Inyan Kara Group was established by Darton (1901), difficulty was encountered in recognizing the base of the Fuson beyond the limits of the Minnewaste Limestone Member. The reason for this difficulty apparently was the variation in facies in both the Fuson and Chilson Members. After these facies were mapped in the area between Hot Springs, S. Dak., and Newcastle, Wyo., however, it became apparent that the Fuson could be traced by detailed mapping beyond the limits of the Minnewaste Limestone Member.

For several miles west of Cascade Springs the Fuson Member rests on an easily identified reddish-brown sandstone in the sandstone and mudstone facies of fluvial unit 2 of the Chilson Member. In some places, however, particularly in the northern part of the Flint Hill quadrangle and the southern part of the Minnekahta quadrangle, variegated mudstone of the Fuson locally rests on similar mudstones of fluvial unit 2. There the Fuson-Chilson contact has been arbitrarily mapped within the mudstone sequence.

Beyond the western limits of fluvial unit 2, the Fuson Member rests on rocks of fluvial unit 1 (pl. 1, north half). The rocks of these two units are generally easily distinguished because of the contrast between carbonaceous sandy beds in the underlying Chilson Member and noncarbonaceous variegated mudstone or white massive sandstone in the Fuson Member. Along the east side of the Elk Mountains in the Dewey quadrangle, where the basal part of the Fuson Member is the conglomeratic sandstone of fluvial unit 3, all the rocks that contain carbonaceous material are placed in the Chilson Member, and all the conglomeratic sandstone is placed in the Fuson Member.

FLUVIAL UNIT 3

Fluvial unit 3 is a conglomeratic crossbedded white to yellowish-brown noncarbonaceous sandstone. It crops out in parts of the Jewel Cave SW, Dewey, Clifton, and Fanny Peak quadrangles. It consists of many intertonguing well-sorted lenses that vary in texture from fine grained to conglomeratic with pebbles locally greater than 3 inches in diameter. Quartz comprises 90 percent of the rock; and chert, feldspar, clay grains, magnetite, zircon, tourmaline, and rutile are minor constituents. Carnotite in uneconomic concentrations has been found in the lower part of the sandstone in the SE¼SW¼ sec. 21, T. 5 S., R. 1 E., Custer County, S. Dak.

The conglomeratic sandstone was deposited on the dissected surface of fluvial unit 1 and, in places, on Jurassic rocks. At the boundary between the Clifton and Dewey quadrangles, the sandstone is in direct contact with either the lower part of the Morrison Formation or the upper part of the Redwater Shale Member of the Sundance Formation of Jurassic age (pl. 1). Crossbeds in the sandstone indicate that the streams that deposited it flowed in a northerly direction. The sandstone interfingers with the variegated mudstone.

Fluvial unit 3 is generally 20–30 feet thick where it is present in the Jewel Cave SW quadrangle. Along the west flank of the Black Hills through parts of the Dewey, Clifton, and Fanny Peak quadrangles the unit ranges in thickness from about 20 to 120 feet and perhaps has an average thickness of about 70 feet.

VARIEGATED MUDSTONE

The variegated mudstone of the Fuson Member was partly or completely removed in many places by widespread erosion prior to deposition of fluvial unit 4. Where it is present the mudstone is as much as 180 feet thick and averages about 100 feet thick. It is nonfissile and noncarbonaceous and is characterized by gray, maroon, and green claystone and siltstone enclosing thin beds of fine-grained sandstone. Silicified logs have been found in the unit, notably in the northeastern part of the Hot Springs quadrangle and the northwestern part of the Edgemont NE quadrangle. Green sandstone float is distinctive, yet the source of this material is rarely exposed. The claystone and siltstone beds generally weather to steep grass-covered slopes. Highly polished subspherical quartzite and chert pebbles and cobbles also characterize this unit and help distinguish the Fuson Member from the Chilson Member. These pebbles and cobbles have been found embedded in the Fuson mudstone in many places, but most are seen littering the mudstone surface. Similar polished pebbles, probably from equivalents of the Fuson Member, around the periphery of the Black Hills have been described by Mapel, Chisholm, and Bergenback (1964, p. C25–C26), Waagé (1959), and many other writers.

Commonly structureless and poorly bedded highly argillaceous silty sandstone that is white or is mottled and streaked with red, pink, and yellow iron oxide stains and cement is characteristic of the unit. The sandstone is lenticular, fine to very fine grained, and noncarbonaceous, and it is as much as 100 feet thick. The most conspicuous exposures of the white structureless sandstone are in the Coal, Craven, and Red Canyons areas, in the Edgemont NE quadrangle. This sandstone is not shown on the geologic map but is shown on the restored cross section.

FLUVIAL UNIT 4

Fluvial unit 4, the youngest rock unit in the Fuson Member, was deposited in channels eroded by northwest-flowing streams during partial dissection of the underlying variegated mudstone. The streams in places incised as much as 150 feet below the surface and cut completely through the variegated mudstone and into units 2 and 1 of the Chilson Member. Subsequently, these valleys were filled with the channel sandstone complex that comprises fluvial unit 4. The sandstone is extensively cemented with calcium carbonate.

The complex is composed predominantly of sandstone; but red or red and gray mudstone is locally present at the top of the unit, and in places along the margins gray mudstone lenses are present. The sand grains are rounded to subrounded and on an average are composed of about 90 percent quartz; chert, kaolinite, illite, feldspar, and sparse mica constitute most of the remaining part. Unit 4 contains almost no organic carbon. The sandstone is resistant to erosion and forms yellowish-gray to light-gray vertical cliffs along the canyons. The basal part locally is conglomeratic, particularly on the crest of the Chilson anticline in the southern part of the Minnekahta quadrangle, but generally the sandstone is fine to medium grained and, except for local clay lenses, is only slightly argillaceous.

The sandstone is intermittently exposed from the Cheyenne River in the southern part of the Flint Hill quadrangle to the southern part of the Clifton quadrangle, a distance of about 35 miles (pl. 1). A tributary channel, in which sandstone was deposited, apparently extended across the western part of the Cascade Springs quadrangle and eastern part of the Hot Springs quadrangle.

Mudstone of variable thickness is locally present in the upper part of fluvial unit 4 west of the Chilson anticline. The mudstone generally forms gentle grass-covered slopes, and little of it can be observed. Where it is exposed it is similar to the red and maroon mudstone in parts of the Fuson variegated mudstone and to varicolored mudstone in the upper part of the Fall River Formation. The maximum thickness of the mudstone, about 50 feet, occurs in the western part of the Edgemont NE quadrangle and the eastern part of the Burdock quadrangle (pl. 1). The mudstone probably was locally derived from the Fuson clays and silts and was deposited on the flanks of the principal channels.

In contrast to the sandstone of other fluvial units, the sandstone of fluvial unit 4 is characterized by many sets of foreset crossbeds, each set ranging in thickness from a few inches near the channel margin to about 4 feet in the central part of the channel. The sets are separated by thin topset beds, none more than 2 inches thick. The crossbeds strike normal to the channel boundaries and dip northwestward. On weathered surfaces many of the individual cross-strata are etched into bold relief, evidently as a result of contrasting textures of adjacent cross-strata. In several places between the southern part of the Flint Hill quadrangle and the southeastern part of the Edgemont NE quadrangle the foreset beds within individual sets are bent downstream in such a manner that a "V" is formed which points upstream. The deformed strata are overlain and underlain by undeformed strata. The deformation of the crossbeds apparently resulted from preconsolidation slumping. According to McKee (1957, p. 132), foreset beds of the type just described result when the base level is raised rapidly, and a series of these sets represents a series of base level rises.

The sandstones of fluvial unit 4 are more extensively cemented with calcite than are the sandstones of the other fluvial units (Gott, 1956; Gott and Schnabel, 1963). Unit 4 sandstones are particularly well cemented along the east side of the Burdock quadrangle, in the southwestern part of the Edgemont NE quadrangle, in the subsurface in the northeastern part of the Edgemont quadrangle, and in various parts of the Flint Hill quadrangle. Most of the calcite contains much manganese and iron, and these metals cause the rock to weather dark gray to black where highly oxidized. The calcite generally is concentrated in spherical nodules, but to a lesser extent it occurs in elongate masses in and marginal to fractures. The nodules are commonly about a half inch in diameter but are locally as much as 4 inches in diameter, and most of them exhibit regularly spaced concentric bands. The cementation apparently grew outward from a nucleus. Where cementation proceeded to completion, the nodules coalesce, and the sandstone in the interstices between the nodules is cemented by calcite; but in many places the internodular sandstone is uncemented.

FALL RIVER FORMATION

The Fall River Formation is composed of sandstone, siltstone, and mudstone. In the southern part of the Black Hills it is 100–160 feet thick. Three units recognized in mapping could be traced over most of the area. (1) Laminated carbonaceous siltstones interbedded with thin sandstones in the basal part of the formation are informally designated as the lower unit. (2) A thick crossbedded fluvial sandstone, which locally truncates the lower unit but which grades laterally into a sequence of alternating thin tabular beds of sandstone, siltstone, and mudstone, is designated as the middle unit. (3) A variegated mudstone 20–25 feet thick and a local overlying sandstone which is similar to the one in the middle unit and which grades laterally into a fine-grained thin-bedded facies are designated as the upper unit.

The lithologic character of the Fall River and Lakota rocks at the formational boundary varies greatly. Because of this, several combinations of lithologic units in each formation are variously present at the formational boundary. Most commonly the lowest part of the Fall River Formation consists of laminated carbonaceous siltstone thinly interbedded with very fine grained sandstone. In most places this unit rests on the variegated mudstone or the white sugary massive sandstone of the Fuson Member. The upper few inches to few feet of the Fuson is bleached, resulting in a strong color contrast between the rocks at the contact. Brownish-red, orange, and yellow siderite spherules commonly occur in the Fuson within 5 feet of the formational contact. These spherules have been discussed by Waagé (1959, p. 55–57) and Gries (1954). In many places, however, the formational contact is much less obvious. In such places the basal Fall River unit was removed by erosion and replaced by sand during middle Fall River time, and in many places this Fall River sandstone, designated fluvial unit 5, rests on the sandstone of fluvial unit 4. At other places the sandstone of fluvial unit 5 is present at the base of the Fall River, but fluvial unit 4 is absent; or fluvial units 4 and 5 are both present but are separated by a thin sequence of the lower unit of the Fall River Formation (pl. 1, north half, restored cross section). The criteria for identifying the contact vary considerably according to which of these combinations is present.

LOWER UNIT

The lower unit of the Fall River Formation is present throughout the southern Black Hills except where it is locally truncated by the sandstone facies of fluvial unit 5. It ranges in thickness from 0 to 50 feet and is composed principally of laminated micaceous carbonaceous siltstone. Interlayered with the siltstone is light-gray very fine grained slightly micaceous sandstone. The sandstone beds are generally less than 1 foot thick and are rarely more than 10 feet thick.

The rock generally contains small ellipsoidal concretionary layers of siltstone or very fine grained sandstone that superficially resemble augen structures of some metamorphic rocks. The unweathered rock contains pyrite nodules a few inches in longest dimension. As a result of oxidation of these nodules and concretions, the weathered sandstone is commonly stained brown or yellowish brown. In general, however, the relatively high carbon content of the siltstones has inhibited oxidation to the extent that they are light or medium gray, particularly on a freshly broken surface.

Some of the thin sandstone beds are covered on the upper surface with ripple marks and a vermiculated pattern of raised ridges that have been interpreted as "worm tracks" (Henry Bell III and E. V. Post, written commun., 1957; Waagé, 1959). Many of the siltstone lenses contain faint low-angle crossbeds that are 1–2 inches in total length, suggesting that the sediment was transported by extremely gentle currents.

Because of the striking contrast between these rocks and those of the underlying Fuson Member of the Lakota Formation, the formational contact where the lower unit is present is easily recognized.

Many small uranium mines have been developed in the lower unit of the Fall River.

MIDDLE UNIT (FLUVIAL UNIT 5)

The middle unit of the Fall River, designated fluvial unit 5, is the fifth of six major fluvial units in the Inyan Kara Group. It comprises a fluvial sandstone and its associated marginal fine-grained deposits. The fluvial sandstone crops out in an irregular band that trends generally northwest throughout most of the southern Black Hills (pl. 1). It is as much as 110 feet thick and is commonly cemented with calcite and silica.

Erosion of part or all of the carbonaceous siltstone in the lower unit locally preceded deposition of fluvial unit 5. In places the lower unit was completely removed, but generally only the upper part was eroded. The fluvial sandstone was then deposited over much of the irregular surface, leaving a plain of low relief. The streams that deposited sand in the principal channelways also deposited extensive overbank flood-plain deposits marginal to the sandstone-filled channels. The irregular lower contact and the relation between the channel and flood-plain facies are shown on plate 1 (north half, restored cross section).

The sandstone is light yellowish gray on freshly broken surfaces, and it weathers to shades of yellow and brown; generally, it is slightly darker than the Lakota sandstones. It forms prominent vertical cliffs along the canyons. The sandstone is composed of about 90 percent subrounded to rounded quartz, less than 5 percent feldspar, and a minor amount of chert. The heavy-mineral content is generally less than 1 percent, and mica is more abundant than in the older, Lakota sandstones. The sandstone is crossbedded, fine to medium grained, and sparsely carbonaceous. Iron sulfide and iron oxide nodules are common, and silicified tree trunks occur in a few places, particularly along the west side of Red Canyon. Calcite cement is abundant in the sandstone near the axis of the Sheep Canyon monocline in the western part of the Flint Hill quadrangle, the eastern part of the Edgemont quadrangle, and the southeastern part of the Edgemont NE quadrangle. It is also abundant in the subsurface in some of the places where fluvial unit 5 is in contact with fluvial unit 4, such as in the southern part of the Edgemont NE quadrangle and the northern part of the Edgemont quadrangle. In other places the sandstone is tightly silicified, particularly on the crest of the Chilson anticline in the southern part of the Minnekahta quadrangle and the northern part of the Flint Hill quadrangle, on Horse Trap Mountain in the southeastern part of the Minnekahta quadrangle, on the Barker dome in the southeastern part of the Jewel Cave SW quadrangle, and at the crest of Battle Mountain in the west-central part of the Hot Springs quadrangle.

The fine-grained facies of the middle unit is composed of alternating thin tabular beds of gray sparsely carbonaceous claystone, light-brownish-gray micaceous very fine grained sandstone, and dark-gray carbonaceous siltstone. This facies is lithologically similar to the underlying carbonaceous siltstone, and thus in places the two are difficult to distinguish. The facies interfingers with the fluvial sandstone and, except for a difference in color, is indistinguishable from the overlying variegated mudstone. The fine-grained facies of the middle unit is 0–50 feet thick.

UPPER UNIT (INCLUDES FLUVIAL UNIT 6)

The upper unit of the Fall River is composed of variegated mudstone at the base overlain by fluvial unit 6, a sequence of fluvial sandstone and fine-grained equivalents of the fluvial sandstone (pl. 1, north half, restored cross section) that is designated the sixth and youngest of the major fluvial units. It crops out in the southeastern part of the southern Black Hills. The thickness of the upper unit ranges from about 40 to 120 feet and averages about 75 feet.

The unit is highly argillaceous and is characteristically mottled red and gray, particularly in the middle part. The top 1–2 feet is normally light gray and locally contains abundant carbonized plant debris.

The mudstone generally is 10–25 feet thick, except in the Angostura Reservoir area, where it includes erratically distributed bodies of sandstone and gray clay and is as much as 60 feet thick. Its lower boundary is gradational with either the fine-grained or the sandstone facies of unit 5. In some places the upper part of the mudstone seems to be gradational with the fine-grained facies of fluvial unit 6; but elsewhere, part or all of the variegated mudstone was removed by erosion prior to deposition of unit 6, and the contact is obviously unconformable.

The mudstone has been recognized and mapped throughout much of the area between Pass Creek, which is in the southwestern part of the Jewel Cave SW quadrangle, and Hot Springs. There is little doubt that equivalents of the mudstone are present to the northwest in the Dewey, Clifton, and Fanny Peak quadrangles, although the unit has lost its easily recognizable color in those areas. Except for patches of variegated mudstone in the vicinity of the Wicker-Baldwin prospect near the north boundary of the Dewey quadrangle and in a few places in the Clifton and Fanny Peak quadrangles, probable equivalents of the variegated unit are various tones of gray ranging from nearly white to dark gray without any of the characteristic red and maroon colors. This makes correlation with the variegated mudstone to the southeast questionable, and for that reason no attempt has been made to map the unit separately in the Dewey, Clifton, and Fanny Peak quadrangles.

Fluvial unit 6 ranges in thickness from about 30 feet in the northwestern part of the Fanny Peak quadrangle to about 100 feet in a few places in the Flint Hill quadrangle. The sandstone facies is most prominent east of the Edgemont NE quadrangle and generally consists of light-gray sandstone that is consistently 10–25 feet thick over large areas. It is generally fine-grained where no more than about 20 feet thick but is crossbedded and medium to coarse grained where very much thicker.

The sandstone grades laterally into a sequence composed of variable proportions of thin alternating tabular beds of fine-grained sandstone, siltstone, and claystone. In general the average grain size of the clastic material increases from predominantly clay in the Fanny Peak, Clifton, and Dewey quadrangles to predominantly silt and sand in the Edgemont NE quadrangle. This sequence, at least in part, appears to represent flood-plain deposits perhaps at the margin of a seaway, as concluded by Waagé (1959).

PETROGRAPHY

A petrographic study was made of sandstones and a few coarse siltstones from fluvial units 1–5 within the Inyan Kara Group and from the underlying Unkpapa Sandstone (fig. 2). Samples from the Unkpapa

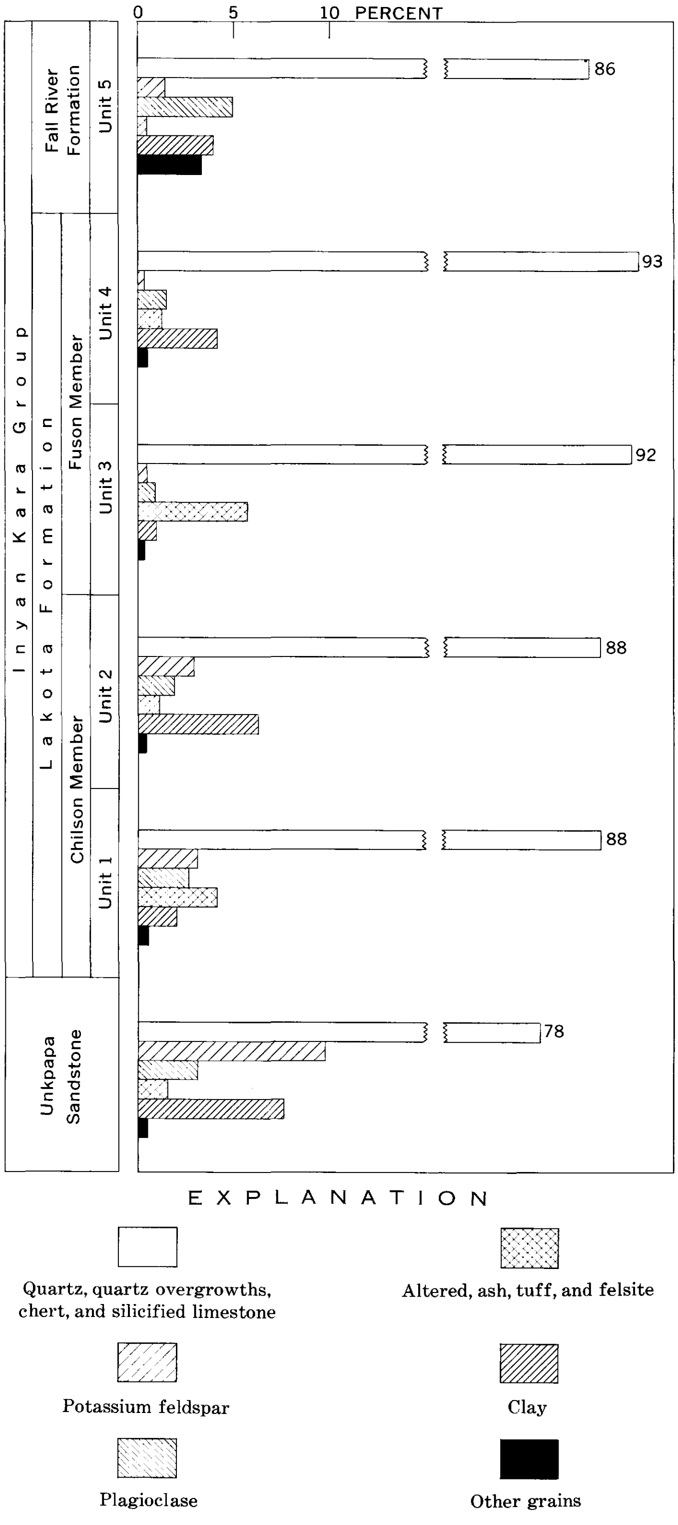


FIGURE 2. — Average mineralogic composition, excluding cement, in percent, of sandstone units in the Inyan Kara Group and the Unkpapa Sandstone.

Sandstone were included because locally the source of some sediments of the Lakota is the Unkpapa. The study was undertaken to determine differences in mineralogy and grain-size distribution for sandstones of each fluvial unit and to provide information for determining the source of sediments and tectonic changes in the source areas and in the Edgemont uranium district.

Chip samples were collected from 84 localities (table 2) for study of the mineralogic composition and texture and for determination of the heavy-mineral content. The thin-section modal analyses and the textural analyses were made by R. A. Cadigan of the U.S. Geological Survey following his reported procedures and classifications (Cadigan, 1959, p. 530, 533, 535). The heavy-mineral studies were done by Wolcott.

In the following sections on composition, grain size, and heavy minerals, the terms "percent by volume," "percent by weight," and "percent of grains counted" are used. The composition was determined by point counts of thin sections which yield the volume of each constituent (Chayes, 1949, 1946). The grain-size-distribution frequencies are based on the weight of each selected size fraction. The heavy-mineral percentages are based on the numbers of each detrital heavy mineral counted.

COMPOSITION

Thin sections of 51 samples were prepared and studied as outlined by Cadigan (1959, p. 533). Potassium feldspars and potassium-bearing clays were stained canary yellow to facilitate their identification. Petrographic modal composition of the rocks was estimated by point-count method using 500 points in each thin section. The composition, in percent by volume of each sample, is shown in table 3, and the average composition of each unit, excluding cement, is shown by histograms in figure 2. On the basis of the average composition, all units of the Inyan Kara Group that were sampled are orthoquartzites (defined as containing more than 60 percent detrital siliceous grains and not more than 25 percent feldspar), and the Unkpapa Sandstone is a feldspathic orthoquartzite. On the basis of mean grain size (table 4), three of the samples (L–3254 in unit 1 of the Lakota Formation and L–3246 and L–3253 of the Unkpapa Sandstone) are coarse siltstones. All the units, as indicated by the presence of chert, quartzite, and silicified limestone grains, were derived in part from preexisting sedimentary rocks.

Some differences in mineral composition among the Inyan Kara sandstones seem to be consistent.

TABLE 2. — *Localities of samples listed in tables 3, 4, and 7*

Field sample (L–)	Section, township, and range[1]	7½-minute quadrangle
INYAN KARA GROUP		
Fall River Formation		
Fluvial unit 5		
3287	NE¼NW¼ sec. 33, T. 7 S., R. 6 E.	Hot Springs.
3288	SW¼SE¼ sec. 29, T. 8 S., R. 5 E.	Cascade Springs.
3289–3290	SE¼NW¼ sec. 4, T. 9 S., R. 4 E.	Flint Hill.
3291–3293	NW¼SE¼ sec. 32, T. 7 S., R. 3 E.	Edgemont NE.
3294	NE¼NE¼ sec. 5, T. 42 N., R. 60 W.	Clifton.
3379	SW¼NE¼ sec. 27, T. 8 S., R. 3 E.	Flint Hill.
3380	NW¼NW¼ sec. 12, T. 9 S., R. 3 E.	Do.
3381	NW¼SE¼ sec. 32, T. 8 S., R. 4 E.	Do.
3382	W½SE¼ sec. 9, T. 42 N., R. 60 W.	Clifton.
3383	SE¼NE¼ sec. 22, T. 6 S., R. 1 E.	Jewel Cave SW.
3384	SW¼NE¼ sec. 24, T. 8 S., R. 4 E.	Cascade Springs.
3385	SE¼NW¼ sec. 20, T. 8 S., R. 6 E.	Angostura Reservoir.
3386	SW¼NE¼ sec. 8, T. 8 S., R. 6 E.	Do.
3387	NE¼SE¼ sec. 16, T. 7 S., R. 6 E.	Hot Springs.
3388	SW¼SE¼ sec. 16, T. 7 S., R. 6 E.	Do.
3389	S½SE¼ sec. 16, T. 7 S., R. 6 E.	Do.
3390	SE¼SE¼ sec. 6, T. 8 S., R. 4 E.	Minnekahta.
Lakota Formation		
FUSON MEMBER		
Fluvial unit 4		
3279	NE¼NW¼ sec. 33, T. 7 S., R. 6 E.	Hot Springs.
3280–3282	SW¼SW¼ sec. 9, T. 8 S., R. 4 E.	Flint Hill.
3283	SE¼NW¼ sec. 4, T. 9 S., R. 4 E.	Do.
3284–3285	NE¼NE¼ sec. 8, T. 8 S., R. 3 E.	Edgemont.
3286	NW¼SW¼ sec. 29, T. 6 S., R. 2 E.	Burdock
3295	NW¼ sec. 18, T. 5 S., R. 1 E.	Dewey.
3366–3368	NW¼SW¼ sec. 12, T. 8 S., R. 3 E.	Flint Hill.
3369	SE¼NE¼ sec. 18, T. 9 S., R. 4 E.	Do.
3370	NE¼NW¼ sec. 20, T. 8 S., R. 4 E.	Do.
3371	NE¼SE¼ sec. 21, T. 8 S., R. 4 E.	Do.
3372	SW¼SW¼ sec. 14, T. 6 S., R. 1 E.	Jewel Cave SW.
3373	SE¼SW¼ sec. 4, T. 7 S., R. 2 E.	Burdock.
3374–3375	NW¼NE¼ sec. 27, T. 7 S., R. 2 E.	Edgemont NE.
3376–3377	SE¼NE¼ sec. 21, T. 7 S., R. 2 E.	Burdock.
3378	SW¼SE¼ sec. 16, T. 7 S, R. 6 E.	Hot Springs.
Fluvial unit 3		
3262	NW¼NE¼ sec. 33, T. 44 N., R. 60 W.	Fanny Peak.
3263	NW¼NE¼ sec. 7, T. 4 S., R. 1 E.	Clifton.
3264	NE¼NW¼ sec. 10, T. 42 N., R. 60 W.	Do.
3265	NE¼ sec. 28, T. 5 S., R. 1 E.	Dewey.
3331	SE¼SW¼ sec. 29, T. 44 N., R. 60 W.	Fanny Peak.
3332–3333	SE¼SE¼ sec. 30, T. 4 S., R. 1 E.	Clifton.
3334	NW¼NW¼ sec. 10, T. 6 S., R. 1 E.	Jewel Cave SW.
3338	SE¼SW¼ sec. 22, T. 43 N., R. 60 W.	Clifton.
3350	NW¼NW¼ sec. 19, T. 6 S., R. 2 E.	Jewel Cave SW.
3399	SW¼SW¼ sec. 14, T. 6 S., R. 1 E.	Do.
INYAN KARA GROUP — Continued		
Lakota Formation — Continued		
CHILSON MEMBER		
Fluvial unit 2		
3266–3270	SW¼SW¼ sec. 9, T. 8 S., R. 4 E.	Flint Hill.
3271	S½SW¼ sec. 2, T. 8 S., R. 4 E.	Minnekahta NE.
3272	NW¼NE¼ sec. 5, T. 8 S., R. 3 E.	Edgemont NE.
3273	NE¼NW¼ sec. 3, T. 9 S., R. 5 E.	Cascade Springs.
3274–3276	SW¼SW¼ sec. 34, T. 8 S., R. 5 E.	Do.
3277–3278	NW¼NE¼ sec. 30, T. 7 S., R. 6 E.	Hot Springs.
3339	SW¼NW¼ sec. 3, T. 8 S., R. 3 E.	Edgemont NE.
3340	NW¼SE¼ sec. 2, T. 8 S., R. 3 E.	Minnekahta.
3341	SW¼SE¼ sec. 18, T. 9 S., R. 4 E.	Flint Hill.
3343–3344	NE¼SE¼ sec. 21, T. 8 S., R. 4 E.	Do.
3346–3349	S½NW¼ sec. 35, T. 8 S., R. 5 E.	Angostura Reservoir.
3352–3353	NE¼SE¼ sec. 1, T. 8 S., R. 3 E.	Minnekahta.
3354–3357	NE¼SW¼ sec. 34, T. 7 S., R. 4 E.	Do.
3358–3359	SW¼SE¼ sec. 29, T. 8 S., R. 5 E.	Cascade Springs.
3360	SW¼SE¼ sec. 4, T. 7 S., R. 6 E.	Hot Springs
3361	SE¼NE¼ sec. 9, T. 7 S., R. 6 E.	Do.
3362–3365	N½ sec. 4, T. 9 S., R. 4 E.	Flint Hill.
3395–3398	NW¼SE¼ sec. 15, T. 8 S., R. 4 E.	Do.
Fluvial unit 1		
3254–3255	SW¼SE¼ sec. 31, T. 8 S., R. 4 E.	Flint Hill.
3256–3257	NW¼NW¼ sec. 30, T. 7 S., R. 3 E.	Edgemont NE.
3258	SW¼NE¼ sec. 22, T. 7 S., R. 2 E.	Do.
3259–3260	NW¼NW¼ sec. 19, T. 6 S., R. 2 E.	Jewel Cave SW.
3261	NE¼NW¼ sec. 32, T. 44 N., R. 60 W.	Fanny Peak.
3319–3320	NE¼NE¼ sec. 33, T. 7 S., R. 3 E.	Edgemont NE.
3321	SW¼SE¼ sec. 18, T. 9 S., R. 4 E.	Flint Hill.
3322–3323	SE¼NW¼ sec. 12, T. 8 S., R. 5 E.	Angostura Reservoir.
3325	NE¼NW¼ sec. 10, T. 42 N., R. 60 W.	Clifton.
3326	NW¼NW¼ sec. 23, T. 6 S., R. 1 E.	Jewel Cave SW.
3329	NE¼NE¼ sec. 14, T. 7 S., R. 2 E.	Edgemont NE.
3330	NE¼SW¼ sec. 1, T. 8 S., R. 3 E.	Minnekahta.
3335	NW¼NW¼ sec. 10, T. 6 S., R. 1 E.	Jewel Cave SW.
3336–3337	E½NE¼ sec. 9, T. 6 S., R. 1 E.	Do.
3394	NW¼SW¼ sec. 16, T. 8 S., R. 4 E.	Flint Hill.
UNKPAPA SANDSTONE		
3245–3247	SE¼NE¼ sec. 9, T. 7 S. R. 6 E.	Hot Springs.
3248	SW¼NW¼ sec. 10, T. 7 S., R. 6 E.	Do.
3249–3251	NE¼NW¼ sec. 26, T. 8 S., R. 5 E.	Angostura Reservoir.
3252–3253	NE¼NW¼ sec. 3, T. 9 S., R. 5 E.	Cascade Springs.
3313	SW¼SW¼ sec. 22, T. 8 S., R. 4 E.	Flint Hill.
3314	NW¼SE¼ sec. 15, T. 8 S., R. 4 E.	Do.
3315	SE¼NW¼ sec. 12, T. 8 S., R. 5 E.	Angostura Reservoir.
3316	NE¼SW¼ sec. 34, T. 7 S., R. 4 E.	Minnekahta.
3317–3318	SW¼NE¼ sec. 4, T. 9 S., R. 4 E.	Flint Hill.

[1]North townships and west ranges are in Wyoming; south townships and east ranges are in South Dakota.

These differences are (1) a decrease in the ratio of potassium feldspar to plagioclase from older to younger beds in the Lakota Formation (fig. 3, table 6), (2) locally abundant chert and silicified limestone grains in fluvial unit 3 of the Lakota Formation (table 3), (3) the highest percentage of volcanic materials in fluvial units 1 and 3 of the Lakota Formation (table 3), and (4) a significantly greater amount of mica in the Fall River compared with underlying units (table 3, fig. 3). The variation in clay content reported is not significant, because matrix material was lost in preparation of some of the thin sections. As would be expected, the feldspar content in general decreases with increasing grain size (fig. 4).

GRAIN SIZE

Particle-size analyses (table 4) were made of 51 samples to determine the properties of their grain-size distributions. The samples, which had also been used for thin-section analyses, were disaggregated and sieved, with sieve sizes graduated at ½-phi intervals from −3 to 0 phi and at ¼-phi intervals from 0 to 4 phi; grains smaller than 4 phi were analyzed by pipette methods using 1-phi intervals to 10 phi. These data were then used in calculating the grain-size distribution by the method of moments as described by Krumbein and Pettijohn (1938). Parameters derived in this manner are not directly comparable to those derived by the graphic methods of Inman (1952) or Folk (1957). As an example,

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TABLE 3. — *Mineralogic composition (in percent by volume) of samples from the Inyan Kara*

[Sample localities

Field sample (L–)	Grains						
	Quartz and quartz overgrowths[1]	Quartzite	Chert and silicified limestone	Potassium feldspar	Plagioclase	Micaceous and mafic rock	Altered ash, tuff, and felsite
INYAN KARA GROUP							
Fall River Formation							
Fluvial unit 5							
3287	91.0	0.0	0.2	0.0	3.4	0.0	0.2
3288	89.8	.0	1.6	.6	6.8	.0	.0
3289	62.8	.0	.2	1.0	10.6	.2	.4
3290	83.0	.0	.0	2.4	8.4	.0	.6
3291	79.2	.6	.8	.4	1.6	.0	.0
3292	87.4	.4	.8	1.6	2.6	.0	.2
3293	81.2	.6	1.4	2.8	4.0	.6	.4
3294	96.0	.2	.4	1.0	1.6	.0	.4
Lakota Formation							
FUSON MEMBER							
Fluvial unit 4							
3279	89.4	0.0	3.2	0.2	0.6	0.0	2.8
3280	81.0	.8	1.4	.0	.2	.0	.2
3281	81.4	.0	.2	.0	1.0	.0	.2
3282	85.6	.0	.4	.0	2.8	.0	.4
3283	96.4	.2	.4	.0	1.4	.0	.0
3284	93.8	.2	.6	.0	1.2	.0	.6
3285	95.0	.2	.8	.0	1.2	.0	.2
3286	94.8	.0	.0	1.0	1.4	.0	1.0
3295	79.2	.0	13.8	.0	2.0	.0	4.0
Fluvial unit 3							
3262	15.2	0.0	77.2	0.0	0.2	0.0	6.6
3263	74.0	.8	16.8	.0	.8	.0	6.6
3264	89.2	.2	2.4	.8	1.6	.0	4.0
3265	54.4	.0	5.0	.4	.2	.0	3.6
CHILSON MEMBER							
Fluvial unit 2							
3266	81.8	0.0	1.8	2.8	1.4	0.0	1.6
3267	86.0	.0	1.0	3.0	1.8	.0	2.0
3268	90.4	.0	1.0	2.0	1.2	.0	1.4
3269	86.8	.2	4.0	1.0	1.0	.0	2.2
3270	92.0	.0	4.4	1.0	.2	.0	.2
3271	89.4	.0	1.0	3.2	1.6	.0	1.8
3272	89.2	.2	.6	1.8	.6	.0	.2
3273	77.4	.0	.4	7.4	5.2	.0	.4
3274	87.4	.0	.0	7.2	2.2	.0	.2
3275	90.8	.0	2.0	2.6	1.6	.0	.6
3276	89.2	.2	1.0	3.0	2.2	.0	1.2
3277	63.4	.0	.0	.0	1.8	.0	.2
3278	83.6	.0	.4	2.4	1.2	.0	.4
Fluvial unit 1							
3254	79.4	0.0	0.4	7.4	7.6	0.0	3.4
3255	94.8	.0	.2	1.6	2.4	.0	.4
3256	87.8	.0	1.6	.6	.6	.0	8.6
3257	95.2	.0	.4	3.0	.6	.0	.8
3258	88.0	.6	.4	1.8	.4	.0	7.0
3259	83.8	.0	.8	2.0	.8	.0	12.2
3260	78.6	.2	.8	6.4	3.6	.2	3.2
3261	91.4	.2	.0	1.6	2.4	.2	.4
UNKPAPA SANDSTONE							
3245	74.4	0.4	0.0	9.4	2.4	0.0	0.6
3246	61.6	.2	.0	10.6	5.2	.0	1.0
3247	76.8	.2	.0	8.4	3.0	.0	2.6
3248	85.4	.0	.0	.0	1.8	.0	1.2
3249	79.2	.2	.2	12.2	3.2	.0	1.4
3250	85.2	.0	.0	9.6	2.4	.0	.0
3251	82.4	.0	.0	11.8	3.0	.0	1.0
3252	82.0	.0	.2	11.4	.6	.0	3.0
3253	69.2	.0	.2	13.8	5.2	.0	1.8

[1]Quartz overgrowths could not be distinguished from quartz grains in most thin sections.
[2]Includes heavy minerals and indeterminate grains.

Group and the Unkpapa Sandstone as determined by point-count analyses of thin sections

are given in table 2]

Grains — Continued		Matrix			Cement			Total grains and matrix	Total cement
Miscellaneous[2]	Mica	Kaolinitic clays	Illite and mica clays	Montmorillonite and related clays	Carbonate and sulfate	Red iron oxide	Silica[3]		
INYAN KARA GROUP — Continued									
Fall River Formation — Continued									
Fluvial unit 5 — Continued									
0.0	0.4	4.4	0.2	0.0	0.2	0.0	0.0	99.8	0.2
.0	.0	.6	.2	.0	.0	.4	.0	99.6	.4
[4]17.6	2.8	4.4	.0	.0	.0	.0	.0	100.0	.0
1.8	.8	2.6	.4	.0	.0	.0	.0	100.0	.0
.0	.0	3.4	4.0	.0	.0	10.0	.0	90.0	10.0
.0	.8	1.2	3.6	.0	.0	1.4	.0	98.6	1.4
.2	.6	.4	5.6	.0	.0	2.2	.0	97.8	2.2
.0	.0	.4	.0	.0	.0	.0	.0	100.0	.0
Lakota Formation — Continued									
FUSON MEMBER — Continued									
Fluvial unit 4 — Continued									
0.2	0.0	2.8	0.2	0.0	0.0	0.6	0.0	99.4	0.6
.0	.0	4.6	.0	.6	.0	4.8	6.4	88.8	11.2
.0	.2	8.2	.0	.4	.0	7.4	1.0	91.6	8.4
.4	.4	6.8	3.0	.2	.0	.0	.0	100.0	.0
.0	.0	1.6	.0	.0	.0	.0	.0	100.0	.0
.4	.4	.0	2.8	.0	.0	.0	.0	100.0	.0
.0	.0	1.6	.6	.0	.4	.0	.0	99.6	.4
.0	.0	.8	1.0	.0	.0	.0	.0	100.0	.0
.0	.0	.2	.0	.0	.0	.2	.6	99.2	.8
Fluvial unit 3 — Continued									
0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.0	99.6	0.4
.0	.2	.0	.8	.0	.0	.0	.0	100.0	.0
.0	.0	.0	1.8	.0	.0	.0	.0	100.0	.0
.2	.0	.0	.0	.0	36.2	.0	.0	63.8	36.2
CHILSON MEMBER — Continued									
Fluvial unit 2 — Continued									
0.0	0.0	1.2	8.0	0.0	0.0	1.2	0.2	98.6	1.4
.2	.0	2.6	3.4	.0	.0	.0	.0	100.0	.0
.4	.0	.0	3.6	.0	.0	.0	.0	100.0	.0
.2	.0	.0	4.6	.0	.0	.0	.0	100.0	.0
.2	.0	1.8	.2	.0	.0	.0	.0	100.0	.0
.0	.0	2.4	.6	.0	.0	.0	.0	100.0	.0
.2	.2	.8	5.2	.0	.0	.8	.2	99.0	1.0
.2	.0	.8	7.8	.0	.0	.4	.0	99.6	.4
.0	.0	.4	1.8	.0	.0	.4	.4	99.2	.8
.0	.0	.2	2.2	.0	.0	.0	.0	100.0	.0
.0	.0	.6	2.6	.0	.0	.0	.0	100.0	.0
.2	.2	2.4	20.8	1.0	.0	10.0	.0	90.0	10.0
.0	.0	1.4	.0	.0	8.4	2.2	.0	89.4	10.6
Fluvial unit 1 — Continued									
0.4	0.0	0.6	0.8	0.0	0.0	0.0	0.0	100.0	0.0
.0	.0	.4	.2	.0	.0	.0	.0	100.0	.0
.0	.0	.0	.6	.0	.0	.2	.0	99.8	.2
.0	.0	.0	.0	.0	.0	.0	.0	100.0	.0
.4	.0	.4	1.0	.0	.0	.0	.0	100.0	.0
.0	.0	.4	.0	.0	.0	.0	.0	100.0	.0
.4	.2	.4	5.6	.2	.0	.0	.2	99.8	.2
.0	.2	.4	3.2	.0	.0	.0	.0	100.0	.0
UNKPAPA SANDSTONE — Continued									
1.2	0.4	0.0	11.2	0.0	0.0	0.0	0.0	100.0	0.0
.4	.0	2.0	18.2	.0	.0	.8	.0	99.2	.8
.4	.0	2.2	6.2	.0	.0	.2	.0	99.8	.2
.0	.0	3.4	7.2	.0	.2	.8	.0	99.0	1.0
.0	.0	1.8	1.4	.0	.0	.4	.0	99.6	.4
.2	.0	2.4	.2	.0	.0	.0	.0	100.0	.0
.0	.0	1.0	.6	.0	.2	.0	.0	99.8	.2
.0	.2	.2	2.4	.0	.0	.0	.0	100.0	.0
.0	.2	5.0	1.8	.0	.0	2.8	.0	97.2	2.8

[3]As authigenic chert.
[4]17.4 percent identified as chlorite.

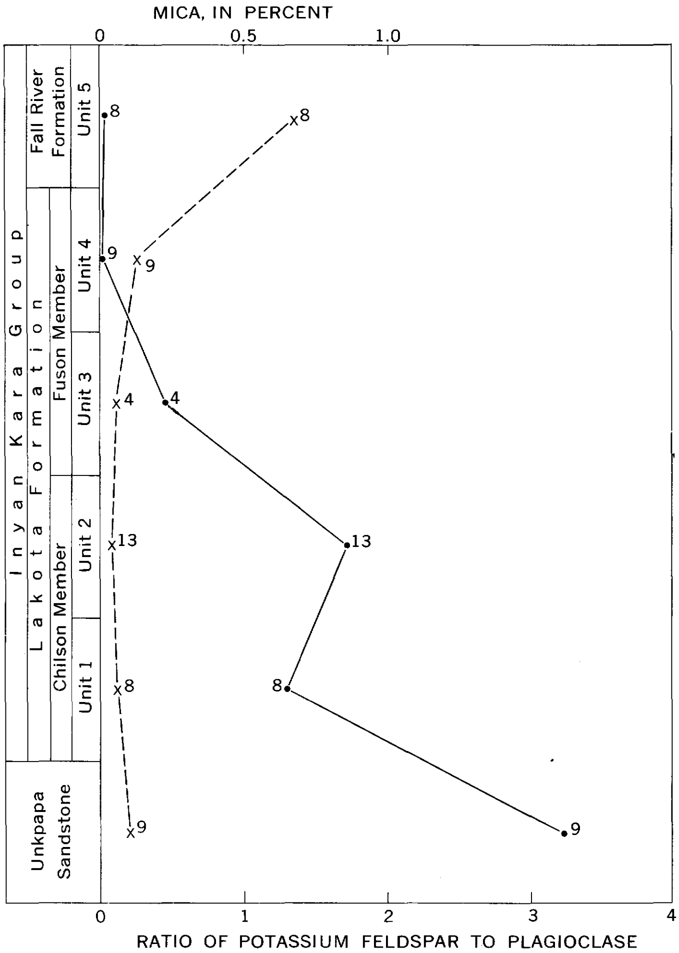

FIGURE 3. — Variation in average mica content (×) and ratio of potassium feldspar to plagioclase (•) by fluvial unit. Number beside symbol indicates number of samples.

table 5 compares mean, standard deviation, and skewness derived by the graphic methods of Inman and Folk with those derived by the method of moments for nine samples of the Unkpapa Sandstone. For all samples shown in table 5, the values of mean grain size are coarsest using Folk's method, intermediate in size using Inman's method, and finest using the method of moments. The standard deviation and skewness for all samples show that Inman's method gives the lowest values, Folk's method gives intermediate values, and the method of moments gives the highest values.

In their study of Jurassic and Cretaceous sandstones, Mapel, Chisholm, and Bergenback (1964) reported the results of grain-size analyses of about 275 samples from 30 localities in the Black Hills; eight of their localities are in the area of this report. They (Mapel and others, 1964, p. C8) used Inman's (1952) method (table 5) for determining standard deviation and skewness and Folk's (written commun.,

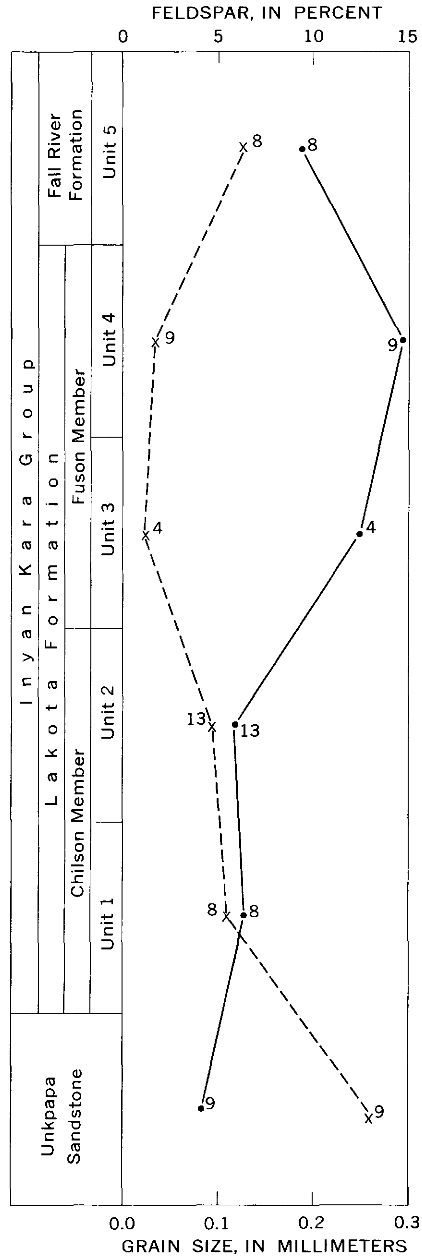

FIGURE 4. — Variation in average percent feldspar (×) and average mean grain size (•) by fluvial unit. Number beside symbol indicates number of samples.

1955) method (table 5) for determining mean grain size.

The mean grain sizes of samples used in this report (table 4) range from very coarse sandstone to coarse siltstone; most of them are in the fine to very fine grained sandstone range. The variation in grain size by stratigraphic unit is shown in figure 5. Samples from the Inyan Kara Group are coarser grained than samples from the Unkpapa Sandstone, which are typically very fine grained. Samples from the

TABLE 4. — *Statistical measures of the phi grain-size distribution of samples from the Inyan Kara Group and the Unkpapa Sandstone*

[Sample localities are given in table 2]

Field sample (L–)	Grain size (millimeters)			Standard deviation (phi units)	Skewness (phi units)	Kurtosis (phi units)	Grain-size distribution by percentiles, in φ-notation						
	Mean	Mode	Median				P_2	P_5	P_{16}	P_{50}	P_{84}	P_{95}	P_{98}
INYAN KARA GROUP													
Fall River Formation													
Fluvial unit 5													
3287	0.15	0.16	0.18	1.06	2.40	27.15	1.88	1.98	2.17	2.47	2.87	3.81	6.74
3288	.21	.24	.22	.90	2.03	28.59	1.43	1.57	1.77	2.17	2.64	3.20	4.47
3289	.14	.15	.16	1.15	1.80	17.37	1.77	1.92	2.18	2.68	3.25	4.55	6.83
3290	.10	.15	.13	1.29	1.46	10.45	2.18	2.27	2.49	2.92	3.87	5.72	8.07
3291	.29	.49	.46	1.77	1.29	7.90	.22	.55	.72	1.12	2.60	5.43	7.94
3292	.22	.24	.23	.82	2.17	36.36	1.45	1.58	1.79	2.12	2.56	3.40	4.32
3293	.15	.15	.16	.71	2.78	45.50	2.28	2.41	2.51	2.66	3.02	3.69	4.79
3294	.23	.24	.24	.80	1.80	23.82	1.35	1.50	1.71	2.04	2.52	3.15	4.21
Lakota Formation													
FUSON MEMBER													
Fluvial unit 4													
3279	0.24	0.30	0.30	1.49	2.10	20.03	0.85	1.03	1.23	1.76	2.53	3.13	9.49
3280	1.08	.60	.82	2.42	.52	2.82	−8.00	−7.13	−2.63	.28	1.58	2.72	6.52
3281	.25	.30	.29	1.32	1.42	9.42	.15	.34	.96	1.79	2.76	3.39	6.51
3282	.14	.14	.15	1.42	1.20	9.17	1.07	1.23	1.62	2.78	3.66	4.65	7.75
3283	.15	.14	.17	1.18	1.64	16.27	1.45	1.67	1.98	2.54	3.23	4.30	6.49
3284	.13	.15	.16	1.27	2.14	19.75	2.12	2.21	2.35	2.68	3.15	4.87	8.57
3285	.28	.31	.30	.79	1.98	29.98	.93	1.07	1.36	1.74	2.21	2.66	3.86
3286	.19	.26	.22	1.19	1.64	16.57	1.05	1.34	1.68	2.17	2.87	3.90	6.04
3295	.14	.24	.18	1.78	1.39	9.00	1.10	1.33	1.72	2.48	3.55	5.90	10.26
Fluvial unit 3													
3262	0.29	0.23	0.25	1.49	−0.10	3.45	−1.85	−0.57	0.84	1.99	2.67	3.58	4.66
3263	.21	.19	.22	1.32	1.00	10.04	−.04	.45	1.29	2.21	2.90	4.30	4.95
3264	.32	.24	.28	1.61	.31	6.71	−2.22	−1.64	.80	1.81	2.48	3.22	4.81
3265	.16	.17	.19	1.21	2.26	24.17	1.69	1.83	2.07	2.38	2.75	3.86	7.50
CHILSON MEMBER													
Fluvial unit 2													
3266	0.12	0.14	0.15	1.36	2.02	17.82	2.22	2.33	2.53	2.72	3.45	4.64	9.65
3267	.10	.14	.15	1.66	1.40	8.30	1.82	2.06	2.33	2.77	3.95	6.99	10.27
3268	.16	.17	.18	.70	3.25	57.53	1.76	1.92	2.16	2.45	2.82	3.62	4.29
3269	.14	.14	.16	1.33	2.47	24.82	1.97	2.11	2.31	2.62	2.94	3.59	10.08
3270	.12	.14	.14	1.29	1.33	11.37	1.49	1.75	2.19	2.86	3.94	4.77	7.45
3271	.12	.14	.15	1.26	1.84	17.00	1.98	2.19	2.40	2.74	3.78	4.70	7.92
3272	.13	.15	.15	1.10	2.00	21.99	1.80	2.06	2.42	2.76	3.46	4.21	6.55
3273	.08	.08	.09	1.05	2.07	22.80	2.69	2.83	3.03	3.45	3.92	4.74	7.20
3274	.13	.15	.15	1.04	2.06	24.48	1.95	2.08	2.37	2.78	3.54	4.18	5.52
3275	.10	.12	.11	1.06	1.54	17.50	1.87	2.09	2.58	3.20	3.88	4.52	5.50
3276	.12	.15	.15	1.34	1.81	15.66	1.82	2.13	2.46	2.78	3.51	4.67	8.93
3277	.07	.12	.10	1.97	1.11	4.46	2.55	2.67	2.74	3.28	4.74	10.04	10.79
3278	.08	.11	.10	1.59	1.34	8.04	2.33	2.53	2.67	3.27	4.28	7.19	10.20
Fluvial unit 1													
3254	0.06	0.03	0.06	1.29	1.12	8.62	2.61	2.73	3.02	4.04	4.74	5.80	8.77
3255	.10	.11	.10	.76	1.40	21.21	2.38	2.85	2.93	3.30	4.26	4.81	4.98
3256	.14	.14	.15	.84	2.42	35.47	2.02	2.17	2.43	2.76	3.16	3.64	4.43
3257	.09	.08	.09	.72	1.53	23.86	2.60	2.71	2.94	3.45	3.93	4.36	4.75
3258	.15	.16	.17	.97	2.26	29.80	1.72	1.82	2.15	2.54	3.17	3.80	4.80
3259	.18	.18	.20	1.43	1.58	16.74	.87	1.08	1.55	2.29	3.22	4.15	8.25
3260	.10	.05	.10	1.23	1.13	10.45	1.52	1.78	2.15	3.28	4.04	4.79	5.65
3261	.17	.21	.19	1.07	1.88	21.15	1.49	1.65	1.85	2.36	2.97	3.93	5.87
UNKPAPA SANDSTONE													
3245	0.09	0.13	0.12	1.79	1.50	8.16	2.33	2.47	2.60	3.07	3.84	8.63	10.55
3246	.05	.09	.08	1.95	1.13	4.22	2.82	2.97	3.22	3.72	4.97	10.27	10.75
3247	.07	.12	.11	2.23	1.18	4.58	2.54	2.66	2.81	3.22	4.86	10.66	10.95
3248	.08	.12	.12	2.08	1.68	5.85	2.47	2.67	2.74	3.05	3.66	10.55	10.88
3249	.08	.12	.12	1.83	1.52	8.70	2.40	2.59	2.79	3.10	3.73	10.17	10.84
3250	.09	.12	.13	1.96	1.43	7.46	1.93	2.12	2.39	2.99	3.65	10.25	10.81
3251	.08	.13	.13	2.00	1.36	6.56	2.53	2.60	2.68	2.98	3.62	10.30	10.82
3252	.11	.11	.13	1.37	1.97	17.57	2.21	2.49	2.59	2.93	3.44	4.35	10.03
3253	.06	.08	.08	1.79	1.45	7.42	2.78	2.92	3.15	3.56	4.24	10.15	10.75

Chilson Member of the Lakota Formation are generally very fine to fine-grained sandstones, and samples from the Fuson Member are chiefly fine- to medium-grained sandstones. With one exception, all samples from the Fuson are at least as coarse grained as the samples from the Chilson. In fact, pebbles and cobbles are commonly present in the Fuson sandstones but are practically nonexistent in the Chilson sandstones. This provides one criterion for distinguishing between these members. Sandstone samples from the

Fall River Formation are typically fine grained and contain less silt and clay than samples from the Lakota or Unkpapa.

The sorting of sandstones is expressed in terms of phi standard deviations of the grain-size distributions; the higher the values, the poorer the sorting. Cadigan (1959, p. 531) has proposed a classification of sorting in phi units which is as follows: Less than 0.5, very well sorted; 0.5 to 1.0, well sorted; 1.0 to 2.0, moderately well sorted; 2.0 to 4.0, poorly sorted; greater than 4.0, unsorted. According to this scheme, as shown in figure 6 and table 4, all the samples from the Unkpapa Sandstone are moderately well to poorly sorted. Those from the Chilson Member of the Lakota Formation are moderately well to well sorted. Samples from fluvial unit 3 in the Fuson Member of the Lakota are moderately well sorted, and those from fluvial unit 4 are chiefly moderately well sorted. The average sorting in samples from the Lakota Formation (table 6) is best in fluvial unit 1 and becomes progressively poorer in the younger fluvial units. In samples from fluvial unit 5 of the Fall River Formation the average sorting is about equal to that in unit 1.

Skewness is a measure of the asymmetry of the grain-size frequency distribution. It is positive where the particles in the finer half of the distribution are more poorly sorted than particles in the coarser half of the distribution, and it is negative where the coarser half of the grain-size distribution is more poorly sorted than the finer half. All the samples studied have positive skewness except one from fluvial unit 3 of the Fuson Member of the Lakota Formation (table 4), and it has only small negative skewness. The relation between skewness and mean grain size is shown in figure 6.

Kurtosis is a measure of the peakedness of the grain-size distribution. Commonly, high kurtosis values occur in well-sorted distributions, whereas low values occur in the poorly sorted distributions. The grain-size distributions for samples from the Unkpapa Sandstone are only moderately peaked (averaging 7.84), whereas the better sorted grain-size distributions from fluvial units 1 and 2 of the Chilson Member of the Lakota are, respectively, very highly to highly peaked (table 5). Grain-size distributions in the moderately well sorted samples from fluvial units 3 and 4 of the Fuson Member are less peaked than the distributions in samples from the Chilson. As expected, the average grain-size distribution for samples from fluvial unit 5 of the Fall River Formation is very highly peaked (even more highly peaked than the distributions in the Chilson Member).

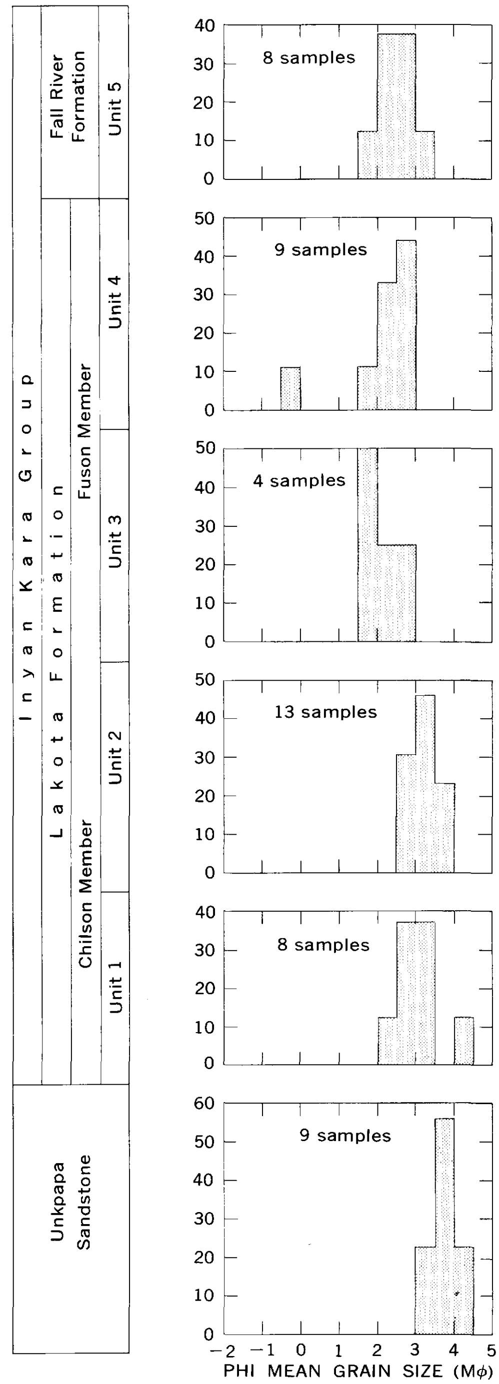

FIGURE 5. — Distributions of phi mean grain sizes of samples from each fluvial unit. The vertical axes represent percent of samples.

The relation of mean grain size to sorting (standard deviation) for each stratigraphic unit reflects the total energy level or tectonic environment of the system and therefore indicates the amount of upwarp of the source area and the amount of subsidence in the area of deposition. This concept, as

TABLE 5. — *Comparison of results of three different methods for determining the phi parameters of the grain-size distribution of samples from the Unkpapa Sandstone*

[All measures are in phi units]

Field sample (L–)	Mean			Standard deviation			Skewness		
	Inman[1]	Folk[2]	Present report[3]	Inman[1]	Folk[2]	Present report[3]	Inman[1]	Folk[2]	Present report[3]
3245	3.22	3.17	3.53	0.62	1.24	1.79	0.24	0.52	1.50
3246	4.10	3.97	4.35	.88	1.55	1.95	.43	.61	1.13
3247	3.84	3.63	3.92	1.02	1.72	2.23	.61	.73	1.18
3248	3.20	3.15	3.63	.46	1.42	2.08	.33	.61	1.68
3249	3.26	3.21	3.55	.47	1.39	1.83	.34	.60	1.52
3250	3.02	3.01	3.48	.63	1.55	1.96	.05	.41	1.43
3251	3.15	3.09	3.55	.47	1.41	2.00	.36	.63	1.36
3252	3.02	2.99	3.15	.42	.49	1.37	.21	.36	1.97
3253	3.70	3.65	4.07	.54	1.37	1.79	.26	.53	1.45

[1]Inman (1952, p. 130) gave the following formulas for determining the phi parameters. The phi values are the grain sizes at the given percentiles:

$$\text{Mean} = \frac{\phi 16 + \phi 84}{2}$$

$$\text{Standard deviation} = \frac{\phi 84 - \phi 16}{2}$$

$$\text{Skewness} = \frac{\phi 16 + \phi 84 - 2\phi 50}{\phi 84 - \phi 16}$$

[2]R. L. Folk (written commun., 1955) gave the following formulas for determining the phi parameters:

$$\text{Mean} = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

$$\text{Standard deviation} = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

$$\text{Skewness} = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

[3]The phi parameters used in the present report were determined by moment calculations (Krumbein and Pettijohn, 1938; Griffiths, 1967).

TABLE 6. — *Averages of selected properties of sandstones from the Inyan Kara Group and the Unkpapa Sandstone*

ROCK COMPOSITION AND TEXTURE[1]

Stratigraphic unit	Number of samples	Composition[1]					Texture	
		Feldspar (percent)	Potassium feldspar: plagioclase (ratio)	Siliceous grains (percent)	Volcanic grains (percent)	Mica (percent)	Mean grain size (mm)	Sorting ($\sigma\phi$)
Inyan Kara Group:								
Fall River Formation, fluvial unit 5	8	6.1	0.2	86	0.3	0.68	0.19	1.06
Lakota Formation:								
Fuson Member, fluvial unit 4	9	1.4	.1	93	1.0	.12	.29	1.43
fluvial unit 3	4	1.0	.4	92	5.7	.05	.25	1.40
Chilson Member, fluvial unit 2	13	4.6	1.7	88	1.0	.03	.11	1.29
fluvial unit 1	8	5.3	1.3	88	4.0	.05	.12	1.04
Unkpapa Sandstone	9	12.7	3.2	78	1.4	.09	.08	1.89

HEAVY MINERALS[2]

Stratigraphic unit	Number of samples	Zircon plus tourmaline (percent)	Angular zircon plus angular tourmaline (percent)	Garnet (percent)	Anatase plus leucoxene (percent)	Other grains[3] (percent)
Inyan Kara Group:						
Fall River Formation, fluvial unit 5	12	32	11	1	58	2
Lakota Formation:						
Fuson Member, fluvial unit 4	13	34	9	1	57	1
fluvial unit 3	7	41	5	3	50	2
Chilson Member, fluvial unit 2	27	51	3	2	42	2
fluvial unit 1	13	47	8	2	41	5
Unkpapa Sandstone	6	44	4	14	22	15

[1]Based on thin-section modal-composition data.
[2]Based on heavy-mineral grain counts.
[3]Dominantly black opaques.

presented by Cadigan (1961), is the basis for interpretations of tectonic activity during the Early Cretaceous which are given later in this report. Briefly, the tectonic concept recognizes that crustal upwarp provides a stream gradient (that is, energy) for the transport of sediment from the source area to the

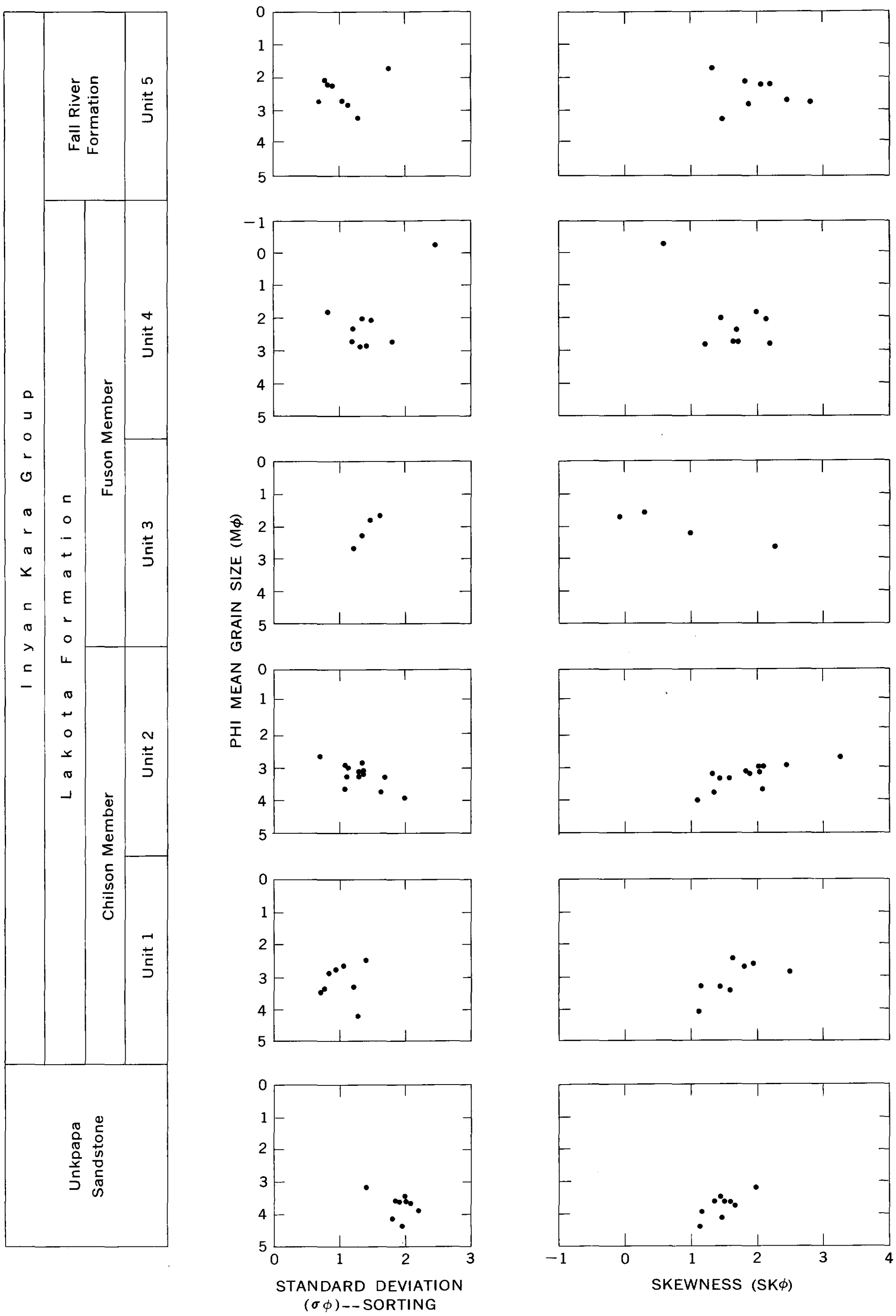

FIGURE 6. — Phi mean grain size measures plotted over phi standard deviation (sorting) measures and over skewness measures of grain-size distributions of samples of sandstone and coarse siltstone from the Inyan Kara Group and the Unkpapa Sandstone.

site of deposition and provides energy for reworking and sorting of the sediment. The grain size of the sediment is limited by the level of available energy. Deposition from streams occurs as the stream gradient (and energy of transport) decreases. Where subsidence is rapid along a stream profile, deposition may be both rapid and permanent, but where subsidence is slow, sedimentary deposits may be exposed to much reworking and sorting.

Values of skewness, kurtosis, and standard deviation are indicators of the amount of reworking and sorting during deposition. According to Cadigan (1961, p. 137), high skewness and kurtosis values indicate

that a large amount of reworking has taken place in and adjacent to the point of deposition of the sample. High kurtosis values * * * combined with very fine grain size indicate low-energy-level reworking. High kurtosis values * * * combined with fine to medium grain size indicate high-energy-level reworking. Either high- or low-energy-level reworking would be indicative * * * that the supply [of material] is below the transporting capacity of the geologic agent in the area of deposition, and that deposition (and subsidence) is taking place at a slow rate.

Therefore, we conclude that sands of the Unkpapa originated from source areas having low tectonic uplift and that rapid subsidence in the southern Black Hills caused a high rate of deposition and little reworking of the sediment. Low tectonic uplift occurred in source areas contributing sediment for fluvial units 1 and 2, and in the slowly subsiding area of the southern Black Hills a low rate of deposition enabled low-energy-level reworking of these sediments before burial. The source areas of sediment for fluvial units 3 and 4 were moderately uplifted causing some high-energy-level reworking before rapid deposition and burial. Source areas for fluvial unit 5 remained relatively high, and much moderate-energy-level reworking and sorting of sediment occurred before final deposition.

HEAVY MINERALS

Heavy-mineral grain counts were made for 78 samples. Grains were separated from the 0.043- to 0.297-mm size fraction because we thought that this size range would yield the greatest variety of readily identifiable minerals. The heavy-mineral content of the samples studied was commonly a few tenths of 1 percent by weight but ranged from 0.02 to 1.32 percent. Grain mounts were made for each sample, and counts were made by traversing each mount along lines 1–2 mm apart and counting all grains that came under the crosshairs. For nearly all samples a minimum of 100 nonopaque grains were counted and a minimum total of 300 opaque plus nonopaque grains. The percentage composition of the detrital-heavy-mineral suites for all samples is shown in table 7. For purposes of deciding whether authigenic or epigenetic minerals were derived from detrital or secondary minerals, the following arbitrary assumptions were made. Anatase and leucoxene probably formed from detrital titanium heavy minerals and were therefore counted. Many, if not most, hematite grains are pseudomorphous after pyrite and were therefore not counted as detrital components. Authigenic barite and pyrite were also excluded, as they are clearly not detrital.

Zircon, tourmaline, and anatase plus leucoxene form the bulk of detrital or detritally derived heavy minerals in the Inyan Kara Group and the Unkpapa Sandstone. Figure 7 shows the average percentages of the minerals by unit. The suites of heavy minerals from all units are very similar and constitute a chemically stable assemblage.

In the units sampled, the proportions of zircon and tourmaline combined range from 16 to 73 percent of total heavy minerals, but most samples contain 30–50 percent (table 7). Zircon is generally more abundant than tourmaline. In the Inyan Kara Group proportions of anatase plus leucoxene range from 22 to 81 percent of the total heavy minerals, but most samples contain 40–60 percent. In contrast, the Unkpapa samples contain less than 30 percent anatase plus leucoxene and average about 22 percent. Garnet is present in amounts less than 5 percent in most Inyan Kara samples but is more abundant in the Unkpapa, where it averages 14 percent. Rutile and staurolite are minor constituents in samples of all units, but staurolite locally constitutes more than 10 percent in fluvial units 4 and 5. Black opaque minerals and miscellaneous grains compose as much as 5 percent of the heavy minerals in samples from the Inyan Kara but average about 15 percent for the Unkpapa.

In their study, Mapel, Chisholm, and Bergenback (1964, p. C23, C30) recognized three fairly consistent nonopaque heavy-mineral zones in sandstones from Jurassic and Cretaceous formations of the Black Hills. The lower zone includes the Hulett Sandstone and Redwater Shale Members of the Sundance Formation, the lower part of the Morrison Formation, and locally the lower part of the Unkpapa Sandstone, all Late Jurassic age. This zone is characterized by having a garnet content averaging 30 percent of the nonopaque minerals. The middle zone consists of the upper part of the Morrison Formation, most of the Unkpapa Sandstone, and, in the southern Black Hills, all the Lakota Formation. This zone is characterized by the dominance of rounded zircon and tourmaline and by a much lesser amount of garnet, which generally forms less than 5 percent

TABLE 7.—*Percentage composition of the heavy-mineral suite in the 0.043- to 0.297-mm size fraction of samples from the Inyan Kara Group and the Unkpapa Sandstone as determined by mineral grain counts*

[0 indicates mineral not found; X indicates mineral present in amounts less than 1 percent. Sample localities are given in table 2]

Field sample (L–)	Zircon			Tourmaline			Zircon and tourmaline			Garnet	Rutile	Staurolite	Anatase and leucoxene	Other[1]	Grains counted
	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total						
INYAN KARA GROUP															
Fall River Formation															
Fluvial unit 5															
3379	3	10	13	7	8	15	10	18	28	X	2	1	68	X	364
3380	3	6	9	7	10	17	10	16	26	0	2	5	66	X	371
3381	0	9	9	9	0	9	9	9	18	2	0	4	68	7	[2]44
3382	3	15	18	8	6	14	11	21	32	0	2	X	63	2	[2]124
3383	8	24	32	3	6	9	11	30	41	3	5	X	50	1	279
3384	9	14	23	6	3	9	15	17	32	X	2	2	55	8	257
3385	4	8	12	9	17	26	13	25	38	2	3	23	32	2	170
3386	4	12	16	5	12	17	9	24	33	3	4	2	57	X	316
3387	1	11	12	8	8	16	9	19	28	0	3	9	56	4	330
3388	5	19	24	5	8	13	10	27	37	0	5	2	54	2	324
3389	1	21	22	5	6	11	6	27	33	0	5	X	59	3	274
3390	3	4	7	8	10	18	11	14	25	0	2	X	69	1	397
Average	4	13	17	7	8	15	11	21	32	1	3	4	58	2	......
Lakota Formation															
FUSON MEMBER															
Fluvial unit 4															
3366	1	9	10	5	5	10	6	14	20	0	X	2	77	0	461
3367	4	15	19	6	11	17	10	26	36	0	4	X	59	1	301
3368	2	25	27	6	14	20	8	39	47	0	2	9	40	2	251
3369	5	14	19	12	11	23	17	25	42	0	3	3	50	2	252
3370	2	16	18	3	8	11	5	24	29	0	2	10	56	3	241
3371	X	4	4	5	16	21	5	20	25	0	2	31	38	4	299
3372	4	32	36	1	27	28	5	59	64	X	1	X	33	X	302
3373	5	23	28	4	4	8	9	27	36	2	4	X	56	X	237
3374	4	7	11	6	6	12	10	13	23	3	0	5	67	1	265
3375	4	11	15	6	15	21	10	26	36	3	1	1	58	1	306
3376	4	16	20	6	5	11	10	21	31	6	1	2	58	2	341
3377	4	7	11	9	9	18	13	16	29	0	4	X	66	X	334
3378	1	9	10	5	7	12	6	16	22	0	X	2	73	2	478
Average	3	15	18	6	10	16	9	25	34	1	2	5	57	1	......
Fluvial unit 3															
3331	2	10	12	1	3	4	3	13	16	X	X	X	81	1	553
3332	3	32	85	1	8	9	4	40	44	3	1	3	47	2	262
3333	1	17	18	1	8	9	2	25	27	3	1	2	67	X	362
3334	5	32	37	1	13	14	6	45	51	7	3	2	35	2	167
3338	1	20	21	2	8	10	3	28	31	4	X	4	59	X	337
3350	3	23	26	3	25	28	6	48	54	4	3	4	32	3	243
3399	3	40	43	2	14	16	5	54	59	X	3	6	28	4	220
Average	3	25	28	2	11	13	5	36	41	3	1	3	50	2	......
CHILSON MEMBER															
Fluvial unit 2															
3339	3	34	37	0	23	23	3	57	60	2	1	1	34	2	348
3340	3	16	19	0	12	12	3	28	31	1	2	2	61	3	310
3341	6	41	47	2	11	13	8	52	60	10	3	X	26	1	263
3343	2	30	32	1	18	19	3	48	51	3	2	1	41	2	302
3344	1	22	23	1	27	28	2	49	51	2	X	1	45	1	284
3346	1	26	27	4	24	28	5	50	55	2	3	X	39	X	230
3347	0	15	15	2	19	21	2	34	36	3	1	2	58	X	281
3348	1	22	23	2	22	24	3	44	47	2	3	1	45	2	330
3349	3	19	22	2	35	37	5	54	59	4	2	X	33	1	321
3352	2	17	19	2	21	23	4	38	42	2	2	2	48	4	344
3353	2	18	20	1	31	32	3	49	52	2	2	1	41	2	293
3354	4	26	30	0	21	21	4	47	51	X	3	3	42	1	302
3355	2	26	28	0	23	23	2	49	51	X	1	4	38	6	229
3356	1	20	21	1	17	18	2	37	39	X	4	X	54	3	282
3357	3	24	27	0	19	19	3	43	46	5	1	1	45	2	304
3358	2	26	28	1	23	24	3	49	52	4	2	4	34	4	231
3359	4	31	35	X	19	19	4	50	54	3	4	0	34	5	354
3360	2	41	43	1	18	19	3	59	62	0	2	1	23	12	177
3361	3	20	23	1	29	30	4	49	53	2	2	X	42	1	294
3362	X	28	28	0	24	24	X	52	52	1	2	X	41	4	268
3363	3	29	32	0	31	31	3	60	63	0	2	X	32	2	299
3364	4	41	45	1	16	17	5	57	62	0	3	0	31	4	310
3365	2	31	33	2	20	22	4	51	55	4	2	X	37	2	374
3395	2	37	39	3	24	27	5	61	66	0	3	0	31	0	[3]116
3396	1	3	4	1	24	25	2	27	29	X	2	2	66	X	319
3397	0	49	49	0	22	22	0	71	71	0	1	5	23	0	[3]83
3398	1	11	12	2	22	24	3	33	36	X	2	6	55	X	123
Average	2	26	28	1	22	23	3	48	51	2	2	1	42	2	......

TABLE 7. — *Percentage composition of the heavy-mineral suite in the 0.043- to 0.297-mm size fraction of samples from the Inyan Kara Group and the Unkpapa Sandstone as determined by mineral grain counts* — Continued

Field sample (L–)	Zircon			Tourmaline			Zircon and tourmaline			Garnet	Rutile	Stauro-lite	Anatase and leucoxene	Grains counted	Other[1]
	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total	Angular grains	Rounded grains	Total						
INYAN KARA GROUP — Continued															
Lakota Formation — Continued															
CHILSON MEMBER — Continued															
Fluvial unit 1															
3319	2	8	10	5	7	12	7	15	22	0	4	X	68	5	366
3320	6	15	21	6	12	18	12	27	39	8	2	1	27	23	200
3321	5	16	21	1	14	15	6	30	36	X	5	X	54	4	316
3322	2	13	15	0	37	37	2	50	52	4	X	3	40	1	212
3323	5	30	35	X	16	16	5	46	51	X	8	0	36	5	295
3325	5	36	41	1	13	14	6	49	55	5	3	X	31	6	333
3326	4	29	33	2	20	22	6	49	55	4	3	1	35	2	284
3329	2	7	9	4	14	18	6	21	27	0	3	0	65	5	319
3330	7	25	32	4	18	22	11	43	54	6	3	4	30	3	310
3335	10	20	30	8	4	12	18	24	42	0	4	0	45	4	277
3336	3	24	27	6	23	29	9	47	56	0	4	1	36	3	194
3337	4	56	60	2	11	13	6	67	73	X	3	X	22	2	284
3394	1	19	20	4	22	26	5	41	46	2	3	X	46	2	357
Average	4	23	27	4	16	20	8	39	47	2	4	1	41	5	......
UNKPAPA SANDSTONE															
3313	3	15	18	2	12	14	5	27	32	6	1	3	23	35	216
3314	3	18	21	1	29	30	4	47	51	10	2	1	29	7	259
3315	1	22	23	1	30	31	2	52	54	8	1	6	28	3	296
3316	6	35	41	1	9	10	7	44	51	13	5	0	28	3	341
3317	2	16	18	0	10	10	2	26	28	18	1	1	9	43	309
3318	X	21	21	0	25	25	X	46	46	33	X	3	16	X	312
Average	3	21	24	1	19	20	4	40	44	14	2	3	22	15	......

[1]Black opaque minerals, biotite, monazite(?), and spinel(?).
[2]Less than 100 nonopaque grains counted because sample was predominantly iron oxide.
[3]Less than 100 nonopaque grains listed because authigenic barite (counted but not listed) more abundant than total of all other nonopaque minerals.

of the nonopaque suite. The upper zone, in the southern Black Hills, consists of the Fall River Formation and the Newcastle Sandstone. It is characterized by predominantly angular grains of zircon and tourmaline. The results of the present study agree rather well with the conclusions of Mapel, Chisholm, and Bergenback (1964), but the results of the two studies cannot be compared directly. In the present study, detrital opaque heavy minerals as well as nonopaque minerals were included, and the 0.043- to 0.297-mm size fraction was used. Mapel, Chisholm, and Bergenback (1964) confined their study to nonopaque heavy minerals, mostly in the 0.062- to 0.125-mm size fraction. The first factor lowers the percentages of the nonopaque heavy minerals listed in the present report; the second factor, which includes larger grain sizes, probably accounts for the greater percentage of rounded grains of the zircon and tourmaline listed in this report. Mapel, Chisholm, and Bergenback (1964, fig. 12) showed that of the combined zircon and tourmaline grains in the 0.062- to 0.125-mm size fraction, a line drawn at 40 percent angular grains separates 92 percent of the Fall River samples from 91 percent of the Lakota samples, with the Fall River Formation containing the most angular grains. A somewhat similar division can be made in the present study. Figure 8 shows the percentage of angular grains of the zircon and tourmaline. A line drawn at 26 percent angular grains separates 92 percent of the Fall River samples from 82 percent of the Lakota samples. The difference between the 26-percent versus 40-percent division is probably the result of greater rounding of coarser grains and differences in operator judgment. All the samples from the Unkpapa Sandstone contain less than 20 percent angular zircon and tourmaline grains. The samples from fluvial unit 4 in the upper part of the Lakota contain a greater percentage of angular zircon and tourmaline grains than samples from older units in the Lakota and are more similar to the samples from the Fall River Formation. This is in agreement with the findings by Mapel, Chisholm, and Bergenback (1964, fig. 12).

SOURCE OF SAND AND THE INFLUENCE OF TECTONIC ACTIVITY UPON DEPOSITION OF LOWER CRETACEOUS SEDIMENTARY MATERIALS

The sandstones that have been sampled have a considerable variation in the composition of the nonsiliceous fraction, the heavy-mineral fraction, and the mean grain size. In general these variations constitute detrital assemblages that characterize the Unkpapa Sandstone, units 1 and 2, units 3 and 4, and unit 5, but some assemblages overlap these stratigraphic units.

The assemblages of characteristic minerals that have been determined by the petrographic study are

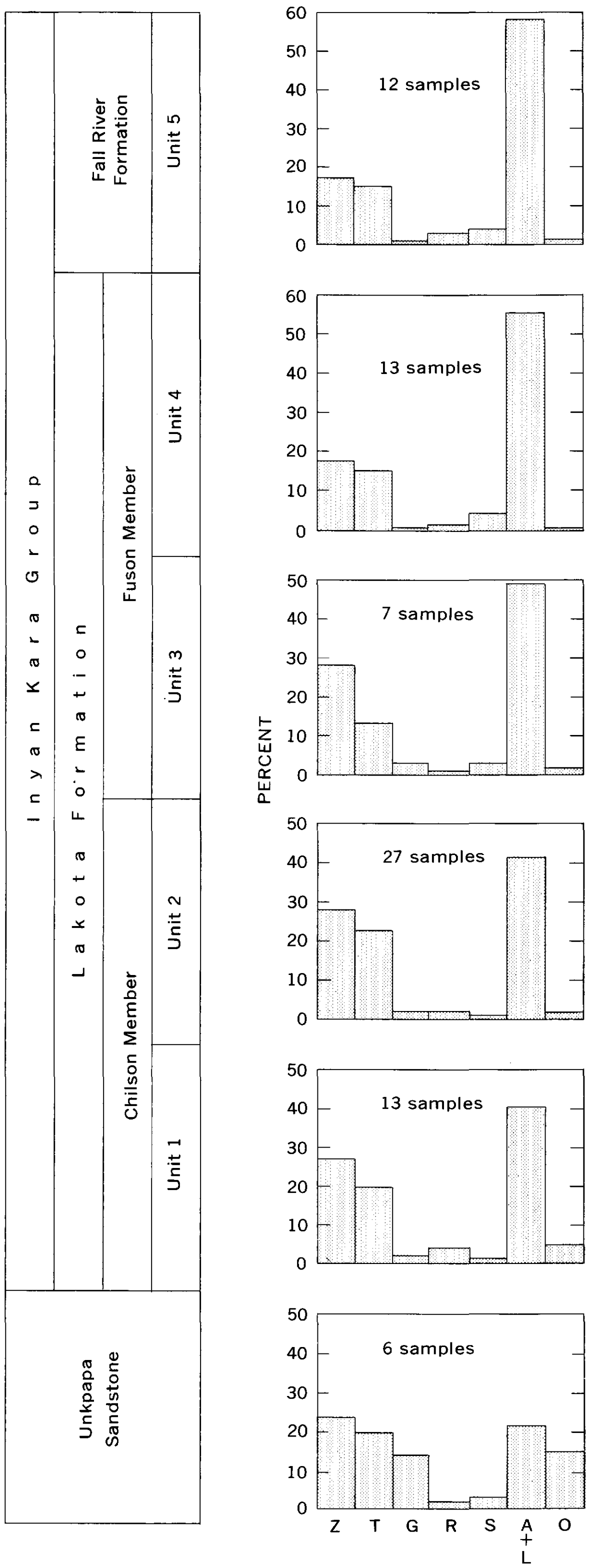

FIGURE 7.—Average percentage composition of heavy-mineral suites in samples from sandstone units in the Inyan Kara Group and the Unkpapa Sandstone. Z, zircon; T, tourmaline; G, garnet; R, rutile; S, staurolite; A + L, anatase plus leucoxene; O, other minerals.

shown in table 8. The data show that the Unkpapa Sandstone is characterized by a very fine grained sandstone and siltstone containing more garnet and feldspar, having a higher potassium-feldspar–plagioclase ratio, and containing less anatase and leucoxene and generally less angular tourmaline than the sandstones of the Inyan Kara Group. Units 1 and 2 contain more rounded and less angular tourmaline and zircon than does unit 5 in the Fall River Formation. Fluvial unit 5 contains much more mica than do the older units, and fluvial unit 3 contains an abnormally high amount of chert and silicified limestone. In general, however, the mineral assemblages of units 3 and 4 of the Fuson Member are transitional in composition between the assemblages of the Chilson Member of the Lakota and those of the Fall River.

All these assemblages are generally similar to assemblages described by Mackenzie and Poole (1962, p. 62–71). From a study of the Dakota Sandstone in the Western Interior, which includes equivalents of the Inyan Kara Group, they found two suites of detrital minerals diagnostic of source areas. (1) The eastern suite, relative to the western suite, contains more feldspar, muscovite, chlorite, chloritoid, angular tourmaline, and heavy minerals in general and contains less chert. They concluded that most of the sandstones were probably derived from the Canadian Shield. (2) The western suite of detrital minerals was derived primarily from pre-Cretaceous sedimentary rocks of the Cordilleran region to the west.

Similar detrital mineral suites are present in the Lakota and Fall River sandstones in the southern Black Hills. By analogy it would appear that these sandstones also were derived from eastern and west-

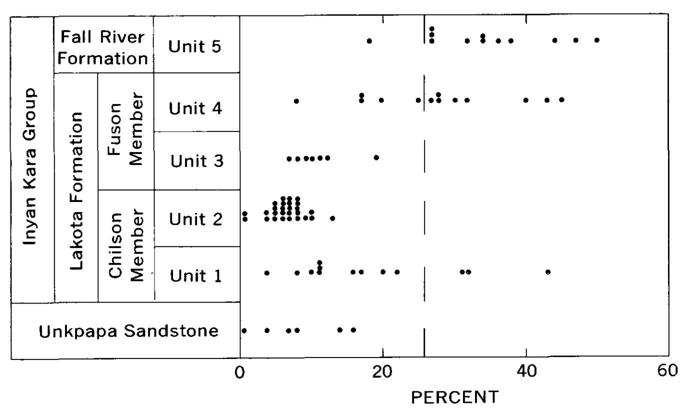

FIGURE 8.—Proportion of angular grains in combined zircon and tourmaline varieties for each of 76 samples (0.043- to 0.297-mm size fraction) from six sandstone units in the Inyan Kara Group and the Unkpapa Sandstone. Each dot represents one sample.

TABLE 8. — *Average percentage of selected minerals in samples from the Inyan Kara Group and the Unkpapa Sandstone*

[High, intermediate, and low percentages for each column were determined by equal interval grouping of log values for the range in each column]

Formation, member, and group	Fluvial unit	Garnet—Percentage of heavy minerals	Total feldspar	Plagioclase	Potassium feldspar	Rounded tourmaline (Percentage of heavy minerals)	Rounded zircon (Percentage of heavy minerals)	Rounded zircon + rounded tourmaline (Percentage of heavy minerals)	Total zircon + total tourmaline (Percentage of heavy minerals)	Total zircon (Percentage of heavy minerals)	Volcanic grains	Chert and silicified limestone	Anatase+leucoxene (Percentage of heavy minerals)	Angular zircon + angular tourmaline (Percentage of heavy minerals)	Angular tourmaline (Percentage of heavy minerals)	Angular zircon (Percentage of heavy minerals)	Mica	
Inyan Kara Group; Fall River Formation		12 samples	8 samples			12 samples					8 samples		12 samples				8 samples	
	Fluvial unit 5	1 (0-3)	6.1 (2.0-11.6)	4.9 (1.6-10.6)	1.2 (0-2.8)	8 (3-17)	13 (4-24)	21 (9-30)	32 (18-41)	17 (7-32)	0.3 (0-0.6)	0.68 (0-1.6)	58 (32-69)	11 (6-15)	7 (3-9)	4 (0-9)	0.68 (0-2.8)	
Inyan Kara Group; Lakota Formation; Fuson Member		13 samples	9 samples			13 samples					9 samples		13 samples				9 samples	Transitional mineral assemblages
	Fluvial unit 4	1 (0-6)	1.4 (0.2-2.8)	1.3 (0.2-2.8)	0.1 (0-1)	10 (4-27)	15 (4-32)	25 (13-59)	34 (20-64)	18 (4-36)	1 (0-4)	2.3 (0-13.8)	57 (33-77)	9 (5-17)	6 (1-12)	3 (X-5)	0.12 (0-0.4)	
		7 samples	4 samples			7 samples					4 samples		7 samples				4 samples	
	Fluvial unit 3	3 (X-7)	1 (0.2-2.4)	0.7 (0.2-1.6)	0.3 (0-0.8)	11 (3-25)	25 (10-40)	36 (13-54)	41 (16-59)	28 (12-43)	5.7 (3.6-6.6)	22.4 (2.4-77.2)	50 (28-81)	5 (2-6)	2 (1-3)	3 (1-5)	0.05 (0-0.2)	
Inyan Kara Group; Lakota Formation; Chilson Member		27 samples	13 samples			27 samples					13 samples		27 samples				13 samples	
	Fluvial unit 2	2 (0-10)	4.6 (1.2-12.6)	1.7 (0.2-5.2)	2.9 (0-7.4)	22 (11-35)	26 (3-49)	48 (28-71)	51 (29-71)	28 (4-49)	1 (0.2-2.2)	1.35 (0-4.4)	42 (23-66)	3 (0-8)	1 (0-4)	2 (0-6)	0.03 (0-0.2)	
		13 samples	8 samples			13 samples					8 samples		13 samples				8 samples	
	Fluvial unit 1	2 (0-8)	5.3 (1.2-15)	2.0 (0.4-7.6)	3.1 (0.6-7.4)	16 (4-37)	23 (7-56)	39 (15-67)	47 (22-73)	27 (9-60)	4 (0.4-12.2)	0.55 (0-1.6)	41 (22-68)	8 (2-18)	4 (0-8)	4 (1-10)	0.05 (0-0.2)	
Unkpapa Sandstone		6 samples	9 samples			6 samples					9 samples		6 samples				9 samples	
		14 (6-33)	12.7 (1.8-19)	3 (0.6-5.2)	9.7 (0-13.8)	19 (9-30)	21 5)	40 (26-52)	44 (28-54)	24 (18-41)	1.4 (0-3)	0.066 (0-0.2)	22 (9-29)	4 (X-7)	1 (0-2)	3 (X-6)	0.09 (0-0.4)	

EXPLANATION

High percentage	Intermediate percentage	Low percentage	3	(9-30)	X
			Average mineral percentage for stratigraphic unit	Range of mineral percentage for each stratigraphic unit	Indicates mineral present in amounts less than 1 percent

ern source areas. The detailed mapping that has been done in the southern Black Hills, however, permits a more detailed account of the stratigraphic distribution of the detrital mineral assemblages than could be given by Mackenzie and Poole.

If we assume that the sandstones making up the Unkpapa Sandstone and the sandstones of the Lakota and Fall River Formations were derived from eastern and western source areas and if we utilize the same criteria to identify the sandstones that were derived from each area, then the depositional history can be surmised.

In Late Jurassic time an eastern source area was subjected to minor tectonic uplift and erosion. Sands with an eastern suite of minerals eroded largely from sedimentary rocks exposed toward the east were redeposited to form the Unkpapa Sandstone of the southeastern Black Hills while finer sedimentary material was being deposited to the west. This material was in part derived from the area east of the zero isopach shown in figure 9.

At the begining of Cretaceous time mild regional uplift accompanied by volcanic activity apparently occurred west of the Black Hills area, possibly to the southwest in central Colorado, and contributed tuff, ash, and felsite to sandstones of fluvial unit 1 of the

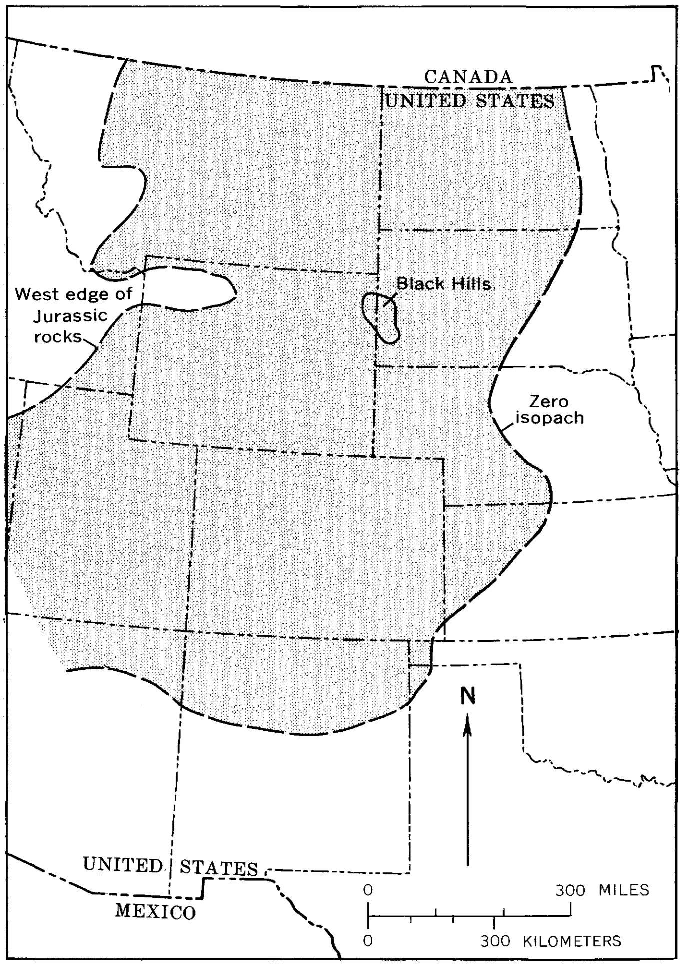

FIGURE 9. — Probable minimum extent of Jurassic rocks (patterned) in the Western Interior region at the end of the Jurassic Period (modified from McKee and others, 1956, pl. 1).

Chilson Member. A contribution from the western source is suggested by the increased chert and decreased mica content of the sandstones. Erosion proceeded simultaneously in eastern South Dakota. Subsidence and deposition by streams along the axis of the Black Hills syncline as described by Bolyard and McGregor (1966) was not as rapid during early Chilson time as during Late Jurassic time; thus, more low-energy reworking and sorting of sediments occurred before burial.

While the sands of fluvial unit 2 were being deposited during late Chilson time, volcanic and tectonic activity was relatively quiescent. This resulted in the deposition of less volcanic material and little change in the grain size of the sand — that is, little change in the energy level of the streams. The proportion of western-suite minerals, including rounded zircon and tourmaline, increased during Chilson time as subsidence shifted the Early Cretaceous syncline eastward and the eastern source areas either were eroded to low topographic relief or were slightly depressed.

At the end of Chilson time renewed tectonic activity caused minor uplift locally along northeast-trending structures (discussed in the structure section). This minor local tectonic adjustment possibly was related to a renewal of uplift to the west, which is indicated by the composition of younger fluvial deposits in the lower part of the Fuson Member. Several lakes were formed, apparently as a result of the tectonic activity, and evaporation of lake waters rich in calcium bicarbonate and calcium sulfate caused precipitation of the Minnewaste Limestone Member of the Lakota.

The Fuson Member is composed mostly of lacustrine mudstones and sandstones, but it also contains the crossbedded sandstones of fluvial units 3 and 4. These sandstones probably were deposited at energy levels generally greater than those at which the other fluvial sandstones of the Inyan Kara were deposited, although the sandstone of fluvial unit 3 locally exhibits foreset bedding suggesting deltaic deposition (Cuppels, 1963). Similarly, the alternating tabular sets of horizontal and cross stratification found in the sandstone of unit 4 (Ryan, 1964) suggest that some of the sandstone was deposited as local deltaic or lacustrine deposits. The paradox of simultaneous high- and low-energy-level deposition probably results indirectly from tectonic activity, which was strongest at the beginning and at the close of Fuson time.

We postulate that, at the end of Minnewaste time, stream erosion or tectonic activity breached natural dams formed by uplift along northeast-trending structures and released large volumes of water stored in the lakes. This release of water, which in some places may have been catastrophic, probably was coupled with relatively high rates of flow. Stream gradients were steepened by local uplift, and channels locally were incised through the Morrison and into the Redwater Shale Member of the Sundance Formation.

The Fuson Member is characterized by mineral assemblages that are transitional in composition between assemblages of the Chilson Member, which contain a large percentage of western-suite minerals, and the assemblage of fluvial unit 5 of the Fall River, which contains an abundance of eastern-suite minerals. This transition is also evident within the Fuson, between the mineral assemblage of fluvial unit 3 in the lower part of the Fuson and the assemblage of fluvial unit 4 in the upper part of the member.

Deposition in fluvial unit 3 is characterized by an abundance of western-suite minerals. Chert commonly ranging in grain size from sand to pebble size is especially abundant. Chert grains may have been derived either from distant sources or from Paleozoic sediments, but the larger chert pebbles probably were derived from local sources including chert lenses in the basal Fuson Member, the Minnewaste Limestone Member, and the Sundance Formation. Other silicified material, consisting of petrified wood and silica-cemented sand and silt from the Lakota, probably is included in the siliceous material of fluvial unit 3. A high percentage of volcanic grains indicates that volcanic activity accompanied a renewed uplift of the western source areas. The limited contribution of sediments of the eastern suite is marked by a low feldspar content and by a clay matrix that contains very little kaolinitic clay but much illitic and mica clay.

Toward the end of Fuson time the eastern source area contributed much sediment to the sandstone of fluvial unit 4. Volcanic material, rounded zircon, and chert are less abundant in this sandstone than in the older fluvial unit 3, whereas the mica content and the proportion of kaolinite to total clay are greater. The uplift of the eastern source areas may have been related to local deformation which shifted the axis of the Black Hills syncline to the west and caused the stream channel of fluvial unit 4 to migrate slightly westward in some areas. This shift of the channel is reflected by the maximum scouring of the channel and the maximum thickness of the fluvial sandstone at the southwest side of the paleodrainage, and by a noticeable thinning of the sandstone at the northeast side of the drainage (Gott and Schnabel, 1963, pl. 13).

By Middle Fall River time the eastern source areas supplied most of the sediment to the southern Black Hills area. Paleocurrent directions in sandstone of fluvial unit 5 in the southeastern Black Hills suggest a streamflow from the east and southeast which deposited much plagioclase feldspar and abundant angular tourmaline and zircon. Corresponding decreases in the abundance of rounded tourmaline and zircon and in the percentage of volcanic grains confirm the decrease in sediment from western source areas. The continued low garnet content in the sediments indicates that significant amounts of garnet were not eroded from the outcrops of Precambrian rocks in the eastern source area at this time.

STRUCTURE

The Black Hills uplift consists of an arcuate north- to northwest-trending dome-shaped anticline that is surrounded by the Missouri Plateau (Fenneman, 1931, p. 79). The mapped area included in the present report has about 6,000 feet of structural relief and lies across the south end of the uplift (pl. 1). The area may be divided into three parts — eastern, central, and western parts — each having a different structural character. (1) The eastern part of the mapped area is folded into three relatively large sinuous south-plunging anticlines and several smaller anticlines (pl. 2) which shape the south end of the uplift. The Black Hills gravity axis coincides with the Chilson anticline 5 miles east of Edgemont, S. Dak. Nearly all the anticlines are asymmetric, having a gentle southeast-dipping flank, a steep west-dipping flank, and a parallel syncline lying about 1 mile west of the crest (pl. 1). The west side of this folded area is bounded by the south-plunging Sheep Canyon monocline along the flank of the Chilson anticline. (2) The central part of the mapped area consists of the southwest-dipping flank of the Black Hills, which is modified by the broad Dewey terrace, by three northwest-trending anticlines, by the northeast-trending normal faults of the Dewey and Long Mountain structural zones (pl. 1, north half), and by smaller normal faults. (3) North of the Dewey terrace, within the western part of the mapped area, major north- and northwest-trending Fanny Peak and Black Hills monoclines form the margin of the Black Hills uplift and the adjoining Powder River basin to the west. These monoclines are transected by small northeast-trending normal faults and by a few northwest-trending faults. In addition, a smaller monocline and two small north-trending anticlines are present. Configuration of the folds in the area is shown on plate 1 by structure contours drawn on the base of the Fall River Formation or on the reconstructed base where the Fall River has been removed by erosion.

FOLDS

The asymmetric, slightly arcuate Dudley anticline, 2 miles east of Hot Springs, S. Dak., can be traced southward for 9 miles along the outcrop of the Inyan Kara Group to the Cheyenne River, 1½ miles north of the Angostura Reservoir. The south-plunging anticline has an amplitude of as much as 600 feet and has about 100 feet of closure (Wolcott, 1967).

The Cascade anticline, 2 miles west of Hot Springs, is the largest fold of the southeastern Black Hills. The anticline has an amplitude of 1,300 feet and has as much as 650 feet of structural closure (Wolcott, 1967). The steep west flank of this asymmetric anticline attains a maximum dip of 70° SW., as contrasted to an average dip of 5° SE. on the east flank. West of Hot Springs the anticline forms a ridge that is held up by dip slopes of the resistant Minnekahta Limestone, and farther south it forms a ridge that is held up by resistant sandstones of the Inyan Kara Group. The south-plunging structure follows a sinuous 17-mile-long course across the area as it trends first to the southwest and then to the south and southeast. The anticlinal axis bifurcates south of Cascade Springs; the main axis continues an additional 8 miles south of the area of this report.

The south-plunging Chilson anticline, 5 miles east of Edgemont, is at least 30 miles long, but only the northern 10 miles of the structure lies within the area discussed here. The asymmetric fold has an amplitude of 800 feet, and its gentle flank dips only 2°–3° SE. Resistant sandstones of the Inyan Kara form a topographic high along the axis of the structure.

The northernmost 3 miles of the gently dipping southwest-trending Cottonwood Creek anticline lies within the mapped area and has little, if any, topographic expression. The fold has an amplitude of only 100 feet, and strata exposed at the surface consist predominantly of easily eroded shales of Cretaceous age.

The south-plunging nose of another asymmetric anticline enters the area 7 miles northwest of Hot Springs and continues southward 4 miles before it terminates. The steep flank dips 10° W. and the gentle flank dips 3° SE., forming a fold with 400 feet of amplitude. Rocks of the anticline exposed at the surface consist of the Minnekahta Limestone, Opeche Formation, and Minnelusa Formation, a stratigraphic sequence of alternating resistant and nonresistant strata that erosion has irregularly dissected to partially mask topographic expression of the fold.

Three southeast-trending anticlines having amplitudes of 100–200 feet are present in the central part of the mapped area. These parallel structural features dip 6°–13° (Braddock, 1963). The longest extends south of the Dewey fault zone for 7 miles and then terminates in a 1½-mile-wide closed structural feature known as the Barker Dome. The two smaller anticlines north of the Dewey fault zone are only 2–3 miles long and less than 1 mile wide.

Two other south-trending anticlines are at the west side of the mapped area, 3 miles northeast of the L A K Ranch and 5 miles south of the ranch. The first-mentioned anticline is at least 5 miles long and has an amplitude of 600 feet. It is bounded on the west side by the Fanny Peak monocline and on the east by an asymmetric syncline. The other anticline, 5 miles south of the L A K Ranch, has an amplitude of 200 feet and is bounded on the west by the Fanny Peak monocline and on the east by a shallow syncline.

A part of the common boundary of the Black Hills uplift and Powder River basin lies within the area and is formed by segments of the intersecting northwest-trending Black Hills monocline and north-northeast-trending Fanny Peak monocline. Northwest of the intersection of these monoclines at the L A K Ranch, 7 miles southeast of Newcastle, Wyo., the basin-uplift boundary is formed by the Black Hills monocline (pl. 1). Sandstones of the Inyan Kara Group crop out on a hogback along the axis of the monocline, and then within a mile they plunge 2,000 feet beneath the shales that underlie the plains. South-southeast of the intersection, the monocline diverges from the margin of the basin and has about 1,000 feet of relief, but within 12 miles the monocline gradually merges into the southwest-dipping flank of the uplift.

The Fanny Peak monocline forms the basin-uplift margin south of the L A K Ranch (pl. 1, north half) and, within the mapped area, has about 2,300 feet of relief. North of the ranch the monocline, exposed lower in the stratigraphic section, is steeper but has only 1,200 feet of relief.

A smaller, unnamed monocline with 800 feet of structural relief lies between the Black Hills and Fanny Peak monoclines north of the L A K Ranch. This monocline trends southward 3 miles from the northern boundary of the area before swinging to the southeast.

About 2½ miles east of Edgemont the west-dipping south-plunging Sheep Canyon monocline at the west margin of the Livingston terrace has 400 feet of relief within a distance of half a mile. The slightly sinuous monocline trends almost due north for 12 miles.

The southwest flank of the Black Hills is modified by the Dewey, Edgemont, and Livingston structural terraces, as well as by several small unnamed terraces indicated by the structure contours on plate 1. The Dewey terrace, bounded by the Fanny Peak monocline on the west and bisected by the Dewey fault zone, covers more than 30 square miles in the Dewey quadrangle and extends south of the mapped area, where it is not as well defined. The Edgemont terrace, which covers about 10 square miles (Ryan, 1964), is present at Edgemont, north of the Cottonwood Creek anticline, and is bounded on the east by the Sheep Canyon monocline. Much of the terrace is overlain by alluvium of Quaternary age, and therefore, details of the structure are not known. The smaller, Livingston terrace, 4 miles northeast of Edgemont, is bounded on the west by the Sheep Canyon monocline and on the east by the Chilson anticline. Rocks of the Inyan Kara Group crop out on the terrace, forming a gentle south-dipping surface. A small unnamed terrace covering 1–2 square miles is adjacent to the northwest side of the Long Mountain structural zone about 8 miles north of Edgemont.

FAULTS

Steeply dipping to vertical northeast-trending normal faults are common in the northwest and central parts of the area but are sparse in the folded eastern part. Generally, the north sides of the faults are upraised, as occurs in the Dewey and Long Mountain structural zones (pl. 2), in the central part of the area.

The Dewey structural zone consists of sinuous en echelon steeply dipping to vertical normal faults that uplift the north side of the zone a total of 500 feet by a combination of fault displacement and drag. The fault zone can be traced for 13 miles northeastward across the Dewey and Jewel Cave SW quadrangles, before the zone bifurcates east of the mapped area (pl. 2). One branch continues east for 6 miles, and the other branch trends an equal distance to the northeast. Although no direct evidence for horizontal movement along the faults is reported, the sinuous en echelon trace of the faults suggests that a minor strike-slip component of movement may possibly exist within the fault zone.

The less well defined Long Mountain structural zone, 7 miles north of Edgemont, consists of small northeast-trending normal faults exposed in rocks of the Inyan Kara Group and Sundance Formation within a zone measuring several miles across. Individual faults within this zone generally have been traced less than a mile, and continuity of the structures is variable. For 2 miles southwest of Long Mountain, where the faults border a structural terrace, the zone is more clearly defined, and the northwest sides of the faults are uplifted. To the north, strata are downdropped toward the center of a wide northeast-trending fault zone. The faults have a displacement of as much as 40 feet, but adjacent to the faults as much as 60 feet of additional structural relief results from folding of the sedimentary strata.

In the Clifton and Dewey quadrangles sinuous and arcuate or ring faults and low-angle faults have been mapped in addition to the usual northeast-trending faults. The sinuous faults are randomly oriented and may be associated with the arcuate faults, such as those 11 miles north of Dewey. There, the faults are present in an area where anomalous gravity measurements indicate high relief on the buried surface of Precambrian rocks. The faults may have resulted from compaction of sediments around the basement high, as was suggested by Cuppels (1963), but they may also have resulted from dissolution and removal of evaporites in the Minnelusa Formation.

Two minor northwest-trending reverse(?) faults in sandstone of fluvial unit 5 of the Fall River Formation 3 miles north of the Dewey fault dip at low angles to the southwest. Dips range from nearly horizontal to 40° SW. and average about 25° SW. Slickensides and breccia along one of the faults were traced about 3 miles. The topography on the exposed fluvial unit 5 sandstone suggests that the southwest side of the faults may have been uplifted as much as 30 feet by reverse movement; however, most of the displacement probably occurred along bedding planes within the sandstone and is not readily discernible.

JOINTS

Joints within the southern Black Hills area are nearly vertical and commonly strike northeast or northwest. The major set of joints within the north and central parts of the area strike northeast, whereas a northwest orientation is dominant in the folded eastern part of the area (fig. 10). The differences in orientation of major joint sets probably reflect divergent stresses that deformed two major basement blocks, as discussed later.

STRUCTURAL INTERPRETATION

Uplift of the Black Hills probably began in Late Cretaceous time and continued until early Eocene time (Bartram, 1940). Chamberlin (1945) suggested that compression in a northeast direction may have produced north and northwest shear zones that determined the outline of the Black Hills; however, Noble (1952) believed that the main structural features of the uplift resulted from vertical forces associated with igneous intrusion. Osterwald and Dean (1961, p. 345–346) noted that structures of Paleozoic and Mesozoic age at the south end of the Black Hills trend parallel to structures of Precambrian age; they suggested that "the original Precambrian structures guided later and recurrent deformation."

PRECAMBRIAN STRUCTURE

The Precambrian structure of a nearby area in the central part of the Black Hills was interpreted by Redden (1968) to have evolved during three periods of deformation. (1) Major north-northwest-trending, west-dipping, isoclinal folds and subparallel faults were formed, and the rocks were metamorphosed. Redden (1968, pl. 34) inferred that displacement along many of the faults resulted in reverse throw. (2) In the metamorphosed rocks, shear deformation, localized along northeast trends, formed

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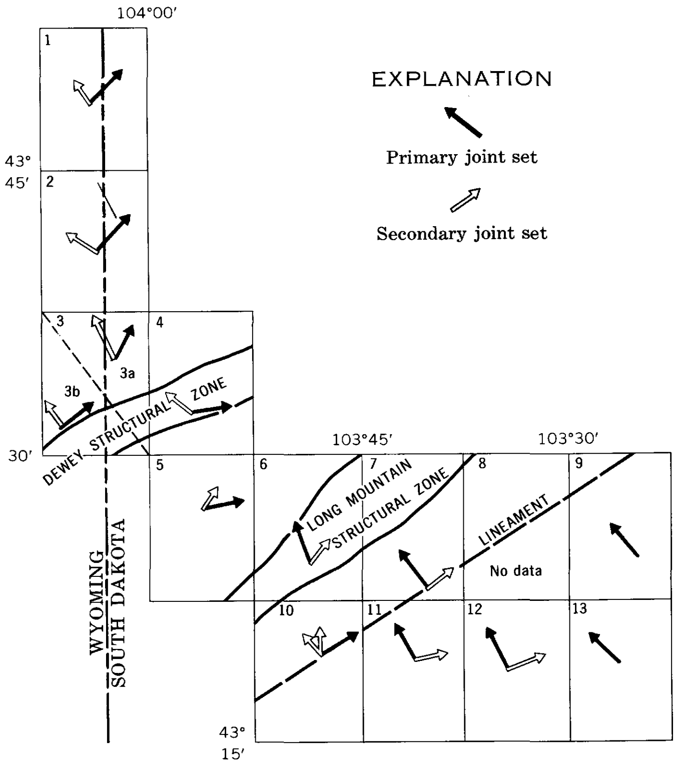


Map No.	Reference	Joint Sets	
		Primary	Secondary
1	Brobst and Epstein (1963)	N. 45° E.	N. 20°–45° W.
2	Cuppels (1963)	N. 40°–50° E.	N. 50°–60° W.
3a	Brobst (1961)	N. 10°–45° E.	N. 10°–40° W.
3b	......do	N. 45°–60° E.	N. 10°–40° W.
4	Braddock (1963)	N. 80° E.	N. 50° W.
5	Schnabel (1963)	N. 75°–85° E.	N. 35°–45° E.
6	Gott and Schnabel (1963)	N. 20° W.	NE.
7	Wilmarth and Smith (1957a, b, c, d)	N. 30°–40° W.	N. 50°–60° E.
8	Wolcott and others (1962)	No data	No data.
9	D. E. Wolcott (unpub. data, 1969)	N. 40° W.	
10	Ryan (1964)	N. 60° E.	N., N. 40° W.
11	Bell and Post (1971)	N. 30° W.	N. 75°–80° E.
12	Post (1967)	N. 20°–40° W.	N. 70° E.
13	J. J. Connor (unpub. data, 1969)	N. 40°–50° W.	

FIGURE 10. — Average orientation of joint sets in the southern Black Hills.

nearly vertical foliation. (3) Intrusion of granite and pegmatite masses domed the rocks. At this time pegmatite dikes were intruded along the northeast-trending shear foliation, as well as along bedding-plane foliation.

RECURRENT DEFORMATION

Sedimentary rocks in the southern Black Hills were repeatedly deformed along northeast trends during the Mesozoic Era and again during the Laramide orogeny. This deformation, which paralleled northeast-trending structures of Precambrian age, is most evident in the Dewey and Long Mountain structural zones, where mild structural adjustments affected deposition of the Inyan Kara Group prior to faulting that displaced the Inyan Kara. Mild structural deformation during the Early Cretaceous diverted the main northwest-flowing consequent streams and affected the courses of their tributaries. Thick fluvial sandstones were deposited where streamflow was restricted to areas of more rapid subsidence, along the axis of a gentle northwest-trending syncline (Bolyard and McGregor, 1966), whereas finer grained and interbedded sediments were deposited on the more stable interstream areas. Locally, sandstone was deposited in small northeast-trending channels where tributaries flowed parallel to the secondary structures.

The Dewey structural zone underwent minor deformation during Middle to Late Jurassic and Early Cretaceous time, prior to the Laramide faulting. Early uplift of the area immediately north of the Dewey fault is indicated by the nearly total absence of the Canyon Springs Sandstone Member in outcrops of the Sundance Formation of Late Jurassic age. At one small outcrop north of the Dewey fault the Canyon Springs rests upon an irregular erosion surface on the Spearfish Formation, but south of the fault the Canyon Springs Member is conformable with the Spearfish (Braddock, 1963). The area north of the fault, therefore, was uplifted or upwarped during Canyon Springs time while sandstones were deposited south of the fault. Later during Early Cretaceous time, mild deformation at the Dewey structural zone affected the course of consequent streams that deposited channel sandstones of the Inyan Kara Group (pl. 1, north half). During deposition of fluvial unit 1 of the Chilson Member, the northwest-flowing stream changed course and flowed westward at the structural zone before resuming its northwest course. Similarly, the stream that deposited fluvial sandstone of unit 4 of the Fuson Member altered course slightly at the structural zone.

Recurrent deformation during Early Cretaceous time also preceded Laramide faulting in the Long Mountain structural zone. Repeatedly, the northwest-flowing streams that deposited fluvial units 1, 2, 5, and 6 were diverted to the northeast at the structural zone as the area north of the zone remained stable or was slightly elevated. Rapid subsidence at the structural zone apparently determined the course of a northeast-flowing tributary during much of Inyan Kara time.

Although direct evidence of Early Cretaceous movement along northeast-trending structures of Precambrian age is lacking, many of these older structures are known. Layered pegmatite dikes of Precambrian age, mapped northwest of Pringle by Redden (1963), mark northeast-trending structures of Precambrian age that are alined with a northern branch of the Dewey structural zone (pl. 2). Similarly, geophysical data indicate a large concealed northeast-trending wrench fault northeast of the Long Mountain structural zone (pl. 2). Another concealed structure of Precambrian age is indicated by the sharp bend in an aeromagnetic anomaly north of Hot Springs (Meuschke and others, 1963). This structure apparently yielded to Laramide deformational stresses and thereby influenced the folding of the asymmetrical anticlines in the eastern part of the area. The concealed structure is coincident with the north end of a lineament that is marked by northeasterly bends and northward terminations of the Dudley, Cascade, Chilson, and Cottonwood Creek anticlines of Laramide age (pl. 2). This lineament trends S. 60° W. for 25 miles to Edgemont, S. Dak.

During the repeated deformation along the structural zones, the Paleozoic rocks probably were badly fractured. Later, when artesian pressures caused ground waters to migrate vertically through the stratigraphic section, these structural zones were especially favorable for the development of solution collapse structures discussed later.

DEFORMATIONAL FORCES

A major vertical force, as proposed by Noble (1952), probably caused the Laramide uplift of the Black Hills, but many structures within the mapped area indicate secondary compressive stresses from a westerly direction. These lateral stresses acted in a northeast to easterly direction and, locally, in a southeasterly direction.

Northeastward compression probably formed the three northwest-trending anticlines in the central part of the area and the low-angle reverse(?) faults north of Dewey. Higher on the flank of the Black Hills, toward the axis of the uplift, the stress was eastward, as indicated by a change of strike of faults in the Dewey structural zone. Similarly, the general northeast strike of major joint sets changes to a more easterly orientation in the Jewel Cave SW quadrangle (fig. 10). The change in stress orientation possibly is related to a buttressing effect by the granitic intrusive at Harney Peak (pl. 2) and to a deflection of the compressive force toward the east.

An eastward compression is also believed to have formed the anticlines in the eastern part of the area. The stress probably was transmitted through a basement block lying north of the lineament previously discussed. The eastward compressive force exerted by the northern block would have imparted both eastward and southward force vectors upon the adjacent southern block, and it would have created a resultant stress acting in an east-southeast direction. This east-southeast force probably caused the eastward deflection of the anticlinal folds along the lineament. The divergent orientation of forces acting upon the two blocks created a different orientation for the major joint sets on each side of the lineament. Although local variations in joint patterns exist, the major joint set on the northern block strikes northeasterly, whereas the major set on the south block strikes northwesterly (fig. 10). To a lesser degree the Dewey and Long Mountain structural zones also appear to have affected the orientation of joint sets.

SUBSIDENCE STRUCTURES

Many structural features consisting of breccia pipes, collapse structures, and, possibly, synclinal folds are solution features formed by dissolution of beds of anhydrite, gypsum, limestone, dolomite, and, perhaps, salt with accompanying collapse or slumping of overlying rocks. Numerous caverns and solution breccias and a few breccia pipes present in the Pahasapa Limestone of Mississippian age locally cause draping and faulting of the overlying lower part of the Minnelusa Formation. More extensive solution has occurred in the upper part of the Minnelusa, where nearly 250 feet of anhydrite and gypsum has been removed, as shown by figure 11 (see also Bowles and Braddock, 1963, p. C93), and subsidence of the interbedded sandstone, siltstone, and dolomite has formed founder breccias (Braddock, 1963).

Most breccia pipes bottom within the founder breccias of the Minnelusa; some pipes are exposed in vertical canyon walls for as much as 200 feet, and a few pipes stope upward as much as 1,300 feet to the Lakota Formation (Bowles and Braddock, 1963). Diameters of the pipes range from tens of feet to several hundred feet. These breccia pipes (fig. 12) consist of disoriented blocks, fragments, and detrital particles of sedimentary rocks which were displaced downward and which later were recemented by calcite deposited from artesian waters. The brecciation and disorientation of displaced blocks within a collapse structure are less intense toward the upper limit of stoping, high above the zone of solution. Where the structure terminates, only minor faulting, slight slumping, or draping may be present near the center of the collapse. Minor collapse at the surface may extend downward into a typical breccia pipe. Similarly, recent sinks within the outcrop of the Lakota Formation (Wolcott, 1967) probably pass downward into cemented or partially cemented breccias.

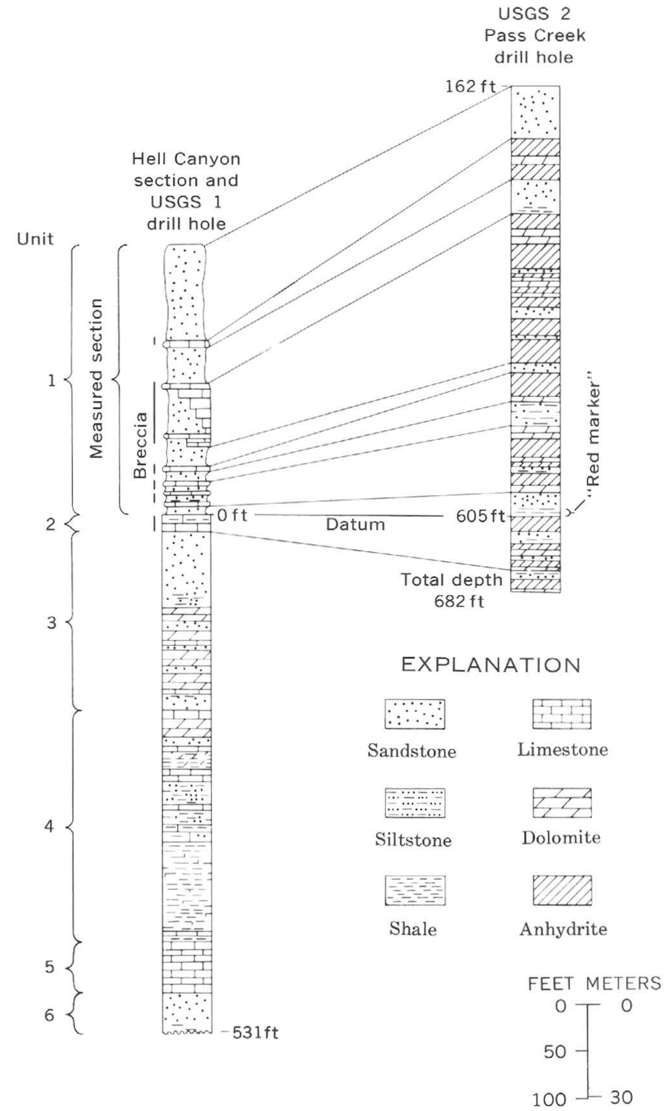


FIGURE 11. — Stratigraphic sections of the Minnelusa Formation, showing correlation of brecciated rocks in outcrop with anhydrite-bearing strata of the subsurface in Custer County, S. Dak. The locations of the stratigraphic sections are: Hell Canyon section, NW¼ sec. 3 and NE¼ sec. 4, T. 5 S., R. 2 E.; USGS 1 Hell Canyon drill hole, sec. 3, T. 5 S., R. 2 E.; USGS 2 Pass Creek drill hole, sec. 1, T. 6 S., R. 1 E. (From Bowles and Braddock, 1963, fig. 83.2.)

Some small synclinal folds in outcrops of Minnekahta Limestone and Spearfish Formation may have been formed in part by solution. Braddock (1963) attributed undulations of the Minnekahta to the solution and extensive removal of underlying anhydrite and gypsum from the Minnelusa, but he believed that the small synclinal folds were formed by gravity sliding during uplift of the Black Hills. Several small east-trending synclines at the center of the Jewel Cave SW quadrangle trend parallel or subparallel to the Dewey structural zone and to the major joint

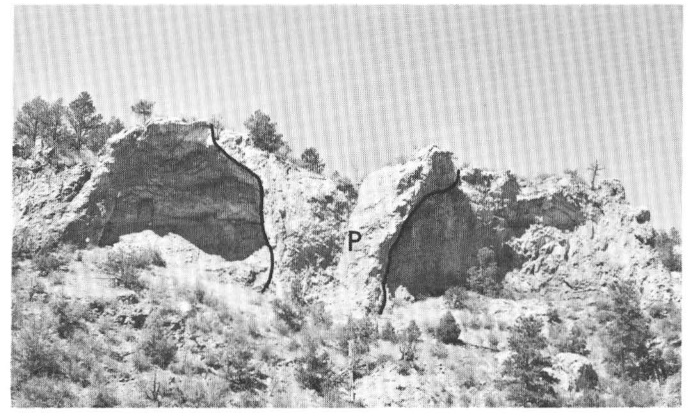


FIGURE 12. — Breccia pipe (p) in the upper part of the Minnelusa Formation in Gettys Canyon, SE¼ sec. 16, T. 3 S., R. 1 E., Custer County, S. Dak. Photograph by J. B. Epstein. (From Bowles and Braddock, 1963, fig. 83.4.)

set north of the zone. These small synclines are present at steeply dipping parts of the southwest flank of an anticline where artesian movement of ground water toward the surface is likely. Possibly these and other small synclines were formed, in part, by solution of evaporites along fracture zones in advance of the general zone of solution and founder breccias.

Since the Laramide uplift of the Black Hills, breccia pipes and collapses probably have formed under artesian conditions. A similar origin has been proposed for fissure caves and vertical shafts in eastern Missouri (Brod, 1964). It is postulated that the pre-Pennsylvanian karst surface on the Pahasapa Limestone provided high permeability and permitted rapid ground-water recharge at Limestone outcrops high on the flanks of the Black Hills. Limestone solution in the Pahasapa formed collapses that fractured, folded, and faulted strata in the lower part of the Minnelusa, permitting artesian ground water to ascend from the Pahasapa and from sandstones in the lower part of the Minnelusa through the overlying evaporites. These waters were unsaturated with respect to anhydrite and gypsum before encountering the evaporites. This permitted calcium sulfate to be dissolved by ascending waters and caused breccia pipes to form as an initial stage of solution, in advance of the general front of solution activity.

Solution collapse is controlled in part by tectonic structure, in part by sedimentary structure, and in part by topography. All three factors may affect artesian movement of the large volumes of ground water required to dissolve enough rock to cause collapse. Continued solution, both of soluble strata peripheral to the collapse and of soluble breccia fragments within the collapse, enables further stoping. Pipes form prior to the development of founder breccias and may be present several miles downdip in advance of the founder breccias. Initially, solution occurs both along bedding planes and along fractures. Breccia pipes are likely to develop at the intersection of fractures, particularly in zones of intense fracturing and (or) faulting, such as the Dewey and Long Mountain structural zones. In these zones breccia pipes are more common on the uplifted side of the faults, where artesian water has a shorter path to the surface and may encounter less resistance to flow en route to a discharge point. An example of this structural control of pipe formation is present in the Jewel Cave SW quadrangle, where two pipes in the Sundance Formation are on the upthrown fault block, only 200 and 400 feet from the Dewey fault (pl. 1).

GROUND WATER

This ground-water study, which tests the theory that ground water introduced uranium into the Inyan Kara Group to form the uranium deposits, was begun after unpublished analyses of water samples from 32 wells marginal to the southern Black Hills were made available through the courtesy of William Chenoweth of the U.S. Atomic Energy Commission. If this theory of mineralization is valid, studies of ground water at the margin of the Black Hills may provide an opportunity to examine the processes of uranium transportation and deposition. Data presented in the following discussion indicate that in the southern Black Hills, uranium apparently is being introduced into the Inyan Kara Group by artesian water from the Minnelusa Formation. Where a strong reducing environment exists at the locality of artesian recharge, uranium is rapidly precipitated and may form economic deposits; elsewhere, uranium introduced by the ground water is disseminated over a wide area to increase the uranium "background" level within the Inyan Kara Group. As erosion of the Inyan Kara progresses, the leaching of low-grade deposits and disseminated uranium may provide an enriched mineralizing solution and result in secondary-enrichment ore bodies similar to roll-type uranium deposits found in several of the Tertiary basins in Wyoming.

SOURCE OF GROUND WATER IN THE INYAN KARA GROUP

Darton (1896, 1909) believed that ground-water recharge occurred at the exposures of what he called the Dakota Sandstone on the flanks of the Black Hills and that the water then migrated through this aquifer eastward under the plains of North and South Dakota. His view was generally accepted until Swenson (1968a, b) presented evidence indicating that much of the ground water obtained from the Dakota Sandstone in eastern North and South Dakota was derived from recharge of the Englewood Formation and the Pahasapa Limestone on the eastern flank of the Black Hills. This ground water flows eastward through the limestone aquifers until upward leakage into the Dakota Sandstone is made possible by the pre-Dakota erosion of the intervening sedimentary formations in the central and eastern parts of North and South Dakota. We believe that ground-water movement and the recharge of the Inyan Kara Group of the southern Black Hills is best explained by the following modification of the basic Swenson theory.

The Minnelusa Formation, as well as the Englewood and Pahasapa Formations, apparently receives a significant amount of ground-water recharge from precipitation and runoff in the Black Hills, whereas only minor surface recharge enters aquifers of the Inyan Kara Group. Streams gaged by Brown (1944) at the east side of the Black Hills lost water — as much as 54 cubic feet per second — to the three major aquifers of Paleozoic age. In contrast, no measurable stream loss was detected at the Inyan Kara outcrop. In a recent study, Gries and Crooks (1968) reported that water losses to the Pahasapa Limestone for eight streams in the eastern Black Hills are roughly proportional to streamflow and that the losses vary seasonally. The total loss that they observed during the study, which did not include water losses to the Minnelusa, ranged from "2.8 cubic feet per second in December 1967 to 164.5 cubic feet per second in June 1967." The high rate of recharge to the deeper aquifers is possible because solution caverns in the limestones of Mississippian age and extensive solution brecciation in the Minnelusa permit rapid ground-water recharge and enable a swift basinward flow. Locally in the outcrop area, ground water from the Minnelusa probably recharges the underlying cavernous Pahasapa Limestone. As a result of the rapid flow of ground water, productive Minnelusa wells are scarce where the formation crops out, and yet, as reported by Whitcomb, Morris, Gordon, and Robinove (1958), large yields occur from some Minnelusa wells farther downdip at the margin of the Black Hills.

The apparently limited recharge of the Inyan Kara Group by surface water seems incompatible with the large flow of water from wells in the Inyan Kara at the southwest flank of the Black Hills, just as it is incompatible with the amount of water produced from the Dakota Sandstone during the last 80 years, discussed by Swenson (1968a). Davis, Dyer, and Powell (1961) concluded that the water "must have moved into the aquifer by some method other than direct recharge at the outcrop." They suggested that deeper aquifers, having appreciable artesian pressure, provide a part of the recharge to the Inyan Kara, even though relatively impermeable confining material intervenes. They also suggested that, locally, the Inyan Kara may be recharged at a high rate by an artesian flow of ground water from deeper aquifers through uncased and caved or cratered wells. Probably of greater significance, a high rate of artesian recharge may occur through the previously described collapses and breccia pipes, which form natural conduits to the Inyan Kara Group.

The recharge of aquifers of the Inyan Kara Group by waters derived from older formations is strongly indicated by the composition of present-day spring waters emanating from formations older than the Lakota and Fall River Formations. Partial analyses of seven such spring waters are given in table 9 (see also Gott and Schnabel, 1963, p. 135) and show that the waters contain a high concentration of sulfate, bicarbonate, calcium, and magnesium. The equivalents per million of calcium and magnesium nearly perfectly balance the equivalents per million of sulfate and bicarbonate. This balance demonstrates that the material being leached is largely anhydrite but includes lesser amounts of dolomite. The only possible source for the sulfate, bicarbonate, calcium, and magnesium in these proportions is the evaporite zone in the Minnelusa Formation.

Numerous collapse structures that served in the past as conduits for artesian flow of water were located during mapping in the southern Black Hills (pl. 1). Direct artesian recharge of the Inyan Kara was possible where these structures penetrated the Lakota Formation. Elsewhere, pipes penetrated no higher than the Sundance Formation, and ground water may have flowed through the Canyon Springs Sandstone Member or other intermediate aquifers before finally encountering fractures that permitted continued upward migration to the Inyan Kara. Just as the older structures once served as conduits for artesian movement of ground water, recent collapses, such as the "Lost Wells" in the Lakota Formation near Hot Springs, S. Dak. (Wolcott, 1967), probably transmit artesian water at present.

Temperatures recorded in water wells in the vicinity of the Black Hills also suggest not only a rapid surface recharge of the more porous and (or) cavernous formations but also, farther downdip, an artesian flow of some of this water into overlying strata. Where rapid recharge of the deeper aquifers by surface water occurs, heat flow from underlying rocks may be insufficient to warm the ground water to a temperature predicted for an average geothermal gradient; conversely, where rapid artesian recharge of the higher aquifers by heated artesian water occurs, the heat flow to the ground surface may be insufficient to permit cooling of the water to the predicted temperatures. Adolphson and LeRoux (1968) reported an average geothermal gradient of 0.9°C per 100 feet for 42 wells that tap aquifers of pre-Jurassic age in the Black Hills area. The geothermal gradients, averaged for each formation, range from 0.7°C per 100 feet for the Minnelusa and Opeche Formations to 1.3°C per 100 feet for the

TABLE 9. — *Calcium, magnesium, bicarbonate, sulfate, and uranium in water from springs in the Minnelusa Formation*

[epm, equivalents per million (milligram equivalents per kilogram); ppm, parts per million; ppb, parts per billion]

Locality (pl. 4)	Field sample	Calcium + magnesium (epm)	Bicarbonate + sulfate (epm)	Calcium (ppm)	Magnesium (ppm)	Sulfate (ppm)	Bicarbonate (ppm)	Uranium (ppb)
				Weston County, Wyo.				
1	2208	33.38	33.25	532	83	1,420	225	12
2	2209	29.96	29.95	472	78	1,260	227	11
3	2210	24.66	24.76	402	56	1,040	190	4.7
(1)	2211	85.60	80.47	1,310	246	3,680	235	17
				Fall River County, S. Dak.				
4	2247	16.76	17.10	252	51	639	232	7.5
5	2249	34.56	35.36	508	112	1,610	112	6.3
6	2250	35.91	35.91	508	92	1,540	235	5.7

[1]Not shown on plate 4 (outside mapped area).

LOCALITIES SAMPLED

Field sample	*Locality description*
2208	SE¼ sec. 31, T. 45 N., R. 60 W.
2209	NE¼ sec. 31, T. 45 N., R. 60 W.
2210	SW¼ sec. 17, T. 45 N., R. 60 W.
2211	About 7 miles north of Newcastle, Wyo., T. 46 N., R. 61 W.
2247	Evans Plunge, Hot Springs, NW¼ sec. 13, T. 7 S., R. 5 E.
2249	NW¼ sec. 35, T. 7 S., R. 5 E.
2250	Cascade Springs, SW¼ sec. 20, T. 8 S., R. 5 E.

Spearfish Formation. Adolphson and LeRoux suggested that relatively low gradients computed for the Black Hills area may be due, in part, to "rapid downward movement of recharging waters in very porous formations" (such as the Pahasapa Limestone or Minnelusa Formation). In addition, their data indicate a progressive increase in the temperature gradient from the permeable Minnelusa Formation upward through relatively impermeable strata to the Spearfish Formation. The increase in the gradient probably results from an artesian movement of water from the Minnelusa Formation.

Temperatures of water from wells and drill holes along the southwest flank of the Black Hills indicate that the warmer artesian flow progresses upward into the Inyan Kara Group. Geothermal gradients calculated for wells in the southern Black Hills ranged from 0.8°C to 7°C per 100 feet (fig. 13). The average geothermal gradient for 19 wells that are deeper than 200 feet is 1.5°C per 100 feet, in contrast to the average gradient of 0.9°C per 100 feet determined by Adolphson and LeRoux (1968) for pre-Cretaceous rocks in the Black Hills area. The higher gradients calculated for temperatures recorded at the shallower wells (fig. 13) are due, in part, to an artesian flow within the Inyan Kara, but

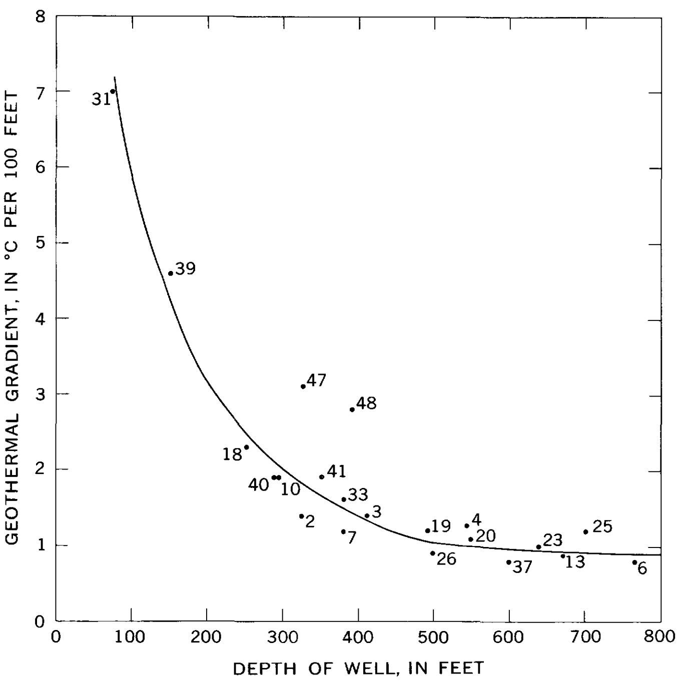


FIGURE 13. — Variation in geothermal gradient with depth of well in the Inyan Kara Group. Numbers indicate selected wells shown on maps and listed in table 10. Temperatures recorded in flow at the surface. Well depths are reported depths.

the magnitude of the gradients in some wells indicates that water probably has been heated in deeper aquifers and then has ascended to the Inyan Kara Group at the margin of the Black Hills. This interpretation of artesian recharge is further supported by the distribution and concentration of tritium in waters of the Inyan Kara and will be discussed later.

COMPOSITION

The present composition of the ground waters probably reflects variations in composition that have existed marginal to the Inyan Kara outcrop since the Black Hills were uplifted and artesian circulation was established in the Paleozoic and Mesozoic rocks. Distribution patterns for the variations in groundwater composition have shifted basinward as erosion has progressively stripped the sedimentary rocks from the uplift and lowered the water table. Ground water in the Minnelusa, Lakota, and Fall River Formations is classified into three general water types — calcium sulfate, sodium sulfate, and sodium bicarbonate — according to the most abundant pairs of cations and anions in solution (fig. 14). This system of classification was modified slightly so that ground-water composition could be mapped (pl. 3*A*) in the detail made possible by a plot of water composition on a multiple-trilinear diagram (pl. 3*B*) of the type proposed by Piper (1944). The water types indicated on the combined cation-anion diagram are separated at the 50th percentiles, and the waters are named for the most abundant pair of cations and anions present in water of average composition for each type. Because some ions, such as calcium and magnesium, are grouped together in the plot, water samples plotted near the 50th percentiles may have other ions in greater abundance than the indentifying pair. However, the grouping of these ions does not obscure the important genetic relationships within the ground water; therefore, the convenience of easy referral to three water types and the advantage of more detailed mapping of groundwater composition provided by this system of classification far outweigh the disadvantage of imprecise identification of an individual water sample.

As the ground water migrates upward to the Inyan Kara Group and then basinward within the Lakota and Fall River aquifers, the composition of the water changes from a predominantly calcium sulfate water to a sodium sulfate water and, locally, to a sodium bicarbonate water (pl. 3*C*). The first detectable change in composition of the ground water occurs within ascending waters where a loss of carbon dioxide causes precipitation of calcite which results in a decrease in the proportion of calcium to other cations remaining in the water. A second significant change takes place within the Inyan Kara Group where a further decrease of calcium ions as well as magnesium ions is accompanied by a proportionate increase in sodium ions in the water (fig. 14). This change is interpreted as a natural base-exchange softening of the waters. A third change in composition of the water, occurring locally within the Lakota and Fall River Formations, results in modification of calcium and sodium sulfate water to sodium bicarbonate water (fig. 14).

The change from sulfate water to bicarbonate water in the Inyan Kara is interpreted as the product of several chemical reactions that probably occur simultaneously. Separate grouping of sodium bicarbonate waters plotted on the anion and combined cation-anion diagram of plate 3*B* suggests that these

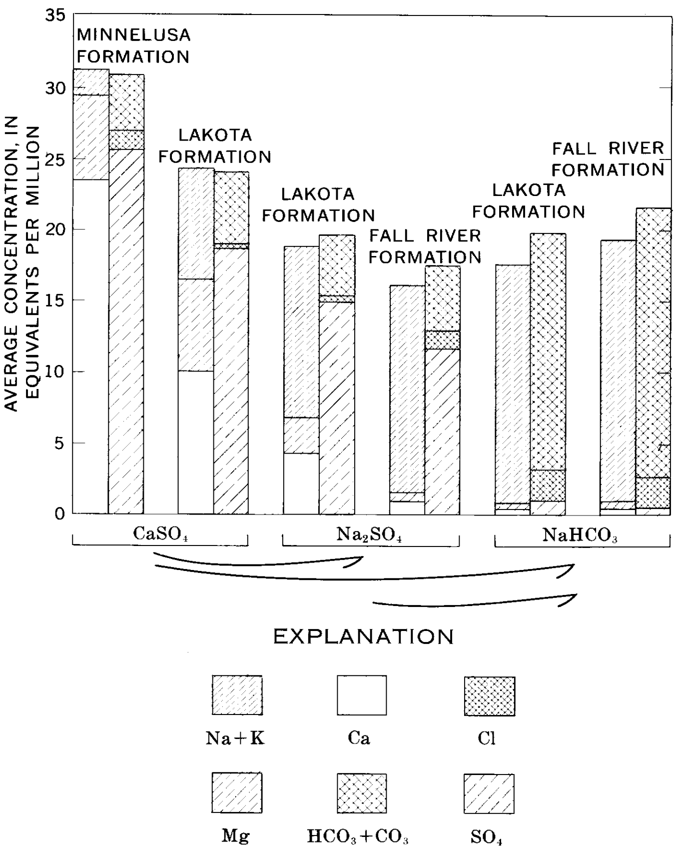


FIGURE 14. — Average composition of calcium sulfate, sodium sulfate, and sodium bicarbonate ground water from the Minnelusa, Lakota, and Fall River Formations. Concentrations are expressed as equivalents per million (epm), that is, the chemical equivalence of a weight concentration (ppm) of ions in solution. Arrows indicate modification of water types. Composition of Minnelusa water is average from water sampled at localities 1–4 (pl. 4). All samples of water from Inyan Kara Group were obtained from wells (pl. 3*A*).

chemical changes take place rapidly to completely transform the water as it flows through a zone less than 1½ miles wide (the minimum spacing between the sampled wells). Chemical reactions yielding high sodium bicarbonate waters were discussed by Foster (1950), who concluded that "carbonaceous material may act as a source of carbon dioxide which, when absorbed by water, enables the water to dissolve more calcium carbonate. If base-exchange materials are also present to replace calcium with sodium, a still greater amount of bicarbonate can be held in solution and high sodium bicarbonate waters * * * result." In the bicarbonate water of the Inyan Kara, a low sulfate content and a concentration of as much as 150 ppm hydrogen sulfide (table 10), together with the isotopic fractionation of the sulfur (T. A. Rafter, 1969, written commun.), suggest that sulfate reduction contributes to the genesis of the high sodium bicarbonate water.

The process of base-exchange softening in the sulfate water and the genesis of bicarbonate water result in two distinct patterns of distribution for the ground-water types in the Inyan Kara Group (pl. 3*A*). The softening of the sulfate water results in a pattern of progressive change from calcium sulfate water near the Inyan Kara outcrop to sodium sulfate water southwestward down the regional dip. Superimposed on this pattern in the vicinity of the Long Mountain structural zone is the distribution pattern for the high sodium bicarbonate water.

The chemical composition of the ground water is influenced by structures that affect the rate and direction of ground-water movement. A higher proportion of calcium may be present in the water where structure favors a rapid flow of artesian water from the Minnelusa. For example, the composition of ground water changes across the Dewey fault, where water on the upthrown, or north, block contains proportionately more calcium and magnesium and less sodium than water on the downdropped, or south, block (pl. 3*A*). Variations in water composition also occur at the southwestward projection of the Long Mountain structural zone (pl. 3*A*).

FLOW (AS INDICATED BY TRITIUM DISTRIBUTION)

The distribution of tritium in ground water at the margin of the Black Hills supports the interpretation of artesian recharge of the Inyan Kara Group and provides a measure of the rate of ground-water flow.

Tritium, a radioactive isotope of hydrogen, has a half life of 12.26 years (Stewart and Hoffman, 1966). It is derived naturally by cosmic radiation in the atmosphere, but the concentrations are low and have been masked by large quantities of synthetic tritium

TABLE 10.—*Analyses of water from wells or drill holes in the Inyan Kara Group*

[Analyses of major ions by Lucius Pitkin, Inc. (unpub. data), prepared for U.S. Atomic Energy Commission; analysis of sample from loc. 19 supplied by Hans Anderson. Analyses by U.S. Geol. Survey analysts: uranium, by V. J. Janzer; tritium, by J. D. Larson, except sample from loc. 33 by L. L. Thatcher; total sulfides reported as H_2S from locs. 22, 35, 44, and 46, by M. J. Fishman. H_2S determined in the field during July–Aug. 1967. Redox potential, pH, and temperature determined in the field during summer and fall of 1968. CO_2 calculated from field measurements of pH and laboratory determinations of HCO_3. Redox potential referred to KCl-saturated calomel electrode. Waters sampled for tritium Aug. 1967 and analyzed Jan.–May 1968. Explanation of abbreviations: ppm, parts per million; epm, equivalents per million (milligram equivalents per liter); mv, millivolts; Tu, tritium unit (tritium atom/10^{18} hydrogen atoms ≅ 3.2 picocuries per liter); ppb, parts per billion. Leaders (......) indicate data not shown or not applicable. Localities for well samples are shown on pl. 3*A*; localities for well and drill-hole samples are listed by section, township, and range at end of table]

Sample loc.	Date of sample collection	Unit of measurement for ions	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved solids	pH	Redox potential (mv)	Free carbon dioxide (CO_2) (ppm)	Hydrogen sulfide (H_2S) (ppm)	Tritium (Tu)	Uranium (ppb)	Temperature (°F)
Weston County, Wyo.																					
1	Aug. 18, 1965	ppm	9	0.7	28	9	600	4	0	383	1,082	18	0.4	2,134	......	−293	......	0.1	......	......	55
		epm	......	......	1.40	.74	26.10	.10	......	6.28	22.53	.51	......	......	......	......	......	......	......	......	......
2			......	......	......	......	......	......	......	......	......	......	......	......	7.1	+45	......	0	......	......	54
3			......	......	......	......	......	......	......	......	......	......	......	......	7.1	+48	......	......	......	1.5	57
4	June 10, 1965	ppm	8	.12	8	4	289	2	0	242	536	15	.6	1,105	8.1	−179	3.1	<.1	247	......	59
		epm	......	......	.40	.33	12.66	.05	......	3.97	10.76	.42	......	......	......	......	......	......	......	......	......
5	Oct. 17, 1965	ppm	10	.16	13	3	350	3	0	220	652	15	.8	1,267	8.0	−156	3.5	<.05	248	.07	58
		epm	......	......	.65	.25	15.23	.08	......	3.61	13.57	.42	......	......	......	......	......	......	......	......	......
6			......	......	......	......	......	......	......	......	......	......	......	......	7.3	+78	......	......	......	.8	57
Custer County, S. Dak.																					
7			......	......	......	......	......	......	......	......	......	......	......	......	7.0	+162	......	......	......	......	55
8			......	......	......	......	......	......	......	......	......	......	......	......	7.4	−48	......	......	......	4.0	60
9			......	......	......	......	......	......	......	......	......	......	......	......	7.8	−114	......	......	......	1.5	55
10	July 20, 1965	ppm	11	0.05	118	37	108	9	0	213	485	9	0.5	991	7.2	−27	24	0	237	6.4	58
		epm	......	......	5.89	3.04	4.73	.23	......	3.49	10.10	.25	......	......	......	......	......	......	......	......	......
11	Aug. 19, 1965	ppm	2	.02	8	14	200	6	12	134	391	14	.4	770	......	−39	......	.05	<100	......	55
		epm	......	......	.40	1.15	8.70	.15	.40	2.20	8.14	.39	......	......	......	......	......	......	......	......	......
12			......	......	......	......	......	......	......	......	......	......	......	......	7.2	−78	......	0	......	2.0	62.6
13	Oct. 17, 1965	ppm	2	1.4	11	6.1	180	7	12	122	310	12	.9	664	......	......	......	......	......	......	......
		epm	......	......	.55	.50	7.83	.18	.40	2.00	6.45	.34	......	......	......	......	......	......	......	......	......
14			......	......	......	......	......	......	......	......	......	......	......	......	8.3	−321	......	<.1	......	.3	57
15			......	......	......	......	......	......	......	......	......	......	......	......	7.7	−204	......	......	......	......	......
16	June 10, 1965	ppm	2	.11	56	20	211	9	0	202	428	24	1.0	953	7.7	−204	4.0	.15	......	1.7	......
		epm	......	......	2.79	1.64	9.24	.23	......	3.31	8.60	.68	......	......	......	......	......	......	......	......	......
Fall River County, S. Dak.																					
17	Oct. 17, 1965	ppm	10	0.92	80	18	170	9	0	207	468	11	0.8	975	7.8	−181	5.2	<0.05	221	0.25	58.7
		epm	......	......	4.00	1.48	7.39	.23	......	3.40	9.74	.31	......	......	......	......	......	......	......	......	......
18	do	ppm	9	.75	39	10	240	6	0	232	482	14	.9	1,034	7.7	−175	7.4	.05	<100	15	56.5
		epm	......	......	1.95	.82	10.44	.15	......	3.80	10.04	.39	......	......	......	......	......	......	......	......	......
19		ppm	1.3	......	50	3.2	143	......	......	202	254	13	......	672	7.8	−245	5.1	.15	......	......	57
		epm	......	......	2.50	.26	6.21	......	......	3.31	4.16	.37	......	......	......	......	......	......	......	......	......
20	Apr. 29, 1965	ppm	10	.20	72	36	185	12	0	234	524	17	1.1	1,091	7.6	−116	4.2	.05	241	.14	56.6
		epm	......	......	3.59	2.98	8.10	.31	......	3.84	10.91	.48	......	......	......	......	......	......	......	......	......
21	Oct. 17, 1965	ppm	10	.75	50	13	270	9	0	268	558	11	1.0	1,191	7.8	−213	12	<.05	113	.35	58
		epm	......	......	2.50	1.07	11.74	.23	......	4.39	11.62	.31	......	......	......	......	......	......	......	......	......
22	Apr. 29, 1965	ppm	10	1.32	260	125	100	20	0	294	1,014	15	.1	1,839	7.3	−147	27	.2	<100	13	56
		epm	......	......	12.97	10.28	4.38	.51	......	4.81	21.11	.42	......	......	......	......	......	......	......	......	......
23	July 21, 1965	ppm	10	.18	62	22	250	12	0	279	552	11	.4	1,199	7.7	......	13	......	257	.26	58
		epm	......	......	3.09	1.80	10.95	.31	......	4.59	11.49	.31	......	......	......	......	......	......	......	......	......
24	do	ppm	15	.25	26	10	282	8	0	238	500	17	1.3	1,098	8.0	−247	3.8	.05	182	.2	59.5
		epm	......	......	1.30	.82	12.35	.20	......	3.90	10.41	.48	......	......	......	......	......	......	......	......	......
25	Aug. 19, 1965	ppm	8	1.6	40	13	257	6	0	232	521	15	.3	1,094	8.0	−264	3.7	.4	<100	1.2	60.5
		epm	......	......	2.00	1.07	11.18	.15	......	3.80	10.85	.42	......	......	......	......	......	......	......	......	......
26	July 21, 1965	ppm	14	.10	152	53	250	20	0	330	852	8	.3	1,679	7.3	−114	26	.05	249	.5	54
		epm	......	......	7.58	4.28	10.95	.51	......	5.41	17.74	.23	......	......	......	......	......	......	......	......	......
27	Apr. 28, 1965	ppm	7	.17	12	6.8	252	7	0	244	420	15	1.9	966	8.3	−237	2.2	......	......	.06	61
		epm	......	......	.60	.56	11.04	.18	......	4.00	8.74	.42	......	......	......	......	......	......	......	......	......
28	July 21, 1965	ppm	12	2.05	40	15	250	9	0	240	490	13	.5	1,076	8.2	−295	2.4	.15	110	.5	64.4
		epm	......	......	2.00	1.23	10.95	.23	......	3.93	10.20	.37	......	......	......	......	......	......	......	......	......
29	Oct. 15, 1965	ppm	13	.22	25	7.9	280	7	0	248	483	19	.9	1,084	8.0	−199	4.5	.05	<100	.1	57.5
		epm	......	......	1.25	.65	12.17	.18	......	4.06	10.06	.54	......	......	......	......	......	......	......	......	......
30			......	......	......	......	......	......	......	......	......	......	......	......	7.8	−60	......	0	......	......	57
31			......	......	......	......	......	......	......	......	......	......	......	......	7.1	−5	......	0	177	.5	55.5
32	July 21, 1965	ppm	16	.07	206	87	283	20	......	409	1,140	8	.4	2,169	7.1	−53	52	0	<100	.4	57
		epm	......	......	10.28	7.15	12.39	.51	......	6.70	23.73	.23	......	......	......	......	......	......	......	......	......

TABLE 10. — *Analyses of water from wells or drill holes in the Inyan Kara Group* — Continued

Sample loc.	Date of sample collection	Unit of measurement for ions	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved solids	pH	Redox potential (mv)	Free carbon dioxide (CO_2) (ppm)	Hydrogen sulfide (H_2S) (ppm)	Tritium (Tu)	Uranium (ppb)	Temperature (°F)
Fall River County, S. Dak. — Continued																					
33	Apr. 28, 1965	ppm	12	.02	11	6.2	325	7	24	706	158	65	.5	1,315	8.2	−306	8.5	>50	14±20+	.04	57
		epm			.55	.51	14.24	.18	.80	11.57	3.30	1.83									
34	Oct. 16, 1965	ppm	12	1.4	9.7	4.7	390	6	70	875	16	91	2.4	1,478	8.3	−408	7		<100	.07	59
		epm			.48	.39	16.95	.15	2.33	14.34	.33	2.57									
35															7.7	−388		120		2.5	55
36															7.6	−50				14	55
37	Apr. 29, 1965	ppm	10	.02	134	80	339	16	0	400	1,102	10	.3	2,091	7.6	−158	16	<.1	<100	.4	55
		epm			6.69	6.58	14.85	.41		6.56	22.94	.28									
38															8.0	−370		>50	240	.07	55
39	Apr. 28, 1965	ppm	11	.21	9	5.3	408	7	57	996	60	82	1.4	1,637	7.9	−407	20		<100	.08	58.5
		epm			.45	.44	17.89	.18	1.90	16.32	1.24	2.34									
40	Oct. 15, 1965	ppm	12	.08	9	6.5	390	6	60	952	11	86	2.2	1,535	8.0	−390	17	>50	114	.06	56
		epm			.45	.53	16.96	.15	2.00	15.60	.23	2.43									
41	do	ppm	14	.24	7	6.0	420	6	96	964	21	77	2.4	1,614	8.0	−402	15	>50			58
		epm			.35	.49	18.26	.15	3.20	15.80	.44	2.17									
42															8.1	−320		>50			
43															8.0	−260				.12	
44	Oct. 17, 1965	ppm	12	.10	8	4.5	380	5	60	952	8	76	2.4	1,508	7.8	−400	24	150	313	.07	56
		epm			.40	.37	16.52	.13	2.00	15.60	.17	2.14									
45															7.8	−42					57
46															7.5	−207		2.8		2.4	60.5
47	Oct. 16, 1965	ppm	12	.07	5.5	3.4	400	4	48	952	28	73	2.3	1,528	7.5	−348	54			.01	64.4
		epm			.27	.28	17.39	.10	1.60	15.60	.58	2.06									
48	do	ppm	10	.13	4.5	2.9	380	3	60	878	41	58	2.0	1,440	7.8	−367	22	>50	128	.03	66
		epm			.23	.24	16.52	.08	2.00	14.39	.85	1.64									
49	do	ppm	11	1.2	5.9	.5	430	2	6	384	503	73	1.2	1,418							
		epm			.29	.04	18.70	.05	.20	6.29	10.47	2.06									
50															7.3	−150				.15	
51	Oct. 16, 1965	ppm	12	.25	37	11	580	4	0	531	822	286	1.0	2,284	7.8	−66	13	.15	154	.1	
		epm			1.85	.90	25.22	.10		8.70	17.11	8.07									

SAMPLE LOCALITIES

Weston County, Wyo.

No.	*Sec.*	*T. N.*	*R. W.*
1	NW¼NE¼ 31	43	60
2	Near E. line, N½ 3	41	60
3	Near E. line, N½ 10	41	60
4	SE¼NW¼ 7	41	60
5	NW¼SE¼ 7	41	60
6	N. ¼ cor. 28	41	60

Custer County, S. Dak.

No.	*Sec.*	*T. S.*	*R. E.*
7	SW¼SW¼ 31	5	1
8	SW¼SW¼ 6	6	1
9	NW¼SE¼ 7	6	1
10	SW¼NE¼ 18	6	1
11	SE¼NE¼ 19	6	1
12	NW¼SW¼ 19	6	1
13	SE¼SE¼ 20	6	1
14	NW¼SW¼ 30	6	1
15	SE¼NW¼ 31	6	1
16	NW¼NW¼ 33	6	1

Fall River County, S. Dak.

No.	*Sec.*	*T. S.*	*R. E.*
17	NW. cor. 3	7	1
18	SW¼NE¼ 5	7	1
19	NW¼SW¼ 9	7	1
20	SE¼NE¼ 9	7	1
21	SE¼SE¼ 9	7	1
22	SW¼SW¼ 11	7	1
23	SE¼SE¼ 16	7	1
24	NW¼SW¼ 17	7	1
25	SW¼NW¼ 19	7	1
26	SW¼SE¼ 23	7	1
27	Center 27	7	1
28	NW¼NW¼ 29	7	1
29	SW¼NE¼ 35	7	1
30	SE¼NW¼ 36	7	1
31	SE¼SE¼ 32	7	2
32	SE¼SE¼ 32	7	2
33	NE¼NE¼ 1	8	1
34	N. ¼ cor. 4	8	1

Fall River County, S. Dak. — Continued

No.	*Sec.*	*T. S.*	*R. E.*
35	SE¼SE¼ 4	8	2
36	SE¼SE¼ 4	8	2
37	NE¼NE¼ 5	8	2
38	NE¼SE¼ 5	8	2
39	NW¼SW¼ 6	8	2
40	NW¼SE¼ 6	8	2
41	SE¼SW¼ 6	8	2
42	Center N½ 7	8	2
43	NE¼NE¼ 8	8	2
44	NE¼NE¼ 8	8	2
45	Center N½ 9	8	2
46	W. ¼ cor. 10	8	2
47	NW¼NE¼ 17	8	2
48	NE¼SW¼ 17	8	2
49	SE¼SE¼ 20	8	2
50	SE¼SW¼ 23	8	2
51	SE¼SE¼ 28	8	2

placed in the atmosphere by thermonuclear explosions. Tritium is dissipated from the atmosphere largely by precipitation, or rain-out, of tritiated water (HTO), which then becomes a part of the surface- and ground-water systems. Since 1952, large quantities of tritium have been added to the atmosphere, and peak concentrations in the water were reported during the winter of 1958–59 and in 1963. In 1963 the average concentration of tritium in rain water in the Black Hills (data reported by Stewart and Hoffman, 1966) was about 3,500 Tu (tritium units)[1] (G. L. Stewart and R. K. Farnsworth, written commun., 1968), or perhaps three times the 1958–59 level of rain-out. During 1964–67, tritium concentration in precipitation steadily declined, and in 1967 the weighted average tritium concentration of precipitation in the southern Black Hills was about 500 Tu (G. L. Stewart and T. A. Wyerman, written commun., 1970). (The average concentration of natural tritium in the water is 2–10 Tu.)

We sampled ground water from 26 wells in the Inyan Kara Group during August 1967 to determine the time in transit and rate of movement of water at the margin of the Black Hills. During January–May 1968, J. D. Larson of the U.S. Geological Survey analyzed the waters by using an analytical method having a minimum detection limit of 100 Tu (table 10).

High concentrations of tritium, ranging from 110 to 313 Tu, were distributed in a lobate pattern, and the southwest, leading edge of the detected tritium concentration was as much as 4 miles downdip from the Inyan Kara outcrop (fig. 15). Ground water containing tritium flowed most rapidly basinward in three areas — one on the Dewey terrace, in the vicinity of Beaver Creek north of the Dewey structural zone, and two in the vicinity of the Cheyenne River, west of Edgemont and southwest of Burdock, S. Dak. High tritium concentrations roughly paralleled the Cheyenne River, and low values (less than 100 Tu) were present southwest of the river. We did not determine whether tritium values decrease to natural background amounts within the area sampled; but L. L. Thatcher (written commun., 1969), by using a more sensitive method than the one used by Larson, analyzed one sample and found a concentration of 14±20 Tu (table 10), apparently slightly more than the natural background level.

The highest tritium values are much lower than peak concentrations in rain-out during the 1958–59 and 1963 periods, indicating a dilution of young, highly tritiated water by an older water containing only natural concentrations of tritium. The amount of dilution can be estimated if the highest measured tritium values are corrected for radioactive decay and the age of the water is assumed. If we assume that the highest tritium concentration was derived from rain-out during 1958–59, then the initial value of the detected tritium, corrected for radioactive decay, was approximately 520 Tu. Similarly, if the highest tritium concentration was derived from rain-out during 1963, then the initial value, corrected for radioactive decay, was about 400 Tu. Both corrected tritium values are much lower than the weighted-average tritium rain-out for either period. The most highly tritiated water sampled in the Inyan Kara must have been diluted by older ground water in the respective proportions of either 1:1, if the tritium is from 1958–59 recharge, or 1:9, if it is from 1963 recharge. The 1:9 dilution ratio best fits the observed data. If the 1:9 ratio of tritiated water to older artesian water is valid, then the tritium concentration in pre-1963 waters is reduced by dilution below the detection level employed in this study, and no lesser tritium pulse is observable. Conversely, if the 1:1 ratio calculated for 1958–59 recharge were valid, then a pulse of approximately 1,500 Tu should be present near the Inyan Kara outcrop. No comparable concentration has been detected.

We concluded, therefore, that the tritiated water recharged the Inyan Kara Group at the outcrop and then was diluted by older artesian water downdip along the margin of the Black Hills. Dilution has apparently occurred in the vicinity of several wells near the Inyan Kara outcrop in the west-central and southeastern parts of the Burdock quadrangle, where less than the detectable amount of tritium (<100 Tu) was present in the water (fig. 15). These older waters are of the calcium sulfate type characteristic of artesian water from the Minnelusa Formation. In the west-central part of the Burdock quadrangle this Minnelusa type water forms the center of a tongue of a rapid basinward flow that apparently mixed with highly tritiated water farther downdip where the tritium content of the water increased to 113 Tu at well 21 and to about 200 Tu at well 24 (fig. 15).

Widely varied rates of ground-water flow in the Inyan Kara are indicated by the tritium distribution. In the west-central part of the Burdock quadrangle, near the confluence of Beaver Creek and the Cheyenne River, a flow of 15 feet per day is required to transmit tritium rain-out of the year 1963 from the recharge area at the Inyan Kara outcrop to the position of the larger tritium concentrations detected by sampling during 1967. To the north, between the

[1] Tu ≅ 1 tritium atom/10^{18} hydrogen atoms ≅ 3.2 picocuries per liter.

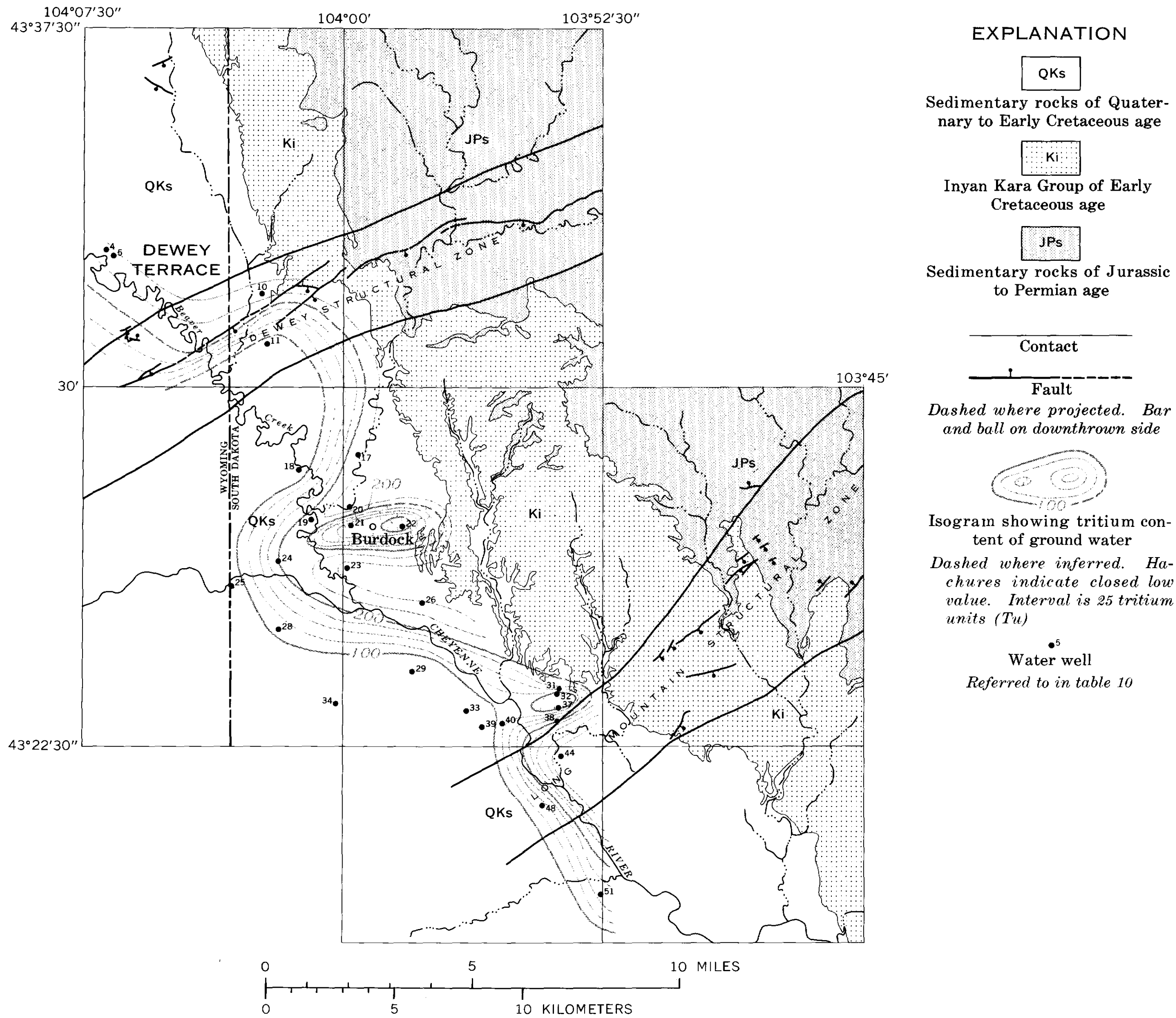


FIGURE 15. — Tritium distribution in ground water of the Inyan Kara Group of the southern Black Hills, August 1967.

Beaver Creek–Cheyenne River area and the Dewey fault, ground water in the Inyan Kara flows less rapidly, but the flow rate cannot be calculated from the available data. The exceedingly rapid flow rate in the Beaver Creek–Cheyenne River area possibly results from artesian discharge of the Inyan Kara water into gravels of the two streams; if so, a high rate of flow would not occur within the Inyan Kara at greater depths in the Powder River basin.

REDUCING ENVIRONMENT

Ground water in the Inyan Kara Group changes from an oxidizing solution near the outcrop to a reducing solution farther downdip. The transition (fig. 16) is very abrupt along the southwest projection of the Long Mountain structural zone, where the water changes from the calcium sulfate type to a very strongly reducing hydrogen sulfide-bearing water of the sodium bicarbonate type. Elsewhere, the reducing environment generally is less intense, and the oxidation-reduction front may be present farther downdip, as along the Dewey structural zone.

HYDROGEN SULFIDE

Hydrogen sulfide in the ground water ranges in content from less than 0.05 ppm in the calcium sulfate water of the Minnelusa Formation to 150 ppm in sodium bicarbonate water in the Inyan Kara Group (table 10). Generally, the sulfate water of the Inyan Kara Group contains a trace of hydrogen sulfide (about 0.05–0.1 ppm H_2S), although none was detected in some water samples.

The presence of hydrogen sulfide in the artesian waters is attributed to bacterial reduction of sulfate within the Inyan Kara. Jensen (1958), Lisitsyn and Kuznetsova (1967), and others have stressed the role of micro-organisms in the reduction of sulfate and the formation of ore deposits. Sulfate may be reduced by several bacteria, including *Desulfovibrio desulfuricans,* to form hydrogen sulfide and other sulfide complexes where sufficient carbonaceous material is available to support the bacteria. Adequate to large flows of calcium magnesium sulfate water transmitted through porous aquifers or collapse structures to highly carbonaceous host rocks support intensive sulfate reduction and the formation of a large quantity of hydrogen sulfide, but sparsely carbonaceous rocks and a flow of ground water that is restricted by low permeability limit the reduction activity. If the supply of carbonaceous material becomes depleted, then reduction activity by the micro-organism is terminated.

The reduction of sulfate is also limited by Eh and pH, as shown by a study of sulfate reduction in soils by Connell and Patrick (1968). They showed that reduction of sulfate in waterlogged soils generally occurs between pH 6.5 and 8.5, and the greatest accumulation of sulfide occurs near pH 7. Reduction occurs at a high rate from pH 7 to 7.8 and then decreases to almost zero at pH 8.5. Their experiments also showed that the reduction of sulfate to sulfide is intense below a threshold Eh of about −150 mv (millivolts) but is very slight at higher Eh values.

OXIDATION-REDUCTION (REDOX) POTENTIAL

The oxidation-reduction (redox) potential of the waters in the Inyan Kara Group was measured (table 10) at the well sites during the summer and fall of 1968 using a portable pH meter with calomel and platinum electrodes. Water was siphoned through an enclosed measuring cell, thus preventing absorption of oxygen from the atmosphere and providing a constant temperature during the measurements. Redox measurements were made 20 minutes after the water was first introduced into the cell, and the values were reported as the potential difference between the saturated calomel reference electrode and the platinum electrode. The redox measurements provide only relative values because equilibration of the platinum electrode was not fully achieved in the more reducing waters. In these waters, redox values, after complete equilibration of the electrodes, may be as much as 50 mv lower than the recorded values. It should be noted, however, that even with complete equilibration, redox (and pH) measurements recorded at the surface in flowing wells cannot exactly duplicate the values present within the aquifer at depth because hydrogen sulfide and carbon dioxide are released from solution as the waters rise to the surface.

At the margin of the Black Hills, redox values (fig. 16) decrease from a high of +162 mv near the Inyan Kara outcrop to less than −200 mv in the sodium sulfate water farther basinward, and within the strongly reducing hydrogen sulfide-bearing sodium bicarbonate water, redox values of −400 mv were recorded. Anomalous redox values are present along both the Dewey structural zone and the projection of the Long Mountain structural zone. A redox value of +78 mv was recorded in well water flowing from a depth of about 700 feet at the Dewey structural zone 3 miles downdip from the Inyan Kara outcrop. Large differences in redox potential probably exist within or marginal to this zone. Within the Long Mountain structural zone, extreme differences in redox potential were measured in waters from closely spaced wells. In part, these differences in oxidation-reduction potential may be related to a separation of waters flowing from different sandstone aquifers; however, some interconnection of the aquifers and mixing of the waters are expected in this area. More likely, the extreme differences in redox potential are caused by the introduction of an artesian calcium sulfate water, having slightly positive to neutral redox potential, into an area where intense reduction of sulfate rapidly lowers the electrode potential.

HYDROGEN-ION CONCENTRATION (pH)

During the summer and fall of 1968 the pH values of the ground water were measured (table 10) at well sites using a portable pH meter. The pH generally increases in a basinward direction from about 7.1 pH in the calcium sulfate water to as much as 8.3 pH in the sodium sulfate water (fig. 17). Values in the hydrogen sulfide-bearing sodium bicarbonate water generally range from 7.5 to 8.0 pH. Release of carbon dioxide and hydrogen sulfide as the water rises to the surface probably causes these pH values to be somewhat higher than true values within the aquifer. However, the release of hydrogen sulfide and carbon dioxide that produces an increase in pH and related chemical reactions is only partially complete at the time the water reaches the surface, because the laboratory determinations of pH average 0.1 pH higher than field determinations for 12 samples of sodium sulfate water, 0.2 pH higher for calcium sulfate water, and 0.8 pH higher for sodium bicarbonate water.

Values of pH, as well as Eh, are affected by differ-

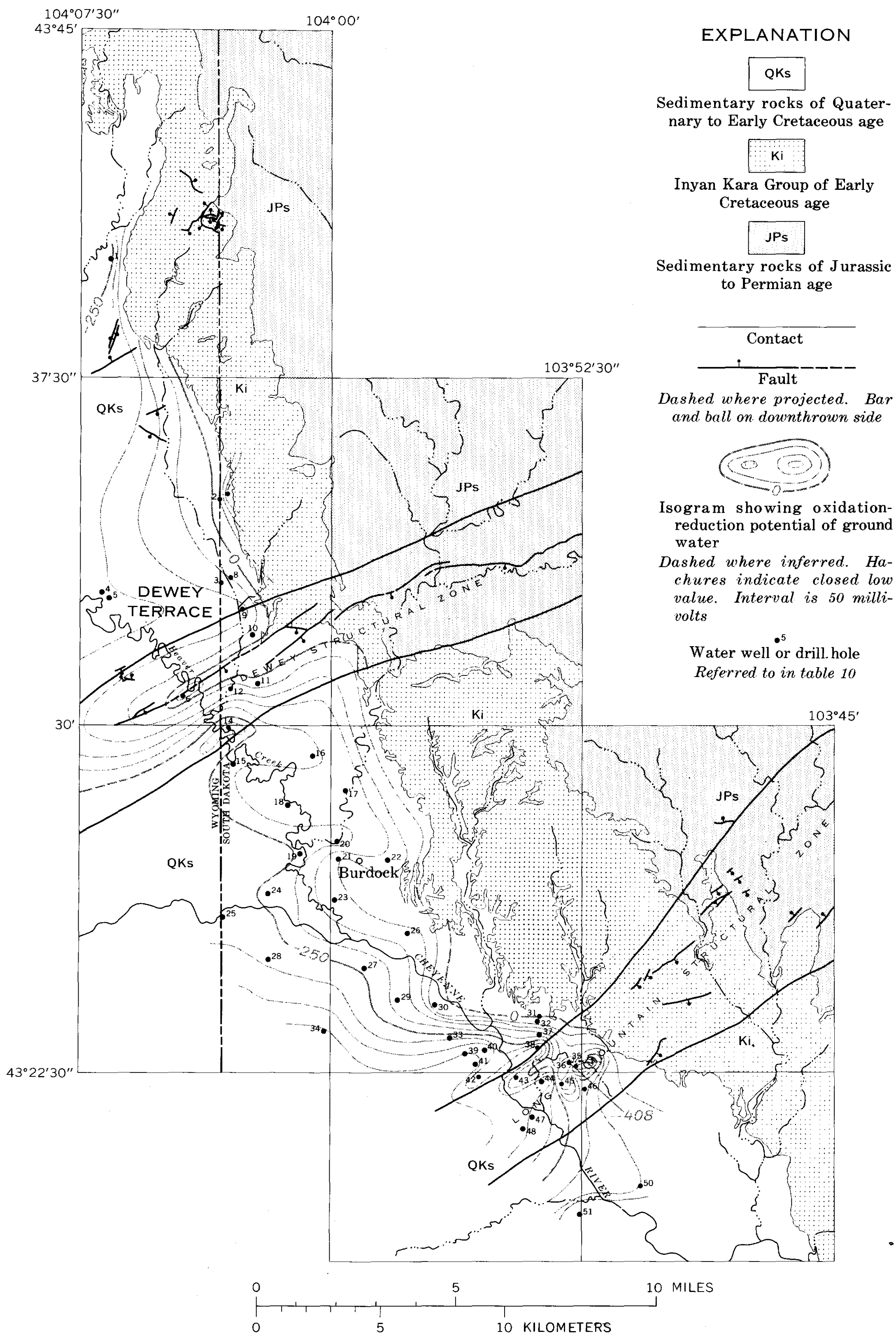


FIGURE 16. — Oxidation-reduction potential (Eh) of ground water in the Inyan Kara Group of the southern Black Hills. Redox potential referred to KCl-saturated calomel electrode.

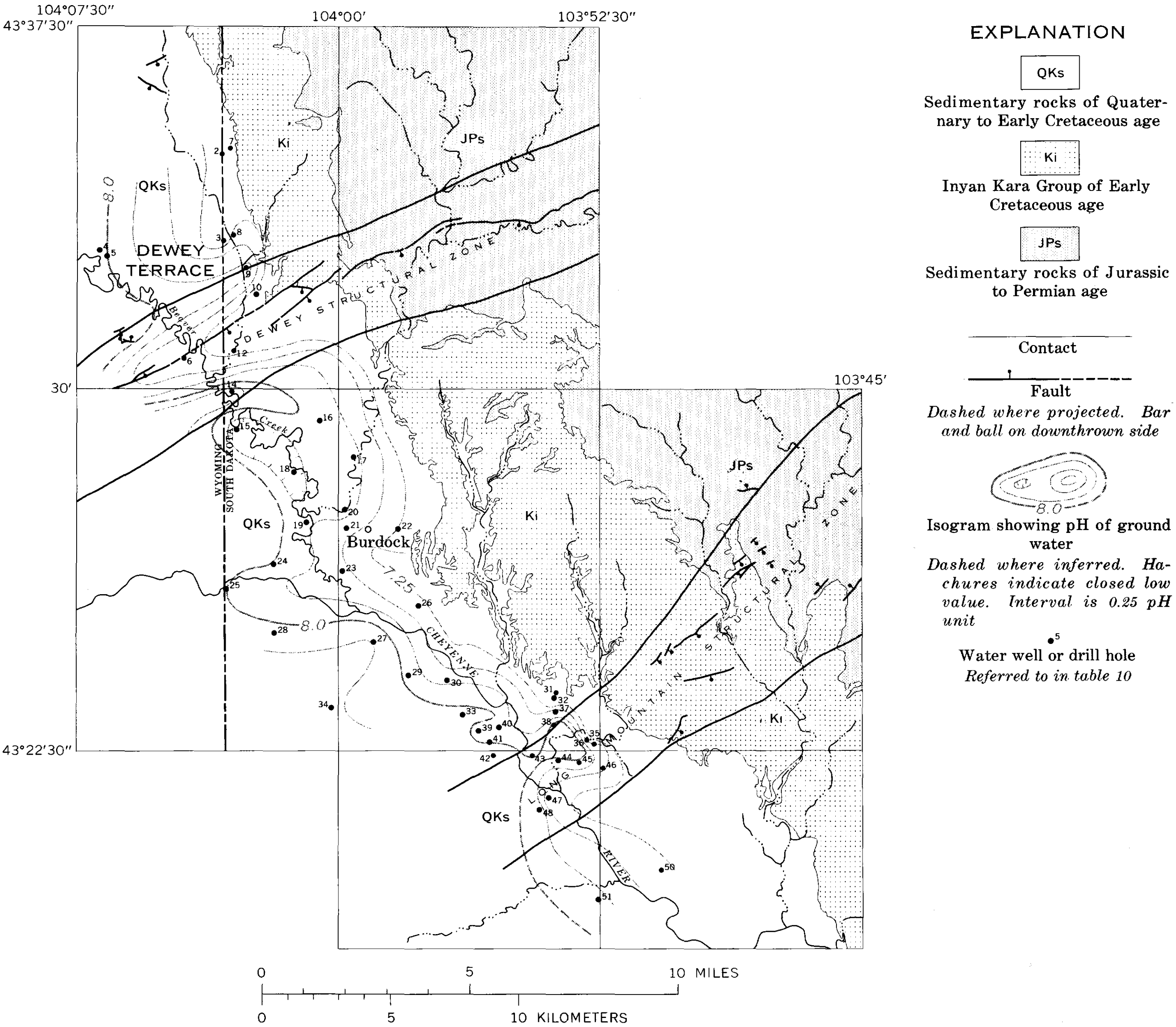


FIGURE 17. — Hydrogen-ion concentration (pH) of ground water in the Inyan Kara Group of the southern Black Hills.

ences in ground-water composition; therefore tectonic, solution, and sedimentary structures that influence the movement of ground water of different compositions also influence the distribution of the pH values. Relatively low pH values are present farther basinward in the vicinity of the Dewey structural zone, where artesian water rises through the section and, at one locality, discharges as a spring. Similarly, along the southwest projection of the Long Mountain structural zone, low pH values are recorded in calcium sulfate water introduced at the margin of an area containing sodium carbonate water of high pH.

CARBON DIOXIDE

The carbon dioxide content of water from 28 wells in the Inyan Kara was calculated from the bicarbonate content and pH of the water (table 10). Field measurements of pH were used in the calculations, rather than laboratory pH determinations made at the same time as the bicarbonate analyses, because pH alters with release of carbon dioxide from the water as the dissolved gases adjust to equilibrium at atmospheric pressure. The pH values changed 0.8 pH in sodium bicarbonate water before the water was analyzed in the laboratory. The calculated carbon dioxide content of these waters is a minimum value, because neither loss of carbon dioxide from the water before it reaches the surface nor precipitation of calcium carbonate prior to analysis is considered in the calculation. The carbon dioxide content of the ground water sampled from the Inyan Kara ranges from 2.2 to 54 ppm CO_2 (table 10). Highest carbon dioxide values are present in samples of calcium sulfate water, which average 32 ppm CO_2. Surprisingly, the carbon dioxide content decreases downdip in samples of sodium sulfate water, which average about 6 ppm CO_2. Samples of sodium bicarbonate water contain intermediate concentrations of carbon dioxide, which average 20 ppm CO_2.

The large concentrations of carbon dioxide in the calcium sulfate waters of the Inyan Kara Group probably are derived chiefly from carbon dioxide species that were present in the water within the Minnelusa Formation. The carbon dioxide content of the calcium sulfate water from the Minnelusa sampled at three springs and one well in the southern Black Hills ranges from 29 to 47 ppm CO_2 and averages 38 ppm (table 11). As the waters rise to the Inyan Kara, some carbon dioxide is immediately released, but more carbon dioxide apparently is released somewhat later as the water migrates downdip within the Inyan Kara and is softened by ion exchange to a sodium sulfate water. The samples of sodium bicarbonate water contain less carbon dioxide than those of calcium sulfate water sampled updip but contain more than the sodium sulfate water. This distribution of carbon dioxide in the sodium bicarbonate water also suggest some loss of carbon dioxide from the artesian water introduced into the Inyan Kara as the water continues to migrate through the group; however, other chemical and biochemical processes probably produce additional carbon dioxide, thereby moderating the effect of this loss of carbon dioxide from bicarbonate ground water.

TABLE 11. — *Carbon dioxide content (calculated) of water from the Minnelusa Formation*

[ppm, parts per million]

Locality (pl. 4)	pH	HCO_3 (ppm)	CO_2 (ppm)
1	7.0	225	36
7	7.0	238	38
6	6.9	235	47
4	7.1	232	29
Average			38

LOCALITIES SAMPLED

No.	Description
1	Spring, SE¼ sec. 31, T. 45 N., R. 60 W., Weston County, Wyo.
7	Flowing well, LAK Ranch, center W½NW¼ sec. 5, T. 44 N., R. 60 W., Weston County, Wyo.
6	Spring, Cascade Springs, SW¼ sec. 20, T. 8 S., R. 5 E., Fall River County, S. Dak.
4	Spring, Evans Plunge, Hot Springs, NW¼ sec. 13, T. 7 S., R. 5 E., Fall River County, S. Dak.

URANIUM DEPOSITION

The conditions necessary for uranium deposition probably have persisted intermittently since the establishment of the present pattern of ground-water recharge and artesian flow following Laramide uplift of the Black Hills. The general requirements for the deposition of uranium consist of a source of uranium, a favorable environment for deposition, and a means of transporting an adequate quantity of uranium to this environment. When these three conditions are fulfilled for a sufficient length of time, an ore deposit can be formed.

Changes in the geochemical environment in the Inyan Kara Group occur continuously along the margin of the Black Hills as erosion progressively lowers the surrounding plains. During erosion, the water table declines, and the zone of artesian recharge, as well as the oxidation-reduction front within the Inyan Kara, migrates basinward. Various stages in the evolution of the geochemical environment in which ore deposits are formed can be observed in the ground water along a line running northeasterly updip to the Inyan Kara outcrop.

EFFECT OF REDUCING ENVIRONMENT

Uranium is precipitated from solution by the reduction of the complex uranyl ion U^{+6} to the uranous ion U^{+4}. This reduction can be brought about by several reducing agents, including those derived from organic material and hydrogen sulfide. Considerable evidence indicates that a reducing environment resulting in the formation of uranium deposits in the southern Black Hills was brought about by the presence of hydrogen sulfide.

The ore deposits are restricted to four stratigraphic units, of which only one is highly carbonaceous. These units are (1) the highly carbonaceous sandstones and siltstones of the lower unit of the Fall River Formation, (2) noncarbonaceous fluvial unit 5, also in the Fall River Formation, (3) noncarbonaceous fluvial unit 4, in the Fuson Member of the Lakota Formation, and (4) moderately carbonaceous fluvial unit 1 in the Chilson Member of the Lakota Formation (pl. 1, north half). The lack of a close spatial association between some uranium deposits and the organic carbonaceous material indicates that in these deposits the organic carbon did not directly cause precipitation of the uranium.

As discussed previously, many of the water wells that were drilled into the Inyan Kara rocks along the southwest side of the Black Hills produce water highly charged with hydrogen sulfide. Where the water in the Inyan Kara changes from a predominantly calcium sulfate water to a sodium bicarbonate water (pl. 3), hydrogen sulfide is abundant. Most likely, the hydrogen sulfide resulted from sulfate reduction by bacteria that depend upon carbonaceous material within the Inyan Kara rocks for their life processes. This reduction resulted in the establishment of a geochemical environment favorable for the formation of uranium deposits.

EFFECT OF THE "PLUMBING" SYSTEM AND THE INYAN KARA STRATIGRAPHY ON LOCALIZATION OF URANIUM DEPOSITS

The route of migration and volume of flow of the ground water are major factors that influence the size and location of the uranium deposits. Extensive channel sandstones permit lateral migration of large volumes of aqueous solutions, and the stacking of channels (pl. 1, north half, restored cross section) permits vertical migration within the Inyan Kara Group. As previously discussed, numerous breccia pipes as well as faults and fractures extend from the Lakota Formation downward to sandstone aquifers and solution breccias in the Minnelusa Formation to complete a complex plumbing system that permits vertical migration of solutions between the Minnelusa and favorable host rocks in the Inyan Kara Group (fig. 18).

Channelways provided by the superposition of fluvial sandstones permit circulation of ground water from the base of the Lakota Formation into unit 5 sandstone in the Fall River Formation, and apparently they significantly influenced the location of the ore deposits by directing the mineralizing solutions into favorable host rocks. This is especially true of

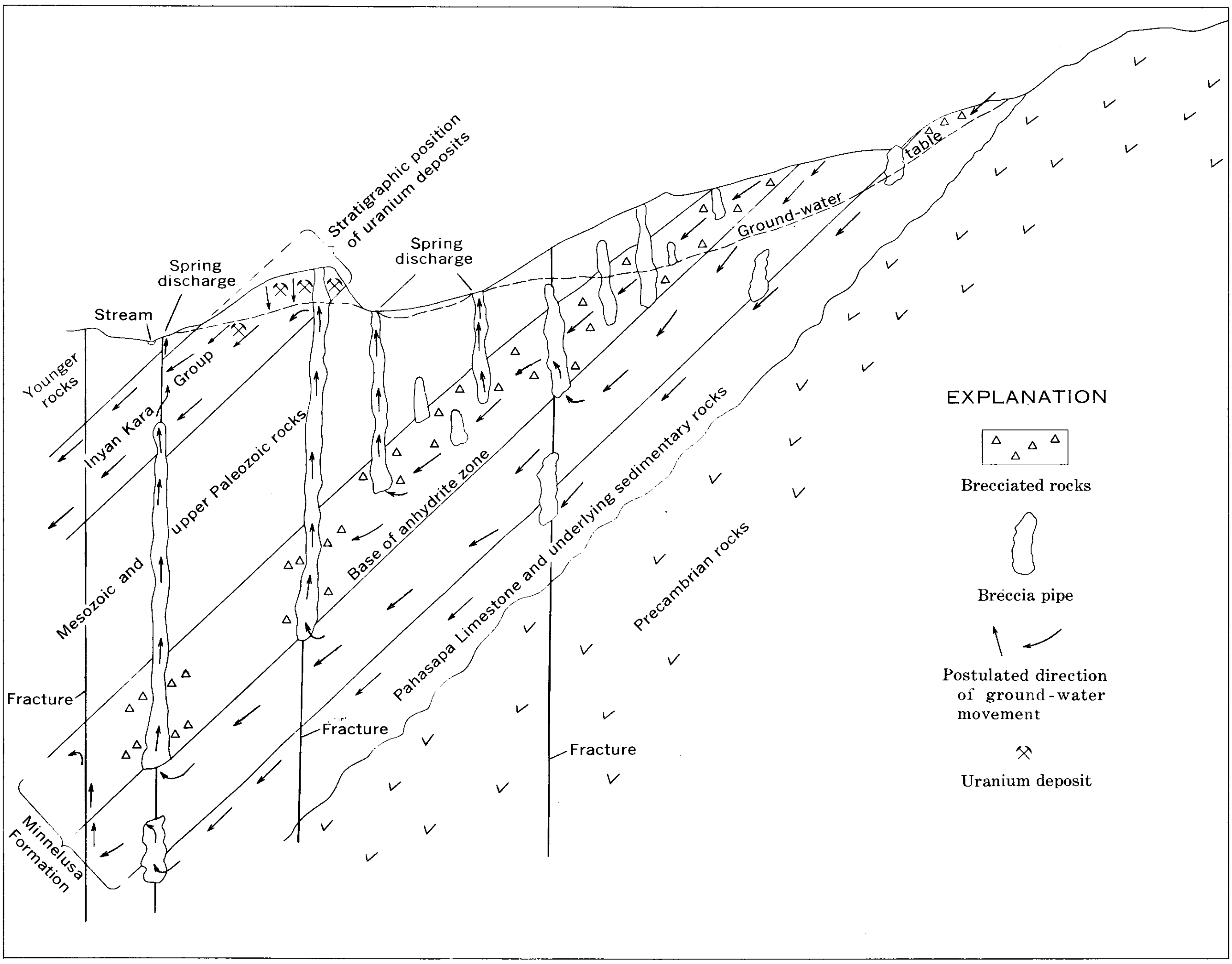


FIGURE 18. — Spatial relation of the uranium deposits to leaching of evaporites, brecciation, and postulated direction of ground-water movement. Diagram not to scale.

fluvial unit 4, which fills irregularities on an erosional surface that partly dissected or completely truncated the Fuson mudstone, an impermeable unit that apparently was laid down as a bed of relatively uniform thickness across units 1 and 2 of the Chilson Member. The Fuson mudstone, therefore, retards or prohibits ground-water circulation between the sandstones of the Chilson Member of the Lakota Formation and the sandstones of the overlying Fall River Formation except where the Fuson mudstone is cut by the channel sandstone of unit 4.

The lower sandstone and siltstone unit in the Fall River similarly retards circulation of ground water from the Lakota Formation into stratigraphically higher units except in those places where the unit is faulted or is cut by the channel sandstone of unit 5.

The "plumbing" system and the Inyan Kara stratigraphy, which control the volume of metals that are transported into favorable host rocks, are influenced indirectly by tectonic deformation. As previously discussed, pipe structures that transmit artesian water to the Inyan Kara are more numerous in the structural zones, where evaporites were fractured by recurrent deformation and thus were more susceptible to dissolution and collapse. In addition to the development of the breccia pipes, the stacking of the channel-fill sandstones of the main streams and their tributaries was influenced by recurrent structural deformation not only along the axis of the regional northwest-trending syncline, but also along secondary northeast-trending basement structures. Therefore, the location of the uranium deposits is indirectly influenced by tectonic structure, which was a factor in the development of the "plumbing" system and also in the location of superposed, or stacked, channel-fill sandstones of the Inyan Kara Group.

MINERALIZING SOLUTIONS

The relations between the reducing environment, the "plumbing" system, and the distribution of the deposits are interpreted to mean that uranium was introduced into the Inyan Kara Group with the calcium sulfate water that flowed from the Minnelusa Formation to recharge the sandstone aquifers of the Lakota. The uranium concentration in water from the Minnelusa sampled at seven springs (table 9) ranges from 4.7 to 17 ppb. Uranium in the water probably was derived from multiple sources, including sedimentary rocks of Paleozoic and Mesozoic age and the exposed granites of Precambrian age in the central part of the Black Hills. During Tertiary time volcanic ash of the White River Group of Oligocene age may have also contributed uranium.

The uranium concentration in ground water of the Inyan Kara Group decreases in a basinward direction (fig. 19) as the calcium sulfate water is modified to a sodium sulfate water (fig. 20) and simultaneously is subjected to minor sulfate reduction. Where intensive reduction of sulfate occurs within the more carbonaceous rocks, and the water is modified to the sodium bicarbonate type, the uranium content decreases very rapidly until less than 0.1 ppb uranium remains in solution.

The decrease in uranium concentration in the basinward-flowing waters is interpreted to be the result of the precipitation of uranium, although possibly absorption and (or) adsorption of uranium by organic matter and by clay minerals may remove some of it from solution. The decrease in uranium concentration does not result from dilution by older, less uraniferous water, because such dilution should everywhere result in the simultaneous dilution of the tritium concentrations in the ground water. Simultaneous dilution of uranium and tritium concentrations does not occur; instead, these concentrations decrease independently.

Values of redox potential and pH recorded in the water flowing from wells (table 10) also indicate the probable precipitation of uranium from the ground water rather than a dilution of the uranium concentration by less uraniferous waters. High uranium values are present in calcium sulfate waters having higher redox and pH values, representing oxidizing conditions. Conversely, low uranium concentrations (less than 0.5 ppb U) are present in sodium sulfate or sodium bicarbonate waters in which low redox and pH values indicate the presence of reducing conditions that could precipitate uraninite.

The primary mineralizing solution appears to be a calcium sulfate type ground water. Where the sulfate water, carrying weak concentrations of uranium, is introduced into highly carbonaceous units of the Inyan Kara, relatively rapid reduction of sulfate and uranium occurs. Rapid precipitation of uranium at the site of modification of the water to the hydrogen sulfide-bearing sodium bicarbonate type follows. Where calcium sulfate water is introduced into sparsely carbonaceous or noncarbonaceous rocks, uranium precipitation may proceed more slowly and occur across a broad zone as the water is modified to the sodium sulfate type; after this modification of water type, most of the uranium has been precipitated. Where ground-water movement is rapid, a low rate of uranium precipitation results in the dissemination of uranium throughout the sandstone of the Inyan Kara, but rapid precipitation results in the formation of higher grade deposits.

Some enrichment-type uranium deposits may have

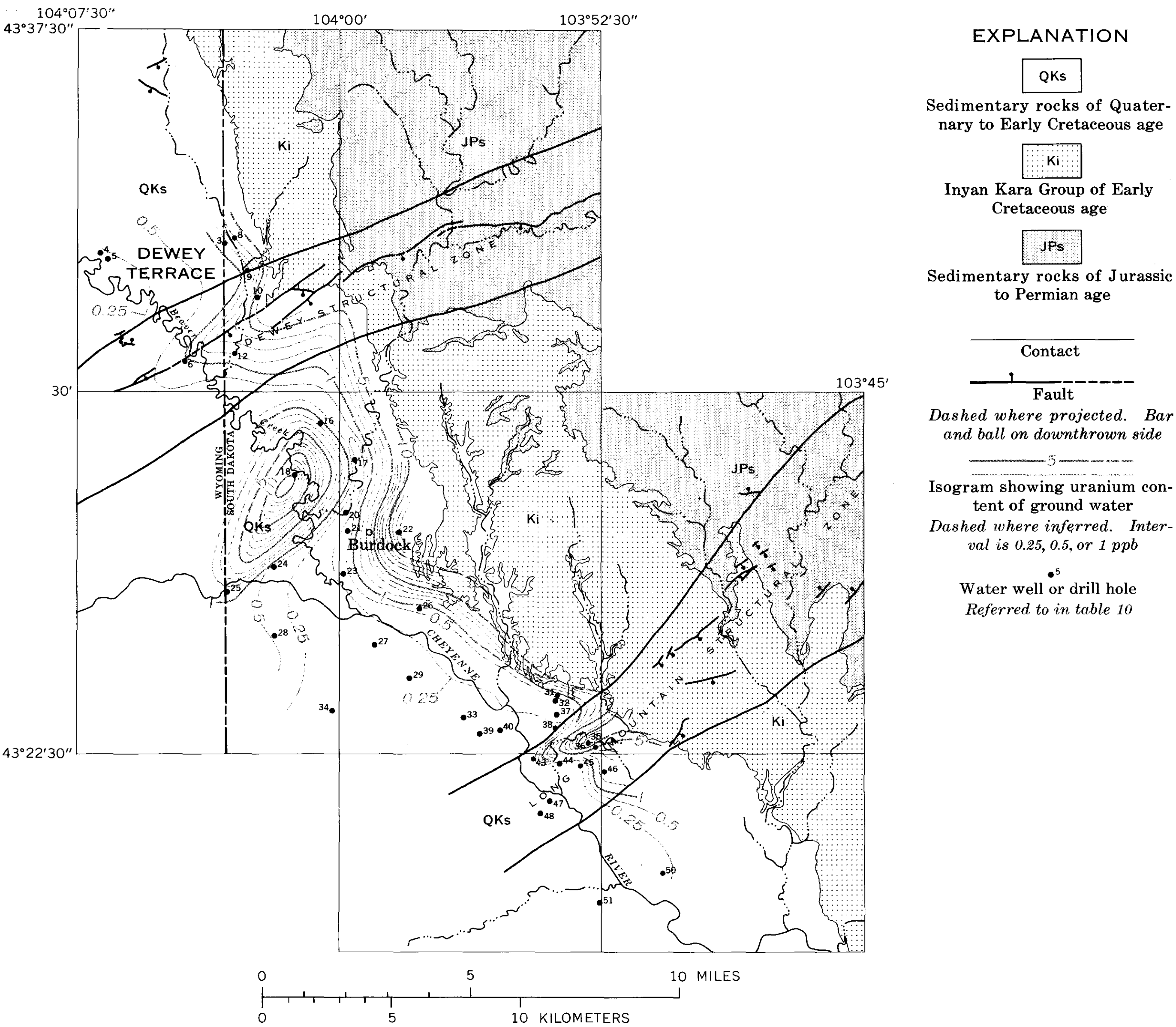


FIGURE 19. — Uranium distribution in ground water of the Inyan Kara Group of the southern Black Hills.

been derived from disseminated uranium and from older deposits in the Inyan Kara at higher elevations. These enrichment- or lateral accretion-type deposits are likely to be along well-defined oxidation-reduction fronts near the Inyan Kara outcrop and may occur as roll-type uranium deposits (Shawe and Granger, 1965). Lateral accretion of uranium can be most rapid where the uranium concentration in the host rocks is highest; therefore, roll-type deposits may lie downdip from areas that, in the past, have had much higher rates of ground-water flow and a significant contribution of uranium derived from artesian recharge. Ground water that forms roll-type deposits probably flows much more slowly than the rate of 15 feet per day calculated for the most rapid flow at the margin of the southern Black Hills; therefore, roll-type deposits are less likely to be present in areas having a high rate of ground-water movement. A low rate of flow, favorable for roll-type deposits, may be indicated by the presence near the Inyan Kara outcrop of sodium sulfate water, softened by ion exchange, as well as by the absence farther downdip of very young water containing high tritium values. The mineralizing solutions for the enrichment-type deposits may contain higher concentrations of uranium than the primary mineralizing solution, thereby permitting uraninite precipitation in a somewhat less reducing environment (a slightly

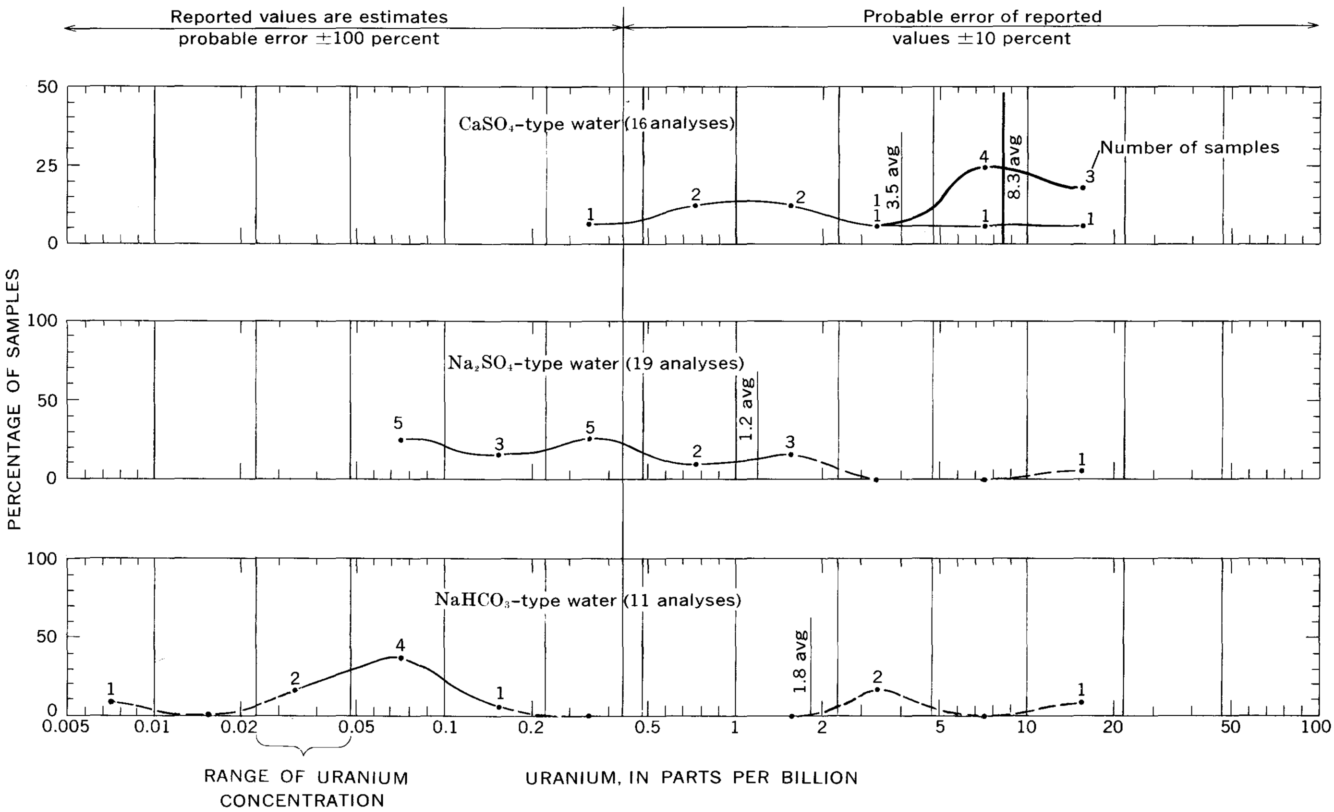


FIGURE 20. — Uranium in samples of three types of ground water from the Inyan Kara Group (light lines) and from the Minnelusa Formation (heavy lines). Points indicate percentage of samples reported for each range of uranium concentration.

higher redox and pH environment) than the environment of primary mineralization. This influence of uranium concentration upon precipitation is indicated by the phase-equilibrium diagrams of Hostetler and Garrels (1962).

ORE DEPOSITS AS RELATED TO THE "PLUMBING" SYSTEM AND THE STRATIGRAPHY

One important factor in the formation of the ore deposits — a "plumbing" system adequate to transmit large volumes of solutions — has already been described. A brief description of representative ore deposits as they are spatially related to this system follows.

In the vicinity of the Runge mine (E½ sec. 1, T. 8 S., R. 2 E.), in the southern part of the Edgemont NE quadrangle, the major sandstones in fluvial units 4 and 5 are in erosional contact (fig. 21). Fluvial unit 5 sandstone cuts through the highly carbonaceous and pyritiferous basal Fall River siltstone and sandstone, thus permitting ground water in fluvial unit 5 access to reducing agents derived from the carbonaceous unit. Ore minerals are extensively disseminated through the two sandstones near the contact.

As shown by figure 22, several metals appear to have a systematic zoning pattern within the Runge mine (V. R. Wilmarth, unpub. data). The zones are identifiable by their mineralogy, color, and grade. They consist of (1) a basal zone which is tightly cemented by calcium carbonate and which contains pods, lenses, nodules, and concretions of unoxidized uranium, vanadium, and iron sulfide-bearing minerals; (2) an unoxidized iron-rich discontinuous zone that overlies zone 1; (3) an oxidized vanadium-rich zone of reddish sandstone, in which iron oxide is concentrated, that overlies both zones 1 and 2; and (4) a discontinuous zone at the top in which arsenic and molybdenum are concentrated. Possibly the molybdenum has been recently redistributed. This zoning pattern suggests that, of all the elements, uranium moved the least distance and arsenic the greatest distance, from the point where waters from the two sandstones intermingled. Iron was present in all zones.

The numerous ore deposits that occur in the basal part of the Fall River Formation in secs. 25 and 26, T. 7 S., R 2 E., could have formed under geochemical conditions similar to the Runge deposit. The deposits

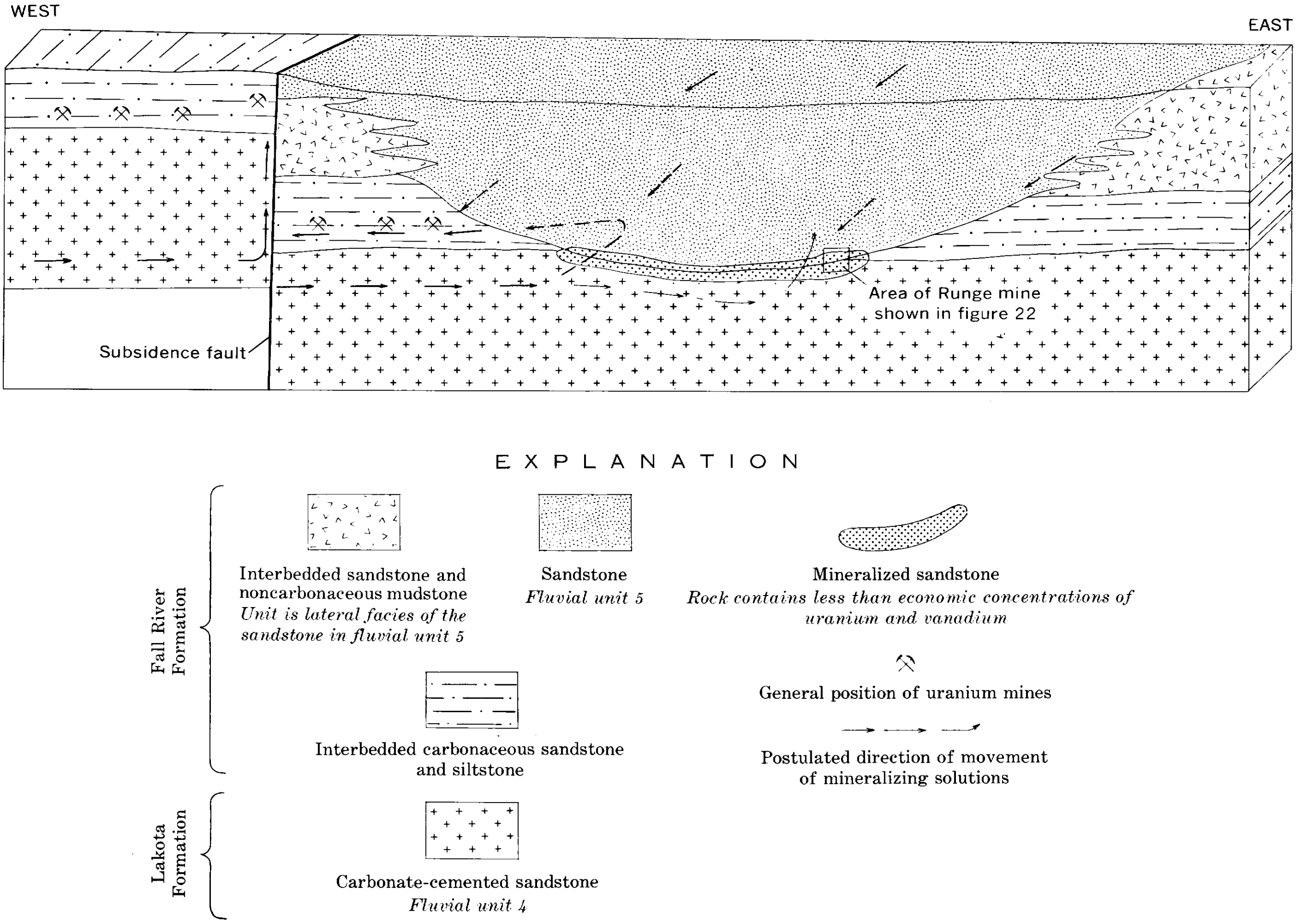


FIGURE 21. — Relation of channel sandstones to uranium deposits, carbonate cement, and postulated direction of movement of mineralizing solutions. Diagram not to scale.

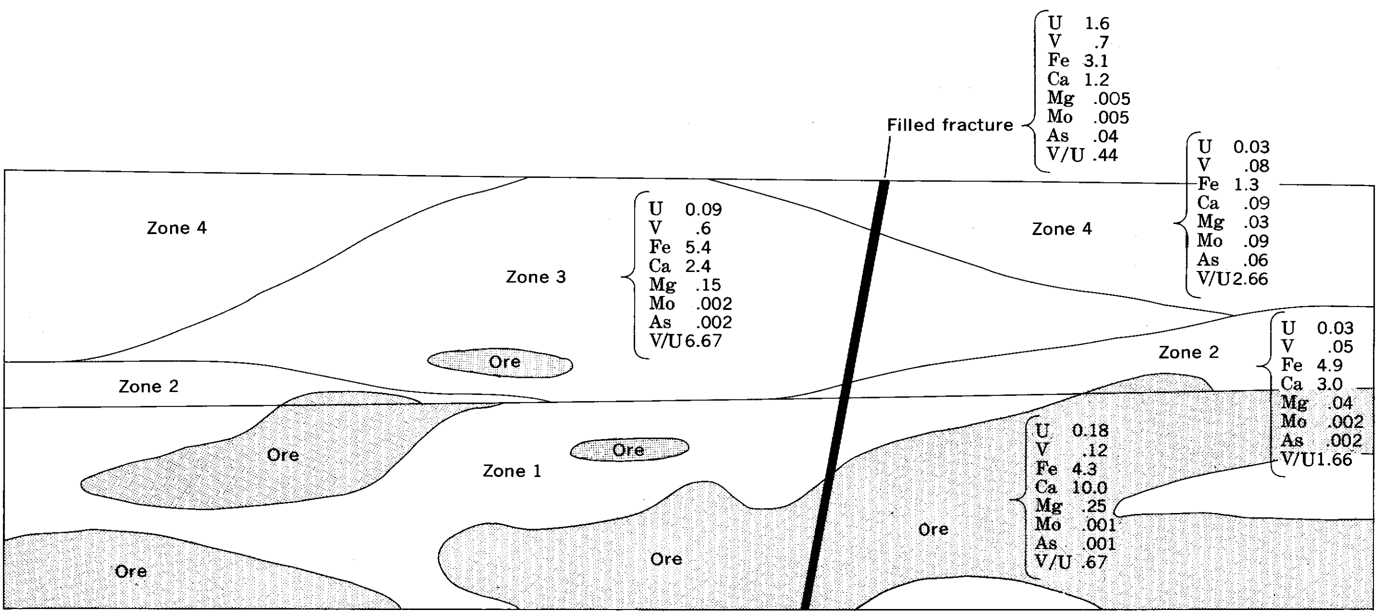


FIGURE 22. — Idealized diagram showing zonal relations of several metals in the Runge mine, Fall River County, S. Dak. Average concentrations of metals in percent. Diagram not to scale.

are partly oxidized and are in a sequence of alternating thin beds of fine-grained sandstone and laminated carbonaceous siltstone. Corvusite, rauvite, carnotite, and tyuyamunite constitute the ore-forming minerals. The deposits occur in the vicinity of several small faults that may be partly of subsidence origin and are also marginal to the western channel boundary of unit 5 sandstone (fig. 21). It seems likely that uranium-bearing solutions migrated upward from unit 4 sandstone into the carbonaceous siltstone-sandstone unit either through the fault zone or by way of unit 5 channel sandstone. Entry of the solutions into the reducing environment of the carbonaceous siltstones and sandstones apparently resulted in precipitation of the uranium and vanadium minerals.

Evidence of vertical migration of mineralizing solutions through collapse structures is seen in the Kellog mine, which is near the center of the Flint Hill quadrangle (pl. 1), and near the northeast margin of fluvial unit 1. The ore minerals occur in a 6- to 8-foot-thick fine-grained sandstone, the basal part of which contains numerous carbonaceous shale and siltstone layers that average about 1 inch in thickness. The sandstone is overlain by a black carbonaceous shale and is underlain by a thin bed of greenish-gray plastic clay that locally contains calcite spherulites. The mine is traversed by numerous small intersecting faults that have displacements of as much as 2.3 feet (fig. 23). In order of decreasing age, they strike north, east, northeast, and northwest. The intersecting faults define numerous relatively small sandstone blocks bounded by the black carbonaceous shale at the top and the greenish-gray plastic clay at the base. Uranium ore occurs in intimate association with carbonaceous material in the lower 2–5 feet of the complexly faulted sandstone, and it also occurs stratigraphically higher along the fault planes. The uranium minerals have not been identified but are assumed to be either uraninite or coffinite or both.

The fault pattern is typical of that formed by subsidence, a pattern similar to that found locally throughout the mining district. The relatively high concentrations of the ore-forming minerals along and marginal to the fault planes indicates that the faults served as pathways of vertical migration for the mineralizing solutions.

Many small oxidized uranium deposits occur along or near the outcrop of the major sandstone in fluvial unit 1. In many of these deposits the uranium minerals are selectively concentrated around carbonized wood fragments and macerated plant remains. In the many other deposits, in which this relation does not exist, the uranium minerals seem to have been precipitated by an ephemeral agent. As discussed previously, there is reason to suspect that biogenically derived hydrogen sulfide has become enriched in the ground water in some areas, and this enrichment probably accounts for those deposits not directly associated with organic material.

It is interesting to speculate about the low vanadium content in these small carnotite deposits. The vanadium-uranium ratio ranges from 0.25 to 0.68 and averages about 0.4 (Gott and Schnabel, 1963, p. 175). This amount of vanadium is barely enough to form the mineral carnotite, and inasmuch as some vanadium is known to be present in the clays, probably all the available vanadium was used in the formation of carnotite. Under such a circumstance uranium may have been lost during oxidation. After all the vanadium had been utilized in the formation of carnotite, excess uranium, if any existed, would have been carried away by ground and surface water. The uranium carried downdip by ground water would have been reprecipitated below the zone of oxidation.

The location of the deposits in fluvial unit 1 may have been influenced by pre-Fall River folding. With few exceptions these deposits as well as those in stratigraphically higher units are restricted to favorable host rocks within a gentle syncline, the center of which trends through the northwestern part of the Flint Hill quadrangle, through the northeastern part of the Edgemont quadrangle, and diagonally northwestward across the Edgemont NE quadrangle (pl. 1; see also Gott and Schnabel, 1963, pl. 14). The syncline apparently was formed by mild structural deformation during Lakota time. The effect of the syncline apparently was to control the position of streams which deposited the thick channel sandstones that constitute the major distributors of migrating solutions.

Calcium carbonate cement seems to be an indicator of the extent and ramifications of the "plumbing" system. The cement impregnating the ore-bearing sandstones is so extensive that it seems evident that the cementing material was imported from an external source, for there is no evidence that an adequate source ever existed within the Inyan Kara rocks. For example, one 10-mile segment of fluvial unit 4 in the southwestern part of the Edgemont NE quadrangle and adjacent areas is estimated to contain more than 1 billion cubic feet of calcite. An extensive segment of the sandstone of fluvial unit 5 is similarly cemented along the axis of the Sheep Canyon monocline along the western part of the Flint Hill, the eastern part of the Edgemont, and the southeastern part of the Edgemont NE quadrangles. Elsewhere, these and other sandstones are cemented with significant volumes of calcite cement. Numerous calcite-cemented breccia pipes extend upward from the evaporite zone in the Minnelusa Formation to the Inyan Kara sandstones, indicating that the source of the calcite was the Minnelusa evaporites. The breccia pipes evidently were the "pipelines" through which large volumes of solutions were supplied to the Lakota Formation, and the calcite-cemented sandstones were the distributors of these solutions through the accessible Inyan Kara rocks.

Polished-section studies show that some of the uraninite is contemporaneous with the calcite cement although in general the calcite is earlier than the uraninite (Gott and Schnabel, 1963). This contemporaneity indicates that the two minerals resulted in part from the same mineralizing process and suggests that uranium, vanadium, calcium, and bicarbonate were transported in a common solution. Solution of evaporites and the formation of breccia pipes to permit circulation of ground water from the Minnelusa Formation to the Inyan Kara Group are, therefore, among the combination of factors that resulted in the localization of the ore deposits.

EFFECT OF THE TERTIARY AND QUATERNARY DRAINAGE SYSTEMS ON LOCALIZATION OF URANIUM DEPOSITS

The Laramide uplift provided the structural and topographic relief necessary for the erosion that exposed Mesozoic and Paleozoic rocks for the recharge of aquifers by surface waters and for the establishment of a pattern of surface- and ground-water flow away from the central part of the Black Hills. Where ground water at the lower flank of the uplift was confined to an aquifer by overlying and underlying impermeable strata, artesian pressure developed that was sufficiently strong to force water up through puncture points or conduits formed by faults, fractures, anastomosing sandstone channels, and solution collapse structures. In places where conduits underlay deeply incised valleys, ground water was forced to the surface to be discharged by springs. At these localities ground-water flow through the Inyan Kara rocks was relatively rapid.

Relocation of drainages occurred as erosion exposed the formations underlying shales of Late Cretaceous age. Structural deformation and the varied resistance to erosion of the older formations resulted in modification of the drainage pattern. The position of Tertiary and Quaternary streams, as indicated by remnant terrace gravels, wind gaps, incised meanders, and shallow upland valleys, is shown on plate 4. Broad gravel terraces along the dip slopes of the Inyan Kara hogback on the southwest flank of the Black Hills indicate a downdip migration of major southeast-flowing streams as erosion progressed. One of the major ancestral drainage courses in the Craven Canyon area is an excellent example of stream relocation. The stream that formed Craven Canyon originally crossed the Chilson anticline and continued southeast through the lower part of Chilson Canyon until it was diverted by stream capture, first into Sheep Canyon and later into the lower part of the present Red Canyon.

The occurrence of uranium deposits near drainages of the Tertiary and Quaternary streams, as well as in the areas of northeast-trending structures (pl. 4), reflects the influence of both vertical and horizontal movement of ground water during formation of the ore deposits. Where artesian water flowed at the maximum rate through the Inyan Kara, proportionately larger amounts of uranium were transported to sites of reduction and precipitation. Continued erosion within the Black Hills and on the adjacent plains, periods of stream aggradation during Tertiary and Quaternary time, and minor structural deformation all contributed to the shifting of the streams, influenced the rate and direction of ground-water movement within the Inyan Kara aquifers, and caused a shifting of the sites of uranium deposition. For example, the upper part of Chilson Canyon, which was deeply eroded prior to the capture of the drainage from Craven and Red Canyons, contains uranium deposits, whereas the lower part of Chilson Canyon, which was eroded by a much smaller discharge of water and which probably has had relatively little effect on ground-water movement, contains no known uranium deposits.

EXPLORATION GUIDES

Exploration for uranium in the Inyan Kara Group of the southern Black Hills can be facilitated by the combined use of stratigraphic, lithologic, structural, and hydrologic guides.

Solution of evaporites in the Minnelusa Formation resulted in subsidence and brecciation of many of the overlying rocks. Of particular significance was the formation of breccia pipes that extend upward from the Minnelusa Formation and permit large volumes of artesian water carrying relatively low concentrations of uranium to ascend into the Lakota and Fall River Formations. Factors within these formations affecting the localization of the uranium deposits pertain mainly to the "plumbing" system, which transmits the mineralizing solutions, and to the geochemical environment in the host rocks. Exploration for concealed uranium deposits, therefore,

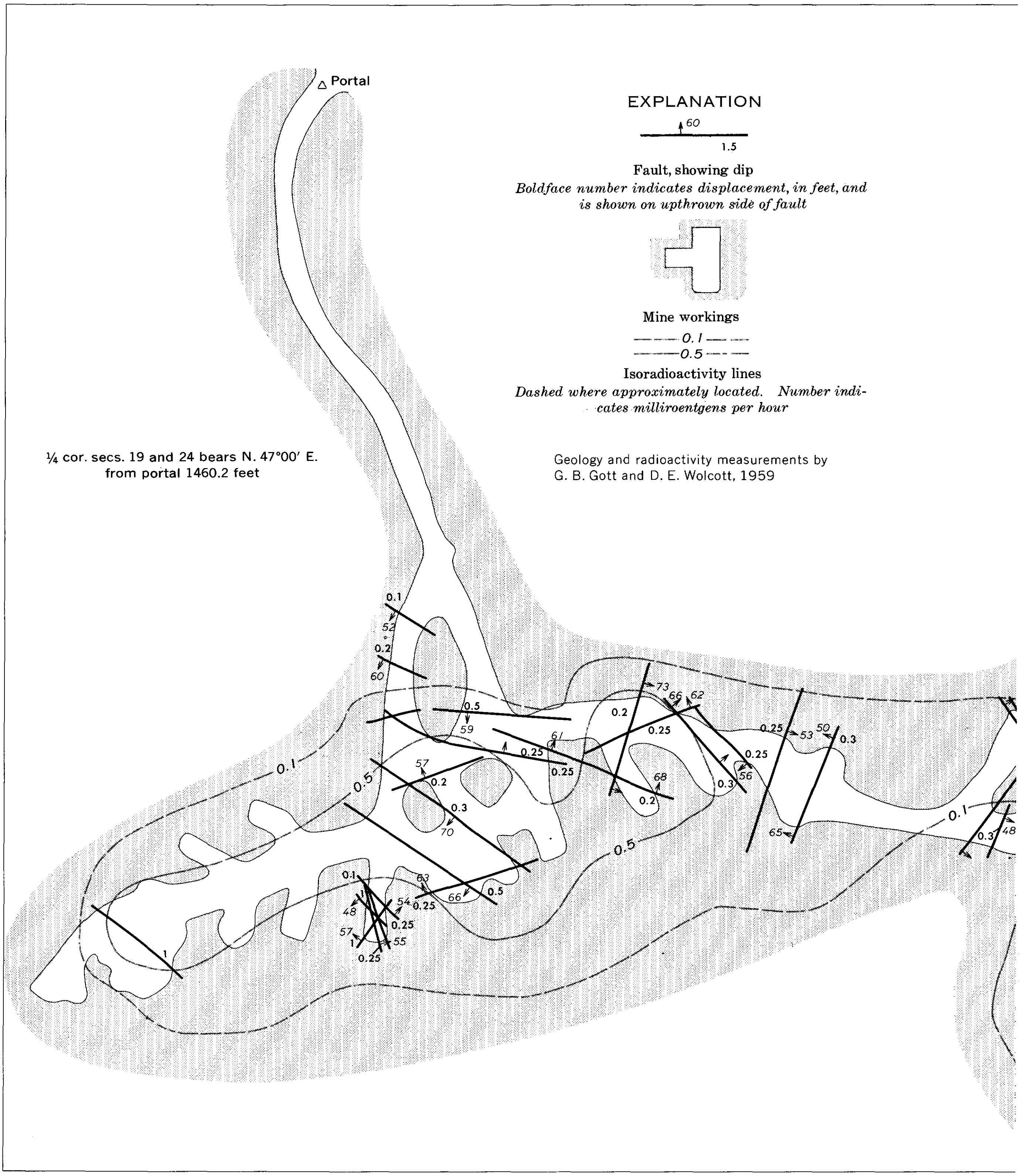
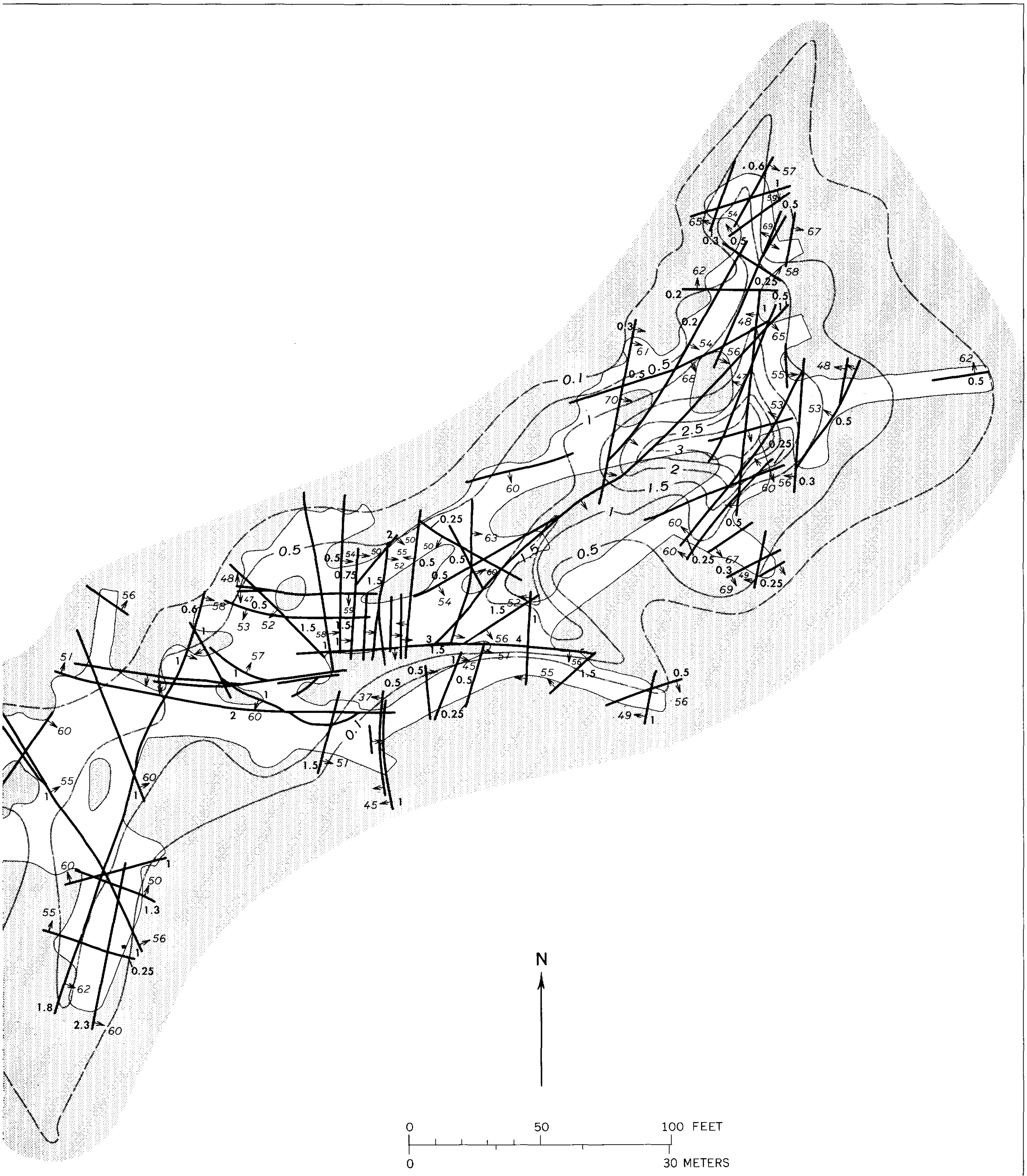


FIGURE 23. — Mine workings, faults, and radioactivity



in the Kellog mine, Fall River County, S. Dak.

should be based on the coincidence of favorable host rocks and vertical conduits caused by the subsidence of rocks overlying the evaporites, particularly in zones of fracturing and faulting.

Many billions of cubic feet of calcium carbonate cement are in the sandstones of the Inyan Kara Group. The cement is continuous from that part of the Minnelusa Formation that has been leached of calcium sulfate, upward through many breccia pipes, and into the Lakota and Fall River Formations. This continuity indicates that the source of the calcite cement is the leached evaporite zone and other carbonate rocks, which were accessible to the ascending solutions, and that the abundance of the cement in the Inyan Kara is evidence that ground water from the Minnelusa has ascended at least as high as these calcite-cemented sandstones. The presence of so much cement would mean that there may have been an adequate volume of solutions to import enough uranium to form an ore deposit, but it would not necessarily mean that a geochemical environment favorable for its precipitation also existed.

Ore deposits are restricted to fluvial units 1, 4, and 5 and to the sandstones and siltstones of the basal Fall River Formation, indicating that sandstones in these units have offered an environment favorable for uranium deposition and therefore favorable for exploration. Conversely, the sandstones of fluvial unit 2 are unfavorable for exploration. Unit 2 is mostly well oxidized and therefore forms an environment in which uranium would tend to be soluble and would not precipitate from solutions migrating through the unit.

One of the requirements for the formation of ore deposits by precipitation of uranium from the ground water is a circulation system within which the circulation is rapid, thereby permitting the influx of a large volume of mineralizing solution. Under ideal conditions, including the flushing of tremendous volumes of ground water through the system, significant amounts of uranium can be derived from minute concentrations of uranium in the ground water.

Both the Lakota and the Fall River Formations normally contain fine-grained, poorly permeable rocks that retard ground-water movement. Examples of these fine-grained rocks are the fissile shales at the base of the Lakota, the Fuson mudstones, and the tabular siltstones interbedded with fine-grained sandstones at the base of the Fall River Formation. Where these fine-grained rocks have been removed by intraformational erosion, the ground water can migrate freely through sandstones of fluvial units 1, 4, and 5, in which the geochemical environment is favorable for precipitation of uranium. The stacking and interconnection of these fluvial sandstones should be considered when planning an exploration program.

Structural deformation has influenced the deposition of the fluvial sandstones, thereby affecting the later flow of ground water through the Inyan Kara Group. The pre-Fall River structural trough shown by Gott and Schnabel (1963, fig. 26) appears to have been a particularly favorable area for the transmission of large volumes of solutions and for the formation of ore deposits. Most uranium deposits within the Edgemont district are in fluvial unit 1, which was deposited along the axis of the structural trough, or in other overlying favorable stratigraphic units to which fluvial unit 1 is connected by superjacent channels. Consideration should be given to exploring this syncline where it extends downdip under the Skull Creek Shale along the toe of the Sheep Canyon monocline and south on the Chilson anticline.

Northeast-trending secondary structures also influenced the position of the main and tributary streams and the deposition of fluvial sandstones that transmit ground water through the Inyan Kara. Within both the Long Mountain and Dewey structural zones, recurrent deformation continually affected sedimentation during Lakota and Fall River time by causing a deflection of the northwest-flowing streams and by defining the courses of tributary streams. Later folding and faulting in these two structural zones also significantly affected ground-water movement. Elsewhere, deformation along northeast-trending structures was more sporadic, but the structural influence on sedimentation, although more limited, does indirectly affect ground-water movement. The effect of these secondary, northeast-trending structures upon ground water movement should be considered when an area is evaluated for possible exploration.

Within the more deeply incised drainages, artesian water from the Inyan Kara Group locally discharges as springs or recharges alluvium and gravel. Near the points of discharge, ground-water flow in the Inyan Kara is accelerated. The possible effect of these high rates of ground-water movement upon mineralization should be considered both for the present drainages and for the ancestral drainages, which are indicated by stream terrace gravels and erosional features.

Ground-water analyses and field measurements of redox potential and pH indicate areas below the Skull Creek Shale where uranium probably is being precipitated now. The analyses suggest that most of the uranium is transported by calcium sulfate water and that it precipitates at the margin of a strong reducing environment, such as the hydrogen sulfide-bearing sodium bicarbonate water. The transition zone between calcium sulfate and sodium bicarbonate waters at the Long Mountain structural zone should therefore be considered as a favorable area for exploration. Conversely, the central part of the area containing hydrogen sulfide-bearing sodium bicarbonate water should be considered unfavorable for exploration unless indications of local recharge of the Inyan Kara by uraniferous water are found.

During the evolution from calcium- and magnesium-rich sulfate water to the sodium-rich sulfate water, uranium is precipitated. Perhaps more rapid precipitation of uranium, and therefore higher grade deposits, occur at the margin of the hydrogen sulfide-bearing sodium bicarbonate water.

Studies of water samples collected from water wells and exploration drill holes should supplement the usual stratigraphic, mineralogic, lithologic, and radiometric studies conducted during exploration, and they probably would aid a systematic search for uranium deposits present below the water table.

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