Geologic Environment of An Oxidized Uranium Deposit in the Black Hills South Dakota

GEOLOGICAL SURVEY BULLETIN 1063-C

Prepared on behalf of the U.S. Atomic Energy Commission and published with the permission of the Commission

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By N. P. CUPPELS

GEOLOGY AND URANIUM DEPOSITS IN SOUTHERN BLACK HILLS

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[Plates are in pocket]

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By N. P. Cuppels

ABSTRACT

One of the largest oxidized deposits of uranium in the Black Hills is at the Gould mine in Fall River County, S. Dak. The mine is on the dip slope of the Lower Cretaceous Inyan Kara group of fluviatile sedimentary rocks that form a hogback peripheral to the Black Hills. The deposit consists of a concentration of hydrated uranium vanadates distributed irregularly through a zone 1 to 15 feet thick near the middle of a thick sandstone unit of the Lakota formation. The eastward-trending zone is 800 feet long and 130 feet wide. The top boundary of the zone is roughly parallel with, and several feet below, an unconformity at the base of a silt-gall conglomerate.

Geochemical data suggest that the deposit is a product of the oxidation and local redistribution of an ancestral low-valent ore body. Comingling of solutions beneath the conglomerate may have been the primary control in localizing the ore. The distribution of uranium within the ore zone has been controlled by fractures and differential permeability within the host rocks.

INTRODUCTION

The history of the Gould mine is similar in most respects to that of other uranium mines in the Black Hills. In the summer of 1953, Matt Brown and Alden Trimble discovered carnotite in a small outcrop. Small-scale mining was begun with pick and shovel until A. F. Ludwig and E. J. Brockman drilled back of the outcrop to determine the extent of the deposit. Sufficient ore was located by the drilling to warrant a modified room-and-pillar method of mining. By November 1955 more than 7,000 tons of ore with a weighted-average grade of 0.274 percent U_3O_8 had been produced, established this mine as one of the largest producers in the Black Hills. Closely spaced drilling east of the mine in May 1956 resulted in a discovery of two new ore bodies. One of these ore bodies is in a stratigraphic interval that correlates with the favorable interval described in this report and the other is 20 feet below that interval.

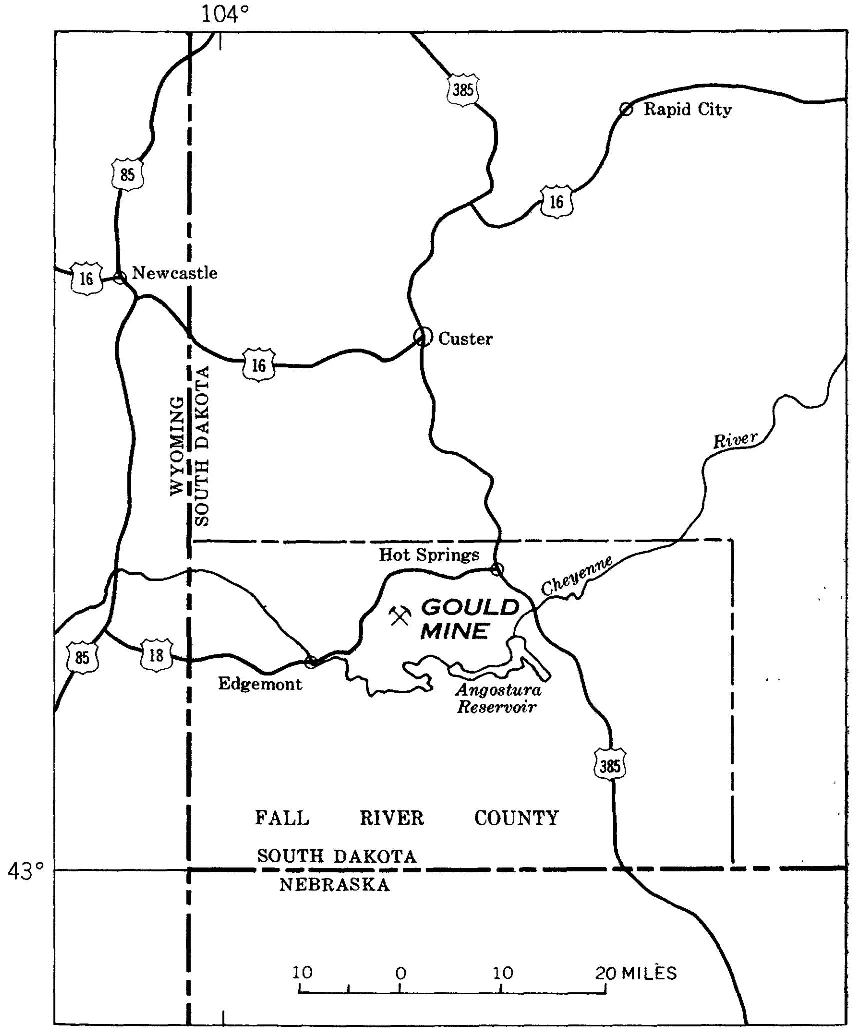

FIGURE 11.—Index map showing the location of the Gould mine, Fall River County, S. Dak.

The mine is in the north-central part of Fall River County, S. Dak. (fig. 11). It is near the eastern margin of the Edgemont mining district which extends northwestward for 30 miles around the southwestern periphery of the Black Hills. Ore from the mine is sold to the U.S. Atomic Energy Commission buying station at Edgemont, S. Dak., 10 miles southwest of the mine. The only paved road in this part of the Black Hills, U.S. Highway 18, connects Edgemont with Hot Springs, S. Dak., 22 miles northeastward. A haulage road 2 miles long leads to the mine from the paved road.

Edgemont, with a population of 1,158 (1950 census), is the trading center for an area whose economy is based chiefly on cattle raising and uranium mining. The town is on the main line of the Chicago, Burlington, and Quincy Railroad, which also serves Hot Springs via a spur that passes within half a mile of the mine. The spur is used for freight only. Western Airlines maintains scheduled flights into the Hot Springs airport 25 miles by road from the mine.

The mine is in an area characterized by erosional features developed on sedimentary rocks in a semiarid climate. Steep-walled canyons are separated by broad, relatively flat interfluves. Structure and variable lithology of the bedrock have exerted a strong control on the development of the present topography. Thick sandstones exposed in canyon walls tend to form cliffs, whereas mudstones and siltstones are generally covered by colluvium and talus or are concealed beneath a grass cover. Local drainage, and most of the regional drainage, is underground. Precipitation is sufficient only to support a grass cover on the uplands and groves of ponderosa pine on northward-facing slopes.

The Gould mine is near the top of the west wall of Chilson Canyon, 800 feet west of a point where the southward-trending wall makes a 90° turn to the west. Near the mine the top of the west wall is 300 feet above the floor of the canyon. The canyon has cut completely through the peripheral hogback of the Black Hills, integrating a part of the interior drainage of the uplift with the exterior drainage of the Cheyenne River, 11.4 miles downstream from the mine. Throughout most of the year the stream channel of the canyon is dry except where it has been dammed locally by ranchers. The drainage divide west of the canyon is a broad structural terrace with a regional southwestward slope of 3° to 4°. In this area dissection of the terrace has been retarded by a northwestward-trending sandstone that reaches a maximum thickness of 90 feet.

Underground mining activities are rarely halted by the weather for more than a few days at a time. The semiarid climate of the southern Black Hills is noticeably less rigorous than the climate of the northern Black Hills or the high plains adjacent to the uplift. Winter storms tend to sweep around the uplift rather than across it, and snow melts quickly. Mud is a more serious obstacle to mining activities than snow. During the spring thaw, many of the haulage roads are nearly impassable and trucks with a gross weight of more than 13,500 pounds per axle are denied the use of paved public roads during the months of March and April. Records of temperature and precipitation for 1950 compiled at the U.S. Weather Bureau station in Hot Springs, S. Dak., are given in table 1. The highest temperature recorded for the year was 100° F on August 29 and the lowest reading was minus 25° F on January 4.

TABLE 1.—*Climatological data recorded by the U.S. Weather Bureau station at Hot Springs, S. Dak., for 1950*

[Source.—U.S. Weather Bureau, 1950, Climatological data for the United States by sections, annual summary: v. 37, p. 213, 214]

Month	Average temperature (°F)	Precipitation (inches)	Month	Average temperature (°F)	Precipitation (inches)
January	16.0	0.16	August	69.2	1.97
February	32.5	.04	September	59.6	3.35
March	29.2	1.45	October	52.7	.33
April	40.7	2.32	November	33.8	.19
May	51.2	1.46	December	29.4	.13
June	65.4	.91	Annual	45.8	14.43
July	69.5	2.12			

The Gould mine was selected for a detailed study because of its large size, favorable location, and the simplicity of its lithology and mineralogy. It is on one of the largest ore bodies in the southern Black Hills and is in an area where the regional geology has been mapped in detail by the U.S. Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission. Preliminary results of the regional mapping have been published as the Geological Survey's Mineral Investigations Field Studies Maps 61 and 66 (Bell and Post, 1957a, b). Data from these maps have been used in this report to supplement a detailed description of the geologic environment of the ore deposit and to assist in the search for features which may have controlled localization of the ore minerals. Concentrations of minerals found in the thick quartz sandstone of the host rock include yellow- to red-brown iron oxides (and possibly sulfates) and yellow- to greenish-yellow uranium vanadates.

Underground mapping was done with telescopic and open-sight alidades at a scale of 1 : 120. Because the workings follow the ore zone by means of inclines, mapping was done at arbitrarily selected levels at the following altitudes, in feet above sea level: 4,185, 4,190, 4,195, 4,200, and 4,205. Distribution of uranium in the rocks was determined by marking 1-, 2-, and 5-milliroentgen-per-hour boundaries on the mine walls by use of a carbide lamp and Geiger counter. The 1-mr-per-hr boundary was selected because it corresponds closely with the lower limit of ore-grade (0.10 percent U_3O_8) material. This correspondence was established empirically by working closely with the miner who used the boundary in mining the ore. The validity of the boundary was subsequently confirmed by analyses of samples and by taking repeated readings with a Geiger counter at the same boundary at intervals of 1 week or more. In establishing the upper surface of the ore zone shown in the isometric diagram of plate 8, the altitudes of the tops of the highest pods of ore were determined at selected places throughout the mine and these altitudes were used as a basis for constructing a structure-contour map from which the isometric drawing was developed. Thirty-nine samples were collected from the workings at places shown on the geologic sections of plate 10. The results of analyses performed on these samples are shown in table 2 and figure 15. In addition, 199 samples were collected by the U.S. Atomic Energy Commission and analyzed for uranium and equivalent uranium. Results of these analyses are used in this report.

The deposit was mapped concurrently with mining; mapping was begun by W. A. Braddock in July 1954 and completed by the author during September 1954 to October 1955. Other members of the U.S. Geological Survey, including E. V. Post, Henry Bell 3d, R. W. Schnabel, and R. D. Smith, assisted in the mapping. Full cooperation was received from members of the geological staff of the U.S. Atomic Energy Commission in Hot Springs, S. Dak., who made available results of a brief survey undertaken by them during the summer of 1955. The author is particularly grateful to A. F. Ludwig and E. J. Brockman of the Edgemont Mining Co., principal owners of the mine at the time of this study, who permitted access to their property and rendered much assistance. Alden Trimble, employed by the owners to mine the deposit, freely shared his knowledge of the deposit with the author during the mapping.

REGIONAL GEOLOGY

STRATIGRAPHY

The Gould deposit is in a thick sandstone unit of the Lower Cretaceous Inyan Kara group of fluvial and lacustrine sedimentary rocks. Regionally, these rocks overlie the Morrison formation of Late Jurassic age except in the southeastern Black Hills where the Morrison wedges out and the Inyan Kara group is underlain by the Unkpapa sandstone. The host rocks at the mine overlie the Morrison near the western extremity of the Unkpapa sandstone.

On the basis of reconnaissance mapping, N. H. Darton (1901) divided the Inyan Kara group into the following formations, in descending order: Dakota sandstone, Fuson formation, Minnewaste limestone, and Lakota sandstone. The aggregate thickness of these formations ranges from 225 feet in the northern Black Hills to 625 feet along the Cheyenne River in the southern Black Hills. Darton's correlation of the thick sandstone unit at the top of the Inyan Kara group in the Black Hills area with the Dakota sandstone of eastern

Nebraska was found to be in error by W. L. Russell (1927), who renamed the unit Fall River sandstone. Division of the Inyan Kara group into four formations has been found unsatisfactory by several members of the U.S. Geological Survey who have recently mapped in detail a large part of the southern Black Hills area. Results of recent mapping show that the Fuson formation and Minnewaste limestone should be incorporated into the Lakota sandstone. In this report the Inyan Kara group comprises the Fall River formation and the Lakota formation, the latter formation including the stratigraphic intervals designated by Darton as the Fuson formation and the Minnewaste limestone.

The Fall River formation is generally a light-brown fine- to medium-grained sandstone within which beds of conglomerate, siltstone, mudstone, and seams of carbonaceous material are abundant locally. Where the overlying Skull Creek shale is in place, the Fall River formation is about 160 feet thick. Sandstone units of this formation are crossbedded in many places and locally seem to fill broad shallow channels that have been scoured into the underlying Lakota formation.

The Lakota formation ranges in thickness from 230 to 500 feet and is commonly a light-brown to buff fine- to medium-grained sandstone. Sandstone units of this formation tend to be more extensive and thicker than similar units of the Fall River formation. Red to gray mudstone or light-colored siltstone is interbedded with the sandstone and is more abundant in the upper part of the formation. The Minnewaste limestone member of the Lakota formation is absent at most exposures of the Inyan Kara group but is conspicuous locally, notably along the southeastern flank of the Black Hills. Here, the base of the limestone is about 325 feet above the base of the Lakota and reaches a maximum thickness of 80 feet. Where best exposed, the Minnewaste is a light- to dark-gray dense limestone that grades laterally into a calcareous sandstone or light- to yellow-brown nodular marl. Rocks of the underlying Lakota formation are coarser, with sandstone constituting most of the basal part of the formation in many places. The thick beds of sandstone, however, commonly lens out, and thin-bedded sandstone and siltstone or mudstone substitute for them. Ostracodes are abundant locally in the siltstones and mudstones.

STRUCTURE

The Gould mine is near the east edge of a southward-plunging structural terrace which is bounded on the east by the Chilson anticline and on the west by a monocline. The southward-trending terrace is several miles wide near the mine but narrows to several hundred feet near the Cheyenne River. It has a regional dip of 3° to 4° SW. The axis of the Chilson anticline emerges from beneath younger sediments of the high plains several miles south of the Cheyenne River and trends sinuously northward. Near the river the anticline has a transverse asymmetry with maximum dips of 2° to 3° on the eastern limb and as much as 14° on the western limb. Limbs of the anticline become less steep northward and are nearly imperceptible 9 miles north of the river.

LOCAL GEOLOGY

STRATIGRAPHY

At the Gould mine uranium has been concentrated in a thick-bedded sandstone unit at the top of the Lakota formation. This unit has been designated in regional mapping as sandstone 4. The sandstone has a regional elongation and has been traced for more than 12 miles west and northwest of the mine and for more than 8 miles east and south. Near the mine, sandstone 4 is about 1 mile wide and 80 to 110 feet thick. It is underlain by thin-bedded sandstone, siltstone, and pyritiferous mudstone, and erosion has truncated its upper surface. Sediments accumulated in this unit by scouring and filling of many small channels. The scour-and-fill process has operated on several scales. On the smallest scale, the process has resulted in truncated deltaic-type crossbeds a few inches to a few feet thick. Strata composed of these crossbedded units and lenses of sandstone fill channels of intermediate size. The intermediate channels may be tens of feet thick and are difficult to delineate unless the area is carefully mapped at a large scale. A channel of this size was partly delineated in the Gould area by mapping the surface geology at a scale of 1:480 and the underground workings at a scale of 1:120. Facies of the channel sediments in this intermediate-sized channel are shown as units *b*, *c*, and *d* in plate 7.

Orientation and dimensions of the intermediate-sized channel have not been definitely determined. Structure contours of the silt-gall conglomerate at the bottom of the channel suggest that it changes direction from west to northwest near the mine (pl. 9). The convex side of the bend probably has been removed by erosion south of the canyon wall shown along the south edge of the facies map (pl. 7). The bottom of the channel can be traced for 860 feet along this canyon wall. No information is available concerning its northeastward or northwestward extensions. The channel is 45 feet deep at the mine, increases in depth northwestward, and decreases in depth southward.

The bottom of the channel is clearly marked in the underground workings by a granule sandstone. It has an undulating surface whose configuration is shown by structure contours in the isometric drawing (pl. 8). The margins and top of the channel are less clearly defined. Along the margins the granule sandstone at the base of the channel interfingers with the underlying sandstone in some places and grades into it elsewhere. The top of the channel has been partly eroded, consequently data on this feature are lacking.

The channel has been cut into a light-brown thick-bedded cross-bedded fine- to medium-grained sandstone which thickens from 45 feet in the western part of the area to 90 feet near the canyon wall in the eastern part of the area. At the mine the channel sediments consist of the following lithologic units, from oldest to youngest: granule sandstone, silt-gall conglomerate, and white siltstone.

GRANULE SANDSTONE

An unconformity at the base of the channel sediments is overlain by a granule sandstone whose textural properties vary widely. The unit is commonly light-brown poorly sorted well-cemented medium- to coarse-grained sandstone consisting of subangular to subrounded grains of quartz. Dark-gray to black grains of chert and white rounded grains of silt or clay are abundant locally. Size analyses of three samples of this unit show a median grain size of 0.300 mm. Grains of the rock seem to be bimodal with the primary mode near 0.400 mm and the secondary mode near 0.147 mm. Nearly everywhere, the boundary of the granule sandstone with the underlying sandstone is sharp, and its boundary with the overlying silt-gall conglomerate is gradational. At some places the granule sandstone grades horizontally into a medium-grained sandstone indistinguishable from the underlying rock. At a few places the texture coarsens to a chert-pebble conglomerate with a matrix of coarse sand and containing chert pebbles that have a maximum intermediate diameter of 16 mm. The granule sandstone ranges in thickness from 0 to 18 feet. It is generally restricted to the base of the channel fill, but thin discontinuous lenses of a similar sandstone are found in several places in the overlying rocks.

SILT-GALL CONGLOMERATE

This unit is an intraformational conglomerate which is here termed a silt-gall conglomerate because of genetic and lithologic similarities with clay-gall conglomerates described by Pettijohn (1949, p. 148). Subangular to subrounded fragments (galls) of white clayey siltstone ranging from ¼-inch to 10 feet in longest dimension are distributed irregularly through a matrix of medium- to coarse-grained sandstone. Although the ratio of lengths to widths of the galls does not seem to be consistent, thicknesses are commonly much less than the other two dimensions, suggesting that the galls are the remnants of a bed of siltstone ruptured and moved a short distance by vigorous stream action. The galls probably would not have survived the corrasion undergone in being transported for more than a few hundred feet.

In many places the texture of the silt galls approximates that of clay. The finer grained galls break with a conchoidal fracture, and it is necessary to test the material with the teeth to detect silt. Clay minerals of the kaolinite group have been identified in some of these galls. Most galls are light gray to white, but some have a dark-brown to black rim where iron oxides have been concentrated. The concentration and average size of these galls vary throughout the mine. In some places they occur singly; elsewhere they constitute 70 to 80 percent of the conglomerate. From place to place, a crude sorting can be observed among the galls where most of them have a maximum dimension of 4 to 5 inches. At most exposures the galls appear to have little or no sorting. The conglomerate is poorly consolidated, and for this reason it is almost invariably concealed by surficial debris. As this unit grades into the underlying granule sandstone and the overlying white siltstone, its thickness is indefinite. Observations of the unit in pits and cuts of the area indicate that it pinches and swells but is probably not more than 12 feet thick.

WHITE SILTSTONE

This unit is a white friable poorly bedded sandy siltstone which characteristically has a bleached hackly appearance in excavations. Like the silt-gall conglomerate, it crumbles readily where exposed to weathering and quickly acquires a grass cover. Both the white siltstone and the silt-gall conglomerate are difficult to detect in surface mapping and could be easily overlooked unless drill cores or artificial exposures are available; consequently they were mapped in this investigation as a single unit (pl. 7). Where exposed in excavations, the mutual boundary of these rocks is indefinite. In the central and western part of the mapped area thin lenses of a light-gray fine-grained sandstone are found in the siltstone. These lenses become more continuous and thicken in some parts of the area. One of these lenses crops out extensively east of the mine and is heavily stained with red-brown iron oxides.

STRUCTURE

An accurate determination of the strike and dip of rocks underlying the area is impractical at the scale of this study because of variable thicknesses and gradational contacts of the lithologic units. However, regional mapping by Bell and Post (1957a) indicates a regional strike of N. 45° W., and a dip of 3° to 5° SW. for the area included within plate 7.

Because of an apparent control exerted by joints on localization of the ore, particular care was observed in mapping the fracture system. An attempt was made to map all joints without regard for size or prominence, consequently the joints plotted on the diagrams of figures 12 and 13 are estimated to represent at least 90 percent of the well-developed fractures and 80 percent of the poorly developed fractures observable in the area. Most of the joints terminate abruptly at the base of the conglomerate. Joint blocks tend to be smaller

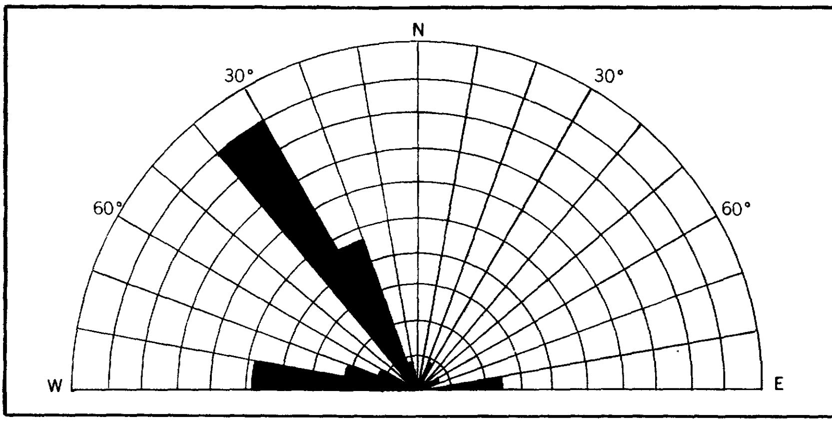

FIGURE 12.—Diagram showing strike of joints mapped in the underground workings of the Gould mine. One division equals 8 joints.

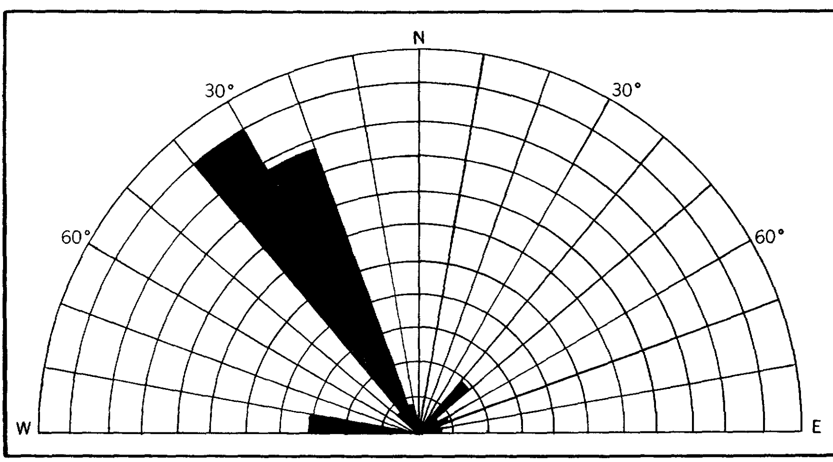

FIGURE 13.—Diagram showing strike of joints in area shown on plate 7. One division equals 6 joints.

within heavily mineralized areas. Most of the smaller joints and many of the larger ones have curved or irregular faces which results in variable strikes and dips at different places along these fractures. Nearly all joints dip northward. A study of the intersecting relations of the different sets of joints indicates that there is no substantial difference in their relative ages. The weak tendency of other joints to terminate at the N. 80° to 90° W. set suggests that this set may be slightly older.

Two sets of joints dominate the fracture system: a master set trends N. 20°–40° W. and a less conspicuous set trends N. 80°–90° W. The strike of the master set is close to the regional strike of bedding, but the westward-trending joints cross the regional dip at an angle of about 45°. Joints in both sets commonly dip northward at high angles, have smooth surfaces, and many have opened sufficiently to provide channelways along which iron and uranium minerals have been deposited. Fractures in both sets tend to be longer than other joints, but few persist for more than 30 feet. The master joints dip at high angles more uniformly than the westward-trending set. Whereas 92 percent of the plotted master joints dip 80°–90° N., only 64 percent of the westward-trending joints have dips within this range; 24 percent of the latter group have dips ranging from 65° to 75° N.

The relation of the fracture system to regional structures is not clear. The smoothness of the joint faces and the angular relations of the two sets suggest that they are conjugate shears. The sets intersect at an angle of about 50° and may have been produced by regional compressive forces in an area where easiest relief was in a horizontal direction. It is unlikely that the fractures are a result of stress-strain conditions associated with the development of the Chilson anticline, whose axis trends northward 8,000 feet east of the Gould area. The angular relations between the joint sets and possible directions of associated compressive forces (N. 60° W. and S. 30° W.) are incompatible with vectorial compressive forces that could have produced the anticline.

ORE DEPOSIT

DISTRIBUTION OF ORE

The ore deposit is near the top of a thick-bedded quartz sandstone which underlies the channel sediments previously described. The ore is irregularly distributed through a zone 1 to 15 feet thick. The top of this zone has an undulating surface which in most places is several feet below the base of the silt-gall conglomerate. The spatial relations between the top of this zone and the bottom of the conglomerate are shown in the isometric diagram (pl. 8). Although the ore zone is discontinuous laterally and comprises four discrete segments (including one of the unmapped new ore bodies), all segments are in about the same stratigraphic interval and are alined in an eastward direction for 800 feet. None of the segments is wider than 130 feet. This marked eastward alinement is emphasized by an elongation of each segment in the same direction. The most productive segment is in the eastern part of the mine where the ore zone pinches and swells forming podlike bodies that are alined in an eastward direction and joined by an attenuated continuation of the zone. Although the overall shape of each segment is elongated eastward, individual pods of ore within segments tend to be oriented with their long dimensions parallel to the northwestward-trending joint set. The distribution of the ore with respect to the joints is shown in the geologic sections (pl. 10).

MINERALOGY AND CHEMISTRY

The host rock is commonly a light-brown medium-grained firmly cemented quartz sandstone with rounded grains of light- to dark-gray chert; subangular grains of light-gray silt and clay comprise an estimated 3 to 15 percent of the rock in some places. Silica, which uniformly cements the sandstone elsewhere, has been partly removed by solution within the ore deposit and replaced by the ore minerals and yellow-brown iron oxides. Because of the inferior bonding properties of the ore minerals and iron oxides, the sandstone is weakly cemented within the deposit. Concentrations of the iron oxides are irregularly distributed throughout the ore zone as nodules, sheets paralleling bedding or fracture surfaces, or in bands peripheral to silt- and clay-galls of the conglomerate. Some of the nodules have a concretionary structure and a core of sandstone weakly cemented by a red friable mineral and outer concentric bands of a dark-brown resinous mineral. Mineralogical analysis of one of these nodules (sample 21, table 2) shows the red mineral of the core to be hematite and the outer concentric bands to be goethite.

No carbonaceous material has been found either in the ore or in exposures of the country rock in the map area. However, a bed of black claystone, 10 to 15 feet thick, was discovered during exploratory drilling 100 feet north of the mine. The claystone underlies a coarse sandstone which correlates with the granule sandstone that overlies the ore throughout much of the mine. The upper 2 feet of the claystone is greenish gray and contains abundant cubes of pyrite. The black color of the claystone may be caused by very finely divided carbonaceous material. This claystone is lithologically similar to one that underlies the ore at a depth of 45 feet. Preliminary results of the drilling indicate that the upper claystone terminates sharply along an eastward-trending line that passes within 75 feet of the mine.

Although no $CaCO_3$ was observed at or near the ore deposit, "lime" was reported in 103 of 144 lots of ore sold to the Atomic Energy Commission buying station. Lime as reported by the Atomic Energy Commission includes all gangue minerals soluble in acids used in milling the ore. Weighted-average grade of lime in the 103 lots was 0.24 percent and values range from 0.10 to 1.20 percent.

Clay minerals of the kaolinite group have been identified by X-ray powder-diffraction analyses of three samples collected from the workings. An electron micrograph of one of these samples (19, table 2) showed the presence of rod-shaped crystals of halloysite.

The percentage of arsenic in rocks associated with the deposits tends to increase with an increase in the abundance of iron. This relation is demonstrated in table 2, where the analyses have been arranged in order of increasing arsenic content. This correlation between iron and arsenic suggests that the iron minerals in the deposit may be oxidation products of pyrite or marcasite which commonly contain greater amounts of arsenic than other iron minerals (Rankama and Sahama, 1950, p. 741).

Barren sandstones of Triassic and Jurassic age on the Colorado Plateau contain selenium in amounts less than 10 ppm (parts per million) compared with 100 to 1,000 ppm selenium in ore deposits in the same formations (Cannon, 1957, p. 404). Selenium seems to have a negative correlation with carnotite at the Gould mine. Of the 23 samples analyzed for selenium, one of the most barren (sample 17, table 2) contains the most selenium (100 ppm).

Semiquantitative spectrographic analyses were made of 30 channel samples collected by James T. Bright of the Atomic Energy Commission in the eastern part of the mine. The samples were cut vertically from sill to back and are more representative of the ore zone than the selected samples collected by the author and listed in table 2. Table 3 shows the 68 elements looked for in the spectrographic analyses. Of these 68 elements, 20 were detected and the ranges in percentages of these elements are shown in figure 14. The detection limits shown on table 3 are revised as laboratory methods are refined.

618234—62——2

TABLE 2.—*Chemical, mineralogical, and radiometric analyses of selected samples collected at the Gould mine. Halloysite of sample 19 identified by electron micrograph; all other minerals identified by X-ray analyses*

[Analyses by the U.S. Geological Survey. Chemical analysts: C. G. Angelo, James Wahlberg, M. Delavaux, Mary Finch, G. Edgington, A. Sweeney, and P. Moore. Mineral Analysts: Jerome Stone and R. P. Marquiss. Analyses arranged in order of increasing arsenic content]

Sample No.	Laboratory serial No.	Arsenic (ppm)	Iron (percent)	Uranium (percent)	Equivalent uranium (percent)	Vanadium (percent)	Selenium (ppm)	Minerals identified	Sample description
16	140914	40	0.47	0.28	0.28	0.15	<3	Carnotite	Sandstone, medium-grained, poorly sorted, a few grains of chert and clay.
15	140913	70	.75	.27	.28	.14	<3	do	Sandstone, medium- to coarse-grained.
13	140911	80	.63	.13	.12	.10	4		Sandstone, medium- to coarse-grained, poorly sorted.
20	140918	100	.58	.088	.085	.10	<3		Conglomerate; dark-gray chert abundant; matrix is light-gray clay and fine- to coarse-grained sandstone.
23	140921	100	.58	.42	.36	.13	<3		Sandstone, fine- to medium-grained, white.
14	140912	110	.68	.55	.49	.17	<3	Carnotite	Sandstone, medium-grained, poorly sorted; grains of dark-gray chert abundant.
5	140904	170	.96	.17	.16	.13	7		Sandstone, medium- to coarse-grained, impregnated with a yellow radioactive mineral.
17	140915	170	1.98	.007	.006	.16	100	Tyuyamunite, metatyuyamunite, kaolin.	Clay, silty, very cohesive; heavy yellow stain (iron sulfide?).
12	140910	210	.89	.40	.41	.18	<3	Carnotite	Sandstone, medium-grained; clay grains abundant; heavy yellow-brown iron stains.
4	140903	210	1.26	.27	.21	.13	20		Sandstone, medium- to coarse-grained, poorly sorted.
11	140909	230	1.05	.25	.26	.20	9		Sandstone, medium-grained; heavy stains of yellow-brown iron; yellow radioactive mineral conspicuous.
10	140908	240	1.03	.46	.43	.21	8		Sandstone, medium-grained; laminae of white clay and silt.
2	140901	340	1.60	.17	.16	.18	10		Sandstone, medium-grained, impregnated with yellow-brown iron oxides and a yellow radioactive mineral.
22	140920	390	1.49	2.20	1.7	.66	<3		Sandstone, medium-grained; a yellow radioactive mineral and nodules of yellow-brown iron oxides abundant.
1	140900	390	1.54	.67	.65	.31	8	Carnotite	Sandstone, medium-grained, impregnated with yellow-brown iron oxides and a yellow radioactive mineral; several nodules of dark-brown iron oxides.
8	140907	410	2.03	.005	.006	.15	50	Kaolinite	Claystone, silty, very cohesive, white to light-gray.
7	140906	450	2.12	.006	.013	.23	20		Sandstone, medium-grained, impregnated with yellow-brown iron oxides.
24	140922	470	1.91	.52	.39	.40	<3		Conglomerate; galls of light-gray silt and clay in a matrix of medium- to coarse-grained sand. Matrix impregnated with yellow-brown iron oxides.
6	140905	490	2.03	.13	.12	.23	40		Sandstone, medium-grained, firmly cemented with dark-brown iron oxide which also forms nodules.
3	140902	510	1.96	.011	.024	.25	7		Sandstone, medium-grained, cemented with dark-brown iron oxides.

21	140919	580	2.08	.012	.03	.23	30	Hematite, goethite	Sandstone, medium- to coarse-grained; some grains have a pale-blue coating; a resinous dark-brown mineral is abundant.
18	140916	690	2.06	1.40	1.00	.67	10	Tyuyamunite, metatyuyamunite.	Sandstone, medium-grained, cemented with yellow-brown iron oxides; a yellow radioactive mineral abundant; grains of dark-gray chert and light-gray clay abundant.
19	140917	900	2.06	.21	.17	.49	10	Halloysite	Sandstone, medium-grained; many grains have gray-blue coating; halloysite identified from blue coating.
60	239133		.92	.07	.059	.14			Conglomerate; light-gray silt galls in matrix of coarse sand and many granules of chert, quartz, and fragments of siltstone; granules are well rounded; interstices contain jarosite and one or more yellow radioactive minerals.
61	239134		.80	.57	.44	.22			Conglomerate; light-gray silt galls in matrix of granule sandstone, heavily impregnated with greenish-yellow radioactive mineral.
62	239135		.89	.50	.43	.33			Sandstone, fine-grained, well-sorted; concentrations of interstitial yellow-brown iron oxide and greenish-yellow radioactive material form laminae in rock.
63	239136		.33	.01	.019	.05			Sandstone, medium-grained, light-gray, well-sorted; contains many grains of light-gray clay and silt.
64	239137		.38	.19	.21	.18			Sandstone, fine- to medium-grained, well-sorted, cemented with yellow-brown iron oxides.
66	239139		1.27	1.82	1.1	.60		Tyuyamunite and metatyuyamunite.	Siltstone, clayey, light-gray, conchoidal fracture, taken from silt-gall conglomerate.
67	239140		.61	.38	.31	.20			Conglomerate; light-gray and clayey silt galls; matrix is granule sandstone containing much light-gray chert.
68	239141		.56	.006	.012	.15			Claystone, silty, light-gray; includes laminae of fine sand and silt; conchoidal fracture; taken from ore zone.
69	239142		2.54	.33	.25	.57		Tyuyamunite and metatyuyamunite.	Conglomerate, chiefly matrix of silt-gall conglomerate; matrix is coarse sandstone containing many granules of chert and quartz, and is impregnated with yellow-brown iron oxides and a greenish-yellow radioactive mineral.

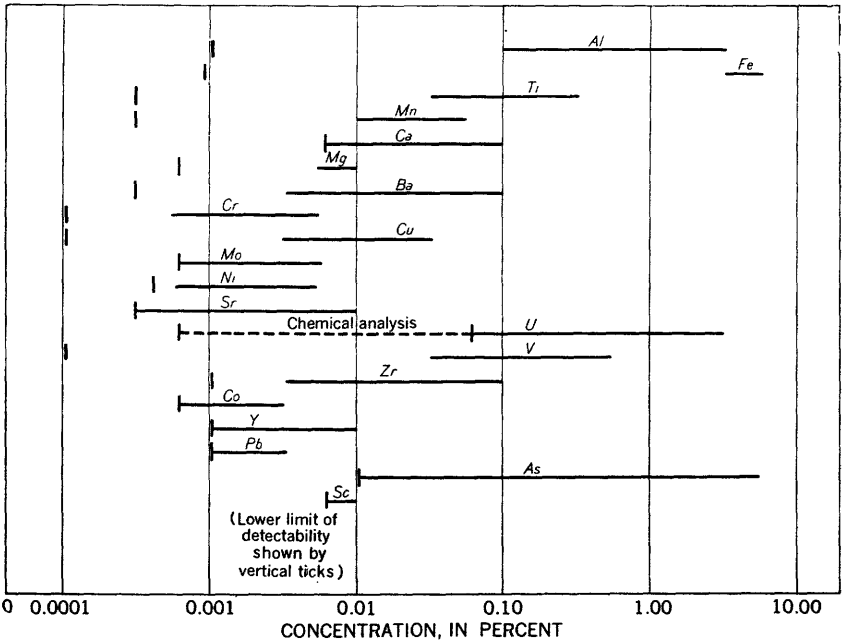

FIGURE 14.—Range of percentages of 20 elements in 30 samples collected from the Gould mine as determined by semiquantitative spectrographic and chemical (dashed line) analyses.

TABLE 3.—*Approximate visual detection limits for the elements determined by the semiquantitative spectrographic methods at the Denver laboratory of the U.S. Geological Survey*

[Revised August 1956]

Element	Percent	Element	Percent	Element	Percent
Si	0.002	Eu	0.05	Sb	.01
Al	.001	Ga	.0002	Sc	.0005
Fe	.0008	Gd	.005	Sn	.001
Mg	.0005	Ge	.001	Sr	.0002
Ca	.005	Hf	.01	Sm	.01
Na [1]	.05 (0.0005)	Hg [1]	1 (0.002)	Ta	.02
K [1]	.7 (0.002)	Ho	.01	Tb	.1
Ti	.0002	In	.001	Te [1]	.1 (.01)
P	.2	Ir	.01	Th	.02
Mn	.0002	La	.002	Tl	.01
Ag	.0001	Li [1]	.02 (0.00006)	Tm	.01
As [1]	.1 (.01)	Lu	.01	U	.05
Au	.002	Mo	.0005	V	.001
B	.002	Nb	.001	W	.01
Ba	.0002	Nd	.01	Y	.001
Be	.0001	Ni	.0003	Yb	.0005
Bi	.001	Os	.01	Zn	.02
Cd	.005	Pb	.001	Zr	.001
Ce	.02	Pd	.0003		
Co	.0005	Pr	.05		
Cr	.0001	Pt	.003		
Cs [1]	2 (0.02)	Rb [1]	10 (0.006)		
Cu	.0001	Re	.005		
Dy	.005	Rh	.005		
Er	.005	Ru	0.01		

[1] A different exposure is required for the detectabilities shown in parentheses.

NOTE: Some combinations of elements affect the detectabilities. Approximate values are given. In unusually favorable materials, concentrations somewhat lower than the values given may be detected. In unfavorable materials the given detectabilities may not be attained for some of the elements.

Probable sources of the 21 elements detected in the samples are as follows:

Element	*Sources*
Fe	Goethite, hematite, and limonite commonly cement or heavily stained rocks of the ore interval. These minerals undoubtedly account for most of the Fe reported in the analyses.
U, V	These elements are from the ore minerals carnotite, tyuyamunite, and metatyuyamunite. Some of the V may be incorporated in clay materials.
Cr, Ti, Zr	Chromite, rutile, ilmenite, leucoxene, and zircon are found in heavy-mineral concentrates from these rocks.
Ca, Mg, Al	Probably chiefly clay minerals, and the "lime" reported by AEC.
As	Pyrite and marcasite.
Sr, Ni, B, Mn, Mo, Cu, Ba, Co, Y, Pb, Sc	Unknown.

X-ray analyses indicate that the ore minerals are carnotite, $K_2(UO_2)_2(VO_4)_2\cdot nH_2O$, tyuyamunite, $Ca(UO_2)_2(VO_4)_2\cdot 5\text{–}8\frac{1}{2}H_2O$ and metatyuyamunite $Ca(UO_2)_2(VO_4)_2\cdot 3\text{–}5H_2O$. In the western part of the mine the ore minerals are chiefly tyuyamunite and metatyuyamunite, whereas in the eastern part of the mine carnotite is probably the chief ore mineral. The tyuyamunite is lemon yellow, has a higher luster, and seems to be more coarsely crystalline than the yellow carnotite ore. All ore minerals are found as interstitial fillings and grain coatings.

By October 30, 1955, 144 lots of ore had been shipped from the mine to the U.S. Atomic Energy Commission buying station at Edgemont, S. Dak. These lots, ranging in size from 6.5 to 76.5 short tons, were analyzed by the Atomic Energy Commission for uranium and vanadium. Weighted average grade of all lots was 0.233 percent U, and 0.206 percent V, giving an overall V/U ratio of 1/1.14. These data for the ore compare with an average grade of 0.391 percent U, 0.248 percent V, and a V/U ratio of 1/1.58 in samples collected by the writer and listed in table 2. Because the combining weights of vanadium and uranium in carnotite and tyuyamunite have a ratio of about 1:4.66, an excess of vanadium is indicated in both groups of samples. Despite a reasonably careful search, no vanadium minerals were detected in or near the deposit. Hewettite is not present, but some of the darker vanadium minerals such as rauvite or corvusite may be associated with the dark-brown iron oxides and consequently may have escaped detection. A comparison of the available V/U ratios indicates a slight relative increase in vanadium with a decrease in grade of uranium, but this decrease is not significant when the overall excess of vanadium is considered. Silt galls of the conglomerate have a U/V ratio as high as 1/30 (sample 8, table 2) suggesting claylike vanadium silicates in the deposit similar to those described by Hathaway (1959, p. 133–138.).

Chemical and radiometric analyses indicate that high-grade ore has a surplus, and low-grade ore a deficiency, of uranium relative to amounts required for radioactive equilibrium between uranium and its daughter products. This is clearly shown by a comparison of the analyses of two sets of samples where one set consists of 199 channel samples cut by geologists of the AEC at 10-foot intervals along all walls and faces in the mine, and another set collected by the writer and listed in table 2 or shown on plate 10 and figure 15. The AEC samples have an average U/eU ratio of 0.75 and an average grade of 0.192 percent uranium compared with an average U/eU ratio of 1.23 and an average grade of 0.391 percent uranium derived from the writer's sample analyses. Because 1 million years is required for uranium to reach equilibrium with its daughter products, the high-grade ore is either younger than 1 million years or daughter products have been leached from it. The radiometric deficiency of uranium in the low-grade ore is a result of the leaching of uranium away from its daughter products or enrichment of the daughter products from a remote source—possibly the high-grade ore. Leaching solutions were probably acidic in some places, resulting from the oxidation of iron sulfides, and alkaline elsewhere, as suggested by the lime in the ore reported by the AEC. Ground-water solutions that leached or precipitated materials of the deposit were controlled, at least partly, by the permeability of the rocks.

To obtain data on relations among permeability, distribution of uranium in the sandstone, and equilibrium conditions of the uranium, seven samples (133–134, 136–140) were collected at localities shown on figure 12, and the results of analytical work are plotted on figure 15. Each sample was cored horizontally (parallel to the bedding) and vertically (perpendicular to the bedding), and the cores analyzed for uranium and equivalent uranium, and tested for permeability. The tendency mentioned previously for high-grade ore to have a surplus of uranium and low-grade ore to have a deficiency is not shown by these samples although the only sample with a deficiency (133H) has a grade of 0.018 uranium. If extensive leaching had occurred, removal of uranium or its daughter products should have been most effective in the most permeable rocks, resulting in anomalous values of equivalent uranium in these rocks. In the absence of these anomalous values, leaching probably has not been severe and has occurred chiefly in the low-grade ore from which uranium has been removed and deposited with the high-grade ore.

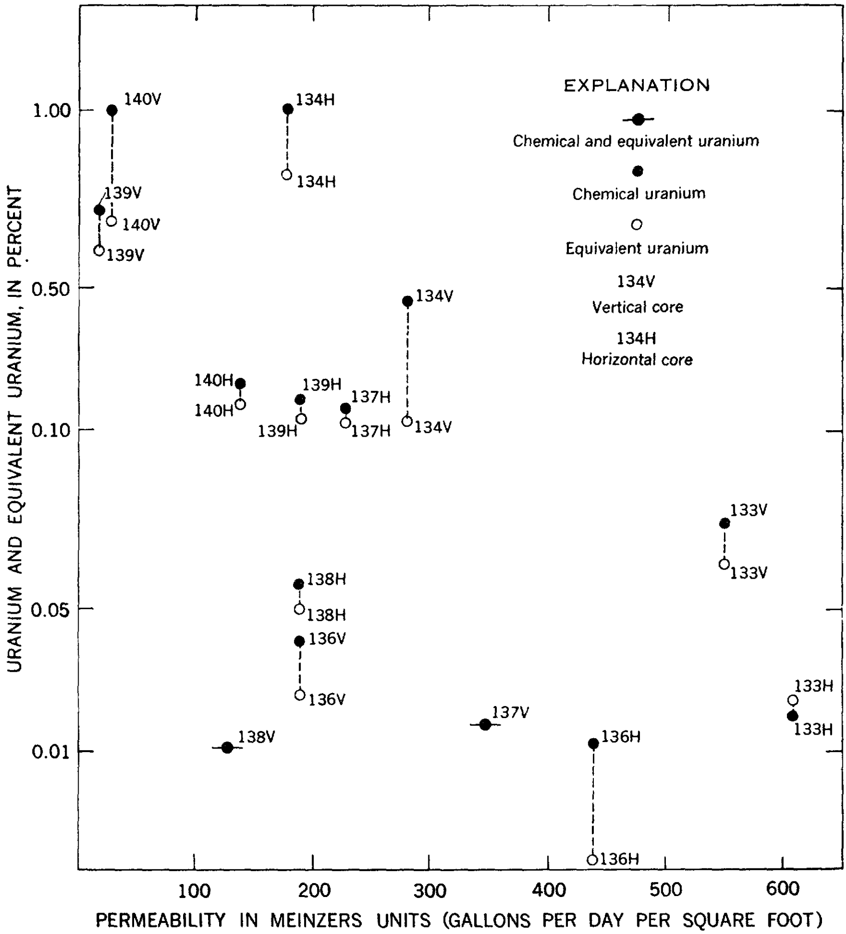

FIGURE 15.—Graph showing relations among uranium, equivalent uranium, and permeability in seven samples collected from the ore zone.

A marked irregularity in the distribution of uranium through short distances in the sandstone is indicated by differences in percentage of uranium between cores from the same sample. These differences range from 2 to 10 times the percentage found in nearby cores of the same sample. The highest concentrations of uranium tend to be in the least permeable rocks. This tendency is particularly noticeable when the vertical and horizontal cores from the same sample are compared, and can also be detected in the general grouping of all samples. The ore minerals as a cementing agent probably have little effect on the permeability as they constitute less than one percent of the rock. The negative correlation between permeability and concentrations of uranium in specific samples contrasts with the apparent positive correlation between the gross permeabilities of the host rock and country rock. The relatively friable well-sorted closely jointed sandstone in the ore zone should make the sandstone much more permeable as a unit than either the overlying or underlying rocks.

CONTROLS IN LOCALIZATION OF ORE MINERALS

One of the most striking and consistent features of uranium deposits in the Black Hills is the tendency of uranium to concentrate in a few stratigraphic intervals. This habit of uranium is one of the most reliable guides to ore in the exploration for uranium in the Black Hills. Nearly all the uranium produced has come from the Inyan Kara group despite the fact that the group accounts for less than 7 percent of the stratigraphic column of sedimentary rocks and that rocks of other formations (notably the Minnelusa and Newcastle formations) have lithologies similar to the host rocks of the Inyan Kara group. This concept of the favorable stratigraphic interval is as true locally as it is regionally. For example, within 8 miles of the Gould mine, favorable stratigraphic intervals are found chiefly near the top and bottom of the Lakota formation. Specific deposits also reflect the tendency of uranium to accumulate in tabular forms conformable with the bedding. This tendency can be seen at the Gould where the top of the ore zone is parallel with, and a few feet below, the erosion surface as shown in plate 8. The agencies which consistently produced this wide lateral and limited vertical distribution of the ore are the primary control in the localization of uranium; secondary controls include differential permeability within the host rock, gross differences in permeability between the host rock and adjacent rocks, and fractures within the host rock. The agencies constituting the primary control are unknown; however, some insight into the nature of these agencies can be gained by a review of recent developments in the geochemistry of uranium.

The great variety of hexavalent uranium minerals found in oxidized deposits like the Gould compared with the relatively few tetravalent minerals (chiefly uraninite and coffinite) found in relatively unoxidized deposits (like those at the Runge and Triangle mines several miles west of the Gould) suggests that the hexavalent minerals are the oxidation products of the tetravalent minerals. Much progress has been made in the study of the behavior of uranium during oxidation by E. P. Bullwinkel, (written communication, 1954), Christ and Clark (1955), Garrels (1955), Gruner (1954), Phair and Levine (1953), and contributors to Garrels and Larsen (1959). Garrels and Christ (1959, p. 87–88) have integrated the results of many of these investigations with their work on the paragenetic oxidation sequence of uranium. According to them, the relatively insoluble UO_2 contained in uraninite will oxidize to the soluble UO_3 in an oxidizing environment free of "fixing" agents such as arsenic, phosphorous, vanadium, or reactive silica. Production of uranyl ions by UO_3 in a water solution is accelerated if the solution contains carbonate or sulfate ions. Thus mobilized, the uranium will migrate with the water solution until the solution evaporates to dryness, is reduced, or the uranium is stabilized by the fixing agents. Pentavalent vanadium, the uranyl ion, and potassium may combine to form a poorly defined vanadium mineral similar to rauvite which converts to carnotite by a solid-state transformation involving the loss of vanadium to solution.

If the ancestral ore body at the Gould was in the form of low-valent uranium, it is likely that uranium was originally concentrated by one of the mechanisms suggested by Garrels and Christ; that is, evaporation, reduction, or stabilization of the uranium by a fixing agent. Evaporation of a sufficient amount of uranium-bearing ground-water solutions to produce an ore body the size of the one at the Gould would also have produced huge quantities of other evaporates such as sodium, magnesium, and calcium sulfates and some bicarbonates (Rankama and Sahama, 1950, p. 281). It is unlikely that these evaporates could have been removed subsequently in ground-water solutions without leaving some evidence of their former existence. For this reason, tetravalent uranium may have been originally precipitated at the Gould by the reduction of uranium-bearing solutions and the precipitate stabilized by pentavalent vanadium. Enough data are reported to permit some inferences regarding a possible reductant and the source of the uranium and vanadium.

At other mines carbonaceous material, petroleum residues, and pyrite are commonly associated with the uranium and provide, or are diagnostic of, a reducing environment. The only evidence of this sort at the Gould is indirect, consisting of the anomalously high percentage of arsenic found in the abundant red-brown iron oxides. The arsenic may be vestigial evidence of a pyritic source for the iron (Rankama and Sahama, 1950, p. 741). Meteoric water could have become enriched in vanadium from the silt galls during its slow passage downward through the silt-gall conglomerate. The mingling of these vanadiferous solutions with uranium-bearing solutions moving down the dip beneath the conglomerate would have resulted in the deposition of a low-valent uranyl vanadate which subsequently oxidized to carnotite and tyuyamunite with some redistribution of the uranium along fractures. The mechanism postulated here to explain localization of the uranium would also account for the marked parallelism between the top of the ore zone and the bottom of the conglomerate.

SUMMARY AND CONCLUSIONS

Carnotite, tyuyamunite, and metatyuyamunite are irregularly concentrated in a zone 1 to 15 feet thick near the middle of a thick-bedded sandstone at the top of the Lakota formation. The shape and position of lenses of ore within the zone are controlled by two sets of joints which strike N. 30°–40° W. and N. 80°–90° W. The long directions of the lenses tend to parallel the N. 30°–40° W. joints, and the lenses are alined parallel with the N. 80°–90° W. joints. The top of the ore zone is roughly parallel with an unconformity at the bottom of a silt-gall conglomerate, with some divergence between the two surfaces in the eastern part of the mine. The ore minerals are a weak cement in a poorly sorted quartz sandstone and are associated with moderate to heavy concentrations of yellow-brown iron oxides. No carbonaceous material is found near the deposit, and lime has been detected only in analyses made by the AEC buying station.

Chemical and radiometric analyses indicate that the high-grade ore has a surplus, and the low-grade ore a deficiency, of uranium relative to amounts required for radioactive equilibrium between uranium and its daughter products. Relations among permeability, distribution of the uranium in the sandstone, and equilibrium conditions of the uranium suggest that high-grade ore is in the least permeable rocks and that daughter products may have been partially leached away from the high-grade ore and deposited with the low-grade ore.

Geochemical data suggest that the pattern of distribution of uranium within the host rock is the product of the local redistribution of an ancestral unoxidized ore body. The regional distribution of ore deposits, the paucity of evidence for a chemical environment favorable for the precipitation of tetravalent uranium, and the spatial relations between the top of the ore zone and the unconformity can be plausibly explained by commingling solutions in a reducing environment produced by a deposit of pyrite which was ancestral to the iron oxides.

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