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Present-day ground water, a possible guide to uranium exploration in the southern Black Hills of South Dakota and Wyoming*

by C. G. Bowles

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*Modified from talk presented at the 12th Annual Minerals Symposium of the American Institute of Mining and Metallurgical Engineers, Moab, Utah, June 24, 1967.

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5. Present-day ground water, a possible guide to uranium exploration in the southern Black Hills of South Dakota and Wyoming, by C. G. Bowles. 24 p., 13 figs., 1 table. 15426 Federal Bldg., Denver, Colo. 80202; 8102 Federal Office Bldg., Salt Lake City, Utah 84111; South Dakota State Geological Survey, Science Center, University of South Dakota, Vermillion, S. Dak. 57069; South Dakota School of Mines, Rapid City, S. Dak. 57701; Geological Survey of Wyoming, University of Wyoming, Laramie, Wyo. 82070.

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by C. G. Bowles

INTRODUCTION

Many small uranium deposits were mined during the 1950's along the southwest flank of the Black Hills. During this time the Geological Survey, on behalf of the U.S. Atomic Energy Commission, mapped fourteen 7½-minute quadrangles in the areas outlined by solid lines in figure 1. Much of the geology discussed in this paper is the result of the work by a number of Survey geologists under the direction of G. B. Gott.

In 1965, William Chenoweth, of the Resource Investigation Division of the Atomic Energy Commission, sampled waters from 32 wells marginal to the southern Black Hills, within the area outlined by the heavy dashed line in figure 1. These waters, which were analyzed by the Commission, provided the basic data presented in this paper, and therefore the author wishes to acknowledge this generous contribution by the Atomic Energy Commission and particularly to express appreciation to William Chenoweth.

General geology

The Black Hills of South Dakota and Wyoming are composed of a central core of granitic and metamorphic rocks of Precambrian age surrounded by an upwarped 3,000-foot-thick sequence of sedimentary rocks ranging in age from Cambrian to Late Cretaceous. The sedimentary rocks form an elongate, north- to northwest-trending dome, with an axis northeast of Edgemont, S. Dak., in the position indicated in the upper portion of figure 1.

Formations of Paleozoic age, having a combined thickness of 1,800 feet, crop out at higher elevations on what Darton called the "limestone plateau." The Minnelusa Formation of Permian and Pennsylvanian age, which is shown on figure 1 by the shaded area, is closely linked to the formation of the ore deposits. Overlying the Minnelusa Formation are the Opeche Formation and the Minnekahta Limestone of Permian age.

The concentric Red Valley, surrounding the limestone plateau, is eroded into the 450 to 600 feet of siltstone and gypsum of the Spearfish Formation of Permian and Triassic age. The outer edge of the Red Valley and lower part of the surrounding hogback are underlain by a 400- to 450-foot-thick sequence of the Gypsum Spring, Sundance, and Morrison Formations, all of Jurassic age. In the eastern part of the southern Black Hills the Unkpapa Sandstone is present at the stratigraphic position of the Morrison Formation. The hogback is capped by the Lower Cretaceous

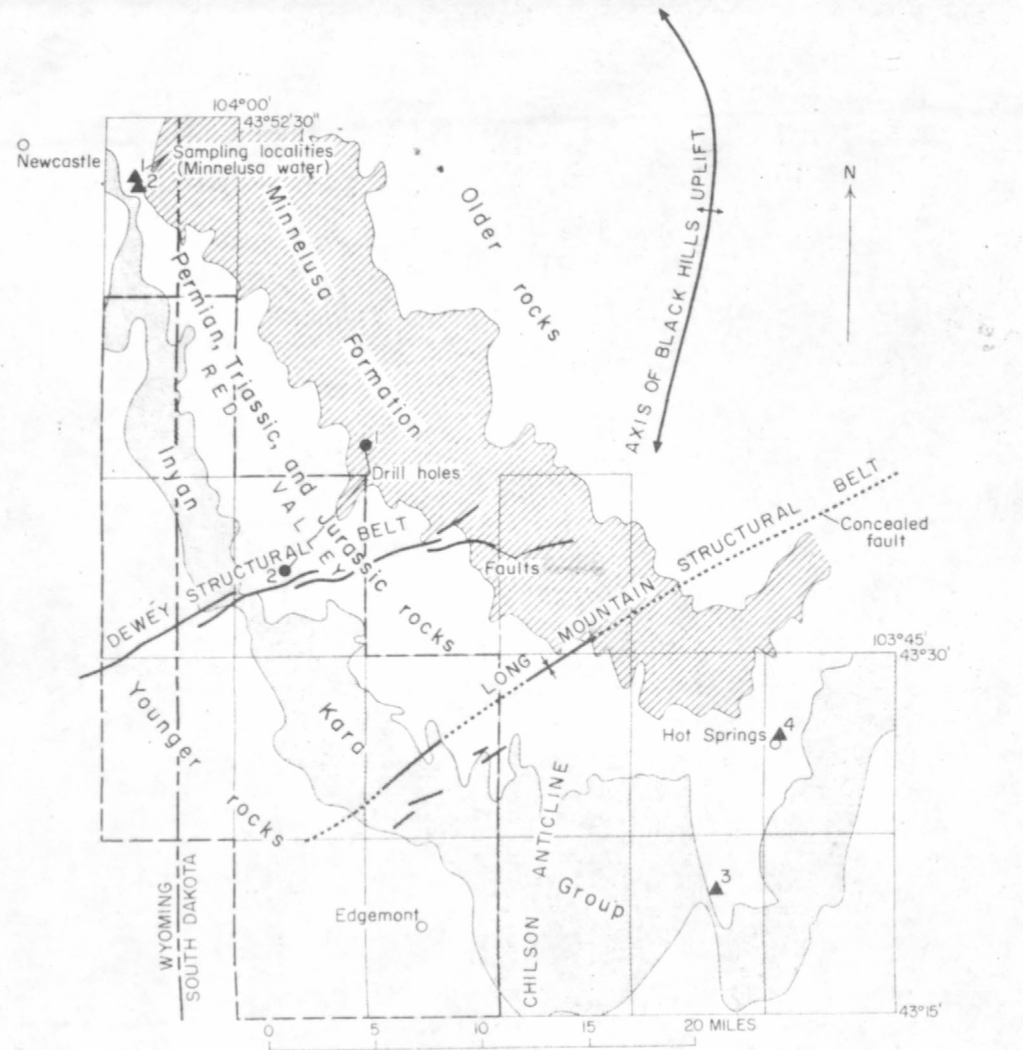

Figure 1.--Index map of the southern Black Hills showing $7\frac{1}{2}$-minute quadrangles mapped by the southern Black Hills project (solid line), area of ground-water study illustrated on figure 13 (heavy dashed line), and outcrop of Minnelusa Formation and Inyan Kara Group.

Lakota and Fall River Formations of the Inyan Kara Group, which are the host rocks for uranium deposits of the Edgemont district. The outcrop of the Inyan Kara Group is shown on figure 1 by a diagonal line pattern. Above the 300- to 700-foot-thick sequence of the Inyan Kara Group are marine shales of Early and Late Cretaceous age that underlie the plains surrounding the Black Hills.

Three major structures lie within the Edgemont uranium district: the Chilson anticline, Long Mountain structural belt, and Dewey structural belt. The Chilson anticline, east of Edgemont, marks the axis of the Black Hills uplift and the east margin of the Edgemont uranium district. Two structural belts extending northeastward across the uplift have been repeatedly deformed. Earliest deformation recorded on the Long Mountain structural belt occurred during the Precambrian. Aeromagnetic and gravity surveys indicate a concealed northeast-trending fault of Precambrian age in the metamorphic rocks. Later deformation recorded in the sedimentary rocks are minor adjustments, controlled by deeper structure in the basement rocks. Deformation along the belt exerted a control on deposition and erosion during Inyan Kara time. During Laramide time, deformation occurred again and northeast-trending normal faults displaced strata of the Inyan Kara Group by as much as 100 feet. Similarly, recurrent movement has occurred along the Dewey structure belt. Geologic mapping by Braddock (1963) and by Brobst (1961) record deformation during the Early Jurassic and again during the Early Cretaceous. The Dewey fault of Laramide age has displaced the strata of the Inyan Kara about 400 feet.

The history of recurrent structural deformation is stressed at this point because the deformation affected deposition of the host rocks for the uranium ore bodies and because the fractures formed by the repeated deformation have permitted vertical movement of mineralizing solutions. Now let us look more closely at the three formations of primary interest.

The Minnelusa Formation achieves a maximum thickness of about 1,100 feet in the subsurface, but is markedly thinner in outcrop. Figure 2 indicates that as much as 250 feet of anhydrite has been leached from outcrops of the formation, forming collapse or founder breccias in the upper part of the Minnelusa (Bowles and Braddock, 1963). An initial phase of the dissolution process is the development of collapse chimneys or breccia pipes. Some pipes have stoped upward as much as 1,300 feet above the Minnelusa Formation into the Inyan Kara Group. Recently formed sinks within the Inyan Kara Group indicate that the process is still continuing down dip from the Minnelusa outcrops.

The Inyan Kara Group, which was deposited in the northwest-trending Black Hills syncline, consists of the Lakota Formation and the Fall River Formation (fig. 3). The Lakota is subdivided into (ascending order) the Chilson Member, Minnewaste Limestone Member, and Fuson Member. The Chilson Member is composed predominantly of sandstones and finer grained equivalents of two fluvial units numbered 1 and 2, from oldest to

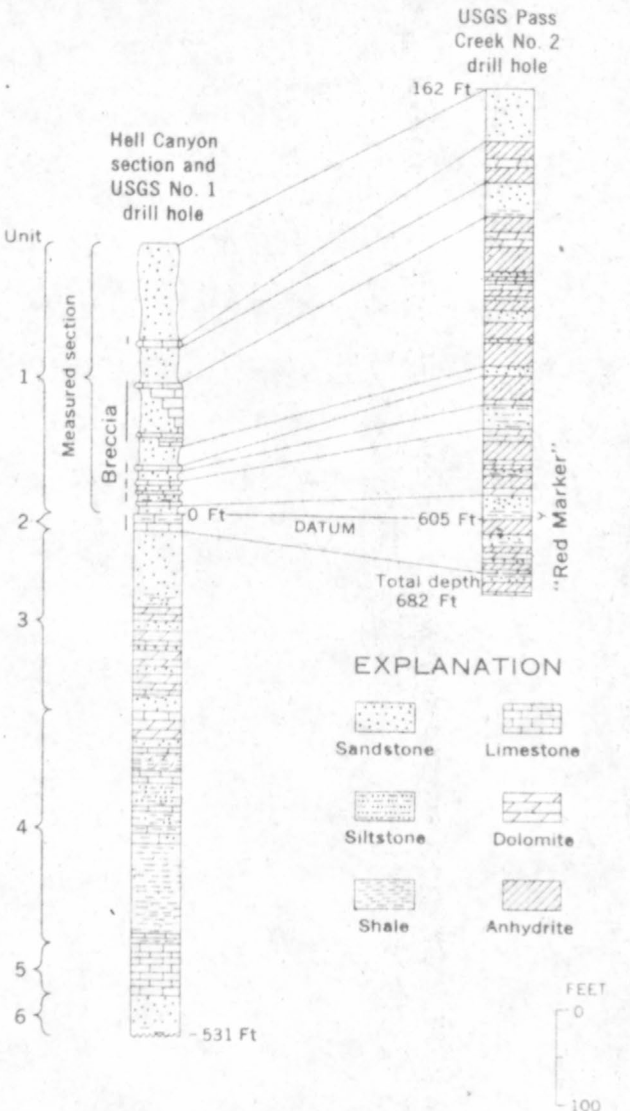

Figure 2.--Stratigraphic sections of the Minnelusa Formation of Pennsylvanian and Permian age showing correlation of brecciated rocks in outcrop with anhydrite-bearing strata of the subsurface in Custer County, S. Dak. The locations of the stratigraphic sections are: Hell Canyon section, NW$\frac{1}{4}$ sec. 3 and NE$\frac{1}{4}$ sec. 4, T. 5 S., R. 2 E.; USGS No. 1 Hell Canyon drill hole, sec. 3, T. 5 S., R. 2 E.; USGS No. 2 Pass Creek drill hole, sec. 1. T 6 S., R. 1 E. (Bowles and Braddock, 1963).

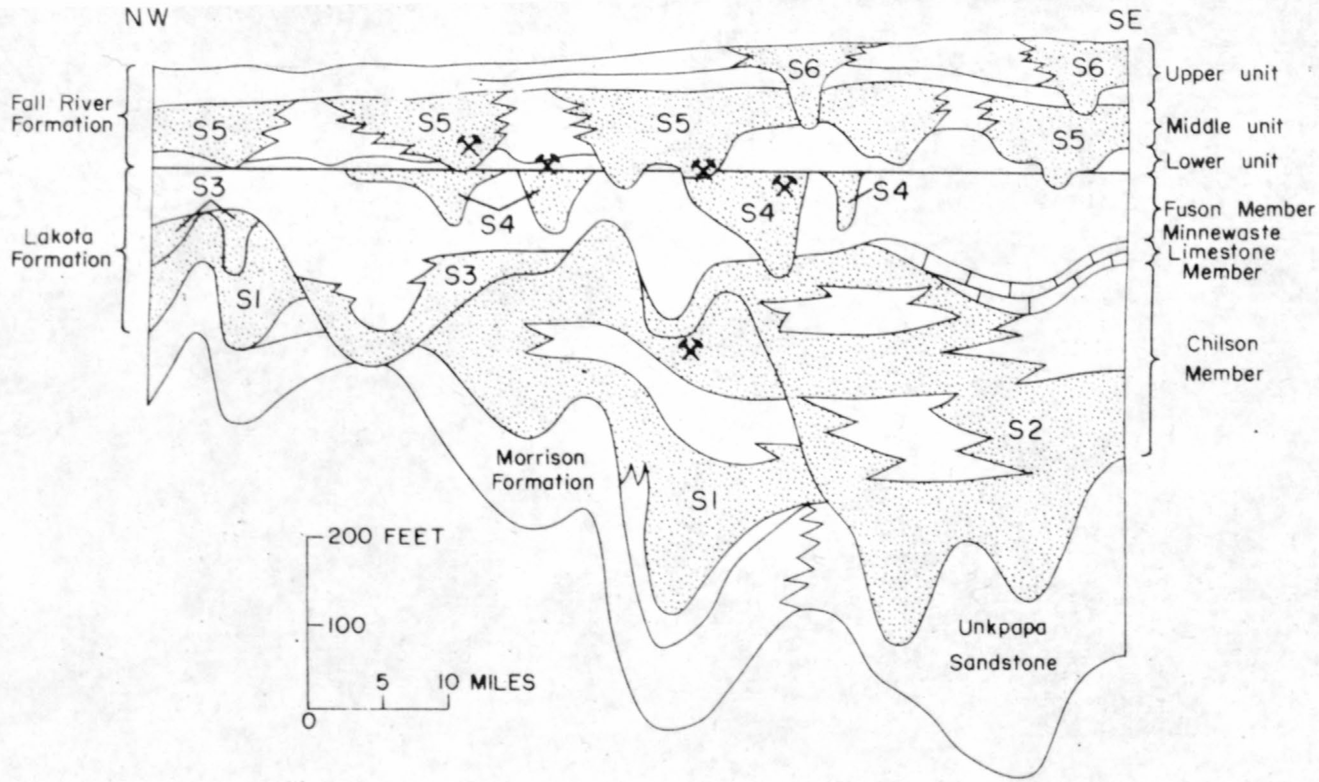

Figure 3.--Diagrammatic cross-section of the Lakota and Fall River Formations of the Inyan Kara Group and underlying formations showing numbered fluvial sandstones (S1-S6) and distribution of uranium deposits (⚒) (D.E. Wolcott and G. B. Gott, written commun., 1960).

youngest, whereas the Minnewaste and Fuson Members are predominantly lacustrine deposits; however, two fluvial sandstones, numbered 3 and 4, are present in the Fuson.

The Fall River Formation consists of a basal unit of interbedded carbonaceous sandstone and siltstone unit, a middle unit containing the No. 5 channel sandstone, and an upper unit of marginal marine sediments.

Uranium deposits are present within fluvial units numbered 1 and 4 of the Lakota Formation, and within the interbedded sandstone and siltstone of the lower unit and the No. 5 fluvial sandstone of the middle unit of the Fall River Formation. All the deposits are present in rocks that either contain organic carbonaceous material or are in close proximity to carbonaceous rocks. Uranium deposits are conspicuously absent from the noncarbonaceous No. 2 sandstone and the lacustrine sandstones of the Fuson Member.

Figure 4 indicates the position of the main streams flowing to the northwest near the axis of the Black Hills syncline during the Early Cretaceous (Bolyard and McGregor, 1966). The numbers refer to the fluvial units indicated in figure 3. Several northeast-flowing tributaries to the main streams are shown in the area between Edgemont and Newcastle. More recent examination of data indicates that in the area of the Long Mountain structure belt, other tributaries flowed into the main stream that deposited the fluvial units 1, 2, 4, and 5.

A thick sequence of shales of Early and Late Cretaceous age were deposited upon the Inyan Kara Group prior to uplift of the Black Hills at the close of the Cretaceous.

The Laramide uplift provided the structural and topographic relief necessary for erosion of the Mesozoic and Paleozoic rocks, and it established a pattern of surface and ground water flow away from the central part of the Black Hills. In the southern Black Hills northwest-southeast oriented drainages were established upon the shales of Cretaceous age outside the Inyan Kara hogback and upon deposits of Tertiary and Quaternary age. As erosion progressed, streams were captured and stream channels shifted as both the structure and the varied resistance of the rocks to erosion assumed an increasingly important role in the relocation of the drainages. The position of Tertiary and Quaternary streams is shown in figure 5. A major ancestral drainage in the Craven Canyon area crossed the Chilson anticline and continued southeastward through the lower part of Chilson Canyon until stream piracy diverted the flow, first into Sheep Canyon and later into the lower part of Red Canyon.

The asymmetrical distribution of broad gravel terraces along the Inyan Kara hogback at the southwest flank of the Black Hills indicate down-dip migration of the streams as erosion progressed.

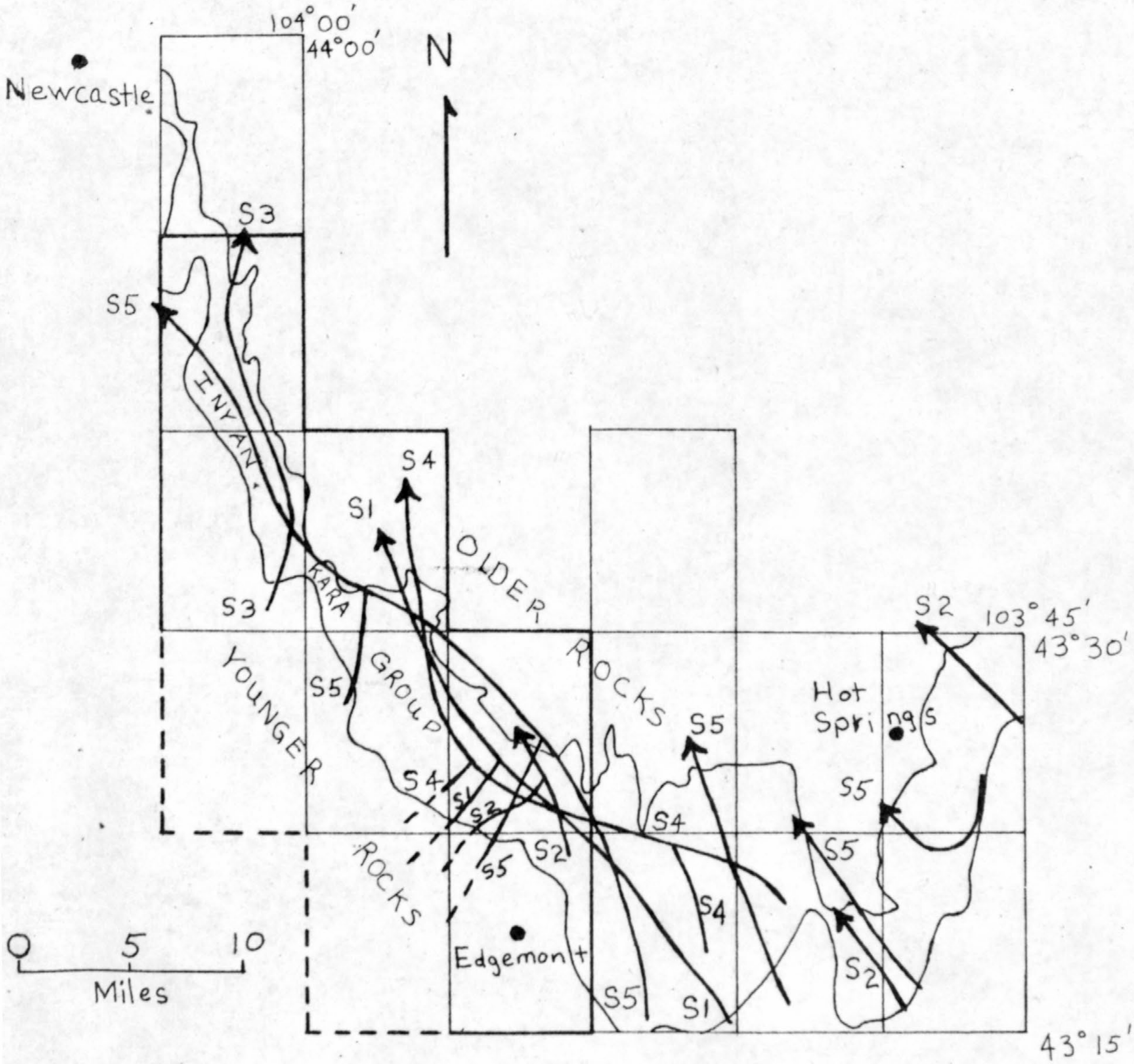

Figure 4.--Map of the southern Black Hills showing position of streams during Early Cretaceous time that deposited channel sandstones, numbered oldest (S1) to youngest (S6). (Modified from D. E. Wolcott and G. B. Gott, written commun., 1960).

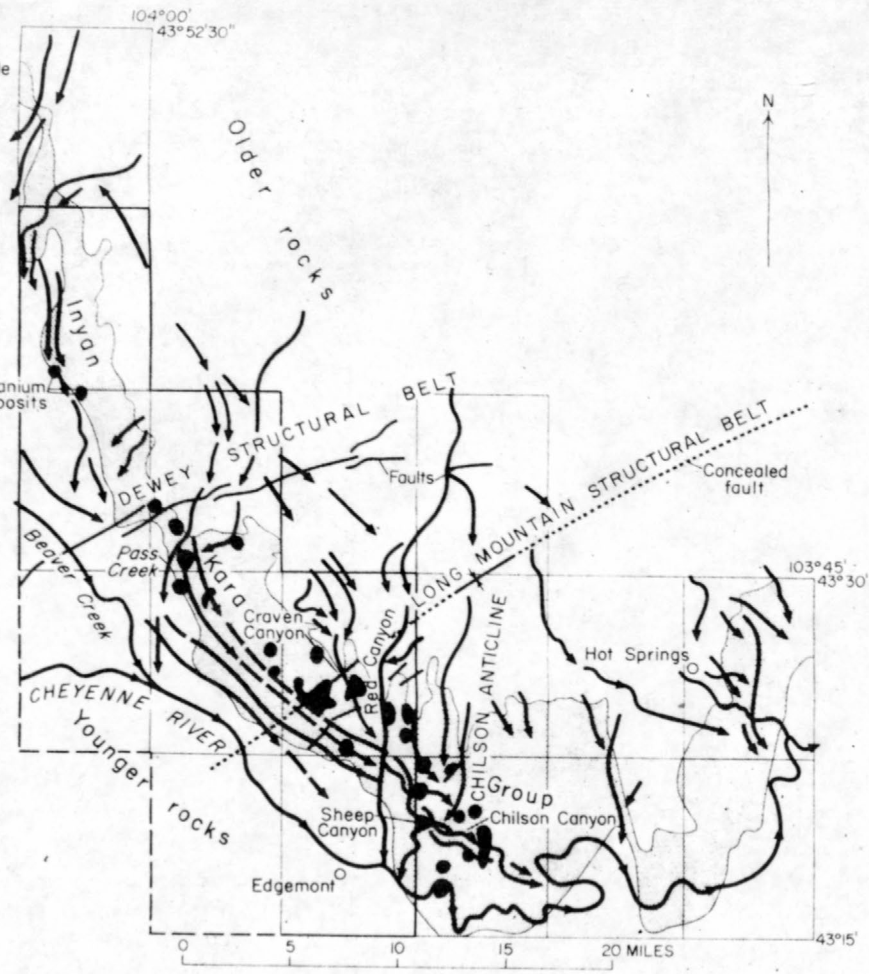

Figure 5.--Map of the southern Black Hills showing distribution of Quaternary and Tertiary streams (arrows) and location of uranium deposits of the Edgemont district (shown in solid black). Area of ground-water study (figure 13) indicated by heavy solid line, dashed where outside mapped area.

Uranium deposits are present in the areas shown in black in figure 5. It is characteristic that the deposits are concentrated along the larger ancestral drainages as well as along the Long Mountain structural belt. In addition, where there were no major drainages, no significant uranium deposits have been found, even though favorable host rocks are present. The association of the three uranium districts of the Black Hills area with the Cheyenne, Belle Fourche, and Little Missouri River drainages was recognized by O. M. Hart (written commun., 1966), but the location of deposits in the Edgemont district indicates that a similar association of deposits also exists with tributary drainages.

GROUND WATER

Most of the surface water that flows from the central part of the Black Hills enters the Pahasapa Limestone of Mississippian age and the overlying Minnelusa Formation (Brown, 1944) to become part of the ground-water system. Ground-water recharge areas, about 1,000 to 1,500 feet above the Cheyenne River at the margin of the Black Hills, readily accept surface runoff. As the ground water migrates down dip, some of the deeper water in the Pahasapa rises into the Minnelusa Formation under artesian pressure. At the margin of the Black Hills, water from the Minnelusa Formation, and possibly from the underlying Pahasapa Limestone, rises along fractures to the Inyan Kara Group. Continued ground-water movement along fractures in the Minnelusa probably dissolves anhydrite, which causes the formation of dissolution collapses or breccia pipes capable of transmitting large volumes of artesian water. Anomalously high temperature of ground water discharging from wells in the Inyan Kara in the vicinity of the Long Mountain and Dewey structural belts, as well as spring discharge through alluvium above the concealed Dewey fault (Brobst, 1961), indicates an artesian discharge to the surface of sulfate water that has circulated at the depth of the Minnelusa Formation.

Where the Inyan Kara is recharged by artesian waters it is postulated that there may be sufficient artesian head within the Inyan Kara to permit waters to rise along fractures through a limited thickness of overlying shale and to discharge to the surface. Such a discharge would be affected by a resistance to upward flow along the fractures; therefore a discharge to the surface is more likely where the thickness of overlying shales is a minimum, or at the lowest elevations in the vicinity of surface streams.

Spring and well waters from the Minnelusa Formation have been sampled (table 1) and the dominant ions determined to be calcium and sulfate with smaller amounts of magnesium and bicarbonate. A similarity of these waters to the calcium sulfate water of the Lakota Formation near the hogback is shown on figure 6.

Water within the Inyan Kara Group may, for convenience, be classified according to the most abundant pair of cations and anions in solution; thus there are three types of ground water present: calcium sulfate,

Table 1.--Chemical analyses (ppm) of spring and well waters from the Minnelusa Formation, Black Hills, South Dakota and Wyoming

	1 [1/]	2 [1/]	3 [2/]	4 [2/]
Sodium	3.6	4	54	86
Calcium	550	520	568	252
Magnesium	67	79	92	51
Sulfate	1,386	1,362	1,540	639
Chloride	8	5	62	112
Carbonate	0	0	0	0
Bicarbonate	226	238	235	232
Iron	0.06	0.06	0.03	0.0
Potassium	2.0	5	6.2	9.8
Fluoride	0.9	0.9	0.9	0.8
Silica	13	13	22	27
Uranium (ppb)	20	20	5.7	7.5
pH	7.3	7.6	7.0	7.0
Date of sampling	October 1965	October 1965	November 1957	November 1957

[1/] Sampled by William Chenoweth, U.S. Atomic Energy Commission; analyzed by Lucius Pitkin, Inc.

[2/] Sampled by U.S. Geological Survey; analyzed by M. J. Fishman and B. P. Robinson.

Localities sampled:

1. Spring, near center SE¼ sec. 31, T. 45 N., R. 60 W., Weston County, Wyo.
2. Well, center W½NW¼ sec. 5, T. 44 N., R. 60 W., Weston County, Wyo.
3. Cascade Springs, SW¼ sec. 20, T. 8 S., R. 5 E., Fall River County, S. Dak.
4. Spring, Evans Plunge, Hot Springs, Fall River County, S. Dak.

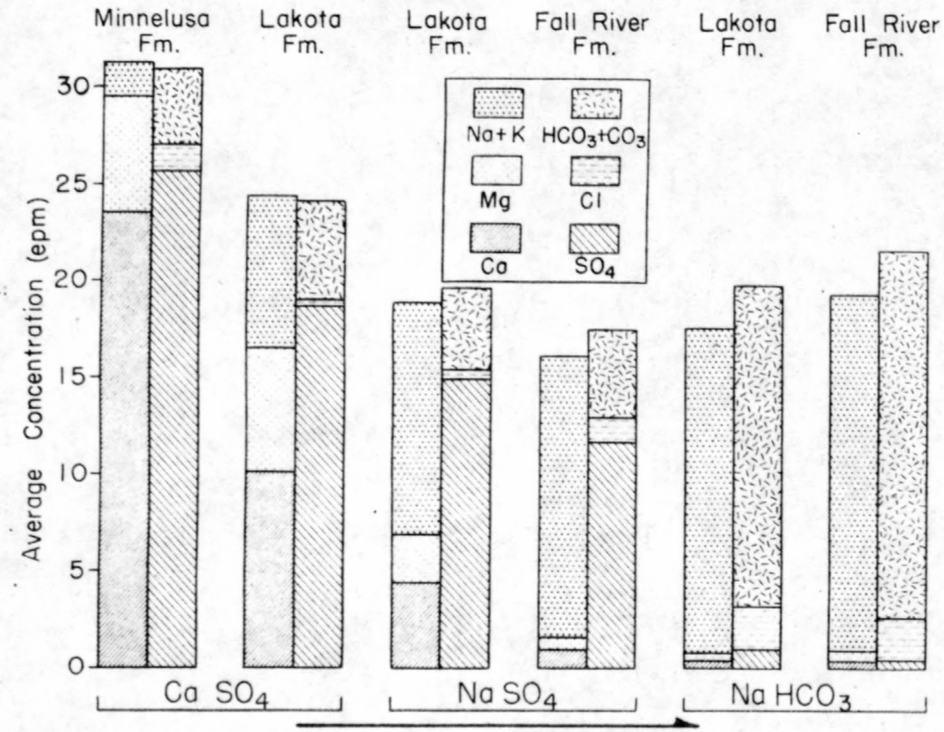

Figure 6.--Average composition of calcium sulfate, sodium sulfate, and sodium bicarbonate ground water from the Minnelusa, Lakota, and Fall River Formations in the southern Black Hills of South Dakota and Wyoming. (Arrow indicates modification of water types.) Concentration expressed as equivalents per million (epm). Composition of Minnelusa water is average from water sampled at localities 1-4 (fig. 1). All samples of water from Inyan Kara Group obtained from wells (fig. 13).

sodium sulfate, and sodium bicarbonate. As indicated by the arrow at the bottom of figure 6, the composition of the ground water changes from calcium sulfate to sodium sulfate as it migrates basinward and rises from the Lakota into the Fall River Formation. In addition, a change from sulfate water to a sodium bicarbonate water may also occur as the water moves through the Lakota and Fall River Formations.

Concentrations of calcium, sulfate, and magnesium decrease consistently as the water migrates basinward. Concentrations of sodium and included minor amounts of potassium, as well as the total concentration of bicarbonate and carbonate ions, increase in a basinward direction. The total concentration of dissolved solids is less in the sodium sulfate water than in the calcium sulfate water, and an intermediate concentration of total solids is present in the sodium bicarbonate water.

Analyses for each sample of water from the Inyan Kara and for the four samples of water from the Minnelusa are plotted on a multiple-trilinear diagram (fig. 7) of the type proposed by Piper (1944) and others. Concentrations of major cations and anions are plotted in the small triangular fields in the lower left and right corners of the diagram, respectively, and the combined relationships among the Na+K, Ca+Mg, CO_3+HCO_3, and Cl+SO_4 ions are plotted in the large diamond-shaped field. Minnelusa waters are shown on the diagram as open circles.

The composition of waters from the Inyan Kara Group fall in a linear distribution pattern within the calcium sulfate and sodium sulfate fields in the upper half of the diamond-shaped diagram. There is a concentration of points in the sodium bicarbonate field in the lower part of the diagram. The analyses for major cations plotted in the triangular field at the left also fall in a linear distribution pattern.

Figure 8 is a plot of the average composition of the waters grouped by water type as shown by the histogram of figure 6. The linear distribution patterns are even more apparent from this plot. An interpretation of the change in water composition is indicated by arrows on the diagram. Water from the Minnelusa Formation is modified by the precipitation of calcite as it rises to the Inyan Kara Group. The magnesium content of the carbonates precipitated increases as the water rises, and then a constant 2:1 ratio of calcium to magnesium is maintained, as carbonates are precipitated in the rocks of the Inyan Kara Group. This ratio is indicated by the projection of the linear plot of the major cations to the position marked by the X on the magnesium-calcium side of the triangular field.

Within ground water in the Inyan Kara Group two chemical reactions take place. A natural softening or cation exchange occurs as the water loses calcium and obtains sodium during the course of basinward migration similar to the change noted east of the Black Hills by Swenson (in press). The second modification is a rapid change to a sodium bicarbonate water.

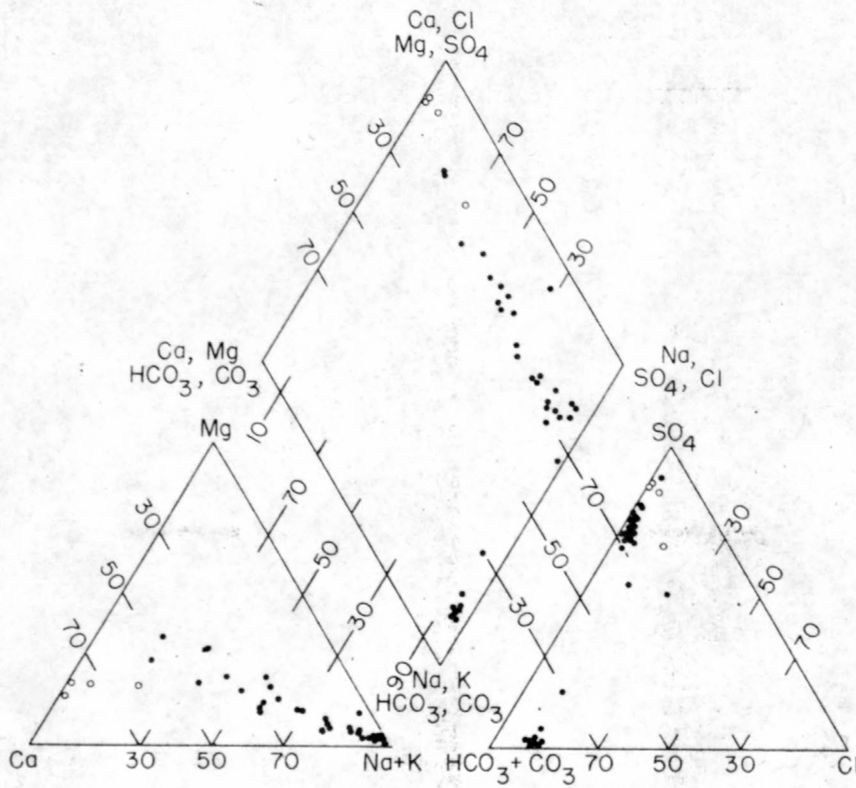

Figure 7.--Multiple-trilinear diagram showing cation, anion, and combined cation-anion percentages for ground water from the Minnelusa, Lakota, and Fall River Formations in the southern Black Hills of South Dakota and Wyoming. (Minnelusa water shown by open circles.) (Diagram after Piper, 1944.)

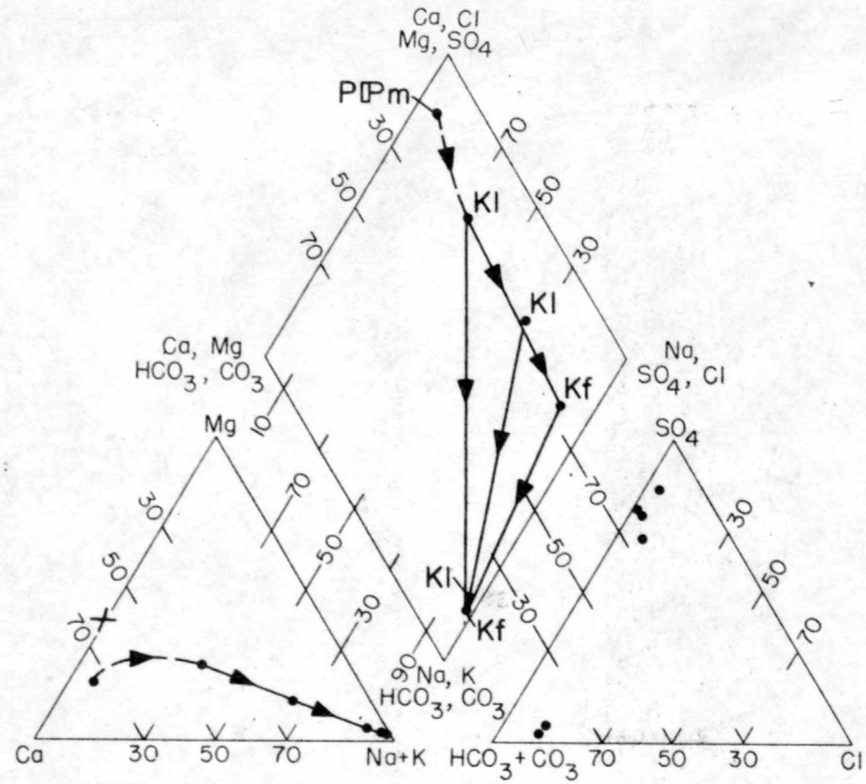

Figure 8.--Multiple-trilinear diagram showing average cation, anion, and combined cation-anion percentages for ground water of calcium sulfate, sodium sulfate, and sodium bicarbonate types from the Minnelusa (PPm), Lakota (Kl), and Fall River (Kf) Formations in the southern Black Hills of South Dakota and Wyoming. Arrows indicate direction of evolution of water composition. X indicates percentage calcium and magnesium cations in precipitates from ground water in the Inyan Kara Group.

The fact that no values between the sulfate and high-bicarbonate water were detected suggests a rapid chemical reaction. The bicarbonate water has a very low sulfate content but more than 4 parts per million hydrogen sulfide. The diagram suggests that hydrogen sulfide is being formed in the ground water at the present time, perhaps by the biogenic reduction of sulfate, but no sulfur isotope analyses are available to confirm this interpretation.

The evolution from sulfate to bicarbonate water may commence with sulfate waters having widely varying calcium-sodium ratios as indicated on figure 8 by the three connecting arrows. Generation of hydrogen sulfide gas from the sulfate waters is indicated by the presence of less than 1 part per million H_2S in two samples of sodium sulfate water and of more than 4 parts per million in the bicarbonate water. Reduction of sulfate in the two samples was minor; therefore the water has not changed to the sodium bicarbonate type.

pH of ground water

As shown in figure 9, the hydrogen ion concentration in the water changes as the water migrates through the Inyan Kara Group. Calcium sulfate water has the lowest pH, about 7.4. The pH of sodium sulfate water increases from 7.7 in the Lakota to 8.3 in the Fall River Formation. The pH of the sodium bicarbonate water averaged about 8.7 for the two formations. Lower pH values in the Lakota than in the Fall River Formation reflect the progressive change that occurs as the artesian water migrates through both formations.

A plot of pH values on the trilinear diagram (fig. 10) indicates the change in average pH for each water subtype. The pH increases slowly within the calcium sulfate water and more rapidly within the sodium sulfate water; it is highest within the area of sodium bicarbonate water.

Uranium in ground water

Uranium in the calcium sulfate water of the Minnelusa and Lakota Formations (fig. 11) averaged 13 and 12 parts per billion, respectively, but the uranium in solution decreases to 5 and 3 ppb as the water migrates through the Lakota and then the Fall River Formation. Uranium is present in somewhat larger concentrations in the sodium bicarbonate water and averages about 4 ppb.

The trilinear diagram in figure 12 indicates a progressive decrease of uranium content in the waters as they evolve in composition. Where there is significant reduction of sulfate in the water, the waters may contain only 1 or 2 ppb uranium. If the difference in water composition results from a modification of an original calcium sulfate water as interpreted, then this diagram shows the average precipitation of uranium at various stages of ground-water evolution. Greatest precipitation

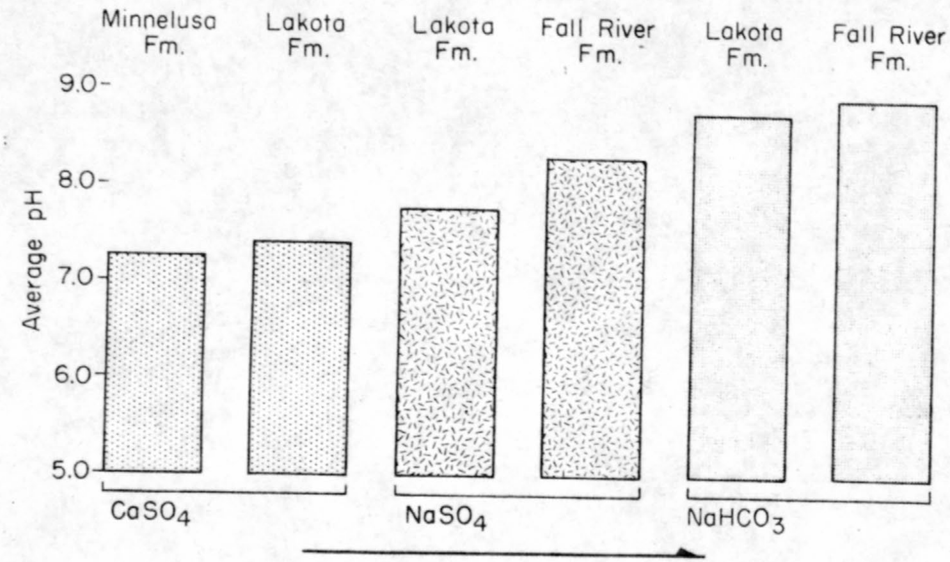

Figure 9.--Histogram showing average pH of calcium sulfate, sodium sulfate, and sodium bicarbonate water in the Minnelusa, Lakota, and Fall River Formations of the southern Black Hills of South Dakota and Wyoming. (Arrow indicates modification of water types.)

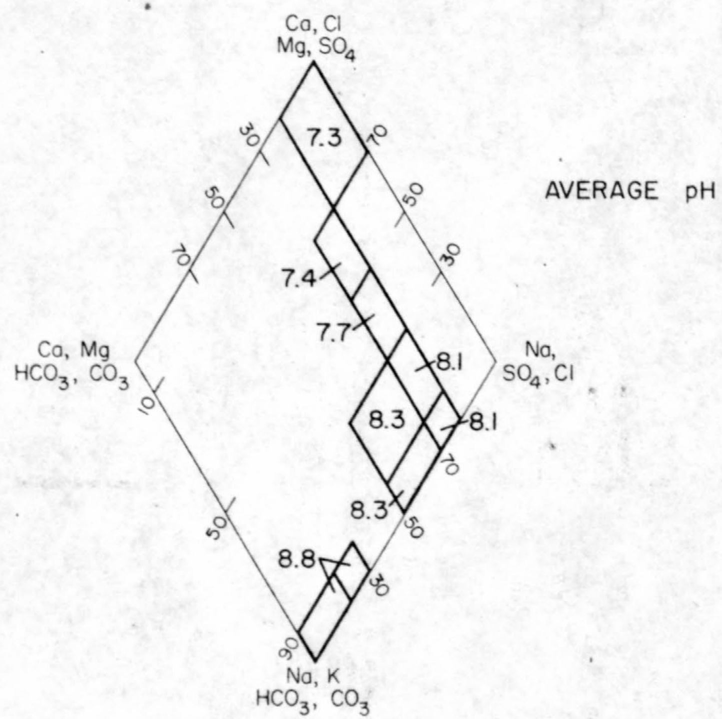

Figure 10.--Trilinear diagram showing average pH for ground-water sub-types in the Minnelusa, Lakota, and Fall River Formations in the southern Black Hills of South Dakota and Wyoming.

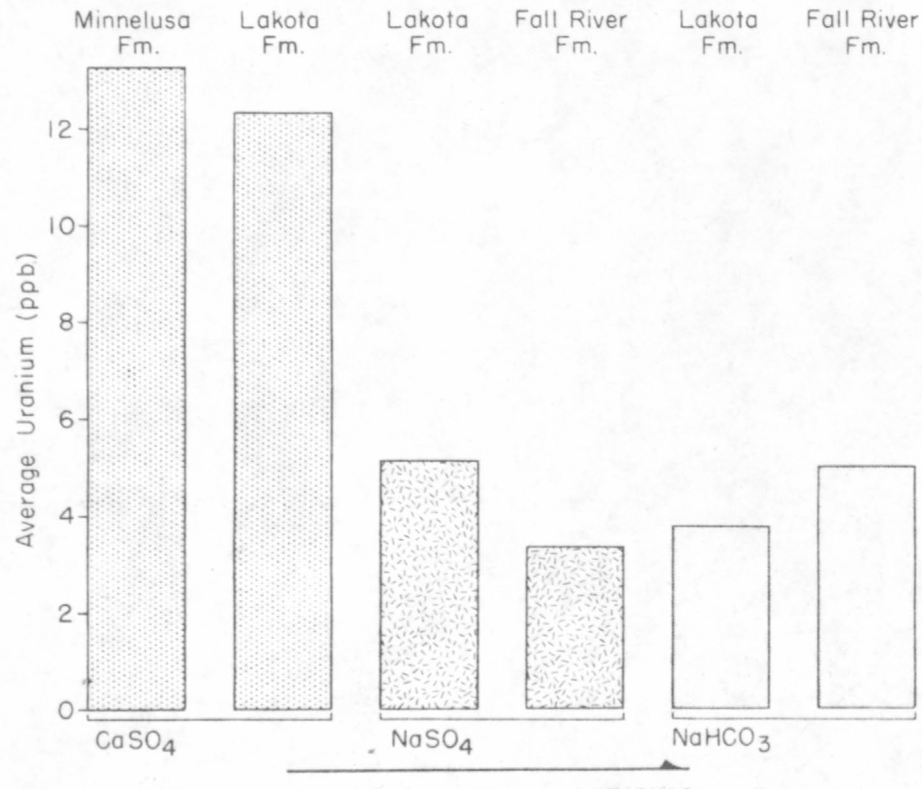

Figure 11.--Histogram showing average uranium content (parts per billion) of calcium sulfate, sodium sulfate, and sodium bicarbonate water in the Minnelusa, Lakota, and Fall River Formations of the southern Black Hills of South Dakota and Wyoming. (Arrow indicates modification of water types.)

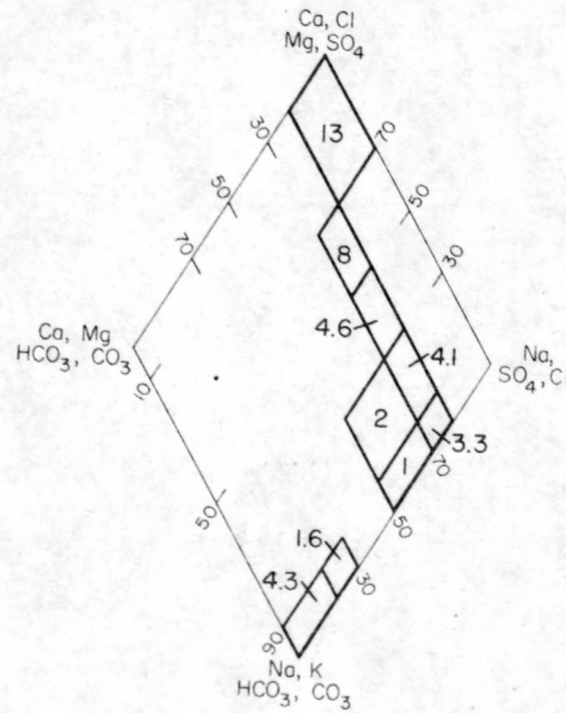

Figure 12.--Trilinear diagram showing average uranium content (parts per billion) in ground-water sub-types in the Minnelusa, Lakota, and Fall River Formations in the southern Black Hills of South Dakota and Wyoming.

occurs from the calcium sulfate water and only slight precipitation is possible from sodium sulfate water which is already nearly depleted of uranium. The diagram also points out that the concentration of uranium in the high sodium bicarbonate water is greater than in waters having a high sodium sulfate content. This fact is attributed to an introduction of uraniferous calcium sulfate water into the area of bicarbonate water. The precipitation of uranium is arrested by an increase in pH caused by intermixing of solutions as well as by the modification that occurs during sulfate reduction.

Distribution of ground water

Figure 13 shows the distribution of the water types marginal to the Black Hills. An increase in Na+K, as a percent of total cations, occurs during softening of the water from calcium to sodium sulfate and is indicated in the illustration. This change takes place in a basinward direction. Superimposed upon the cation percent is the concentration of CO_3+HCO shown as a percent of total anions. An increase in this percent, as occurs during the reduction of sulfate, is indicated in figure 13.

ENVIRONMENT OF URANIUM DEPOSITION

The most favorable environment for rapid precipitation of uranium is present either where uraniferous calcium sulfate water is marginal to the sodium bicarbonate water, or where it rises along fractures, faults, and in breccia pipes of the Long Mountain structural belt into the bicarbonate water (fig. 13). The uraniferous calcium sulfate water having a pH of about 7.4 would be subjected to a reducing environment as biogenic(?) reduction of sulfate occurs. In these waters reduction of the uranyl ion to the quadrivalent state and precipitation of uranium probably occurs. In addition to the favorable Eh-pH environment, a large flow of artesian water in the area of the structural belt is indicated, and rapid ground-water movement through the Inyan Kara is suggested by the proximity of the Cheyenne River. The presence of a large concentration of hydrogen sulfide in the ground water suggests that favorable host rocks are present, because biogenic reduction of large volumes of sulfate is possible only where large volumes of sulfate water are continually brought into contact with abundant carbonaceous material. This condition is best fulfilled in the permeable carbonaceous sandstones which are the host rocks for the majority of the uranium deposits in the district.

SOURCE OF URANIUM

The question arises, "If the calcium sulfate waters are the mineralizing solutions, what is the source for the uranium?" Uranium probably is derived from a multiple source, including both the slightly uraniferous rocks higher on the Black Hills uplift and the older uranium deposits in the Inyan Kara Group. Oxidation of older deposits undoubtedly contributes

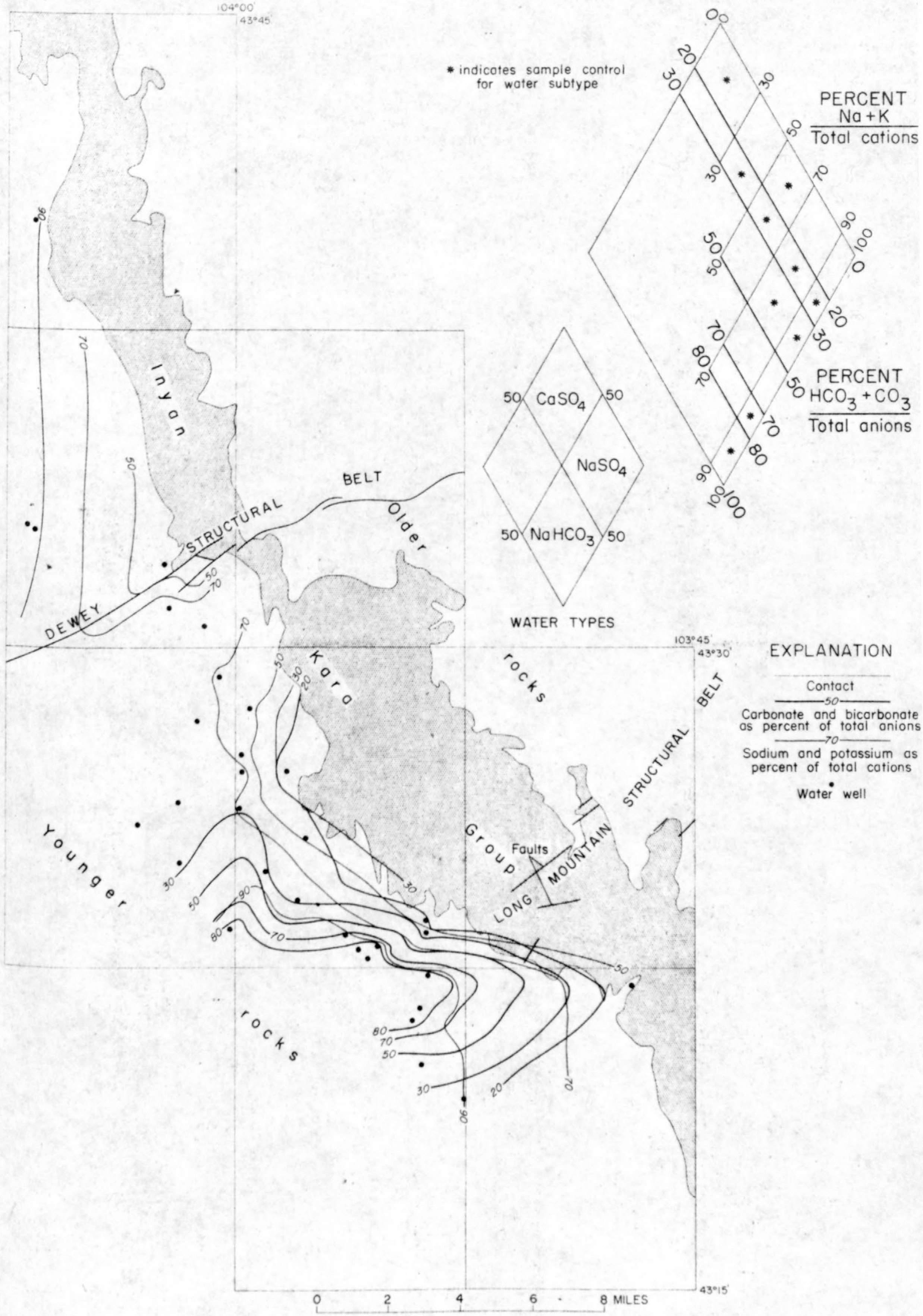

Figure 13.--Map showing carbonate and bicarbonate as percent of total anions, and sodium and potassium as percent of total cations in ground water of the Inyan Kara Group; southern Black Hills, South Dakota and Wyoming.

some uranium to the ground water, but the water analyses do not indicate the highly uraniferous waters that usually are found in the vicinity of oxidizing uranium deposits. The largest single source of uranium today is the anhydrite in the Minnelusa Formation. Anhydrite of Permian age (fig. 2) sampled from a drill core of the Minnelusa Formation at Pass Creek contains 1 to 9 ppm uranium. The average uranium content of 3.6 ppm determined for the 200-foot aggregate thickness of anhydrite probably is about the average concentration of uranium in anhydrite beds of the Minnelusa throughout the southern Black Hills. A comparison of the uranium-sulfate ratio of the anhydrite to the uranium-sulfate ratio of the ground water from the Minnelusa Formation indicates that 50 percent of the uranium in the ground water probably is derived from the anhydrite. Analyses of dolomites, and of limestones formed by calcitization of the dolomite, indicate that additional uranium in the water is derived from dissolution and calcitization of dolomite in the Minnelusa. The remaining uranium in the water is derived from other sources, which probably include the granites of Precambrian age in the central part of the Black Hills.

The amount of uranium which has entered the ground water in the Edgemont district can be estimated. Up dip from the major concentration of uranium deposits and parallel to strike, in the area between the Chilson anticline and the Dewey fault, anhydrite has been leached since Eocene time from a zone 20 miles long and 2 to 3 miles wide. During dissolution of the anhydrite 85,000 tons of uranium associated with the evaporite were also taken into solution. This is equivalent to the leaching of a 17.5-million-ton uranium ore body that averages 0.5 percent U_3O_8. The total uranium taken into solution from all sources by the ground water in this area must have been twice this amount, as indicated by the present-day ground water. During the Pleistocene alone, it is conservatively estimated that 10 million pounds of uranium entered the ground water in this area, excluding the uranium leached from preexisting deposits of Tertiary age in the Inyan Kara. It is therefore concluded that sufficient uranium has been leached from anhydrite and the rocks that crop out in the southern Black Hills to have formed the ore deposits of the Edgemont district, which to date have yielded about 1 3/4 million pounds of U_3O_8, and to have formed other as yet undiscovered ore deposits in the district.

EXPLORATION GUIDES

Gott and Schnabel (1963) discussed the localization of uranium deposits of the Edgemont district and offered guides to future exploration. Ground-water data are in basic agreement with their conclusions. Uranium is present in low concentrations in the ground water, and, as they suggest, "the source of the uranium and other metals... [is] of less importance than their transportation and the cause of precipitation." Present-day ground water indicates that uranium is carried in a sulfate solution rather than a carbonate solution. However, as interpreted from figure 13, sandstones in areas most favorable for uranium precipitation transmit first a sodium bicarbonate solution from which calcite precipitates, and then a calcium sulfate solution following a basinward shift of the water types as erosion on the plains continues and the ground-water table is lowered.

Water analyses (fig. 12) suggest that the major precipitation of uranium occurs in water of the sulfate type marginal to the bicarbonate water. Precipitation probably results primarily from the reduction of uranium by an H_2S environment, although locally organic acids may have affected reduction and deposition.

Ground-water analyses indicate areas where precipitation of uranium deposits is most likely to occur at the present time. Calcium sulfate waters having less than 50 percent of the total cations as Na+K are the most favorable mineralizing solution. Sulfate reduction commences in waters having 20 to 30 percent of the total anions as HCO_3+CO_3 and is rapid in water having over 30 percent HCO_3+CO_3. Where calcium sulfate water may be locally introduced along the Long Mountain structural belt into the sodium bicarbonate water (>50 percent HCO_3+CO_3) or into marginal areas, precipitation of uranium probably occurs. Sodium sulfate water high in Na+K has less than 4 ppb uranium in solution and a pH of 8.0 or higher; therefore it is less likely to have deposited significant amounts of uranium, even where reducing conditions are present.

Sample control for the ground-water distribution is widely spaced; therefore areas favorable for uranium precipitation are not closely defined, particularly where artesian water is introduced into the strong reducing environment of the bicarbonate water. Closer spacing of water samples would permit more accurate definition of the areas for uranium precipitation. Water sampling during drilling exploration would supplement the usual stratigraphic, mineralogic, lithologic, and radiometric studies conducted during exploration and probably would aid a systematic search for uranium deposits below the water table.

If the interpretation of the environment of uranium precipitation is correct, it is likely that the same conditions were present in the past at somewhat higher elevations on the flank of the Black Hills. Favorable carbonaceous sandstone host rocks deposited by the tributary streams that flowed along the Long Mountain structural belt probably underlie the terrace gravels of late Quaternary age. The areas in the vicinity of the terrace gravels up dip from the present favorable reducing environment offer a favorable target for exploration above the water table.

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