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Alteration and Element Distribution Associated with Selected Uranium Deposits of the Great Divide Basin, Sweetwater County, Wyoming

by

Katherine McCarville Weber
A thesis submitted to the Faculty and the Board of
Trustees of the Colorado School of Mines in Partial
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Date 30 April 1985

Signed: Katherine M. Weber

Katherine M. Weber

Approved:  

Dr. Richard H. De Voto

Thesis Advisor

Golden, Colorado

Date 4-30-85

Dr. Joseph J. Finney

Head, Department of Geology
ABSTRACT

The stratigraphic setting, alteration features and distribution of selected elements were studied in the REB uranium deposit, Sweetwater County, Wyoming. The purpose of the study was to determine ore guides that might be used in further exploration in the area.

The REB deposit occurs in the REB interval of the Lower Eocene Battle Spring Formation, an alluvial-fan complex deposited to the south of the uplifted Granite Mountains. The REB interval in the study area consists of interbedded coarse arkosic sandstones and carbonaceous siltstones. The unit is approximately 140 ft (50 m) thick, and is situated between two anomalously radioactive, carbonaceous mudstones of the Wasatch Formation.

Results of this study suggest that a stratigraphic control on uranium deposition in the REB interval does exist. The linear and continuous nature of the mineralization trend, the relationship of the terminus of the roll front to an increase in the number of fine-grained units, and the location of the deposit near and subparallel to the transition from coarse-grained rocks of the Battle Spring Formation to finer grained rocks of the Wasatch Formation all support the conjecture that uranium deposition may be related to that transition. The orientation of
sandstone bodies deposited in southwest-trending Eocene paleostream channels does not appear to be related to the trend of the deposit.

Samples of drill core were classified as altered, slightly altered or fresh on the basis of the presence of iron oxides, pyrite and colored feldspar grains. Pyrite and calcite are associated with mineralized rock. Altered orange feldspars are found exclusively in mineralized rock; altered pink feldspars are found in slightly altered rock ahead of the roll fronts. Coloration of these feldspars is pervasive and is due to disseminated hematite-limonite within the feldspar grains. These grains have not been altered to other minerals.

Analyses for silver, calcium, copper, iron, lithium, magnesium, manganese, molybdenum, sodium, selenium, thorium, vanadium and uranium were carried out. Silver, calcium, iron, lithium, magnesium, manganese, and rubidium have been leached from altered rocks. Element zoning, as delineated in this study, might be used to distinguish altered from fresh rock on a statistical basis.

Results of this study show that visual classification of samples as altered, slightly altered or fresh is a valuable and fairly accurate tool for locating mineralization. The best ore guide in the REB deposit is
the presence of colored feldspar grains. Gamma logs are also useful in locating ore because radiometric equilibrium has been, for the most part, reached and maintained within the REB deposit. The presence of colored feldspars can be used as an immediate and reliable indicator of mineralization in the REB deposit, prior to gamma logging of drill holes. The effectiveness and simplicity of visual techniques make careful inspection of samples more cost-effective than chemical analysis.
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INTRODUCTION

Purpose

The purpose of this study was to examine the alteration and the distribution of selected elements associated with roll-front uranium deposits in the study area. Objectives were to establish the stratigraphic setting of the deposits, to determine the types of alteration that occur within the study area and to study the distribution of alteration features and of trace elements. The study was aimed at finding controls on mineralization, alteration features or element distribution patterns that might be used in further exploration and development in or near the study area.

Scope of Work

The study area is located in the Great Divide Basin of Wyoming, a part of the greater Green River Basin (fig. 1). The Eocene Battle Spring Formation is the host for roll-front uranium mineralization within the study area.

This study was undertaken beginning in the summer of 1980, when the author was employed by Minerals Exploration Company, a subsidiary of Union Oil Company of California. The Battle Spring Formation is poorly exposed and heavily
Figure 1. Simplified tectonic map of south central Wyoming, showing outlines of Tertiary basins, Precambrian exposures, and uranium districts (modified after Childers, 1970).
weathered at the surface, so subsurface sampling was chosen to give more consistent geochemical results. Drill holes were selected to give the widest possible coverage of the study area. Geophysical and lithologic logs from eight cored drill holes and 57 rotary drill holes were used in this study. Lithologic and electric logs were acquired and are published herein with the consent of Union Oil Company of California. The author has logged numerous drill holes within the study area, but not necessarily the specific holes that are used.

One hundred seventy-nine samples were taken at one-foot intervals from the eight cored drill holes. These were examined using a binocular microscope; eleven samples were examined in thin section. Three pan concentrates were examined for heavy mineral content. Petrographic descriptions are presented in Appendix III. Samples were sieved to obtain quantitative size-fraction data. X-ray diffraction was used to analyze clay-size material from a suite of 17 samples.

Samples were analyzed by flame atomic absorption methods for Ag, Ca, Cu, Fe, Li, Mg, Mn, Na, and Rb. Delayed neutron activation was used to analyze for U. Samples from one core were analyzed for Mo, Se, Th and V. Analytical methods are discussed in Appendix I. Accuracy and precision
of analyses are presented in Appendix II. Statistical
treatment of the data is discussed later in this paper.

Location and Geography

The study area is located within the Great Divide
Basin, about 40 mi (60 km) northwest of Rawlins in northern
Sweetwater County, Wyoming (fig. 2). The area is covered by
the Rawlins 1x2-degree Quadrangle of the National
Topographic Map Series (NTMS). Principal towns in the area
are Rawlins to the southeast, Rock Springs to the southwest
and Jeffrey City to the north (fig. 2). The study area
comprises contiguous portions of Townships 23 and 24 North
in Range 94 West, Sixth Principal Meridian.

Access to the area from Interstate 80 is provided by
the unpaved Crooks Gap Road north from Wamsutter, Wyoming,
located approximately 60 mi (100 km) east of Rock Springs,
Wyoming. An alternate route is via U.S. Highway 287 north
from Rawlins approximately 15 mi (25 km) to a paved mine
road leading west (fig. 2).

The Great Divide Basin is both a structural and
topographic feature. It is bounded on the north by the
Granite Mountains and Wind River Range, on the east by the
Rawlins Uplift, on the south by the Wamsutter Arch and on
the west by the Rock Springs Uplift (fig. 2). The basin is
located between two branches of the Continental Divide and its drainage is entirely internal. The topography in the study area is essentially flat, with low bluffs at the extreme south. The average elevation is 6500 ft (2000 m). The flora and fauna are typical of the high plains of the western United States with the notable exception of a small herd of wild horses.
PREVIOUS INVESTIGATIONS

Uranium was discovered in the Great Divide Basin by the late Mrs. Minnie McCormick in about 1935 (Wyant, Sharp and Sheridan, 1956). Uranium-bearing coal was discovered in the basin by Slaughter in 1945 and was first described by Wyant, Sharp and Sheridan (1956). Sheridan and others (1961) described the Lost Creek schroeckingerite deposits, which are located about 5 mi (3 km) west of the study area. Pipiringos (1961) and Masursky (1962) described the stratigraphy and geology of the basin with emphasis on the uranium-bearing coals. Stephens (1964) described the lithology of the Wasatch and Battle Spring Formations in his study of uranium deposits in the Crooks Gap area. Bailey (1969, 1972) discussed the uranium deposits of the Great Divide Basin.

Love (1970) compiled the Cenozoic history of the Granite Mountains area of central Wyoming, including parts of the Great Divide basin. Pipiringos and Denson (1970) discussed the Battle Spring Formation of south-central Wyoming. In 1970, Groth described roll-front uranium deposits in the Battle Spring Formation in the Green Mountain area, about 15 mi (25 km) east of the study area. He briefly described the alteration associated with the deposits as similar to that in other Wyoming uranium


The source of the uranium in Wyoming roll-front uranium deposits has been addressed by Waters and Granger (1953), Houston (1969), Rosholt and Bartel (1969), and Rosholt, Zartman and Nkomo (1973), and Stuckless (1979), as well as many others. Stuckless (1977) summarized uranium-related studies of the Precambrian rocks of the Granite Mountains of Wyoming. Love (1970) and others believe Oligocene tuffaceous beds to have been the source of at least part of the uranium. Current work on the Great Divide Basin uranium deposits includes the multidisciplinary studies carried out by Bendix Field Engineering Corporation in the immediate
vicinity of the study area (Wayland and Rood, 1983; Wayland and Sayala, 1983).
REGIONAL GEOLOGY AND TECTONIC HISTORY

Structural Geology

The REB uranium mineralization trend is located in the Great Divide Basin in south central Wyoming. The basin is one of the Tertiary basins of the Wyoming Basins province and is bounded by Precambrian-cored uplifts. Like most of these basins, the Great Divide Basin contains uranium mineralization in Tertiary host rocks (fig. 1). The structural history of the area has been described in detail by Love (1970), and is briefly presented here primarily from that source.

The last extensive marine sediments deposited in central Wyoming are the Upper Cretaceous Lewis Shale and the Meeteetse Formation. The retreat of the Lewis sea in latest Cretaceous time was caused by the uplift of a northwest-trending block which roughly corresponded to the present Granite Mountains. The beginning of basin formation in latest Cretaceous time was marked by deposition of the fine-grained clastic Lance Formation in the deepest parts of the Great Divide Basin. As the Granite Mountains block continued to rise through Paleocene time, overlying Paleozoic strata were eroded and areas of Precambrian rocks were exposed and supplied large amounts of arkosic debris.
The most active episode of Laramide uplift and deformation occurred in earliest Eocene time. Uplift of the mountains outpaced infilling of the basins, and folding and thrust faulting began in response to compressional forces. Several thousand feet of relief was developed and this high gradient, combined with the humid climate of the time, made the major streams extremely competent. The arkosic wet alluvial fan deposits of the Battle Spring Formation were deposited by a southwest-flowing drainage system (Childers, 1970; Love, 1970). Deposition of these fans was interrupted by Laramide thrust faulting which disrupted the drainage systems and emplaced Precambrian rocks on younger strata.

Through early Eocene time, volcanic activity in the Yellowstone-Absaroka region furnished airborne pyroclastic material to sediments being deposited in the Great Divide Basin. The Great Divide Basin, along with parts of the Green River and Washakie Basins, continued to subside causing the formation and expansion of lakes and the eventual formation of Lake Gosiuie. At the close of early Eocene time the Granite Mountains block again underwent significant uplift.

During the middle Eocene, alkalic volcanic activity began in the Rattlesnake Hills area approximately 50 mi (80 km) to the northeast of the study area. The amount of
debris extruded was reportedly not large and did not affect sediments being deposited much more than 30 mi (50 km) from the source.

Uplift and erosion occurred before deposition of Oligocene rocks, so these beds were deposited across the truncated edges of all the older rocks, including the Eocene beds (Love, 1970). The Oligocene and younger parts of the section in the Great Divide Basin and throughout Wyoming contain many tuffaceous beds which are postulated by some to be the source of uranium in many Wyoming roll-front deposits (Pipiringos, 1961; Love, 1970; Harshman, 1972). Another period of uplift and erosion removed some or all of the Oligocene strata before deposition of Miocene rocks.

In early to middle Pliocene time, tilting and uplift resulted in the formation of Moonstone Lake north of Crooks Gap. More than 1000 ft (300 m) of tuffaceous sediments accumulated in and around the lake. Some beds contain high concentrations of uranium and thorium, which Love (1970) believes may be the source of part of the uranium in the Crooks Gap and Gas Hills districts. Regional uplift in the late Pliocene or early Pleistocene began the establishment of present-day physiography. Locally, though, blocks within the Granite Mountains have been relatively downdropped. Love (1970) proposes that tectonic movements affected
groundwater systems carrying uranium and that many of the uranium ore bodies were formed or modified at this time.

Important structural features in the immediate vicinity of the study area are the Sweetwater anticline, the Red Desert syncline, and the Niland Basin syncline (fig. 3). The Sweetwater anticline is a gentle upwarp; its axis trends northwest and passes to the east of the study area. The asymmetric Red Desert syncline trends northwest and has superimposed upon it the Niland Basin syncline near the north boundary of the study area. Generally, the rocks dip very gently to the north, northwest or west in the study area.

Two orthogonal sets of faults cut the rocks in and near the study area (figs. 4 and 5). They trend northwest and east-northeast and the north side is generally downdropped on both sets of faults (Masursky, 1962; Peterson, 1979). Age relationships between the two sets of faults are not clear. The present-day drainage pattern appears to be influenced by these faults.

Pre-Tertiary Stratigraphy

The Granite Mountains are a Precambrian-cored east-west-trending uplifted block approximately 85 by 30 miles (50 by 20 km) in extent. An extensive discussion of
Figure 3. Sketch map showing approximate location of major fold axes in the immediate vicinity of the study area (modified after Masursky, 1962).
Figure 4. Generalized geologic map, eastern Great Divide Basin (modified after Sherborne and others, 1980).
Figure 6. Geologic map of the study area, using information from Masursky (1962) and Peterson (1979).
these rocks is not within the scope of this paper, but because they are the principal provenance for the sediments which host the uranium mineralization, a brief description is included.

According to Love (1970), the Precambrian section in the Granite Mountains can be divided into rocks of at least three ages and types. The oldest rocks are a metasedimentary sequence of schist, slate, phyllite and quartzite. The major portion of the Granite Mountains is made up of granite that is younger than the metasedimentary sequence, but which may be of more than one age. Black mafic dikes cut the granite and were truncated before deposition of the first Cambrian sandstone. All the rocks are older than 2500 m.y., and thus, they are Archean (Stuckless and Peterman, 1977).

Phanerozoic sedimentary rocks also furnished some detrital material to the Tertiary formations. The Paleozoic rocks are primarily marine limestones, dolomites and sandstones. The Mesozoic rocks include marine and nonmarine limestones, siltstones and shales (Love, 1970).

Tertiary Stratigraphy

The oldest Tertiary unit in the study area is the Paleocene Fort Union Formation, a fine-grained
fluvial-lacustrine-paludal sequence. The Fort Union Formation was deposited on a unconformity surface, and in the study area it overlies the Cretaceous Lance Formation (Boberg, 1979).

The Green River, Wasatch and Battle Spring Formations are early to middle Eocene in age and unconformably overlie the Fort Union Formation. These three units have been correlated as laterally equivalent facies of the same depositional system (Masursky, 1962) (fig. 6). The Green River Formation is predominantly lacustrine; the Wasatch Formation is a low-energy fluvial sequence and the Battle Spring Formation is their coarser-grained, sourceward equivalent and represents a wet alluvial-fan complex.

Deep petroleum wells indicate that the Cenozoic section is between 12,000 ft (4,000 m) and 20,000 ft (6,100 m) thick in the area (Wayland and Sayala, 1983; Bucurel, 1981). Uranium mineralization is found almost exclusively in the Battle Spring Formation, but is also present in the Fort Union Formation (Boberg, 1979). The coals and lignites of the Green River and Wasatch Formations contain anomalous amounts of uranium (Wyant, Sharp and Sheridan, 1956; Pipirinogos, 1961; Masursky, 1962).
Figure 6. Generalized cross section showing relationships between Battle Spring, Wasatch and Green River Formations in the eastern Great Divide Basin. Box near center encloses portion of section shown in figure 7 (modified after Sherborne and others, 1980).
URANIUM OCCURRENCES IN THE GREAT DIVIDE BASIN

Three types of uranium deposits occur within the Great Divide Basin area. Low-grade, high-tonnage deposits are associated with Eocene sub-bituminous coals and carbonaceous shales of the Wasatch Formation in the central and eastern parts of the basin (Wyant, Sharp and Sheridan, 1956; Pipiringos, 1961; Masursky, 1962). Small, low-grade caliche-type deposits containing schroeckingerite, a secondary uranium mineral, occur in fine-grained Eocene rocks of the Wasatch Formation at Lost Creek (Sheridan and others, 1961). Relatively high-grade roll-front deposits occur in the Eocene conglomerates and sandstones at Crooks Gap (Stephens, 1964; Bailey, 1969), Lost Soldier-Green Mountain (Groth, 1970), Cyclone Rim (Bailey, 1969), the Sweetwater Mine (Sherborne and others, 1980), and elsewhere within the Great Divide Basin (fig. 4).

All of the sedimentary rocks in the Great Divide Basin are unusually radioactive. The average uranium content is greater than the most common value for sedimentary rocks, 1.3 ppm (Evans and Goodman, 1941, in Wyant, Sharp and Sheridan, 1956).

Abnormally radioactive lignites and carbonaceous shales were discovered by Slaughter and Nelson in 1945 (unpublished report, 1946; in Wyant, Sharp and Sheridan, 1956).
Considerable work was done in delineating these deposits immediately after their discovery. These are very low-grade deposits containing approximately 30 ppm U₃O₈, but there are probably 60 million pounds of uranium in coals and carbonaceous mudstones of the eastern Great Divide Basin (Bailey, 1969).

The schroeckingerite deposits were discovered in 1935. Schroeckingerite, NaCa₃(UO₂)(CO₃)₃(SO₄)F·10H₂O, is a bright yellow-green water-soluble uranium salt. The deposits are formed either by oxidation of previously formed uranium deposits or by secondary concentration of uranium in a caliche-forming environment, where loss of water from evaporation and transpiration exceeds recharge. Uraniferous opal and other uranium-containing minerals are also present in the deposits. Clay, gypsum and aragonite are commonly associated with schroeckingerite. The Cyclone Rim fault zone, along which nearly all of the occurrences are found, is of primary importance in localizing the deposits. A stratigraphic control is also noted, as schroeckingerite is deposited preferentially in claystone, shale or siltstone beds (Wyant, Sharp and Sheridan, 1956). This deposit is probably of greatest value as a mineral-collecting locality rather than as a uranium resource because of its small size and discontinuous nature.
Roll-front uranium deposits were discovered at Crooks Gap in 1953. The Crooks Gap deposits occur in conglomeratic facies of the Eocene Battle Spring Formation. These deposits are similar to most other Wyoming roll-front uranium deposits in that the host rocks are arkosic, lower Eocene sandstones and conglomerates derived from the Granite Mountains. The most important ore mineral is uraninite and the bulk of the high-grade mineralization is concentrated at a contact between altered and unaltered rock (Bailey, 1969). Coffinite is also reported from the Crooks Gap area, as well as other Wyoming deposits (Ludwig and Grauch, 1980). Pyrite and calcite are concentrated in the ore. Alteration related to mineralization is present in the Crooks Gap area. In the altered rocks, pink to brown staining occurs due mostly to oxidation of iron. Unaltered rocks are white to tan (Bailey, 1969).

The Cyclone Rim area exhibits red and pink-stained altered rocks. Although it has not been reported, spacing of drill holes in the area suggests that mineralization has been found (Bailey, 1969). Similar deposits, also hosted in Eocene Battle Spring rocks, exist in the nearby Lost Soldier-Green Mountain area. Groth (1970) briefly described the alteration associated with these deposits as resembling alteration in other Wyoming districts. Cisneros (1970)
reported on the investigation of a possible roll-front uranium deposit at the Silver Bell prospect.

Since 1966, drilling in the deeper portions of the Great Divide basin has resulted in the discovery of the Sweetwater, ENQ, REB, and other deposits (Sherborne and others, 1980). The Sweetwater deposit is hosted by a tabular sandstone of the Battle Spring Formation (Sherborne and others, 1980). Although it is located in a zone along the contact between altered and unaltered rocks, the Sweetwater deposit is unlike most other Wyoming roll-front deposits in that it is more nearly tabular in shape and lower in grade. Zones of reddish orange, tan and buff altered sandstone associated with the deposit are generally quite extensive. The zones are analogous to alteration zones described by Davis (1969) and Rubin (1970) associated with uranium mineralization in the Powder River Basin (Sherborne and others, 1980).

The ENQ deposit is stratigraphically higher than the Sweetwater deposit. The deposit is fairly high in grade and typical roll-front geometry is common. Protore, also called "seepage" mineralization, is found in front of the roll for a distance of up to 1000 ft (300 m) (Sherborne and others, 1980). In the western portion of the deposit, both the highest grades and the narrowest protore zones are found.
This may be due to higher carbonaceous content in the bounding mudstones, creating a more reducing environment and hence a higher Eh/pH gradient across the roll. Alteration at the ENQ deposit resembles that associated with the Sweetwater deposit, but in the western portion of the deposit, the mineralization is separated from visibly discernible alteration by a gray-green zone that is visually indistinguishable from unaltered rock. Pervasively altered orange feldspars are found coincident with mineralization (Boberg, 1979; Sherborne and others, 1980).

The REB deposit occurs on the west side of the same altered tongue that hosts the Sweetwater deposit and is generally narrower and of higher grade than the latter (Sherborne and others, 1980). The alteration in the REB deposit includes zones of iron-oxide staining and pervasively altered orange feldspars in the mineralized zone.

The REB deposit, as discussed by Sherborne and others (1980), was approximately 6 mi (9 km) long and open-ended on the south. Continued exploration drilling has since extended the deposit to the south an additional 4 mi (3 km). The southern extension is known as the Battle Spring deposit, but because the deposits are contiguous, I will refer to the entire trend as the REB deposit. The "REB"
designation has no meaning as an acronym. The "UBS" and "BS" designations on drill holes stand for "Union Battle Spring" and "Battle Spring," respectively.

Uranium mines in the Great Divide Basin have been producing since 1957. The Crooks Gap deposits have been mined by several companies in both open-pit and underground operations. Total reserves for the Crooks Gap district were estimated by the U.S. Atomic Energy Commission in 1969 at over 11 million pounds $\text{U}_3\text{O}_8$ of which more than 7 million pounds have already been mined. The Green Mountain deposit contains in excess of 30 million pounds (Anaconda Copper Company, 1979). Minerals Exploration Company, a subsidiary of Union Oil Company, began open-pit mining on the Sweetwater deposit in 1978. Reserves in the Sweetwater deposit are approximately 16 million pounds $\text{U}_3\text{O}_8$ (Sherborne and others, 1980). Mining activity in the area is virtually at a standstill at this time, due to the current low uranium price.
THE REB STRATIGRAPHIC INTERVAL

Stratigraphy

The study area is located near the transition between distal wet alluvial-fan deposits of the Battle Spring Formation and paludal and fluvial facies of the Wasatch Formation (figs. 4 and 6). In the study area, the Battle Spring and undifferentiated Green River and Wasatch Formations are exposed at the surface (fig. 5).

In this investigation, gamma and resistivity logs have been used to distinguish between sandstones and siltstones or shales. Resistivity can be used to distinguish permeable zones (Asquith and Gibson, 1982), and in rocks like those in the study area, permeable zones can be equated with sandstones, whereas less permeable zones represent finer grained units. Intermediate values on the resistivity curve represent rocks of intermediate grain size. Lithology logs were used in cases where geophysical log interpretation was in doubt. Gamma curves are used to delineate mineralization. Also, certain beds exhibit characteristic gamma curves, aiding in the correlation of units. A type electric log and generalized stratigraphic section are shown in figure 7.
Figure 7. Generalized cross section and type electric log, REB interval and adjacent lignites.
The REB stratigraphic interval, which hosts uranium mineralization in the study area, varies in thickness from 121 ft (40 m) to 161 ft (50 m) and is bracketed above and below by carbonaceous radioactive lignites of the Wasatch Formation (figs. 6 and 7). The lower and upper lignites are correlative with the Hadsell and Sourdough lignites of Masursky (1962). The upper lignite and upper portions of the REB interval have been removed by erosion in some areas in the southern portion of the study area. Where this has occurred, rocks of the REB interval may be as thin as 30 ft (10 m). The Hadsell and Sourdough lignites are easily identified in the subsurface by their characteristic signatures on the the gamma curve of electric logs (fig. 7).

Electric log-stratigraphic sections of the REB interval within the study area are shown on plates 2-6. The locations of the sections are shown on plate 1, a drill-hole location map of the study area.

The REB interval has been informally divided into five units--A, B, C, D and E--by Minerals Exploration Company geologists (Sherborne and others, 1979) (fig. 7). Within the study area, these units commonly contain discontinuous mudstones or poorly sorted silty beds which only rarely display a radioactive signature or contain visible carbon.

The basal E unit shows little scouring into the lower
lignite. It is normally fine grained and composed of intercalated silty/shaly and sandy beds. A thick and fairly continuous sandstone within the E unit is best developed in the northern part of the study area (pl. 6), but the E unit hosts less than 5 percent of the mineralization found within the REB interval in the study area.

The laterally more continuous, thicker and coarser-grained sandstones of the D and C units host approximately three-fourths of the uranium mineralization in the REB trend. The D-unit sandstone, a tabular, coarse- to medium-grained sand body, hosts the most continuous and highest grade uranium mineralization in the REB trend. The ore is nearly continuous within the D unit along the length of the trend (fig. 8). It occurs most commonly as typical roll-front bodies, but may also be found at the basal contact of the sandstone with underlying mudstones. Pyrite is also commonly found at these surfaces. The continuous nature of the D-unit sand is well demonstrated by its appearance on all of the cross sections (pls. 2-6). The C-unit sandstone is composed of coarse- to medium-grained lenticular sandstone bodies. The C-unit sandstone is well developed and mineralized in the study area (pl. 3). The sands of the D and C units commonly form one thick sand body with no intervening fine-grained beds, and significant
Figure 8. Uranium roll-front map of the study area. Letters indicate which unit within the REB interval hosts the roll front.
mineralization may occur in this setting (pl. 2).

The A and B units are thinner and tend to be finer grained than the C and D units. Sandstone lenses are present locally within the A and B units and host some mineralization. Together, the A and B units host about 20 percent of the mineralization within the study area. The A and B units are best shown on plate 2, but they are absent or truncated due to erosion in the area of plates 3 and 4.

Sedimentary structures noted in cores include scour-and-fill, rip-up clasts of siltstone and mudstone, basal conglomerate layers, planar crossbedding, and possibly load casts in siltstone beds. Wavy laminations defined by mica flakes were seen in thin section within a silty unit (Sample 175-413B). Fining-upwards sequences are common and are clearly visible in many of the electric logs. Mudstones and siltstones at the tops of these sequences are commonly scoured by the basal unit of the overlying sequence.

Structure

A structure contour map (fig. 9) on the top of the Hadsell lignite shows the generally gentle (1°) north-northwest dip of the strata. The structural low in the southern part of the area is due to folding. Significant changes in the thickness of the REB interval
near the center of the isopachous map of the study area (fig. 10) reveal the location of a fault. This fault was not noted by Peterson (1979), but had been mapped earlier by Masursky (1962). The sense of movement on the fault is the same as that for east-northeast-trending faults in the southern portion of the study area (fig. 6).

Stratigraphic and Structural Controls on Uranium Deposition

Several maps of the study area were constructed and compared to investigate the possibility of stratigraphic or structural controls on uranium deposition. Comparison of the geologic map of the study area (fig. 5) and the deposit trend map (fig. 8) show no apparent relationship between faulting and ore deposition. The geologic map of the eastern Great Divide Basin (fig. 4) shows the same lack of spatial relationships between major faults and uranium deposits. One exception is the schroekingerite deposit at Lost Creek, where the Cyclone Rim fault zone is nearby, and is thought to have channeled water into the area and thus contributed to the formation of the deposit.

Another structural control on deposition of uranium involves the effects of folding and faulting on the hydrologic regime during deposition. The present study does not address this problem, although it is an important one.
because of its bearing on the determination of the age of these deposits.

Contour maps of amount of sandstone as percent of total thickness of the REB interval and total number of sandstone beds in the REB interval are shown in figures 11 and 12, respectively. Comparing the location of the uranium trend with the percentage of sandstone in the interval might reveal a relationship between mineralization and channel systems in the REB interval. A central core of high percentage of sandstone may reflect a cross section through a sandstone body deposited in Eocene southwest-trending stream channels (Childers, 1970; Love, 1970). If so, this indicates that the strike of the uranium trend is approximately perpendicular to the trend of Eocene channel sandstone bodies, and that no clear relationship exists between these two features. Permeable sandstone bodies might serve as conduits, carrying uranium-bearing fluids to the site of deposition. More data from widely spaced drill holes might better delineate the trend of the sandstone bodies.

Contouring of the total number of sandstone beds in the interval could show a control on deposition of uranium as permeable sandstone beds thin and pinch out into finer-grained rocks. Permeable sandstone beds allow ingress
Figure 11. Contour map of amount sandstone as percentage of total thickness of REB interval in the study area.
Figure 12. Contour map of study area showing the number of sandstone beds within the REB interval.
of uranium-bearing fluids into host rocks, and sufficient reductants, such as pyrite and carbonaceous material associated with the finer grained units, are required to cause precipitation of uranium. A general trend from many sandstone beds (>10 beds) in the north and east, toward fewer sandstone beds (<5 beds) in the south and west is discernible (fig. 12). If some component of the flow of uranium-bearing fluids was from northeast to southwest, the effects of the reduction in number of permeable beds may have included slowing or diverting the fluids and may have contributed to the formation of the deposit at its present location. The roll fronts are generally located in areas with an intermediate number of sandstone beds (5-10 beds). This implies a control on uranium deposition involving not just the percentages of sandstone or finer grained rocks, but the morphology of the interbedding of the two kinds of rocks, suggesting that the presence of each rock type contributes to localizing the deposit.

To further examine the possibility of stratigraphic control on uranium deposition, a generalized cross section of a roll front in the REB deposit was constructed. Assuming that relative uranium content across an idealized roll front approximates the pattern shown in figure 13, the cores were arranged by their uranium concentration profiles
Figure 13. Generalized cross-sectional diagram of roll-front uranium deposit showing roll front morphology and relative uranium concentration curves.
Figure 14. Composite cross section of the REB uranium deposit based on uranium concentration curves for cored drill holes. Uranium concentration is contoured. Heavy dashed line shows approximate location of oxidation-reduction interface. Drill-drill-hole locations are shown on plate 1.
(fig. 14). The vertical scales were distorted where necessary, but not by more than 50 percent in any case. The horizontal scale is entirely arbitrary. The actual location of the cored drill holes is shown on plate 1. Using the same arrangement of data points, a section showing lithology was constructed (fig. 15). The section shows a correspondence between the location of the terminus of the roll front and an increase in the number of fine-grained units. A central core of coarse-grained sandstone is also present.

Mineralogy

One hundred seventy-nine samples from the REB interval were examined using a binocular microscope. Eleven thin sections were examined with a petrographic microscope, and slabs from which the sections were cut were stained for quartz, potassium feldspar and plagioclase. Three samples were panned for heavy-mineral concentrates. The clay-size fraction in REB interval rocks was examined by x-ray diffraction techniques using 17 samples (table 1). Results of these studies are tabulated in Appendices II and III, except where otherwise noted. The cross sections showing mineralogical features use the same base as figure 14.
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<th>Dolomite</th>
<th>Talc</th>
<th>Mica</th>
<th>Chlorite</th>
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P = Present  
NP = Not present  
NA = Not analyzed
The sandstones of the REB interval are of arkosic composition. They contain approximately 60 percent quartz and 40 percent feldspar. Most quartz grains are angular, whereas feldspar grains are angular to subrounded. As determined by staining, about one-third of the feldspar is potassium feldspar. Microcline, perthite and myrmekite were identified in thin section. The sandstones are grain supported, fairly porous and permeable, and contain little matrix material. Average grain size in the sandstones is medium to coarse and sorting varies from very good to poor.

Lithic fragments are fairly common in the sandstones. Most of the lithic fragments contain only quartz and feldspar, but some contain epidote and sericite as well. Feldspars containing epidote or sericite may indicate a metamorphic component in the rocks from which the sediments were derived. Polycrystalline quartz grains are fairly common, and are further evidence for metamorphic rocks in the provenance of the sandstones.

A few mafic lithic fragments or mafic mineral grains, altered to soft chloritic material, were observed. In thin section, these grains were found to consist of a fine-grained mixture of chlorite and epidote. X-ray diffraction reveals that the sandstones also contain talc, which could be another product of alteration of mafic
minerals (table 1). Other possible sources for the talc are drilling fluids, sample containers, and laboratory contamination. Two types of drilling fluid were used in coring, a sodium montmorillonite-based abandonment mud (PetroPlus) and a galactomannin gum coring fluid (REVERT). The manufacturer of PetroPlus is no longer in business, but sources at drilling companies, core analysis laboratories, and the Petroleum Engineering Department at the University of Wyoming all agree that talc is not a common drilling fluid additive. The manufacturer of REVERT claims that it contains only galactomannin. Some types of sample bags are reputed to contain talc, but it would be difficult to get enough of this material into the sample to show in the analysis. Laboratory contamination is also possible.

Other detrital minerals identified in the sandstones include chlorite, seen in binocular microscope examination and thin section, and green biotite, identified in thin section. Brown biotite is very rare, and where observed, it is a light bronze color and appears altered. A gray-green clay mineral that commonly displays an angular, flaky habit appears to be a clastic constituent in some samples. It may represent pyroclastic material incorporated into the sediments at the time of deposition and subsequently altered to gray kaolinite.
Wayland and Rood (1983) state that the Battle Spring Formation in the Great Divide Basin region contains a diagnostic assemblage of detrital, nonopaque, heavy minerals including epidote, blue-green hornblende and garnet which indicate first-cycle sediments derived from a primarily plutonic and metamorphic provenance. In their work in the immediate vicinity of the study area, Wayland and Rood (1983) found epidote, biotite and garnet, but no hornblende.

In the current study garnet, sphene, epidote and possibly zircon were identified in binocular microscope examinations; epidote and zircon were identified in thin section. Garnet and epidote were by far the most common; sphene and zircon are extremely rare. Epidote was observed both as detrital grains and as inclusions within other grains. Authigenic epidote is reported from the Cathedral Bluffs member of the Wasatch Formation in the Oregon Buttes area of the Great Divide Basin (Vine and Tourtelot, 1970), but this was not observed in the present study. Three pan concentrates were made from samples which showed high garnet concentrations. Heavy minerals made up less than one percent of the samples tested. Minerals identified from the pan concentrates were magnetite, ilmenite, red and pink garnets, and epidote.

As described elsewhere (Blatt, 1982), the most common
cementing agents in arkoses are calcite, hematite, and both
detrital and authigenic clays. During diagenesis, feldspars
in arkosic sandstones may be altered to kaolinite and
illite, which may be dissolved and reprecipitated as
cements. Cementing agents in the arkosic beds of the REB
interval include calcite, pyrite, iron oxides and clays.
Calcite cement is found both in irregular pods in
unaltered rocks and in larger bodies associated with uranium
mineralization (fig. 16). Calcite cement formed during
normal diagenesis probably accounts for the irregular pods
in fresh rock. Carbonate forms important complexes for
solution transport of uranium in low-temperature, moderate
pH, aqueous environments (Langmuir, 1978). If uranium was
transported to the roll front in carbonate complexes,
precipitation of the uranium might result in precipitation
of carbonates as well. Calcite cement is prominent in thin
sections of mineralized rock (fig. 17) and x-ray diffraction
data indicates that dolomite is present in some samples
(table 1). Siderite was not found.
The oxidation state of iron and the minerals that it
forms indicate position with respect to the roll front (fig.
18). Pyrite is a minor cementing agent and occurs as
isolated cubes or frambooids in reduced green mudstones, at
the contact of mudstones and overlying unaltered sandstones,
Figure 16. Distribution of calcite cement, composite cross section, REB uranium deposit. Heavy dashed line shows approximate location of oxidation-reduction interface.
Figure 17. Photomicrograph of calcite cement in mineralized rock, sample from core REB 175 at a depth of 407 ft (136 m), crossed nicols, 10X magnification.
and in unaltered sandstones. Pyrite also occurs in mineralized rock, forming small rounded nodules cementing a few detrital silicate grains.

Iron-oxide cement, consisting of yellowish to red-brown material that is a mixture of hematite and limonite, is found in altered sandstones (fig. 18). The distribution of small blebs of hematite-limonite in altered rocks is similar to that of pyrite crystals in unaltered rocks. This may be due to in-place oxidation of pyrite to hematite-limonite. Within the study area, some iron oxides have formed in response to surface weathering, a process that is particularly noticeable where the upper lignite has been removed by erosion. Euhedral hematite crystals formed in pore spaces were observed with the binocular microscope.

At least four kinds of clays are found in the rocks of the REB stratigraphic interval. White powdery kaolinite is very common. It appears to have crystallized last or very late in the diagenetic history of the rocks and may have originated from diagenetic alteration of feldspars. White or cloudy altered feldspars are common in the REB interval and their distribution is unrelated to the position of the roll front. Kaolinite occurs in all the samples that were analyzed by x-ray diffraction (table 1).

A greenish gray clay occurs mixed with white clay and
Figure 18. Distribution of iron minerals, composite cross section, REB uranium deposit. Where both oxides and pyrite are present, pyrite is shown. Heavy dashed line shows approximate location of oxidation-reduction interface.
associated with chlorite. In some samples it appears to be an alteration product of chlorite, as it forms between crystal layers. The greenish clay is more common in fresh samples, and may be a gray kaolinite. Also, authigenic chlorite has grown around detrital grains to form aggregates up to several millimeters in diameter, and chlorite grains have served as sites of nucleation for other clays which have participated in cementation of the rocks. X-ray diffraction data reveal the presence of an expansive clay, most likely a smectite or a mixed-layer clay containing smectite (table 1). There is no evidence that the distribution of clays was affected by the processes that formed the uranium deposit.

Pink- to red-orange-colored altered feldspars are common in the REB interval. The coloration of these grains is caused by minute inclusions of hematite-limonite within the grains (figs. 19 and 20). The presence of such grains is an excellent indicator of high uranium content. Colored feldspars are not seen outside the immediate vicinity of uranium mineralization and the intensity of this type of alteration is related to proximity to areas of high uranium content. Both the intensity of color within a given grain and the number of colored feldspars increase as the mineralization is approached from the unaltered side of the
Figure 19. Photomicrograph of altered orange feldspar, sample from core REB 175 at a depth of 413 ft (138 m), crossed nicols, 10X magnification. Feldspar grain is approximately 1 mm long. (Same field of view as shown in fig. 20).
Figure 20. Photomicrograph of altered orange feldspar, sample from core REB 175 at a depth of 413 ft (138 m), plane-polarized light, 10X magnification. Feldspar grain is approximately 1 mm long. (Same field of view as shown in fig. 19).
roll front. Pink feldspars are found first, then light orange, and finally intensely colored red-orange feldspars (fig. 21). Small grains appear to be affected first and more intensely. Pink and orange feldspars can be found in sandy siltstones underlying mineralization as well as in the mineralized sandstone. The altered feldspar grain in figures 19 and 20 is from 1.5 inches (4 cm) below the hematite-stained contact between a green sandy siltstone and an overlying mineralized sandstone.

A hand-picked sample of the colored feldspars from the REB interval were powdered and analyzed by x-ray diffraction. No minerals except feldspar and quartz were identified. The x-ray data matched standard oligoclase patterns fairly closely, but a mixture of grains of differing compositions is not ruled out. The colored feldspars were determined to be plagioclase by a staining method using hydrofluoric acid and sodium cobaltinitrite (Appendix I). Optical techniques proved of little use in determining feldspar composition because of the many inclusions in the grains.

Red- or orange-colored feldspars have been reported from vein-type uranium deposits, including the Bancroft district in Ontario, Canada, and St. Simeon, Quebec (Nishimori and others, 1977), as well as many others. Most
Figure 21. Distribution of color varieties of altered feldspar grains, composite cross section, REB uranium deposit. Heavy dashed line shows approximate location of oxidation-reduction interface.
probably, ferrous iron in the feldspar crystal lattice is oxidized to ferric iron. Because the ferric iron is not tolerated within the lattice, platelets of hematite are formed. One theory about the formation of oxidized iron associated with uranium concentrations suggests a physical oxidation reaction caused by gamma radiation (Adams, personal communication, 1985), analogous to the process by which irradiation may produce smoky quartz.

Chlorite and biotite may show zoning with relation to the uranium mineralization, but since much of the biotite is green, considerable additional petrographic work would be required to adequately determine their relationships in the REE deposit. Chlorite is concentrated in the ore zone in some roll-type and tabular deposits in New Mexico and Wyoming (Granger, 1962; Files, 1970). The presence of chlorite and biotite in samples examined in hand specimen and with binocular microscope is tabulated in Appendix III.
GEOCHEMISTRY

Introduction

One hundred sixty-three samples from eight cored drill holes (plate 1) were analyzed for Ag, Ca, Fe, Li, Mg, Mn, Na, and Rb; 121 samples were analyzed for Cu; and eight samples were analyzed for Mo, Se, Th and V using flame atomic absorption methods. Appendix I contains the results of these analyses and table 2 lists detection limits, precision and laboratories where analyses were performed. A hot nitric-acid digestion was used, with the intention of putting into solution mainly those elements in the coatings on the exteriors of detrital grains. Such a digestion should be sufficient to put most loosely adsorbed metals and all common sulfides into solution, but will not decompose the more stable rock-forming minerals (Levinson, 1980). Nitric acid may cause some interference in analyses by atomic absorption (Levinson, 1980), however, digestions using hydrochloric acid were not effective in releasing elements from a group of test samples. Also, a relatively fast, simple analytical method was desirable so it could be used in conjunction with a drilling program if ore guides were discovered. Uranium analyses were done by delayed neutron activation. Basic statistics (Appendix II) and
<table>
<thead>
<tr>
<th>Element</th>
<th>Number of Samples</th>
<th>Detection Limit (ppm)</th>
<th>Number of Duplicates</th>
<th>Precision (as percent of amount present)</th>
<th>Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>163</td>
<td>0.2</td>
<td>7</td>
<td>6%</td>
<td>Geology Dept., Colorado School of Mines</td>
</tr>
<tr>
<td>Ca</td>
<td>163</td>
<td>1</td>
<td>7</td>
<td>15%</td>
<td>Geology Dept., Colorado School of Mines</td>
</tr>
<tr>
<td>Cu</td>
<td>121</td>
<td>0.5</td>
<td>7</td>
<td>11%</td>
<td>Geology Dept., Colorado School of Mines</td>
</tr>
<tr>
<td>Fe</td>
<td>163</td>
<td>1</td>
<td>7</td>
<td>23%</td>
<td>Geology Dept., Colorado School of Mines</td>
</tr>
<tr>
<td>Li</td>
<td>163</td>
<td>0.2</td>
<td>7</td>
<td>&lt;1%</td>
<td>Geology Dept., Colorado School of Mines</td>
</tr>
<tr>
<td>Mg</td>
<td>163</td>
<td>1</td>
<td>7</td>
<td>11%</td>
<td>Geology Dept., Colorado School of Mines</td>
</tr>
<tr>
<td>Mn</td>
<td>163</td>
<td>1</td>
<td>7</td>
<td>4%</td>
<td>Geology Dept., Colorado School of Mines</td>
</tr>
<tr>
<td>Mo</td>
<td>8</td>
<td>2</td>
<td>-</td>
<td>2%</td>
<td>Wyoming Analytical, Laramie, Wyoming</td>
</tr>
<tr>
<td>Na</td>
<td>163</td>
<td>1</td>
<td>7</td>
<td>7%</td>
<td>Geology Dept., Colorado School of Mines</td>
</tr>
<tr>
<td>Rb</td>
<td>163</td>
<td>2</td>
<td>7</td>
<td>15%</td>
<td>Geology Dept., Colorado School of Mines</td>
</tr>
<tr>
<td>Se</td>
<td>8</td>
<td>0.1</td>
<td>-</td>
<td>2%</td>
<td>Wyoming Analytical, Laramie, Wyoming</td>
</tr>
<tr>
<td>Th</td>
<td>8</td>
<td>2</td>
<td>-</td>
<td>1%</td>
<td>Wyoming Analytical, Laramie, Wyoming</td>
</tr>
<tr>
<td>U</td>
<td>153</td>
<td>0.1</td>
<td>16</td>
<td>5%</td>
<td>Uranium West, Los Angeles, California; Nuclear Activation Services, Hamilton, Ontario, Canada</td>
</tr>
<tr>
<td>V</td>
<td>8</td>
<td>2</td>
<td>-</td>
<td>2%</td>
<td>Wyoming Analytical, Laramie, Wyoming</td>
</tr>
</tbody>
</table>
correlation analyses were used to interpret the data.

Elements were chosen for their reported associations with uranium in roll-front deposits. Cu, Mo, Se and V are reported to be pathfinder elements for roll-front uranium deposits (Levinson, 1980). Ag could be expected to behave much like Cu. Ca, Mg and Mn are all mobile to varying degrees in low-temperature, aqueous systems. In addition, it was hoped that analysis for Ca would give a quantitative value for calcite. The oxidation state and distribution of Fe are affected by processes involved in forming roll-front uranium deposits. Zoning of these and other elements is described in other Wyoming roll-front uranium deposits by King and Austin (1966), Davis (1969), Rubin (1970), Harshman (1972) and Harris (1984). Li, Na and Rb distributions might be affected by changes in clay-mineral assemblages which are reported across some deposits (Davydov, 1979; Reynolds and others, 1980).

Samples were visually classified as fresh, slightly altered or altered on the basis of presence or absence of iron oxides, pyrite and colored feldspar grains. The distribution of these three rock types with respect to a composite cross section of the REB deposit (fig. 14) is shown in figure 22. Most of the samples are arkosic sandstones, but some silty sandstones are included. All
Figure 22. Distribution of altered, slightly altered and fresh rock. Composite cross section, REEuranium deposit. Heavy dashed line shows approximate location of oxidation-reduction interface.
samples were disaggregated, using a porcelain mortar and pestle where necessary, and sieved to collect quantitative grain-size data. Each sample was separated into three fractions, +60, -60/+200 and -200, and each fraction was weighed. Percent of total sieved sample in each size fraction was computed for each sample (Appendix I). This quantitative measure of grain size was used in correlation analyses to examine the effect of grain size on the distribution of the elements. Chemical analyses were performed on only the -60/+200 fraction in an attempt to minimize grain-size/surface-area effects. Each sample was of limited total size, so to obtain sufficient sample for analysis, a fairly wide range was required.

Another factor expected to affect values obtained for elements in this study was adsorption of elements by iron and manganese oxides, which are present in the altered samples and most of the slightly altered samples, and which are not visible in the fresh samples. It was expected that elements might be enriched in altered rocks as a result of the presence of iron oxides; however, most elements studied were relatively enriched in fresh rocks.

A one-gram portion of the -60/+200 fraction of each sample was analyzed by delayed neutron activation at one of two commercial laboratories (table 2). This method gives a
whole-rock value for uranium concentration. This is an acceptable approximation of uranium in the roll front deposit because the amount of uranium contained within the detrital grains is negligible.

Precision and Accuracy

Duplicate samples, blanks, and standard samples were analyzed to establish analytical control. Approximately eight percent of the samples were duplicates, blanks or standards. These were used in determining precision and accuracy and in detecting possible sources of contamination. The results from analysis of duplicate samples (Appendix II) were used to assess precision of analytical results. Approximately five percent of samples were duplicates. Table 2 lists the average analytical precision and the number of duplicate analyses for each element. Duplicates were not analyzed for Mo, Se, Th and V. The stated precision of the laboratory for these elements is given in table 2. Average analytical precision for Ag, Ca, Cu, Fe, Mg, Mn, Na, Rb, and U is between 4 percent and 23 percent of the amount present (table 2). Good precision was obtained for Ag (6%), Mn (4%), Na (7%) and U (6%). Ca (15%), Cu (11%), Mg (11%) and Rb (15%) exhibit moderate precision, while Fe (23%) shows the lowest precision.
Detection limits for all elements are given table 2. Results for Ag and Cu were commonly below their respective detection limits, while results for all the other elements were nearly always well above the detection limit.

Six standard geological samples were also analyzed (Appendix II). Results of these analyses were intended to be used for estimating the accuracy of the analytical methods. The usefulness of these analyses is very limited for two reasons. First, analytical results have been published (Gladney and others, 1979; Abbey, 1980) for only four of the elements (Cu, Mg, Na and Rb) studied, and second, complete digestion methods were used. Consequently, results obtained in this study are much lower than the published values. It is not possible to estimate accuracy from these data. In this study, however, relative changes in element values are more important than absolute concentrations.

Basic statistical analysis, including calculation of arithmetic mean, median, maximum and minimum values, and variance and standard deviation, were compiled for each element and grain-size fraction. The same statistical parameters were tabulated for the populations of altered samples, slightly altered samples and fresh samples. These data are presented in tables 3-6.
Table 3. Basic Statistics for All Geochemical Samples

(Element values are in ppm; grain-size values are weight percent of total)

<table>
<thead>
<tr>
<th>Element</th>
<th>Number of Analyses</th>
<th>Mean</th>
<th>Median</th>
<th>Maximum Value</th>
<th>Minimum Value</th>
<th>Variance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>163</td>
<td>0.39</td>
<td>0.3</td>
<td>2.3</td>
<td>0.2</td>
<td>0.8200E-01</td>
<td>0.2863</td>
</tr>
<tr>
<td>Ca</td>
<td>163</td>
<td>772</td>
<td>265</td>
<td>30490</td>
<td>13</td>
<td>0.9121E+07</td>
<td>0.3020E+04</td>
</tr>
<tr>
<td>Cu</td>
<td>121</td>
<td>1.5</td>
<td>1.2</td>
<td>4.4</td>
<td>0.5</td>
<td>0.5425</td>
<td>0.7366</td>
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<tr>
<td>Fe</td>
<td>163</td>
<td>503</td>
<td>420</td>
<td>2700</td>
<td>130</td>
<td>0.8269E+05</td>
<td>0.2875E+03</td>
</tr>
<tr>
<td>Li</td>
<td>163</td>
<td>0.46</td>
<td>0.5</td>
<td>1.0</td>
<td>0.3</td>
<td>0.1976</td>
<td>0.1406</td>
</tr>
<tr>
<td>Mg</td>
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<td>160</td>
<td>160</td>
<td>290</td>
<td>30</td>
<td>0.3838E+04</td>
<td>0.6195E+02</td>
</tr>
<tr>
<td>Mn</td>
<td>163</td>
<td>8.95</td>
<td>6.8</td>
<td>227</td>
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<td>0.3240E+03</td>
<td>0.1800E+02</td>
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<tr>
<td>Na</td>
<td>163</td>
<td>24</td>
<td>23</td>
<td>79</td>
<td>7</td>
<td>0.1342E+03</td>
<td>0.1159E+02</td>
</tr>
<tr>
<td>Rb</td>
<td>163</td>
<td>5</td>
<td>4</td>
<td>18</td>
<td>2</td>
<td>0.6821E+01</td>
<td>0.2612E+01</td>
</tr>
<tr>
<td>Th</td>
<td>8</td>
<td>265</td>
<td>233</td>
<td>764</td>
<td>65</td>
<td>0.4100E+05</td>
<td>0.2025E+03</td>
</tr>
<tr>
<td>U</td>
<td>153</td>
<td>716.8</td>
<td>104.0</td>
<td>13000</td>
<td>4.4</td>
<td>0.2412E+07</td>
<td>0.1553E+04</td>
</tr>
<tr>
<td>V</td>
<td>8</td>
<td>83</td>
<td>25</td>
<td>256</td>
<td>&lt;2</td>
<td>0.8611E+04</td>
<td>0.9279E+02</td>
</tr>
</tbody>
</table>

Grain Size*

<table>
<thead>
<tr>
<th>Size*</th>
<th>159</th>
<th>7</th>
<th>4</th>
<th>53</th>
<th>1</th>
<th>0.6454E-02</th>
<th>0.8033E-01</th>
</tr>
</thead>
<tbody>
<tr>
<td>-200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+200/-60</td>
<td>159</td>
<td>18</td>
<td>15</td>
<td>70</td>
<td>5</td>
<td>0.1518E-01</td>
<td>0.1232</td>
</tr>
<tr>
<td>+60</td>
<td>159</td>
<td>75</td>
<td>81</td>
<td>93</td>
<td>9</td>
<td>0.3211E-01</td>
<td>0.1792</td>
</tr>
</tbody>
</table>

*U.S. Standard Sieve Sizes
Table 4. Basic Statistics for Geochemical Samples of Altered Rocks
(Element values are in ppm; grain-size values are weight percent of total)

<table>
<thead>
<tr>
<th>Element Analyses</th>
<th>Number of Analyses</th>
<th>Mean</th>
<th>Median</th>
<th>Maximum Value</th>
<th>Minimum Value</th>
<th>Variance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>74</td>
<td>0.35</td>
<td>0.3</td>
<td>1.1</td>
<td>0.2</td>
<td>0.3250E-01</td>
<td>0.1803</td>
</tr>
<tr>
<td>Ca</td>
<td>74</td>
<td>312</td>
<td>47.8</td>
<td>2939</td>
<td>17.6</td>
<td>0.1745E+06</td>
<td>0.4177E+03</td>
</tr>
<tr>
<td>Cu</td>
<td>68</td>
<td>1.45</td>
<td>1.3</td>
<td>3.2</td>
<td>0.5</td>
<td>0.4323</td>
<td>0.6575</td>
</tr>
<tr>
<td>Fe</td>
<td>74</td>
<td>438</td>
<td>400</td>
<td>1000</td>
<td>130</td>
<td>0.3959E+05</td>
<td>0.1989E+03</td>
</tr>
<tr>
<td>Li</td>
<td>74</td>
<td>0.45</td>
<td>0.4</td>
<td>0.9</td>
<td>0.3</td>
<td>0.1736</td>
<td>0.1318</td>
</tr>
<tr>
<td>Mg</td>
<td>74</td>
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<td>270</td>
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<td>0.5794E+02</td>
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<tr>
<td>Mn</td>
<td>74</td>
<td>6.8</td>
<td>4.8</td>
<td>15.1</td>
<td>3.5</td>
<td>0.6341E+01</td>
<td>0.2518E+01</td>
</tr>
<tr>
<td>Na</td>
<td>74</td>
<td>24.6</td>
<td>21</td>
<td>62</td>
<td>9</td>
<td>0.1363E+03</td>
<td>0.1168E+02</td>
</tr>
<tr>
<td>Rb</td>
<td>74</td>
<td>4</td>
<td>4</td>
<td>12</td>
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<tr>
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<td>15.5</td>
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<td>0.2046E+04</td>
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</table>

Grain Size*
-200  74  5  3  53  1  0.3769E-02  0.6139E-01
+200/-60  74  15  12  52  5  0.9856E-02  0.9928E-01
+60  74  80  84  93  30  0.1733E-01  0.1316

*U.S. Standard Sieve Sizes
Table 5. Basic Statistics for Geochemical Samples of Slightly Altered Rocks
(Element values are in ppm; grain-size values are weight percent of total)

<table>
<thead>
<tr>
<th>Element</th>
<th>Number of Analyses</th>
<th>Mean</th>
<th>Median</th>
<th>Maximum Value</th>
<th>Minimum Value</th>
<th>Variance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
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<td>0.36</td>
<td>0.2</td>
<td>1.3</td>
<td>0.2</td>
<td>0.4305E-01</td>
<td>0.2075</td>
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<tr>
<td>Ca</td>
<td>57</td>
<td>906</td>
<td>265</td>
<td>30490</td>
<td>13.2</td>
<td>0.1578E+08</td>
<td>0.3972E+04</td>
</tr>
<tr>
<td>Cu</td>
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<td>1.5</td>
<td>1.2</td>
<td>4.4</td>
<td>0.5</td>
<td>0.7499</td>
<td>0.8660</td>
</tr>
<tr>
<td>Fe</td>
<td>57</td>
<td>480</td>
<td>420</td>
<td>1200</td>
<td>170</td>
<td>0.5402E+05</td>
<td>0.2324E+03</td>
</tr>
<tr>
<td>Li</td>
<td>56</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
<td>0.3</td>
<td>0.9997E-02</td>
<td>0.9998E-01</td>
</tr>
<tr>
<td>Mg</td>
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<td>160</td>
<td>160</td>
<td>250</td>
<td>30</td>
<td>0.3481E+04</td>
<td>0.5900E+02</td>
</tr>
<tr>
<td>Mn</td>
<td>57</td>
<td>11</td>
<td>6.5</td>
<td>227</td>
<td>2.2</td>
<td>0.8427E+03</td>
<td>0.2903E+02</td>
</tr>
<tr>
<td>Na</td>
<td>57</td>
<td>22</td>
<td>20</td>
<td>79</td>
<td>7</td>
<td>0.1502E+03</td>
<td>0.1225E+02</td>
</tr>
<tr>
<td>Rb</td>
<td>57</td>
<td>5</td>
<td>4</td>
<td>13</td>
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<td>3140</td>
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Grain Size

<table>
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<tr>
<th></th>
<th>Number of Analyses</th>
<th>Median</th>
<th>Maximum Value</th>
<th>Minimum Value</th>
<th>Variance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>-200</td>
<td>56</td>
<td>7</td>
<td>4</td>
<td>39</td>
<td>2</td>
<td>0.4590E-01</td>
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<tr>
<td>+200/-60</td>
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<td>21</td>
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<td>70</td>
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<td>0.1907E-01</td>
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<td>+60</td>
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<td>72</td>
<td>80</td>
<td>92</td>
<td>19</td>
<td>0.3534E-01</td>
</tr>
</tbody>
</table>

*U.S. Standard Sieve Sizes
Table 6. Basic Statistics for Geochemical Samples of Fresh Rocks

(Element values are in ppm; grain-size values are weight percent of total)

<table>
<thead>
<tr>
<th>Element</th>
<th>Number of Analyses</th>
<th>Mean</th>
<th>Median</th>
<th>Maximum Value</th>
<th>Minimum Value</th>
<th>Variance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>31</td>
<td>0.5</td>
<td>0.4</td>
<td>2.3</td>
<td>0.2</td>
<td>0.1711</td>
<td>0.4136</td>
</tr>
<tr>
<td>Ca</td>
<td>32</td>
<td>1598</td>
<td>533</td>
<td>22800</td>
<td>33.8</td>
<td>0.1675E+08</td>
<td>0.4093E+04</td>
</tr>
<tr>
<td>Cu</td>
<td>8</td>
<td>1.4</td>
<td>1.2</td>
<td>2.4</td>
<td>0.9</td>
<td>0.2294</td>
<td>0.4789</td>
</tr>
<tr>
<td>Fe</td>
<td>32</td>
<td>690</td>
<td>590</td>
<td>2700</td>
<td>310</td>
<td>0.1868E+06</td>
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</tr>
<tr>
<td>Li</td>
<td>32</td>
<td>0.6</td>
<td>0.6</td>
<td>1.0</td>
<td>0.3</td>
<td>0.2059E-01</td>
<td>0.1435</td>
</tr>
<tr>
<td>Mg</td>
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<td>210</td>
<td>210</td>
<td>290</td>
<td>100</td>
<td>0.2265E+04</td>
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<tr>
<td>Mn</td>
<td>32</td>
<td>11.1</td>
<td>7.2</td>
<td>63.1</td>
<td>6.3</td>
<td>0.1151E+03</td>
<td>0.1073E+02</td>
</tr>
<tr>
<td>Na</td>
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<td>25</td>
<td>23</td>
<td>58</td>
<td>9</td>
<td>0.9487E+02</td>
<td>0.9740E+01</td>
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<tr>
<td>Rb</td>
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<td>6</td>
<td>5</td>
<td>18</td>
<td>2</td>
<td>0.1436E+02</td>
<td>0.3789E+01</td>
</tr>
<tr>
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<td>31</td>
<td>185</td>
<td>14.8</td>
<td>5110</td>
<td>4.4</td>
<td>0.8092E+06</td>
<td>0.9000E+03</td>
</tr>
</tbody>
</table>

Grain Size *

| -200   | 29 | 10 | 5 | 47 | 2 | 0.1470E-01 | 0.1213 |
| +200/-60 | 29 | 21 | 16 | 53 | 6 | 0.1686E-01 | 0.1298 |
| +60    | 29 | 68 | 79 | 92 | 9 | 0.5175E-01 | 0.2275 |

*U.S. Standard Sieve Sizes
Element Distribution

Histograms of analytical values for each element are presented in Appendix I. The histograms include representation of the population (altered, slightly altered or fresh) to which samples belong.

Silver

Silver occurs as a trace element in the analyzed fraction. Extractable silver values are commonly at or near the detection limit of 0.2 ppm. The values for all rocks range from less than 0.2 ppm to 2.3 ppm. The mean is 0.39 ppm. The groups of altered and slightly altered samples have slightly lower average values, 0.35 and 0.36 respectively. Fresh samples have the highest absolute silver values and the highest average value. Silver is leached during alteration.

Calcium

Extractable calcium in the rocks of the study area ranges from 13 ppm to over 30000 ppm. Most of the samples have calcium contents below 1000 ppm. The mean value for all rocks is 772 ppm; this is considerably higher than the median value of 265. This skewness is caused by a few extremely high values. Altered samples have comparatively low calcium content. They average 312 ppm and range from
17.6 to 2939 ppm. Slightly altered samples have a higher mean value of 906 ppm and the average value for fresh samples is higher still, at 1598 ppm. Calcium is leached during the alteration process.

Calcium content as determined in this study cannot be used as a quantitative measure of calcite. This is demonstrated by comparison of the composite cross section showing calcite distribution (fig. 16) and the same section showing calcium distribution (fig. 23). Calcium might also be expected to be concentrated by adsorption on clays, but no relationship is visible between the distribution of fine-grained rocks (fig. 15) and calcium (fig. 23).

Copper

Mean extractable copper content of the study area rocks is 1.5 ppm. Values range from 0.5 ppm to 4.4 ppm. Mean values for altered, slightly altered and fresh samples are 1.45, 1.5 and 1.4 ppm, respectively. Copper values were commonly found below the detection limit. No significant difference in copper content is found between the three rock types.

Iron

Extractable iron content of the fraction analyzed averages 503 ppm and ranges from 130 ppm to 2700 ppm in the
Figure 23. Distribution of extractable calcium, composite cross section, REB uranium deposit. Heavy dashed line shows approximate location of oxidation-reduction interface.
rocks of the study area. Fresh samples are enriched in iron, with a mean value of 690 ppm, and a range of 310 to 2700 ppm. Slightly altered samples are relatively poorer in iron, with a mean iron content of 480 ppm. Sample values range from 170 to 1200 ppm. Altered samples are close to but a bit lower than slightly altered samples in iron content; they average 438 ppm and range from 130 to 1000 ppm. High iron concentration (fig. 24) coincides to some extent with the presence of pyrite (fig. 18).

Lithium

Extractable lithium content in the rocks of the study area averages 0.46 ppm and ranges from 0.3 to 1.0 ppm. Altered samples are relatively poor in lithium, averaging 0.45 ppm and ranging from 0.3 to 0.9 ppm. Fresh samples are relatively enriched in lithium; they average 0.6 ppm and range from 0.3 to 1.0 ppm. Slightly altered samples are intermediate in lithium content. The range for slightly altered samples is 0.3 to 0.7 and they average 0.5 ppm. Lithium may be leached during alteration.

Magnesium

Mean extractable magnesium content for rocks of the study area is 160 ppm. Analytical values range from 30 to 290 ppm. Magnesium is relatively enriched in fresh samples.
Figure 24. Distribution of extractable iron, composite cross section, REB uranium deposit. Heavy dashed line shows approximate location of oxidation-reduction interface.
They average 210 ppm and range from 100 to 290 ppm. Altered samples are poor in magnesium, ranging from 40 to 270 ppm and averaging 139 ppm. Slightly altered samples are intermediate in magnesium content. The mean value is 160; the range is 30 to 250 ppm. Magnesium is leached during alteration.

Magnesium might be expected to be concentrated by adsorption on clay minerals. No relationship is seen between the distribution of fine-grained rocks (fig. 15) and magnesium content as determined in this study (fig. 25).

Manganese

Manganese values for all the rocks of the study area average 8.95 ppm and range from 2.2 to 227 ppm. Altered samples are low in manganese; the mean is 6.8 ppm and the range is 3.5 to 15.1 ppm. Slightly altered and fresh samples have similar mean values: 11 and 11.1 ppm, respectively. The range for slightly altered samples shows the most variable distribution, ranging from from 2.2 to 227. Values for fresh samples occur over a narrower range, 6.3 to 63.1. Manganese is leached from altered rocks.

Molybdenum

Eight samples were analyzed for molybdenum. None of the samples contained molybdenum in greater amounts than the
detection limit of 2 ppm.

Sodium

Sodium as analyzed in the rocks of the study area displays and average value of 24 ppm and a range of 7 to 79 ppm. Slightly altered samples are lowest in sodium, but only marginally so. The average value is 22 ppm, the range 7 to 79 ppm. The mean sodium contents of altered and fresh samples are 24.6 and 25 ppm, respectively. The range for altered samples is from 9 to 62 ppm. The range for fresh samples is 9 to 58 ppm. The ranges for altered and slightly altered samples is slightly wider than that for fresh samples. Extractable sodium is clearly not related to mineralization.

Sodium can interfere with the analysis of many elements by flame atomic absorption because of its strong spectral lines. The relatively constant sodium concentrations in the samples analyzed mean that any interference was approximately equal across all samples, so no correction was applied.

Rubidium

Mean extractable rubidium content of all the rocks of the study area is 4.7 ppm. The range is from 2 to 18 ppm. The average values for altered, slightly altered and fresh
rocks are very close: 4, 5 and 6 ppm respectively. However, they do show a trend towards enrichment in fresh rocks. In altered rocks, rubidium contents range from 2 to 12 ppm. In slightly altered rocks, the range is 2 to 13 ppm. In fresh rocks, the range is 2 to 18 ppm. Rubidium may be leached during alteration.

Selenium

Eight samples were analyzed for selenium. None of the samples contained selenium in greater amounts than the detection limit of 0.1 ppm.

Thorium

Eight samples were analyzed for thorium. The mean value is 265 ppm, with a range of 65 to 764. Because of their different solubilities under conditions of surface weathering, uranium and thorium content can be used to demonstrate the hypogene origin of some uranium deposits. Low thorium-to-uranium ratios in a uranium deposit indicate its formation under low-temperature conditions, when uranium is much more mobile. Table 7 shows the ratios of thorium to uranium for the eight samples analyzed for thorium. Higher thorium-to-uranium ratios in fine-grained rocks may reflect the presence of thorium-containing resistate minerals.
<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Alteration Designation</th>
<th>Lithology</th>
<th>Th/U Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>445-302</td>
<td>Slightly altered</td>
<td>Fine grained sandstone</td>
<td>22:1</td>
</tr>
<tr>
<td>445-304</td>
<td>Slightly altered</td>
<td>Coarse grained sandstone</td>
<td>9:1</td>
</tr>
<tr>
<td>445-306</td>
<td>Slightly altered</td>
<td>Coarse grained sandstone</td>
<td>3:1</td>
</tr>
<tr>
<td>445-309</td>
<td>Altered</td>
<td>Coarse grained sandstone</td>
<td>1:2</td>
</tr>
<tr>
<td>445-314</td>
<td>Altered</td>
<td>Medium grained sandstone</td>
<td>1:2</td>
</tr>
<tr>
<td>445-316</td>
<td>Altered</td>
<td>Medium grained sandstone</td>
<td>1:2</td>
</tr>
<tr>
<td>771-594</td>
<td>Fresh</td>
<td>Fine grained sandstone and siltstone</td>
<td>10:1</td>
</tr>
<tr>
<td>771-617</td>
<td>Fresh</td>
<td>Sandy mudstone</td>
<td>32:1</td>
</tr>
</tbody>
</table>
Uranium

Mean uranium content of all samples is 716.8 ppm or 0.07 percent. This is considerably enriched in comparison with the most usual value for sedimentary rocks, 1.3 ppm (Evans and Goodman, 1941, in Wyant, Sharp and Sheridan, 1956). The range is from 4.4 to 13000 ppm. Altered rocks are enriched in uranium, averaging 1324 ppm and ranging from 15.5 to 13000 ppm. Fresh samples are relatively poor in uranium. The mean value is 185 ppm and the range is 4.4 to 5110 ppm. The single high value of 5110 ppm skews the average considerably; the median value for fresh samples is 14.8 ppm. Slightly altered samples are intermediate in uranium content, averaging 277 ppm and ranging from 4.5 to 3140 ppm. Again, the mean is skewed by a few very high values. The median value of 66.7 ppm is much lower than the average.

The distribution of uranium values among the three classes of rocks indicates that the visual classification method used in this study is a fairly accurate method of estimating uranium content in the REB deposit. A similar method, including use of the gamma log, is used by geologists drilling in the REB deposit to determine position with relation to the roll front.
Vanadium

Eight samples were analyzed for vanadium content. Values range from below the detection limit of 2 ppm to 256 ppm. The mean is 83 ppm. In general, vanadium values vary sympathetically with uranium. However, they appear to be highest on the fresh side of the highest uranium values.

Correlation Analyses

Correlation analyses were performed using the parameters of Ag, Ca, Cu, Fe, Li, Mg, Mn, Na, Rb, and U concentration and grain-size percents. Correlations were done for the population of all rocks in the study area, and then for altered, slightly altered and fresh rocks. Correlation coefficients for all parameters are listed in tables 8-11.

A correlation coefficient is a statistical measure of the correspondence between two parameters. A high correlation coefficient indicates that one parameter can be predicted with some degree of certainty from the other by a mathematical formula. The higher the correlation coefficient, the better the precision of the prediction.

Statistical correlations were made on an element-by-element basis to account for differences in the number of samples analyzed for various elements.
Table 8. Correlation Matrix of Geochemical Data for the Population of All Samples

<table>
<thead>
<tr>
<th></th>
<th>Ag</th>
<th>Ca</th>
<th>Cu</th>
<th>Fe</th>
<th>Li</th>
<th>Mg</th>
<th>Mn</th>
<th>Na</th>
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Ag, Ca, Cu, Fe, Li, Mg, Mn, Na, Rb, U
Table 9. Correlation Matrix of Geochemical Data for the Population of Altered Samples

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<td>Mn</td>
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Table 10. Correlation Matrix of Geochemical Data for the Population of Slightly Altered Samples

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Table 11. Correlation Matrix of Geochemical Data for the Population of Fresh Samples

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Note: Insufficient Cu analyses to perform correlation.
Correlations were performed using computer programs which used the PFIT subroutine from STATLIB, produced by the National Bureau of Standards Center for Applied Mathematics, Statistical Engineering Laboratory at Boulder, Colorado. A linear least-squares technique with a fitted third-degree polynomial was used. Correlation coefficients of over 0.5 are considered significant. The correlation coefficients calculated for this study are strictly binary, and only the two elements involved are used in determining the correlation. Correlation analysis was not performed with chemical data for Mo, Se, Th and V or for Cu in fresh rocks because of the small number of samples.

Correlations for all rocks produced only one correlation coefficient over 0.5. Mn and Ca are highly correlated (table 8). This correlation indicates that the distribution of these elements as analyzed in this study was not significantly affected by the processes that formed the REB uranium deposit, or by processes that occur due to the presence of the deposit.

Correlations for altered rocks only produced one significant correlation. The correlation coefficient for Fe and Mg is 0.649 (table 9). This may reflect adsorption of Mg on iron oxides, or coprecipitation of Fe and Mg in oxide minerals. The lack of significant correlations in altered
rocks may mean that more than one population is included in this classification. Indeed, this is true, for this classification contains both barren and mineralized altered rocks. A further subdivision of this classification was not attempted because of the small number of samples in the resulting subclasses.

Correlations for slightly altered rocks revealed three significant correlations (table 10). Ca and Ag, Mn and Ag, and Mn and Ca are highly correlated. These correlations may reflect scavenging of Ag by manganese oxides, and the involvement of Ca in a similar adsorption reaction. These correlations indicate that the distribution of these three elements was affected by processes that resulted in deposition of uranium, or by subsequent processes that were affected by the presence of the roll front. A less significant correlation exists between Mg and Fe. As in the altered rocks, this correlation may reflect adsorption of Mg on iron oxides, or coprecipitation of Fe and Mg in oxide minerals.

Fresh rocks show several significant correlations (table 11). Mn and Ca are highly correlated, as they are in all populations. Their distribution is probably unrelated to the mineralizing processes. Rb and Li, and percent clay and Rb concentration are highly correlated and percent clay
and Li are correlated less significantly, probably reflecting association of Rb and Li with clay minerals through adsorption. The mineralizing process may disrupt these associations by introducing iron and manganese oxides into the system, which may adsorb Rb and Li less strongly than do clays. In addition, percent fine sand and Ag are moderately well correlated, while percent coarse sand and Ag are less significantly correlated. Less significant correlations are seen for Fe and Ag, Mg and Fe, and percent clay and Fe. These relationships may reflect original distribution of elements by detrital and diagenetic processes. Alternatively, the proximity of the roll front to the locations of fresh samples in this study allows the possibility that these samples were affected by processes that formed the roll front.
SUMMARY AND CONCLUSIONS

The Great Divide Basin of Wyoming is a Laramide feature, in which the arkosic sandstones and carbonaceous mudstones of the Eocene Battle Spring Formation were deposited. Source rocks for the sediments were primarily granitic and metamorphic Precambrian rocks of the Granite Mountains. In the study area, the REB interval consists of arkosic, fairly coarse-grained sandstones interbedded with discontinuous, poorly sorted siltstones and mudstones that may be carbonaceous or radioactive. The REB interval is defined by overlying and underlying radioactive carbonaceous mudstones of the Eocene Wasatch Formation.

The REB interval hosts the REB roll-front uranium deposit. Both the composite cross section and the contour map of number of sand beds in the REB interval suggest that a stratigraphic control on uranium deposition in the REB interval does exist. The linear and continuous nature of the uranium mineralization trend, as well as its location near, and subparallel to, the transition from coarse-grained rocks of the Battle Spring Formation to finer-grained rocks of the Wasatch Formation support the conjecture that uranium deposition may be related to that transition. The percent-sandstone contour map shows a central zone with a high percentage of sandstone, which may represent a channel
sandstone body formed by a southwest-trending Eocene stream. If so, the orientation of the uranium roll front system perpendicular to the channel direction suggests that such channels do not exert primary control on uranium deposition. Such channels, however, might well conduct uranium-bearing fluids to a site of deposition.

Figure 25 summarizes the alteration patterns and geochemistry across a roll front in the REB uranium deposit. The lack of colored feldspar grains in the altered rocks behind the roll front imply that the deposits in the REB interval could not have formed by a slow process of multiple migration-accretion (Gruner, 1956), or at least that the movement of the roll front must have been rapid with respect to the process by which red feldspars are formed. If they had migrated very slowly, there should be altered orange feldspars behind the roll front in the altered rocks. There is no evidence that the colored feldspar grains are altered to other minerals.

Correlation analyses for element concentrations and grain-size percentages revealed few significant correlations. In the population of all rocks, the only significant correlation is between Ca and Mn. This implies that the distribution of these elements as analyzed in this study is not affected by mineralization. In the population
Figure 25. Generalized cross section through a uranium roll front, REB uranium deposit, showing alteration features and geochemistry.
of fresh samples, significant correlations exist for Mn and Ca; Rb and Li; percent clay and Rb; percent clay and Li; percent fine sand and Ag; percent coarse sand and Ag; Fe and Ag; percent clay and Fe; and Mg and Fe. These associations could be expected in detrital rocks. In altered and slightly altered rocks, significant correlations are found between Mn and Mg; Ca and Ag; Mn and Ag; Mn and Ca; Fe and Mg; and Na and Mg. These associations and the disruption of correlations that exist in fresh rocks imply that these elements have been redistributed by the mineralizing processes.

Mineralization in the REB interval can be accurately located by visually classifying samples as altered, slightly altered or fresh on the basis of presence of iron oxides, pyrite and colored feldspar grains. The presence and intensity of colored feldspar grains is the most accurate ore guide in this deposit and these features can be used in development drilling on the REB trend when gamma logging is delayed or impossible. Because of the effectiveness and simplicity of visual classification, careful inspection and logging of samples, in combination with gamma logging, is more cost-effective than chemical analysis.
SUGGESTIONS FOR FURTHER WORK

The mechanism by which feldspars become colored feldspars might be experimentally testable, and could reveal the reason for large amounts of oxidized iron associated with uranium deposits of many types. While not addressed in this study, the age of mineralization in Wyoming roll-front uranium deposits remains in question, as does the source of uranium. Both problems may have multiple answers, different in different districts. Detailed studies of paleohydrology might yield more information on the history of deposits.
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APPENDIX I: ANALYTICAL METHODS AND RESULTS
Sample Collection

One hundred ninety-seven samples were collected from cores owned by Union Energy Mining and Union Minerals Exploration. Half of a one-quarter split was taken from each one-foot interval. Most of the samples were disaggregated to some degree at the time of sampling.

Sample Preparation

Samples were gently disaggregated using a porcelain mortar and pestle. For the 14 samples analyzed by X-ray diffraction, a portion of the sample was reserved. Samples were sieved to +60, -60/+200 and -200, U.S. Standard Sieve Sizes. Each size fraction was weighed, allowing the computation of percent of total for each fraction. All chemical analyses, including those for uranium, were carried out on -60/+200 material in an attempt to minimize interference due to variations in surface area.

Chemical Analyses

For flame atomic absorption analysis, one gram of the -60/+200 fraction of each sample was weighed on a digital balance into a test tube. A hot nitric acid digestion was used to avoid breaking down silicate minerals. Samples
were subsequently diluted to 10 ml with deionized water for analysis.

One hundred seventy-four samples were analyzed by flame atomic absorption for Ag, Ca, Fe, Li, Mg, Mn, Na and Rb. One hundred forty-one samples were analyzed for Cu by flame atomic absorption. These analyses were carried out by the author and laboratory technician Peggy O’Mara at the Geology Department of the Colorado School of Mines using a Perkin-Elmer 303 atomic absorption spectrophotometer.

One-gram portions of 153 samples were weighed into plastic vials using a digital balance in the Geology Department at the Colorado School of Mines. These were analyzed for U by delayed neutron activation at one of two commercial laboratories. Uranium West Laboratory, Los Angeles, California and Nuclear Activation Services, Hamilton, Ontario, Canada performed the uranium analyses. Eight samples were analyzed for Mo, Se, Th and V by Wyoming Analytical Laboratories, Laramie, Wyoming, using a nitric-acid digestion and flame atomic absorption.

**X-ray Diffraction**

Clay-slide preparation technique:

1) 1 Tbl. sample to 200 ml DI H#O; add 20 ml Calgon
solution.

2) Wash in ultrasonic 15 min; settle for 10 min.

3) Decant and save supernatant clay-H#O solution; discard coarse fraction.

4) Add 1 g MgCl$_2$. Allow to sit until deflocculation is complete or nearly so.

5) Pipette 1 ml of deflocculated clay from bottom of flask onto slide.

6) Allow slide to air dry.

Samples were scanned at 2 per min from 6 to 60. Analyses were performed by laboratory technician Peggy O'Mara in the Geology Department at the Colorado School of Mines.

In addition, two slides were glycolated to test for expansive clay components. This was done by placing the slides on a rack in a large container, the bottom of which was filled with ethylene glycol. The container was placed in a dessicating oven at 125 °F for 1.5 hr. Slides were x-rayed immediately upon removal from the container, and were scanned at 2 per min from 6 to 30. These samples were analyzed by the author.
Staining Technique

Slabs were stained for potassium feldspar, plagioclase and quartz using a method described by Hutchison (1974; p. 18). Slabs were etched by immersion in concentrated HF for 15 to 20 sec. After dipping in water to remove the acid, a saturated sodium cobaltinitrite solution was applied to the cut surfaces with an eye dropper. After 1 to 2 min, the slabs were rinsed and allowed to dry. Using this technique, potassium feldspar stains bright yellow, plagioclase turns a chalky white, and quartz is dull gray.

By visual estimation, approximately one-third of the feldspars are potassium feldspars. The remainder of the feldspars are plagioclase. Colored altered feldspars stain as plagioclase.
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Relative Frequency Diagrams

Classification bars on the frequency diagrams do not include values of the high bounding value. In other words, the values represented by a given bar are greater than or equal to the lower bound and less than the upper bound.
APPENDIX II: PRECISION AND ACCURACY
Precision

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### DUPLICATE ANALYSES FOR U

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Log-log plot of silver duplicate analyses (ppm)
Log-log plot of calcium duplicate analyses (ppm)
Log-log plot of lithium duplicate analyses (ppm)
Log-log plot of iron duplicate analyses (ppm)
Log-log plot of copper duplicate analyses (ppm)
Log-log plot of magnesium duplicate analyses (ppm)
Log-log plot of manganese duplicate analyses (ppm)
Log-log plot of sodium duplicate analyses (ppm)
Log-log plot of rubidium duplicate analyses (ppm)
Log-log plot of uranium duplicate analyses (ppm)
## COMPARISON OF PUBLISHED USGS VALUES AND VALUES OBTAINED IN THIS STUDY FOR CU, RB, MG AND NA

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APPENDIX III: PETROGRAPHIC DESCRIPTIONS
Microscopic Examinations

One hundred seventy-nine samples were examined under a binocular microscope for alteration characteristics. Eleven thin sections were examined for petrographic information and alteration characteristics. The impregnated slabs from which the thin sections were cut were stained to distinguish relative amounts of potassium and plagioclase feldspars.

Pan concentrates were made from three samples to confirm the presence and identification of heavy minerals. Samples were chosen for this analysis on the basis of abundant heavy minerals observed during binocular microscope examination.
175-402

Location: Core REB 175 at a depth of 402 feet

Fine-grained, arkosic sandstone; grains angular to subangular; good sorting; fairly good induration.

Mineralogy

75% feldspars
25% quartz
Cement: calcite and white-argillaceous material

Common: chlorite, green biotite
Frequent: epidote
Rare: magnetite and ilmenite

Notes Epidote occurs both as detrital grains and within feldspar grains. 60% of feldspars are affected by sericitic alteration. Some grains contain epidote.
175-403

Location: Core REB 175 at a depth of 403 feet

Medium-grained, arkosic sandstone; grains angular to subrounded; fair sorting; fairly good induration.

Mineralogy

65% feldspars
35% quartz
Cement: calcite and white argillaceous material

Common: chlorite, green biotite
Frequent: epidote
Rare: magnetite, ilmenite, felsic lithic fragments

Notes
Epidote occurs both as detrital grains and within feldspar grains. Quartz displays patchy extinction. One grain which consisted entirely of chlorite and epidote was observed. Void spaces are lined with chloritic-argillic material and filled with calcite. 30% of the feldspars are appreciably sericitically altered; some appear quite fresh. Some altered feldspars also contain epidote. Chlorite-epidote grains may be altered mafic minerals.
175-404

Location: Core REB 175 at a depth of 404 feet

Medium- to fine-grained, arkosic sandstone; grains angular to subangular; fair to good sorting; good induration.

Mineralogy

60% feldspars
40% quartz
Cement: calcite and white argillaceous material

Common: chlorite, biotite
Frequent: magnetite, ilmenite
Rare: sphene, epidote-chlorite grains, muscovite

Notes
Void spaces are filled with calcite. Epidote occurs both as detrital grains and within feldspars. Minute zircons were observed as inclusions in quartz. 20% of feldspars are sericitically altered. Some feldspars contain epidote. Epidote-chlorite grains may be altered mafic minerals.
175-405

Location: Core REB 175 at a depth of 405 feet

Mineralogy

- 60% feldspar
- 40% quartz
- Cement: calcite, micas, white argillaceous material
- Common: chlorite, biotite
- Frequent: epidote
- Rare: magnetite, ilmenite, hematite-limonite, felsic lithic fragments

Notes
Some chlorite is authigenic, growing at right angles to the edges of detrital grains. Epidote occurs both as detrital grains and within feldspars and felsic lithic fragments. Void space is filled with calcite. 40% of feldspars are appreciably altered. Alteration is sericitic, argillic and hematitic. Some feldspars contain epidote. Plagioclase feldspars and the plagioclase-rich centers of zoned feldspars are more severely altered. Alteration follows cleavage and twin planes.
175-407

Location: Core REB 175 at a depth of 407 feet

Coarse-grained, arkosic sandstone; grains angular to subrounded; poor sorting; poor induration; high porosity and permeability.

Mineralogy

70% feldspars
30% quartz
Cement: Calcite, hematite-limonite and gray argillaceous material

Common: chlorite, pyrite, felsic lithic fragments composed of quartz and feldspar
Frequent: opaque minerals
Rare: biotite, mafic lithic fragments

Notes
Quartz displays patchy extinction and many grains are polycrystalline. Magnetite and ilmenite commonly occur along cleavage planes in chlorite and biotite. The single mafic lithic fragment is very rounded and appears altered. Pyrite is in nodular intergranular masses, appears almost drusy in some places and is tarnished. Hematite-limonite is observed rimming an opaque mineral, probably pyrite. Void spaces are lined with iron oxides or brownish micaceous minerals then calcite and filled with a mixture of quartz, hematite-limonite, opaque minerals, chlorite and argillaceous material. 50% of feldspars are affected by sericitic alteration as selvages and/or along cleavage and twin planes. Many altered feldspars also show pervasive hematitic alteration in thin section.
175-408

Location: Core REB 175 at a depth of 408 feet

Coarse-grained, arkosic sandstone; grains subangular to subrounded; fair to poor sorting; poor induration.

Mineralogy

65% feldspar
35% quartz

Cement: Gray and white argillaceous material, calcite, chlorite, hematite-limonite

Common: chlorite, biotite
Frequent: epidote
Rare: magnetite, ilmenite, blue molybdenum(?) mineral

Notes
Quartz shows patchy extinction and there are many polycrystalline grains. Epidote occurs both as detrital grains and within feldspars. Cracks in some grains contain authigenic chlorite. 50% of feldspars are altered sericitically; some are argilllic alteration is present. Some feldspars contain epidote. Orange feldspars are common in this sample.
175-410

Location: Core REB 175 at a depth of 410 feet

Coarse-grained, arkosic sandstone; grains angular to subrounded; poor sorting; fair to poor induration.

Mineralogy

60% quartz
40% feldspars
Cement: Hematite-limonite, and gray-green and white argillaceous material

Common: hematite-limonite
Frequent: biotite, chlorite
Rare: pyrite

Notes
Polycrystalline quartz grains are common. 70% of the feldspars show appreciable sericitic alteration. Some argillic alteration is present. Many feldspars have numerous hematite-limonite inclusions. Plagioclase feldspars may be more severely altered than others. Alteration is more intense along cleavage and twin planes.
175-413A

Location: Core REB 175 at a depth of 413 feet

Coarse- to medium-grained, arkosic sandstone; grains angular to subrounded; fair to poor sorting; fair induration.

Mineralogy

60% feldspars
40% quartz

Cement: white and green-gray argillaceous material, calcite

Common: chlorite
  - biotite
Frequent: magnetite, ilmenite
Rare: epidote

Notes
Epidote occurs within feldspar grains. 75% of feldspars are appreciably altered; alteration is mostly sericitic but argillic alteration is present. Colored feldspars containing abundant hematite-limonite inclusions are common. Plagioclase feldspars or the plagioclase-rich centers of zoned feldspars are more severely altered. Some feldspars contain epidote.
175-413B
Location: Core REB 175 at a depth of 413.5 feet

Argillaceous sandy siltstone; matrix supported with isolated angular grains of feldspar and quartz; good sorting; fair induration.

Sedimentary structures

1-mm thick layers of fine-grained chlorite are crumpled and curved. They may define deformed bedding.

Mineralogy

90% argillic matrix
5% feldspars
5% quartz

Common: hematite-limonite
Frequent: carbonaceous fragments
Rare: zircon(?)

Notes

Hematite-limonite occurs in splothy discontinuous bodies and is most common near the contact with the overlying sandstone. Orange feldspar grains are present below the contact with the sandstone. Hematite-limonite probably represents oxidized pyrite, which is commonly found at and near the contact between siltstones and overlying sandstones.
175-415

Location: Core REB 175 at a depth of 415 feet

Very fine-grained, sandy, argillaceous siltstone; sand grains angular to subangular; fair sorting; fair induration.

Mineralogy

40% quartz
40% feldspars
20% matrix

Cement: white argillaceous material, micas, minor calcite

Common: chlorite, biotite
Frequent: magnetite, ilmenite, epidote
Rare: hematite-limonite, carbonaceous fragments

Notes

Epidote occurs both as detrital grains and within feldspars. Opaque minerals are associated with chlorite and biotite. Within mica-rich layers, micaceous minerals are oriented subparallel to bedding. 20% of feldspars are sericitically altered. Several feldspars contain abundant hematite-limonite inclusions. Some feldspars contain epidote.
175-416

Location: Core REB 175 at a depth of 416 feet

Fine-grained, arkosic sandstone; grains angular to subrounded; good sorting; fair induration.

Mineralogy

45% feldspars
45% quartz
10% argillic matrix
Cement: white argillaceous material, minor calcite

Common: biotite, chlorite
Frequent: epidote
Rare: hematite-limonite

Notes
Mica grains are mostly biotite. Epidote occurs as detrital grains. 15% of feldspars are sericitically altered. A few small feldspars contain hematite-limonite inclusions.
Lithology and Alteration from Binocular Microscope Examination and Lithology Logs

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Lithology and Alteration from Binocular Microscope Examination and Lithology Logs

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# Lithology and Alteration from Binocular Microscope Examination and Lithology Logs

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Lithology and Alteration from Binocular Microscope Examination and Lithology Logs

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