THE GEOLOGICAL SURVEY OF WYOMING
Gary B. Glass, State Geologist

REPORT OF INVESTIGATIONS NO. 25

ALTERATION AND MINERALIZATION ASSOCIATED WITH SANDSTONE URANIUM OCCURRENCES, MORTON RANCH AREA, WYOMING

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1933
GEOLOGICAL SURVEY

ABSTRACT

Uranium concentrations occur at the boundary of an oxidized sandstone tongue of the Eocene Wasatch Formation in the Morton Ranch area, Powder River Basin, Wyoming.

Five major zones of alteration associated with uranium mineralization were recognized in the Morton Ranch area, using descriptions of outcrops, studies of heavy mineral distribution, and trace-element data. Recognition of these alteration zones from surface mapping, drill cores, and cuttings can direct the exploration geologist to mineralized zones in similar sedimentary uranium regions.

The uranium occurrence in the Morton Ranch Area was formed by an influx of oxidizing water into a calcareous, pyrite-bearing sandstone unit. The oxidizing water contained dissolved uranium as well as vanadium, molybdenum, selenium, and possibly copper and silver. The boundary of the zone of oxidation migrated down the ground water flow gradient at a rate slower than the ground water flow. This boundary became the location of pyrite and organic carbon which precipitated uranium and other trace elements.

INTRODUCTION

This report describes the physical and chemical changes of the host rocks associated with known uranium occurrences in the Morton Ranch area of the Southern Powder River Basin Uranium District, Wyoming. These changes can guide exploration in this area and, with some modification, may prove useful for exploration in other sedimentary rocks.

Characteristics of the uranium occurrences were determined by field observation including outcrop and core examination, and by bore hole electrical logs, chemical analysis for trace elements, and heavy mineral determinations.

ACKNOWLEDGMENTS

Funding for this study was provided by Teton Exploration Drilling Company of Casper, Wyoming under the direction of the late Dr. Philip N. Shockey and of Richard Lisco, President of Teton Exploration. This report is a synthesis of a part of a Master of Science thesis (Harris, 1982) under the direc-

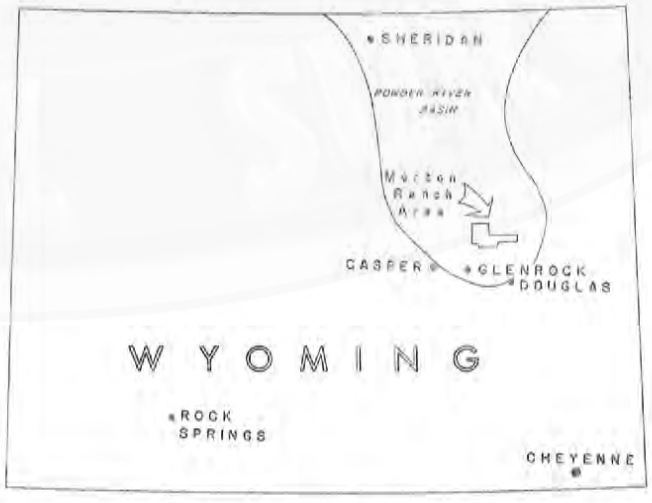


Figure 1. Index map, Morton Ranch area.

tion of Dr. Robert S. Houston, University of Wyoming. Permission to publish this report was granted by Teton Exploration. The logs used in Plate 1 were provided by the Tennessee Valley Authority.

LOCATION AND ACCESS

The Morton Ranch area is located in the southern Powder River Basin of eastern Wyoming, about 20 miles north of Glenrock (Figure 1). Douglas is 30 miles southeast of the area, and Casper is about 50 miles west. The area is accessible from either Douglas or Glenrock by paved county roads leading to Exxon Mineral Company's Highland Uranium Mines. From the Highland Mine area, numerous graded roads lead to much of the Morton Ranch area. Field work for this project was completed in 1970, at which time the Highland Mine property was under development. The uranium deposits of the Morton Ranch Area are currently being developed by Silver King Mines, Inc., under a contract with the Tennessee Valley Authority.

GEOLOGICAL SETTING

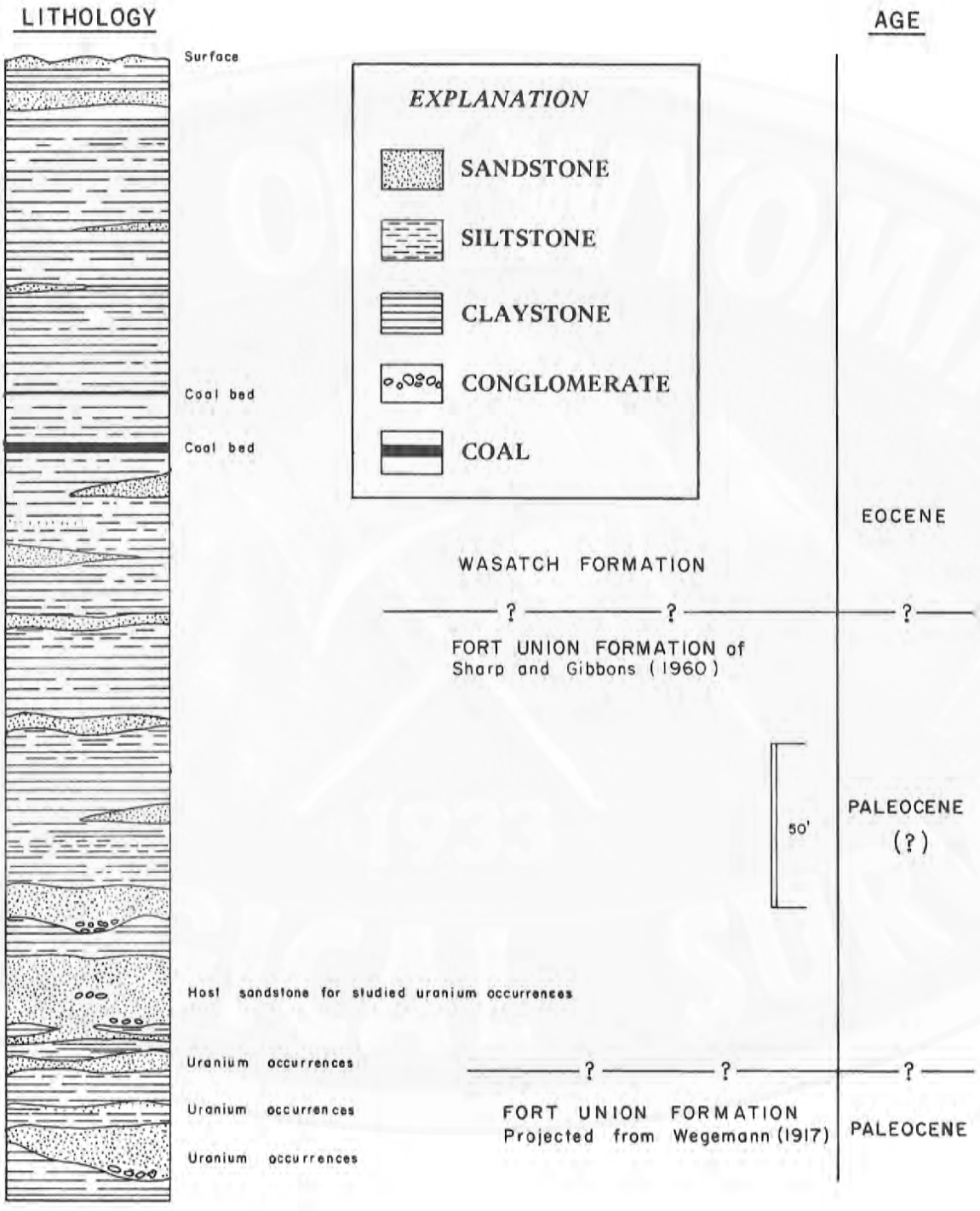
The Powder River Basin is a large structural and topographic depression covering much of northeastern Wyoming and part of southeastern Montana. The basin is asymmetric with the basin axis located near the western margin. Rocks west of the axis dip steeply into the basin from the Bighorn Mountains and the Casper Arch. Rocks east of the axis have average dips into the basin of less than two degrees. The Morton Ranch area is located immediately to the east of the basin axis, near the deepest part of the basin. Dips average one or two degrees to the west-southwest (Sharp and Gibbons, 1964). Faulting within the basin is minor, and no faults have been mapped in the area.

The rocks exposed in the Morton Ranch area consist entirely of fluvial claystones, siltstones, arkosic sandstones, and conglomerates of the Paleocene Fort Union and early Eocene Wasatch Formations (Figure 2). Near the study area, the Wasatch overlies the Fort Union Formation with angular unconformity, but in the area the contact is conformable and the position of the Wasatch - Fort Union boundary is uncertain.

At Pumpkin Buttes, near the center of the Powder River Basin and north of the area of study, the Wasatch is overlain by tuffaceous sediments of the Oligocene White River Formation. South of the area, the White River sediments overlie dipping beds of the Fort Union and older formations with angular unconformity (Sharp and Gibbons, 1964). The sediments of the White River Formation presumably once overlay the Wasatch Formation in the Morton Ranch area and have been removed by erosion (Love, 1952).

The uranium deposits of the Morton Ranch area are found in 20- to 70-foot-thick, cross-bedded, arkosic sandstones interbedded with shales, silstones, and coals. The sands occur within either the upper part of the Paleocene Fort Union Formation (Sharp and Gibbons, 1964) or the lower part of the Eocene Wasatch Formation (Davis, 1969) — due to the similarities of lithology of the Wasatch and Fort Union, and to the lack of diagnostic fossils and depositional breaks, these formations are not distinguishable from one another in the study area.

The Wasatch Formation consists of interbedded sandstone, conglomerate, and claystone. Coarse-grained units are common in the lower part of the formation and make up a greater proportion of the formation at the south end and in the center of the Powder River Basin. The coarse-grained units generally thin and become less common northwards and



Figures 2. Columnar section, Morton Ranch area.

towards the eastern and western basin margins (Sharp and Gibbons, 1964). Channel cut-and-fill and festoon cross-stratification are characteristic of the sandstones, though massive to flaggy, parallel-bedded units are common, particularly with the finer-grained sediments. Remnants of organic material are preserved throughout the formation as coalified organic debris. In a few localities, silicified wood has been found.

The age of the Wasatch Formation in the Powder River Basin was established as Eocene from fossil evidence near Pumpkin Buttes (Wegemann, 1917).

Sandstones of the Fort Union Formation in the Morton Ranch area are identical to those of the Wasatch, according to Sharp and Gibbons (1964), with the exception of certain heavy minerals. Wasatch sands contain hornblende, actinolite, monazite, and rare tremolite and spinel while Fort Union sands do not contain these but do contain andalusite (Sharp and Gibbons, 1964, p. 315). Since all of these heavy minerals were found together in the Morton Ranch area, Sharp and Gibbons' data are not diagnostic there.

The host sandstones in the Morton Ranch area are arkosic, and average 35 percent quartz, 31 percent feldspar, 9 percent chert, 2 percent muscovite, and 12 percent other minerals.

The source of the host sandstones in the Morton Ranch area is inferred to be the Laramie Mountains. Although some authors, including Love (1952), suggest that the Granite Mountains area of central Wyoming was the source of the sediments of the Wasatch and Fort Union Formations, recent studies by the U.S. Geological Survey (Seeland, 1976) show that the Laramie Mountains were the primary source for the sediments in the Morton Ranch area, with a small contribution from the Hartville Uplift. Directional studies of sediment transport, including cross-bedding, grain size distribution studies, and mineralogical studies (Sharp and Gibbons, 1964), also favor the Laramie Mountains. In particular, the mineralogy of the sands implies a metamorphic terrain in the source area. Metamorphic units are present in the Laramie Mountains, but are minor constituents of the Granite Mountains. According to Seeland (1976), the Granite Mountains were an important source area for the western Powder River Basin.

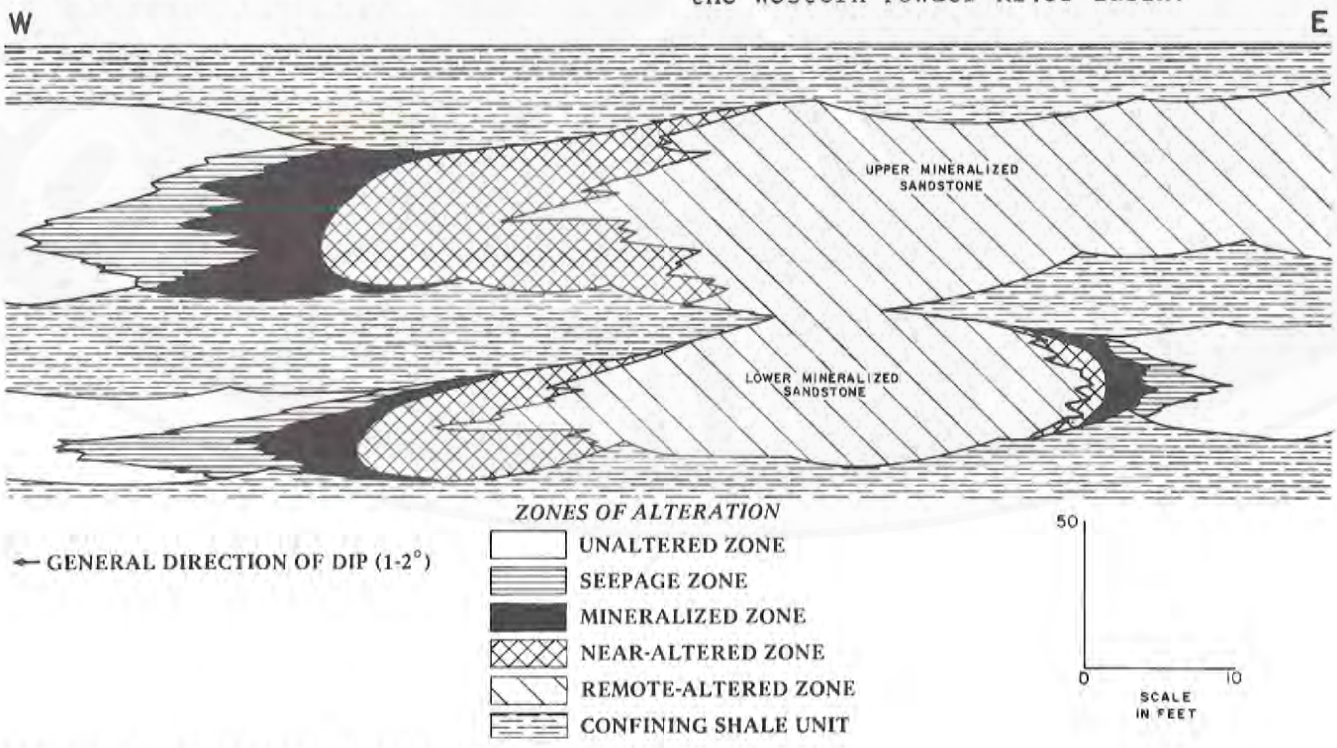


Figure 3. Idealized Morton Ranch roll front.

FIELD DESCRIPTIONS OF ALTERATION

Five distinct zones of alteration are recognized in sandstone of the Wasatch Formation in the Morton Ranch area. These zones represent the changes produced by a geochemical cell, which is the boundary region between sandstone containing reductants and sandstone containing oxide and hydrous oxide minerals. The spatial relationship of the zones is shown in Figure 3. Each zone is characterized by distinctly recognizable features in both surface exposures and drill core samples. The zones, from unaltered ground to altered ground, are (1) the Unaltered Zone, (2) the Seepage Zone, (3) the Mineralized Zone, (4) the Near-Altered Zone, and (5) the Remote-Altered Zone. (this zonation is modified after Rubin's nomenclature, 1970.) Recognizing these zones in the field and in cores and cuttings, aided by gamma logs, is a major aid in locating the mineralized zones.

UNALTERED ZONE

The Unaltered Zone represents the host rock unaffected by mineralizing solutions. The recognition of this zone is important when comparing the effects of the mineralizing solutions on the host rock with normal weathering and diagenesis.

Unaltered Wasatch sandstone in the Morton Ranch area (and the Powder River Basin in general) is characteristically light to medium grey (N7 to N5)* on fresh outcrops or in drill cores. Organic debris in the form of carbon films or recognizable plant remains is common. The carbon is uncorroded, relatively hard, and flaky but not powdery. The presence of such organic carbon is perhaps the best and most reliable indication of the Unaltered Zone. This zone is also characterized by the presence of pyrite, abundant black heavy-mineral grains, grey, grey-green, or dark red clay lumps or galls, and often but not always, calcite in the matrix of the sand.

On gamma-ray and electric logs, the Unaltered Zone is indistinguishable from the Near-Altered and Remote-Altered Zones. An increase in conductivity should occur due to the presence of pyrite, but this was not detected in the observed logs (see log MXC 13 *vs* MXC 2, Plate 1).

There may be some alteration due to diagenesis or weathering. Feldspar grains may be partially altered to clay minerals, and dark clay galls may have a light-colored rim. Iron-, manganese-, or calcite-cemented concretions are common.

Surficial weathering, which extends five to fifteen feet below the surface in the Powder River Basin, may destroy or mask certain characteristics of the Unaltered Zone. Weathered Unaltered Zone outcrops are colored pale yellowish brown to yellowish orange by limonite (10YR 6/2 to 10YR 7/6). Calcite is enriched in the rocks in the zone of weathering, and surficial oxidation may destroy organic carbon along with pyrite and black heavy minerals. Concretions, particularly calcite-cemented concretions, may preserve some of the original characteristics of the unweathered rock due to their relative resistance to weathering compared with the rest of the sandstone unit. In weathered outcrops, concretions may provide the only means of identifying the zone of alteration.

*Note: All color references conform to standard GSA nomenclature (Geological Society of America, 1970).

SEEPAGE ZONE

The Seepage Zone in the Morton Ranch

area is characterized by the first appearance of limonite staining in unweathered rocks. This colors the rock a yellowish grey (10YR 7/1). Limonite first appears as small areas of stain on individual grains and increases as the Mineralized Zone is approached until as many as 20 percent of the grains are coated with yellow or orange limonite stain. Limonite staining may be particularly intense around pyrite or magnetite grains; generally the pyrite and magnetite grains appear etched and corroded. Carbon debris is present, and is usually surrounded by a zone up to one half inch wide in which limonite staining does not occur. Carbon may occur as a powdery coating and may be slightly corroded. The calcite content of the rock increases in this zone, reaching a maximum at the contact between the Seepage Zone and Mineralized Zone. Quartz and feldspar grains are unaltered, except for the kaolinitization of some of the feldspar grains, noted previously in the Unaltered Zone. Sometimes, as a Mineralized Zone is approached, gamma-ray logs indicate higher radiation (see MCV 5, Plate 1). This is the only observable gamma and electric log characteristic, and forms the basis for Rubin's (1970) classification of the Seepage Zone. Often, however, this increase is not present or is too slight for detection by downhole gamma radiation detectors.

Unfortunately, the characteristics of this zone are identical to the effects of surface weathering upon the Unaltered Zone. These effects include an increase in calcite content and the corrosion of pyrite. Therefore, an examination of weathered outcrops cannot distinguish the Seepage Zone from the Unaltered Zone. Concretions, also, are not helpful. Drill cores or cuttings of unweathered rock, however, will identify this zone.

MINERALIZED ZONE

Characteristics of this zone vary greatly between mineralized areas and even between samples taken along strike in one area. As an example, minable-grade uranium mineralization is not present everywhere along a roll. Although there are even sections of the zone that may contain no uranium mineralization, the eye cannot distinguish these barren zones from the mineralized zones.

In cross section, this zone is usually a modified "C" shape, with the concave side next to the Near-Altered Zone and a diffuse convex boundary next to the Seepage Zone. This shape is called a "roll," a term first used by miners of eastern Utah and western Colorado uranium deposits in the early 1950's. The trend of the Mineralized Zone in the Morton Ranch area, as elsewhere in similar deposits, is called a "roll front."

Electric and gamma-ray logs distinguish the Mineralized Zone. Discounting the effects of gamma-ray disequilibrium due to the chemical segregation of uranium-daughter products such as radium, thorium, and lead, the Mineralized Zone shows gamma-ray maxima due to the uranium present (see log MXC 15, Plate 1). However, if uranium is not present in the Mineralized Zone, the gamma-ray effect is absent or a result of daughter product decay. Porosity is attenuated because of mineralization. This is especially notable on log MXC 15, which shows a porosity decrease in the Mineralized Zone in sandstone below unmineralized sandstone. Porosity determinations carefully made from electric logs may be used to distinguish between mineralized sandstone not containing uranium and unmineralized sandstone.

Characteristic of the unweathered Mineralized Zone is its dark-grey to black

color (N3 - N1). Surficial weathering will oxidize some of the dark uranium minerals to brightly colored yellow and yellow-green species. The dark-grey to black color is due to a dark coating on the grain surfaces, which may be coating caused by carbon, uranium minerals, manganese minerals, or any combination of these. Carbon is enriched in this zone, sometimes forming the matrix of the rock; sometimes, carbon apparently replaces quartz and feldspar grains. Pyrite is also abundant, and sometimes forms the matrix of the rock. Small spheres, one eighth to three quarters inches in diameter, consisting of sand cemented by pyrite, are often found in the ore zone. Calcite is present in discrete areas within the Mineralized Zone. Coalified plant material may be present, sometimes replaced in part by pyrite or uranium minerals. Smoky quartz, formed by the radioactive bombardment of quartz grains (Forman, 1951), may be present. Smoky quartz is restricted to the Mineralized Zone: it apparently reverts to clear quartz in the altered zones (Forman, 1951). In the Felder uranium deposit of south Texas, smoky quartz is the most diagnostic indicator of the uranium-rich zone (Klohn and Pickens, 1970). Smoky quartz may be a reliable guide to the Mineralized Zone in other uranium deposits as well (Saucier, 1972). Weathered outcrops of the Mineralized Zone show intense dark brown or dark red iron staining in many cases, masking the dark grey color of the zone. If uranium is present, surficial oxidation produces brightly colored yellow or green uranium minerals.

NEAR-ALTERED ZONE

The Near-Altered Zone is characterized by limonite and hematite staining with the limonite predominating, giving the rock a greyish orange to light brown color (10YR 7/4 - 5YR 5/6). This zone extends from the ore zone to the area where hematite predominates over limonite (the boundary with the Remote-Altered Zone). The width of the zone varies between a few inches or less to a few hundred feet. Within the Near-Altered Zone, limonite staining is not uniform, and some areas have little limonite stain. Rings and bands of limonite, resembling Liesegang Rings, are common. Hematite is usually present in small lumps, in Liesegang Rings, or in small areas of stain. Organic carbon is present only in small, badly corroded fragments. These are powdery, dusty, or sooty; recognizable plant fragments were not seen in this zone in this study. The organic carbon remains are usually surrounded by an area in which limonite stain is less common or absent. Pyrite is present as badly corroded fragments, but decreases in abundance with distance from the Mineralized Zone. Magnetite and other black heavy minerals are rare. Calcite is absent. Some clay galls are soft and crumbly, others appear unaltered, and some may have a dark rim. Quartz grains are clear and unaltered, and no smoky quartz has been observed in this zone or anywhere outside of the Mineralized Zone: it has apparently reverted to clear quartz as suggested by Forman (1951).

Weak remnant gamma-ray anomalies may occur in this zone, marking the position of a former locus of the Mineralized Zone. These "ghost rolls" may mislead an unwary geologist unless cuttings or core are examined for alteration zone characteristics and checked for uranium by chemical analysis. The "ghost rolls" are produced by remnant concentrations of immobile radioelement daughter products such as Thorium-230 or Bismuth-214. Another distinguishing characteristic of this zone is an increase in porosity due to the removal of pyrite, organic carbon, and calcite matrix. This porosity increase is detectable on electric logs. Two gamma-ray peaks known as "rabbit ears" sometimes mark the Mineralized Zone. When present, the "rabbit ears" are found above and below the Near-Altered Zone (log MXC 2, Plate 1).

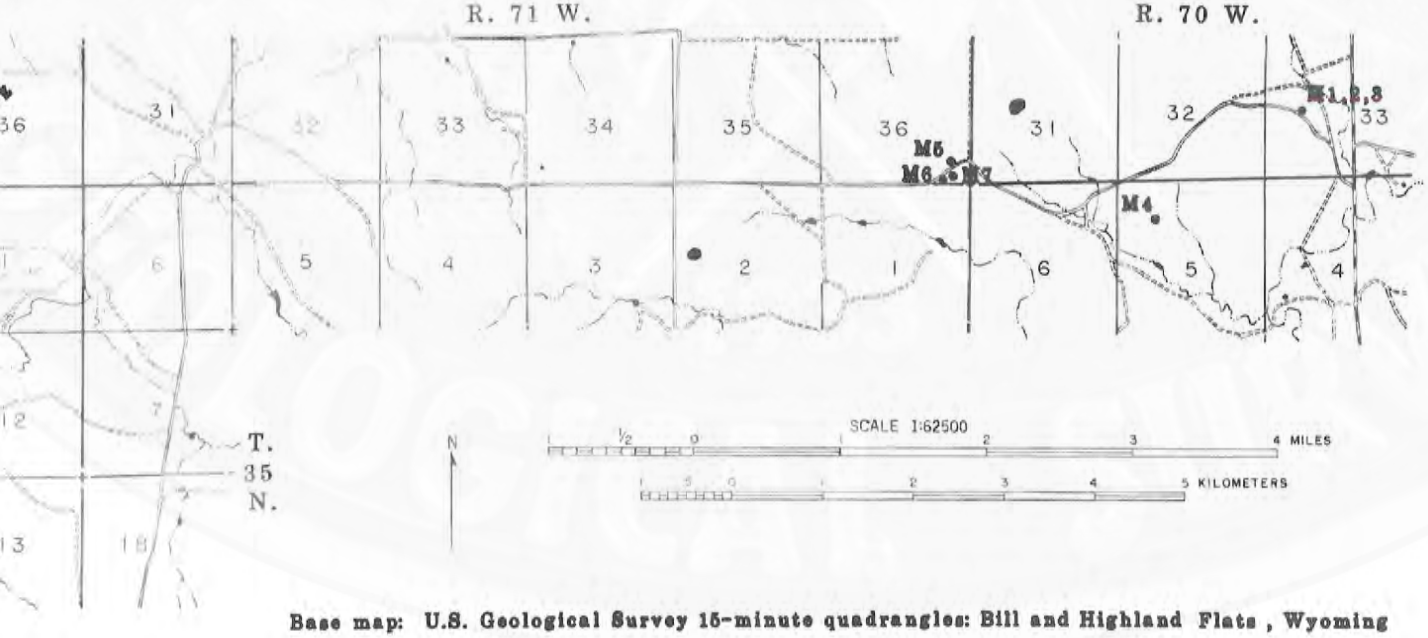
EXPLANATION

M14 — Sample number

Roll front boundary, dashed where approximate. Arrow shows direction of cell movement from altered into unaltered rock.

B — B′ Cross section

INDEX MAP



Base map: U.S. Geological Survey 15-minute quadrangles: Bill and Highland Flats , Wyoming

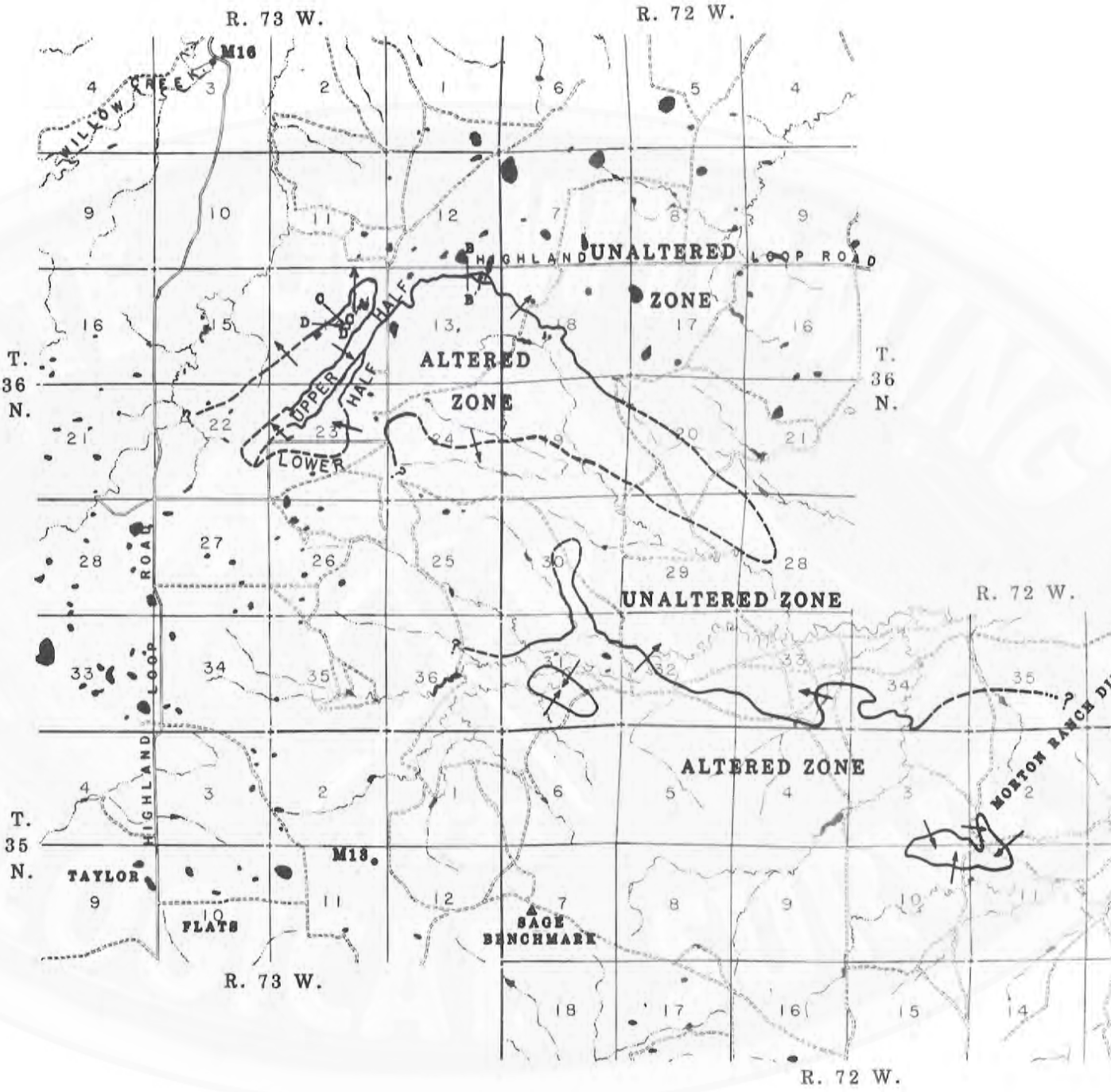

R. 73 W.
R. 72 W.
M16
WILLOW CREEK
HIGHLAND
UNALTERED
LOOP ROAD
ZONE
UPPER
HALF
ALTERED
ZONE
LOWER
T. 36 N.
UNALTERED ZONE
R. 72 W.
HIGHLAND LOOP ROAD
ALTERED ZONE
MORTON RANCH DI
T. 35 N.
TAYLOR
M18
FLATS
SAGE
BENCHMARK
R. 73 W.
R. 72 W.

Figure 4. Map of Morton Ranch area, upper roll front.

Figure 5. White alteration, Morton Ranch area.

Surface weathering has little or no effect upon the characteristics of the rocks of this zone. Details of some features may be obscured, such as Liesegang Banding, but the overall aspect of the rocks is unchanged. The only observed near-surface change is the addition of calcite, which is emplaced by the surface evaporation of calcium-carbonate-bearing water (calichification).

REMOTE-ALTERED ZONE

Four subzones of the Remote-Altered Zone were observed within the Morton Ranch area. Each subzone is a rather unique manifestation of alteration, and the spatial relationships of these subzones do not reveal a standard succession except that the Red Subzone sometimes occurs close to a Mineralized Zone.

Gamma-ray and electric logs do not indicate the presence of the Remote-Altered Zone. A slight decrease in porosity due to limonite and hematite cement may occur, but other factors, particularly depositional variables, could reduce porosity. Only an examination of cuttings or core will document limonite and hematite cement. Gamma-ray and electric logs also do not distinguish between the subzones of the Remote-Altered Zone. As in the Near-Altered Zone, smoky quartz is not present.

Baill's Pink Subzone. The Baill's Pink Subzone is the most extensive type of remote alteration. It is widely found on the surface and in drill samples. Characteristic of this type of alteration is a moderate red color (5R 5/2 to 5R 5/4), known locally as Baill's Pink. This color more or less uniformly stains the rock, sometimes enhancing stratification, and may be present over wide areas without any color variation. In the Morton Ranch area, the best exposures of this type of alteration are found along Morton Ranch Divide, particularly near Sage, and just north of Taylor Flats along the Highland Loop Road (Figure 4). Another characteristic of this zone is the absence of carbonaceous plant remains,

pyrite, magnetite, and calcite. Trace amounts of corroded lumps of concretionary limonite are also characteristic. Surface alteration, again, has little effect on this zone except to add calcite.

White Subzone. The White Subzone of the Remote-Altered Zone was only observed in surface outcrops. The white coloration is due to the production of kaolinite by surface processes unrelated to the mineralizing solutions. Large amounts of kaolinite as grain coatings color the outcrops a greyish-white to white (N8 to N7). This type of alteration is best exposed in the northwest corner of the study area along Willow Creek (Figures 4 and 5). Characteristic of this zone is the absence of carbon, pyrite, magnetite, and calcite. Surface alteration may add calcite, and also may add a limonite stain which colors weathered exposures a very pale orange (10YR 8/2). Kaolinite has not been found in Unaltered Zone rocks.

Red Subzone. The Red Subzone is characterized by intense hematite staining, coloring the rock dusty red to moderate red (5R 3/4 to 5R 4/6). This alteration

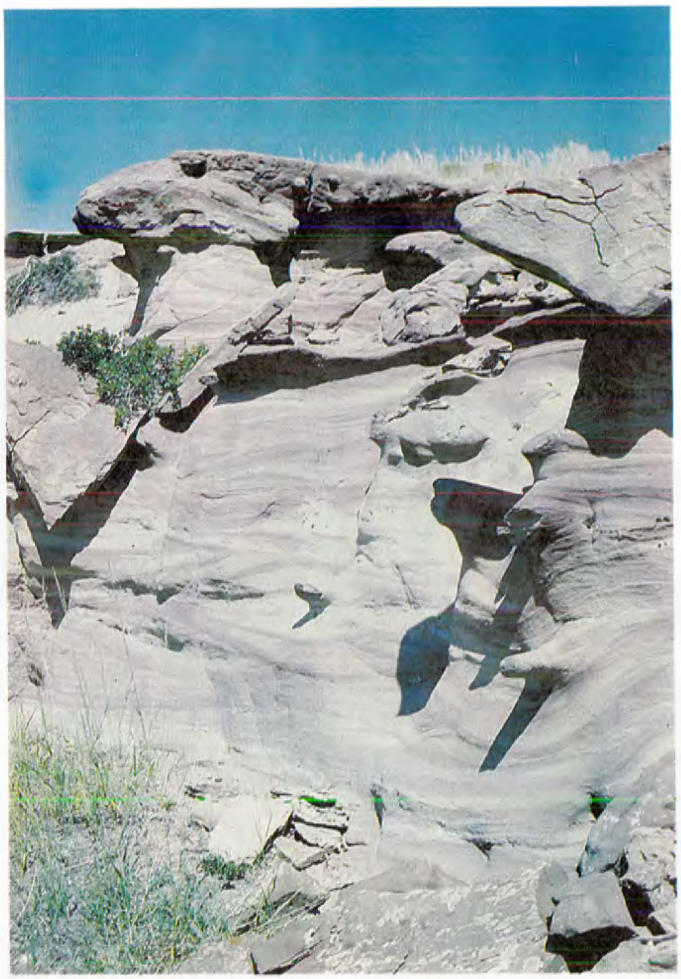


Figure 6. Red alteration, Morton Ranch area.

Figure 7. Liesegang banding, Morton Ranch area.

apparently is located nearest the boundary of the Remote-Altered Zone with the Near-Altered Zone. This alteration has been observed both in drill cores and on surface outcrops. Excellent exposures are located along the Morton Ranch Road immediately west of the Old Box Creek mining district in Sections 12 and 13, T.35N., R.72W. (Figures 4 and 6). Striking solution banding features resembling Liesegang Rings are exposed in areas in which cross-stratification is strongly accentuated by red alteration (Figure 7). This banding was also observed in drill cores. Carbon and pyrite are absent except for isolated concretionary relicts. Nodular calcite concretions surrounding silicified wood were found in this zone along the Morton Ranch Road. The effects of surface alteration are apparently minor and limited to an increase in calcite and probably an increase in feldspar alteration to kaolinite.

Green Subzone. The Green Subzone of the Remote-Altered Zone was only observed in several drill core samples, where it occurred near the base of the sandstone unit, near the lower "rabbit ear". This subzone is characterized by a dark greenish grey (5G 4/1) coating on all the grains and the matrix. Small spots of dark red hematite stain occur scattered throughout most of the subzone. No calcite, pyrite, or carbon was observed in samples of green alteration. Its apparent restricted occurrence limits its usefulness as a guide to ore. The green color is apparently a clay mineral, but it is not crystalline chlorite.

ZONAL MORPHOLOGY

Information from cores and subsurface logs was used to prepare four cross sections of the Mineralized Zone and related zones in the Morton Ranch area. These cross sections — A-A', B-B', C-C', and D-D' — are plotted on the map of the Morton Ranch area, Figure 4, which also shows the location of the upper geochemical cell boundary and the position of the altered and unaltered zones in plan view.

Figure 8, cross section A-A', shows a simple roll front morphology, broken by two clay seams. The Remote-Altered Zone (Red Subzone) was encountered in cores MXC 1 and 2. The Seepage Zone was encountered in holes MXC 4 and 5 and the Unaltered Zone was penetrated by MXC 5. This section is typical of a simple roll front.

Figure 9, cross section B-B', shows a complex roll front developed in three sand units separated by impermeable clays. The upper zone, from elevation 4,880 feet to 4,900 feet, is a simple roll. This roll exhibits relict "tails" of Mineralized Zone material at the lowest boundary of the sand — especially in a channel cut into the clay at the position of core MXC 8. These tails were possibly left by reduced groundwater flow rates in the channel. A remnant zone of limonite alteration of the Near-Altered Zone, surrounded by the Red Subzone of the Remote-Altered Zone, is present in MXC 7.

The middle roll front, from elevation 4,857 feet to 4,875 feet, is a simple roll although it is complicated by a number of clay breaks. This roll is offset towards the altered side of the upper roll.

The lower mineralized zone occurrences are of great interest. Between holes MXC 6 and MXC 7, the lower confining clay unit of the middle zone was breached by a sand channel. The geochemical cell entered the lower sand (4,848 to 4,854 feet) through this break and migrated outward from the break, producing an updip (or reverse direction) migrating roll front as seen in MXC 6.

This phenomenon has been encountered elsewhere in the Morton Ranch area. Figure 10 shows the location, from drill data, of the roll front formed in the lower of two sandstone units. A closed roll front is centered in sections 3,4, 9, and 10, T.35N., R.72W. This is a larger-scale manifestation of the phenomenon seen in section B-B' (Figure 9). This area is beneath the altered zones of the roll front formed in the upper sandstone that is plotted on Figure 4.

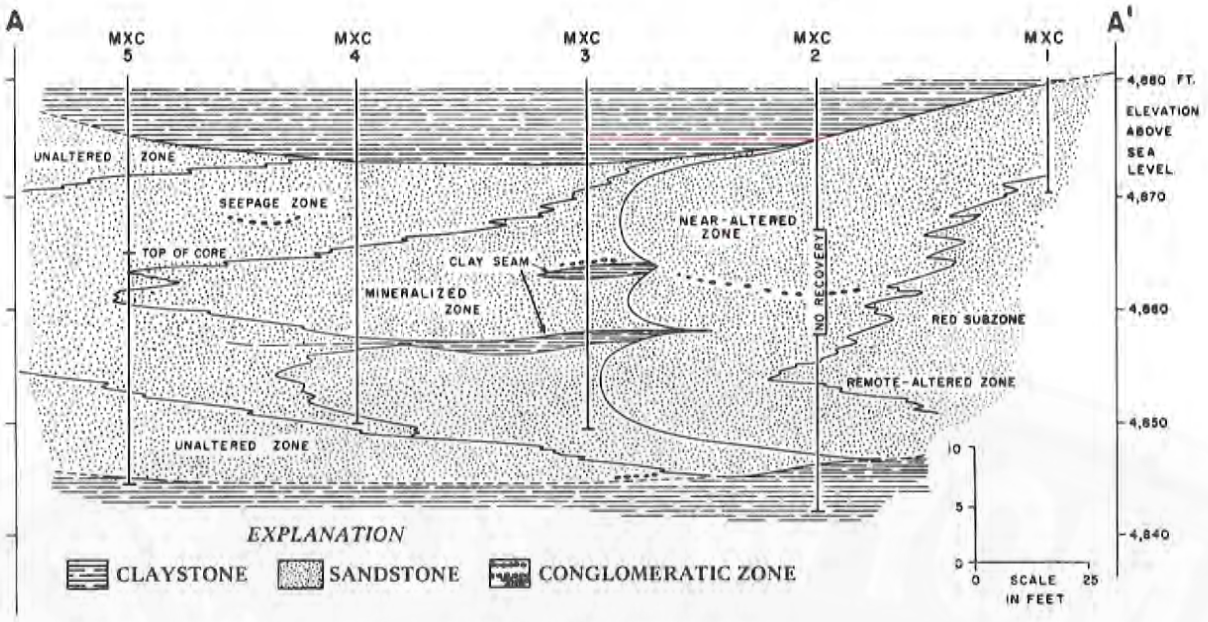


Figure 8. Cross section A-A', Morton Ranch area

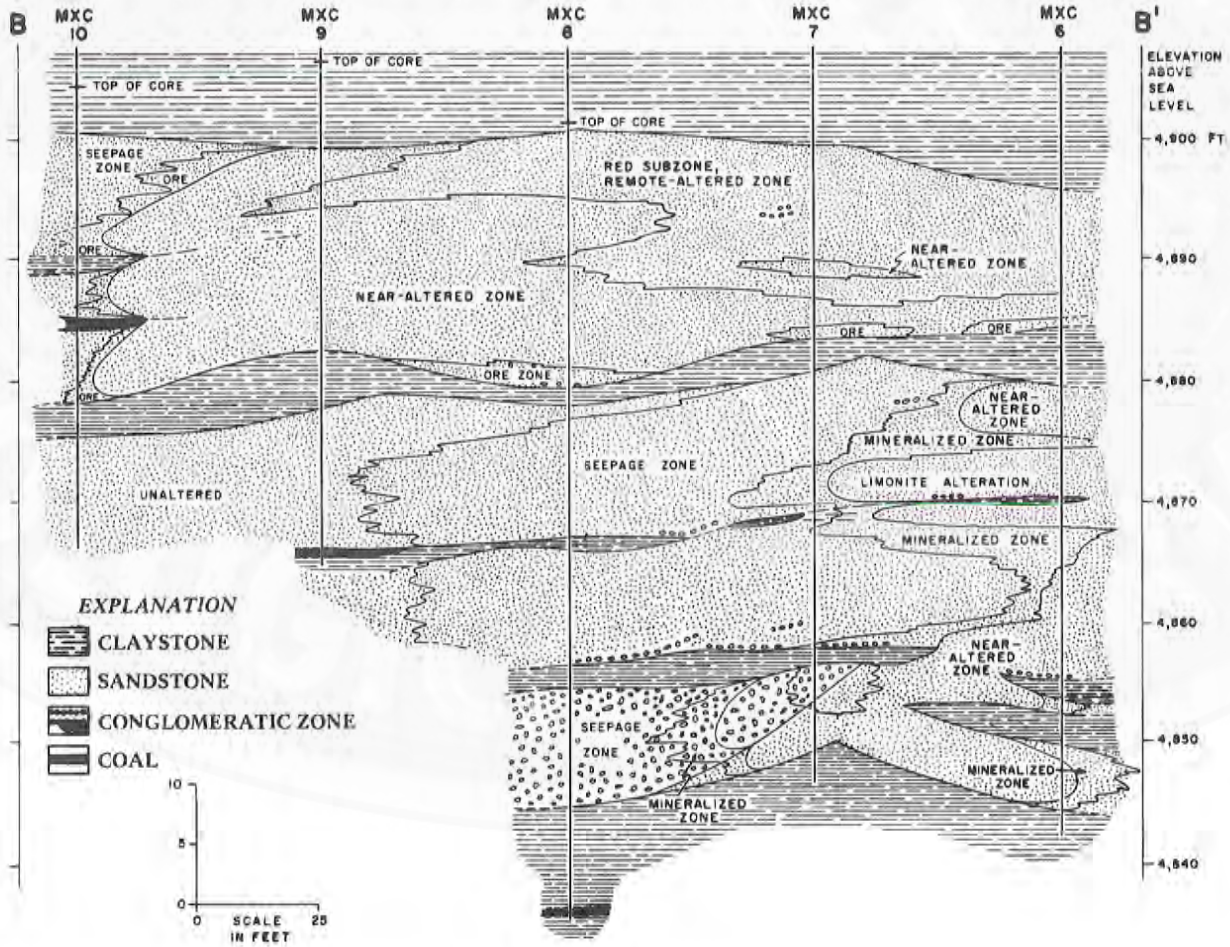


Figure 9. Cross section B-B', Morton Ranch area

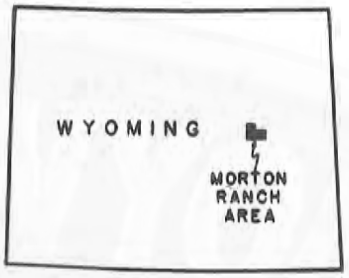
Figure 10. Map of Morton Ranch area, lower roll front.

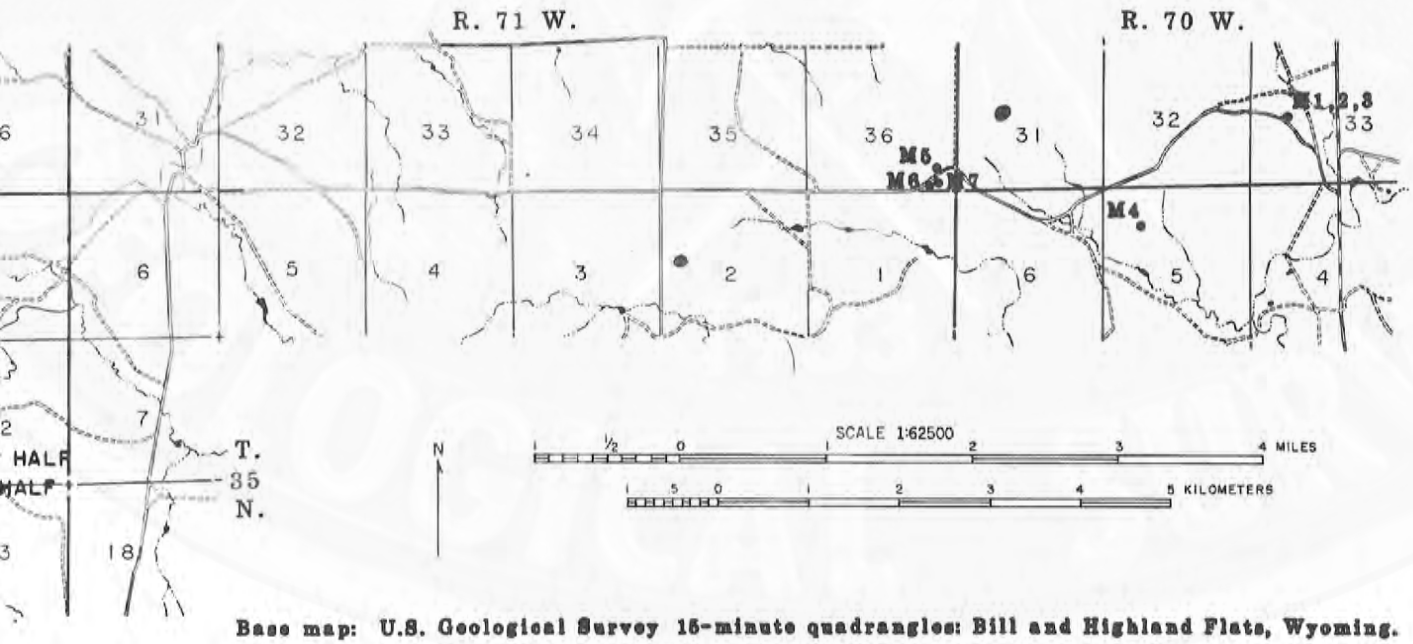
EXPLANATION

M14 Sample number

Roll front boundary, dashed where approximate. Arrow shows direction of cell movement from altered into unaltered rock

INDEX MAP





Base map: U.S. Geological Survey 15-minute quadrangles: Bill and Highland Flats, Wyoming.


R. 73 W.
R. 72 W.
M16
WILLOW CREEK
LOOP ROAD
UNALTERED ZONE
HIGHLAND
UPPER HALF
LOWER HALF
T. 36 N.
ALTERED ZONE
HIGHLAND LOOP ROAD
T. 35 N.
TAYLOR FLATS
M18
SAGE BENCHMARK
MORTON RANCH DIV
ALTERED ZONE
UNALTERED

(Smaller closed rolls noted from Teton Exploration's drilling program of the Morton Ranch area are not shown on Figure 10.) When geochemical cell migration occurs in an updip direction, all such closed roll fronts show downdip migration distances much greater than updip migration distances. Apparently, updip migration of the roll front against a small downdip flow of ground water in the lower sandstone unit is possible if the flow is not the only cause of roll front migration. Other possible causes are a migration of oxygenated water to areas of lower oxygen content by diffusion, or migration due to bacterial action as suggested by Jensen (1963). Alternatively, groundwater movement in these small, partially closed aquifers may be outward from the point of contact with the major aquifer. The surrounding shales and silts act as an aquatard, reducing rather than preventing the passage of ground water.

Figure 11, cross section C-C', shows a simple roll front. An area of hematite alteration observed at elevation 4,869 feet may intersect the main body of hematite alteration but perpendicular to the cross section. Coal beds seen in core MXC 13 were destroyed by the passage of the cell, illustrating the mobilization and removal of carbon from the Unaltered Zone due to the passage of the roll front.

Figure 12, cross section D-D', again illustrates a simple roll. The passage of the roll has been retarded by a less permeable silty claystone, and the location of the roll may be influenced by the constriction of the permeable host sandstone.

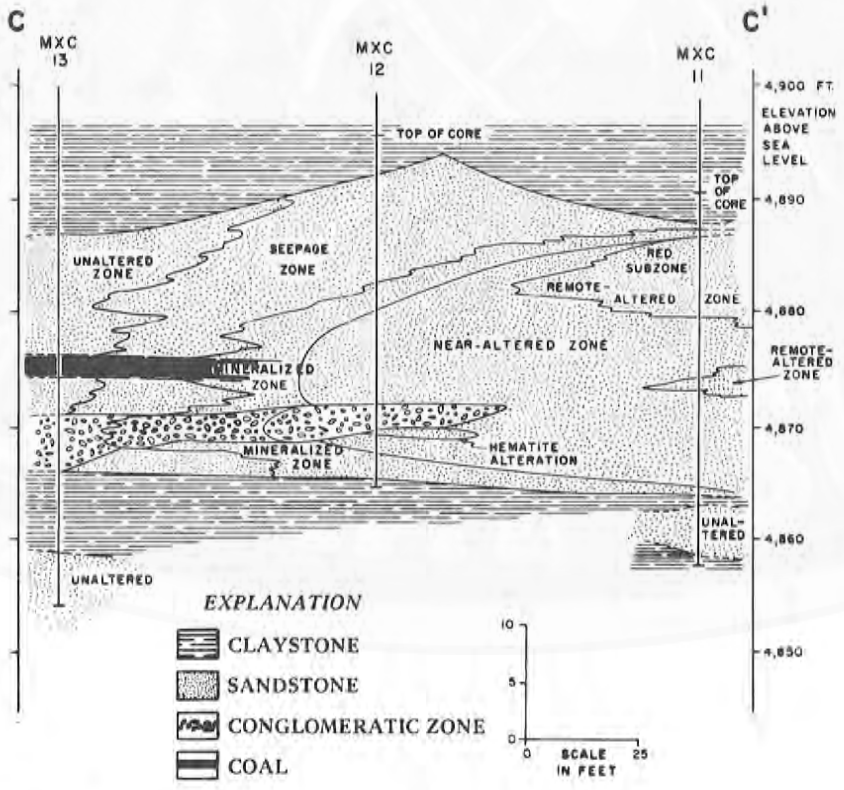


Figure 11. Cross section C-C', Morton Ranch area.

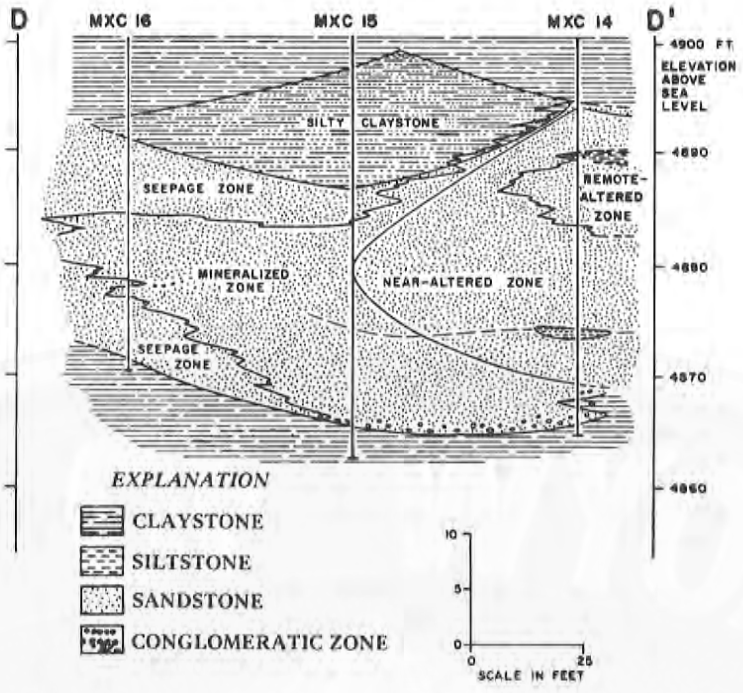


Figure 12. Cross section D-D', Morton Ranch area.

ANALYTICAL DATA

This section is an element-by-element and mineral-by-mineral description of the data given in Tables 1 through 3. The zones of alteration and mineralization described in this section are the same as those of field descriptions. No modification of these zones is necessary as a result of this data.

WHOLE-ROCK CHEMISTRY

Methods. Analytical information for this study was provided by the sponsoring company, Teton Exploration, through their contracts with commercial analytical laboratories. Samples of rocks were analyzed for uranium by X-ray fluorescence. Analyses for arsenic and selenium were by wet chemical methods. The remaining analyses were by atomic absorption in laboratories at the University of Wyoming's Department of Geology and Geophysics. Replicates were submitted, and good correlation was shown by duplicate samples.

Uranium. Uranium is present in detectable amounts only within the Mineralized Zone (Table 1). However, it is not always present in the Mineralized Zone. Because the uranium content of the other zones is below the detection limit (0.010 percent) of the method used, no difference in the uranium content of those zones is noted. Harshman (1972), in his discussion on the Shirley Basin deposits, reports that essentially unmineralized altered sandstone has a slightly greater content of uranium (6-15 ppm) than does the unaltered sandstone (4-8 ppm). On the other hand, Renfro (1969), reporting on uranium deposits in the Cretaceous of the Black Hills area, shows that unaltered sandstone averages somewhat higher in uranium content than does altered sandstone, 14 ppm *vs.* 5 ppm.

From the data (Table 1), it may be seen that uranium is not a definitive constituent of the Mineralized Zone. Harshman (1972, page 59) reports uranium grades in altered zone material in the Shirley Basin within a few

Table 1. Uranium, arsenic, selenium and vanadium analyses, Morton Ranch area cores.

Core #	Elevation	As%	Se%	U%	V%
MXC-1	4884	ND	ND	ND	0.018
MXC-1	4881	0.003	0.005	0.178	0.010
MXC-1	4878	0.002	0.004	ND	0.015
MXC-1	4875	0.005	0.021	ND	0.009
MXC-2	4879	0.004	0.001	ND	0.056
MXC-2	4876	0.008	0.001	0.010	0.015
MXC-2	4873	0.007	0.008	0.286	0.026
MXC-2	4871	0.003	0.001	0.323	0.056
MXC-2	4869	0.001	0.018	ND	0.004
MXC-2	4858	0.005	0.014	ND	0.005
MXC-2	4853	0.012	0.019	ND	0.035
MXC-2	4851	0.010	0.086	0.052	0.047
MXC-2	4849	0.008	0.004	1.16	0.091
MXC-2	4847	0.005	0.002	0.443	0.026
MXC-2	4845	0.009	0.008	ND	0.041
MXC-3	4874	ND	ND	ND	0.038
MXC-3	4871	0.004	0.007	0.104	ND
MXC-3	4868	0.016	0.005	0.262	0.045
MXC-3	4866	0.016	0.103	ND	0.034
MXC-3	4862	0.008	0.015	ND	0.006
MXC-3	4860	0.004	0.007	0.114	0.010
MXC-3	4858	0.011	0.008	0.027	0.002
MXC-3	4856	0.007	0.010	0.233	0.014
MXC-3	4853	0.002	0.005	0.471	0.003
MXC-3	4850	0.003	0.002	0.263	0.018
MXC-4	4865	0.010	0.002	ND	ND
MXC-4	4862	0.002	0.002	0.092	ND
MXC-4	4860	0.010	0.006	0.305	ND
MXC-4	4858	0.003	ND	0.198	ND
MXC-4	4856	0.007	0.012	0.197	ND
MXC-4	4854	0.007	0.006	0.181	0.001
MXC-4	4852	0.005	0.008	0.047	0.003
MXC-4	4849	0.006	0.002	0.044	ND
MXC-5	4865	0.008	0.005	ND	0.004
MXC-5	4860	0.010	0.006	ND	ND
MXC-5	4855	ND	ND	ND	ND
MXC-5	4850	ND	0.006	ND	0.004
MXC-5	4846	0.008	0.004	ND	0.007

ND = Not detected

inches or a few feet of the Mineralized Zone boundary. This may indicate that groundwater flow has changed direction, redistributing some of the uranium from the mineralized zone, or it may represent an area within which the uranium is not in equilibrium with other minerals or solutions in the altered zone and is being actively removed.

Vanadium. Vanadium has a mode of occurrence similar to that of uranium. It is present in significant quantities only within the Mineralized Zone, but is not always present. The uranium-vanadium ratio increases towards the convex side of the Mineralized Zone. Vanadium is not a definitive element within the Mineralized Zone.

Selenium and Arsenic. In the Morton Ranch area, selenium occurs in the Near-Altered Zone near the Mineralized Zone contact, and within the Mineralized Zone near that contact. Selenium generally occurs with arsenic. Although the richest selenium values are within the Near-Altered Zone, the highest arsenic values occur within the Mineralized Zone.

Harshman (1972) reports that selenium values average ten to eighty times higher in the altered zone than in the unaltered zone in the Shirley Basin. Harshman's altered zone corresponds to the Near-Altered Zone of the present study.

Selenium apparently is concentrated in a narrow band adjacent to and slightly overlapping the Mineralized Zone contact within the Near-Altered Zone. Generally, the selenium concentrations follow the "C" shape of this contact. Apparently, the seleium concentration increases steadily across the band from the convex to the concave side, and drops abruptly at the concave edge.

Iron. Iron is more abundant in the altered zones than in the unaltered zones. The highest iron values, however, are found in the Mineralized Zone (Table 2).

The highest iron content outside of the Mineralized Zone is found within the Red Subzone of the Remote-Altered Zone. The Seepage Zone contains the least iron. Within the Mineralized and Unaltered Zones, the iron occurs in pyrite and, particularly in the Unaltered Zone, in magnetite and amphibole minerals. Within the Altered Zones, the iron is primarily in limonite and hematite. The highest values of iron in the Mineralized Zone correspond to areas of pyrite concentration.

Manganese. The manganese content of the rocks in the area generally increases with increasing alteration.

Surface samples are generally enriched in manganese over subsurface samples. As expected, manganese concretions found on the surface in the Morton Ranch area contain the most manganese of all samples. No manganese concretions were encountered at depth although manganese crusts and solution features similar to those seen at the surface were noted in core samples. It seems, therefore, that these concretions are a feature related to surface weathering and not to the alteration produced in connection with the uranium deposits.

Cobalt. In the Morton Ranch area, cobalt is most abundant in the Unaltered Zone. It is next most abundant in both the Seepage and Mineralized Zones, and least abundant in the Near-Altered Zone. Cobalt values are also low in surface samples.

Nickel and Zinc. Amounts of nickel and zinc appear constant in all zones (Table 2). An exception is the relatively low zinc content of the Unaltered Zone in the Morton Ranch area. The zones are indistinguishable from each other by their nickel content.

Copper. In the Morton Ranch area, copper is most abundant in the Mineralized Zone, least abundant in the Unaltered Zone. Copper and uranium appear to be deposited in the Mineralized Zone in a similar manner.

Table 2. Results of atomic absorption analyses[1] - Morton Ranch area.

Surface sample#	Location (Section, Township, and Range)	Zone of alteration	As	Co	Cu	Fe%	LOI%[2]	Mn	Mo	Ni	Pb	V	Zn
M-1	S33 T35N R70W	Unaltered - weathered	50±5	0	27	1.86	1.6	50	0.5	5.5	3.5	8	16
M-2	S33 T35N R70W	Unaltered - weathered	50±5	0	5	6.7	2.9	64	8.5	8.5	0	10	9
M-3	S33 T35N R70W	Unaltered - concretion	3±2	13	55	.85	0.8	2900	0	15	3	0	32
M-5	S30 T35N R70W	Unaltered - concretion	T	13	25	1.3	1.3	1600	T	17	1	0	17
M-7	S30 T35N R70W	Unaltered - weathered	10±2	0	12	1.5	1.8	80	1.0	8	2	11	11
M-13	S11 T35N R73W	Remote-Altered - weathered	ND	1	3	0.85	1.3	1400	T	7	1.5	0	15
M-16	S 3 T36N R73W	Remote-Altered - weathered	ND	3	5.5	0.70	1.9	96	1.0	8.5	1	9	12
Core #	Depth												
MXC 8	4873	Unaltered	4±1	6.5	8	1.3	1.6	96	1.0	16	1	0	17
MXC 10	4892	Unaltered	3±1	4	4	1.09	1.2	66	0.5	7	1	0	17
MXC 10	4879	Unaltered	4±2	6	7	1.60	2.3	160	0.5	13	1	22	26
MXC 10	4876	Unaltered	T	5	5.5	1.07	2.2	140	0.5	12	0	15	12
MXC 10	4890	Seepage	3±2	1	3	0.76	1.0	66	0.5	5.5	1	10	15
MXC 10	4889	Seepage	ND	3	3	1.00	0.8	180	T	7	0	0	15
MXC 10	4887	Seepage	3±2	4	5.5	0.41	0.7	68	T	9	0	9	12
MXC 6	4884	Mineralized	T	8.5	9	1.20	1.6	121	1.5	16	1.5	30	35
MXC 7	4895	Near-Altered	T	5	5.5	1.15	1.7	88	0.5	9	4	13	22
MXC 7	4889	Near-Altered	4±2	3	8.5	1.00	1.3	88	0.5	12	6.5	0	34
MXC 9	4897	Remote-Altered	3±2	1	4	0.93	1.3	560	0.5	6	2.5	93	13
MXC 9	4881	Remote-Altered	4±2	4.5	10.5	0.95	2.2	140	0.5	12	0	14	76

[1] ppm except for Fe and LOI.

[2] Explanation of abbreviations: T = trace. ND = not detected. LOI = loss on ignition.

Silver. Only a few samples were analyzed for silver. It appears that the values for silver are too low to indicate any difference whatsoever between the zones. However, a roll-front type deposit has been discovered, near Paoli, Oklahoma, whose major economic mineral, which is located in the Mineralized Zone, is silver (Shockey, 1974). The writer has noted high silver values associated with copper carbonate minerals (malachite and azurite) near uranium concentrations in the Shinarump and Moss Back Members of the Triassic Chinle Formation on the north and west flanks of the Abajo Mountains in southeastern Utah.

Apparently silver can be concentrated in sedimentary deposits in a manner similar to uranium deposition. Such deposits may be the copper-silver-zinc occurrences in the Triassic-Jurassic Nugget Sandstone in the overthrust belt of western Wyoming. Differences in form (Hausel, 1982) and plausible alternative origins for these metals (Boberg, 1983) make this hypothesis speculative at this time.

Because silver and uranium are apparently concentrated by similar processes in some instances, mineable occurrences of silver in sandstone may be detectable using prospecting techniques similar to those used in the search for uranium.

Lead. Lead is unusual in that its distribution is affect both by its solution and precipitation in ground water and by the distribution of uranium, which produces lead as a radioactive decay product. Therefore, higher concentrations of lead in a Mineralized Zone would indicate that uranium has not moved for a relatively long period of time. Anomalous amounts of lead are present in the Mineralized Zone within the Jackpile sandstone of the Jurassic Morrison Formation in the Laguna District, New Mexico, indicating that these ore bodies have been in place for a relatively

long (but not determined) period of time (Harris, 1982).

In the Morton Ranch area, no difference is noted in the distribution of lead among the zones (Table 2). Apparently, the Morton Ranch uranium occurrences have been in their present location for a relatively short time, not long enough to produce detectable amounts of radiogenic lead.

Molybdenum. Molybdenum is concentrated in the Mineralized Zone. Samples from zones other than the Mineralized Zone are near the lower detection limit for molybdenum, and no difference was noted.

Loss On Ignition (LOI). Loss on ignition of the samples is due to carbon and sulfides which are vaporized upon heating and to the loss of water of hydration.

Loss on ignition is greatest in the Mineralized Zone (Table 2). This is where sulfide minerals and carbon are concentrated. No difference was noted between the unaltered and altered zones' loss on ignition.

HEAVY MINERALS

The variability of heavy minerals reflects (1) changes due to alteration, (2) differing suites due to different depositional settings, and (3) changes due to post-depositional events not associated with the ore-associated alteration. Only those changes that are due to the ore solutions will be reflected as noticeable differences between zones.

Heavy minerals which do not reflect changes due to the altering solutions associated with the mineralized zone emplacement but which were identified in the host rocks include zircon, garnet, tourmaline, rutile, epidote, monazite, sphene, apatite, sillimanite, kyanite, andalusite, staurolite, xenotime, cassiterite, corundum, dumortierite, hypersthene, and topaz (Table 3).

Heavy minerals which show differences between zones due to the mineralizing solutions include amphiboles, pyroxenes, biotite, magnetite, pyrite, and ilmenite-leucoxene (Table 3).

Method. Heavy minerals were prepared according to standard procedures by which the samples were disaggregated using a rubber pestle, separated with tetrabromoethane, split, and mounted in Lakeside 70. Magnetite was removed with a hand magnet. Weight percents were determined before and after separation and removal of magnetite. Minerals were identified and percentages calculated using a petrographic microscope equipped with universal and mechanical stages.

Amphiboles, Pyroxenes, and Biotite. Amphiboles, pyroxenes, and biotite are considered together because they show identical alteration sequences related to the same destructive processes. Nondetrital euhedral amphiboles, pyroxenes, or biotite were not observed in any sample. The changes that these minerals have undergone are therefore due to destructive processes only.

These minerals are destroyed during the passage of the geochemical cell. Destruction begins in the Seepage Zone with initial corrosion of the grains, continues at a reduced rate in the part of the Mineralized Zone adjacent to the Seepage Zone, ceases in the Mineralized Zone (but without recrystallization), and continues at an accelerated rate in the Near-Altered Zone. Only a few ragged, colorless remnants of these minerals are present in the Remote-Altered Zone.

This destruction begins as corrosion of the detrital grains. Corrosion increases and the grains become colorless in the Near-Altered Zone. While only a few amphiboles are colorless in the Unaltered Zone, all remnant, ragged, corroded amphiboles in the Remote-Altered Zone are colorless. It may be that colorless amphiboles are more resistant to destruction. However, the progressive

Table 3. Heavy mineral proportions, Morton Ranch Area (Percent of total heavy

Core #	Elev-ation	Zircon	Tour-maline	Garnet	Epidote	Amphi-bole	Hypers-thene	Rutile	Mona-zite	Xeno-time	Sphene	Kyanite	Anda-lusite	Silli-manite
MXC 6	4894	16.60	-	8.91	15.38	6.88	T	1.62	1.21	T	5.67	2.32	T	-
MXC 7	4894	7.63	-	6.43	21.69	1.20	-	1.20	T	T	2.41	T	T	-
MXC 7	4889	5.95	T	6.49	34.59	2.16	-	T	T	-	2.70	1.08	1.08	-
MXC 8	4872	4.25	-	3.64	2.02	74.09	-	T	T	-	-	T	T	-
MXC 9	4895	6.19	T	5.86	28.99	9.77	-	-	1.00	T	8.14	1.63	1.30	T
MXC 10	4886	6.19	T	4.42	8.85	50.88	-	T	T	-	3.98	1.77	T	T
MXC 10	4879	26.77	T	11.90	11.52	4.46	-	3.35	1.12	T	2.60	1.49	-	2.23
MXC 10	4876	3.21	-	3.57	10.36	28.93	-	-	-	-	T	-	-	-
MXC 11	4887	18.18	3.46	8.23	47.62	0.87	-	2.16	4.33	-	9.52	1.30	T	-
MXC 11	4890	15.61	T	4.78	33.76	1.59	-	2.23	1.91	T	4.46	T	1.91	-
MXC 9	4879	11.81	1.86	5.54	23.25	14.02	-	T	1.11	-	4.06	1.11	T	-
MXC 10	4892	5.98	T	2.39	16.73	38.65	-	1.20	0	-	-	T	T	T
MXC 10	4889	3.82	T	3.47	10.42	60.07	-	1.39	1.39	-	1.39	0	T	T
MXC 10	4889	6.48	T	2.73	20.82	43.54	-	1.37	1	T	-	T	1.02	-
MXC 10	4887	13.14	2.10	9.09	19.58	6.99	-	1.40	1.05	T	7.69	T	2.45	T
MXC 11	4887	5.17	2.13	4.26	34.04	7.60	-	T	-	-	1.82	T	-	-
MXC 11	4879	8.09	T	5.11	45.96	3.40	-	-	-	-	3.83	T	-	-
MXC 11	4875	14.15	T	5.97	39.62	3.77	-	T	T	-	4.09	T	T	-
MXC 11	4873	3.97	-	4.64	57.28	2.98	-	T	T	-	2.65	T	T	-
MXC 11	4869	5.45	T	6.06	54.24	3.64	-	T	-	-	3.03	T	T	-
MXC 11	4867	3.79	T	4.96	54.23	1.46	-	T	T	-	3.50	1.17	T	-
MXC 11	4864	7.55	T	4.53	36.25	20.85	-	T	T	-	2.11	-	-	-
MXC 12	4882	4.93	T	7.25	36.23	20.00	-	T	T	-	1.45	T	-	-
MXC 12	4881	3.85	-	6.73	46.79	12.18	-	T	-	-	2.56	T	T	-
MXC 12	4878	6.73	T	1.83	45.87	9.17	-	T	-	-	2.14	T	T	-
MXC 12	4875	8.15	-	5.52	37.50	2.03	-	T	T	-	6.10	T	-	-
MXC 12	4871	6.61	T	6.06	49.86	5.79	-	T	T	-	2.20	T	T	-
MXC 12	4870	10.37	T	3.66	42.68	2.74	-	T	-	-	3.66	2.13	T	T
MXC 12	4868	17.06	1.02	4.44	30.03	T	-	T	1.02	-	3.75	T	1.02	-
MXC 12	4862	9.63	2.99	5.65	42.52	3.32	-	T	T	T	4.65	T	-	-
MXC 13	4885	8.28	-	2.98	46.36	5.96	-	T	T	-	2.32	T	T	-
MXC 13	4879	5.65	1.13	1.98	34.75	26.27	-	T	T	-	2.26	T	-	-
MXC 13	4977	7.69	T	3.69	23.08	1.23	-	T	-	-	2.15	T	-	-
MXC 13	4873	3.93	7.02	3.37	14.61	44.38	-	T	-	-	1.12	1.12	-	-
MXC 13	4868	5.24	T	3.78	27.91	40.70	-	1.16	T	-	3.2	-	-	-

minerals by volume).

Staurolite	Biotite	Apatite	Pyroxene	Dumortierite	Corundum	Topaz	Barite	Cassiterite	Total Opaques	Pyrite	Magnetic weight % of sample	Alteration Zone
-	T	T	-	-	-	-	-	1.21	36.44	T	1.03	Mineralized
-	-	-	-	-	-	-	-	-	55.02	1.60	.17	Near-Altered
-	-	-	-	-	-	-	-	-	43.78	-	.61	Near-Altered
-	-	-	-	-	-	-	-	-	10.53	4.05	1.27	Seepage
-	-	-	T	-	-	-	-	-	34.20	2.28	.40	Seepage
-	-	-	1.48	-	-	-	-	-	33.58	1.11	.32	Seepage
-	-	-	1.99	-	-	-	-	-	30.38	7.57	.50	Unaltered
-	-	-	T	-	-	-	-	T	15.97	1.39	.86	Unaltered
-	-	-	1.02	-	-	-	-	-	21.50	T	2.19	Unaltered
-	T	-	-	T	-	-	-	-	33.93	5.59	1.13	Seepage
-	-	-	-	-	-	-	-	-	18.14	1.77	1.09	Mineralized
-	T	-	T	-	-	-	-	-	3123	T	1.11	Seepage
-	-	-	T	-	-	-	-	-	8.57	43.21	.70	Unaltered
1.73	-	T	-	-	T	-	-	T	43.29	-	.34	Altered
2.23	T	T	-	-	T	T	-	T	26.75	-	.20	Altered
-	-	-	-	-	-	-	-	-	41.03	2.74	.91	Altered
-	-	T	-	-	-	-	-	-	32.32	3.40	.40	Altered
T	T	-	-	-	-	-	-	-	28.62	T	.97	Altered
T	-	-	-	-	-	-	T	-	25.50	T	.43	Altered
-	-	-	-	-	-	-	-	-	23.33	1.82	.62	Altered
-	-	-	-	-	-	-	-	-	28.86	-	.49	Altered
T	-	-	-	-	-	-	-	T	23.56	2.11	1.57	Mineralized
-	T	T	-	-	-	-	T	-	26.96	1.16	.73	Mineralized
1.92	-	-	-	-	T	T	-	-	24.36	-	.44	Near-Altered
T	-	-	-	-	-	T	-	-	20.18	10.40	.41	Altered
-	-	T	-	-	-	-	-	-	39.24	T	.72	Altered
1.38	-	-	-	-	-	-	T	-	23.97	T	.70	Altered
-	-	-	-	-	-	-	-	-	16.46	16.16	.37	Altered
T	T	1.02	-	-	-	T	T	-	36.51	-	.35	Mineralized
-	1.00	T	-	-	T	T	T	-	23.26	10.40	1.41	Mineralized
T	-	-	-	-	-	-	-	-	27.15	4.30	.32	Mineralized
-	T	1.30	-	-	T	-	-	-	13.56	11.30	.60	Seepage
-	T	-	-	-	-	-	-	-	59.38	T	.69	Seepage
-	-	-	-	-	-	-	-	-	4.77	19.10	.77	Seepage
T	-	-	-	-		-	-	-	11.05	5.52	.50	Seepage

lightening of color of green and brown amphiboles and pyroxenes with increasing corrosion shows that the color change is a result of the destructive process.

Magnetite. Magnetite is also removed during the passage of the geochemical cell. The iron appears in the oxidized and hydrated iron minerals of the Seepage and Altered Zones, and possibly in the pyrite of the Mineralized Zone.

Pyrite and Marcasite. Pyrite and marcasite undergo both destructive and constructive alteration during the mineralization and alteration. The pyrite and marcasite initially present in the rock occur in two forms. Ragged or rounded anhedral grains in the Unaltered Zone may be detrital, having been transported some distance. Euhedral pyrite crystals of the octahedral form are probably products of early diagenesis due to burial in a reducing environment conducive to pyrite formation. Some anhedral pyrite grains show overgrowths of octahedral pyrite, diagenetic pyrite formed on detrital grains.

Seepage Zone pyrite and marcasite demonstrate the effects of alteration. They are corroded, pitted, and sometimes coated by a thin layer of iron oxide mineral. The iron released in this process may in part form the faint yellow-orange limonite stain of the Seepage Zone. In the Mineralized Zone, euhedral crystals of pyrite, of both octahedral and pyritohedral morphology, and aggregates of minute crystals — the morphology of which is invisible at maximum microscope magnification — are formed. These aggregates may be marcasite rather than pyrite. The pyrite and marcasite content of the Mineralized Zone is greater than the pyrite and marcasite content of any of the other zones as a result of this crystallization.

Marcasite is also found concentrated at the concave boundary of the Mineralized Zone, and within the Near-Altered Zone coincident with the selenium- and arsenic-rich zone. The marcasite appears as minute crystals and irregular masses showing progressive oxidation towards the Altered Zone.

Opaque Minerals. Opaque minerals as a group show differences between the zones of alteration. They are most abundant in the Mineralized Zone, where they represent ore minerals such as uraninite and coffinite.

Ilmenite and its alteration product, leucoxene, make up the majority of the opaque minerals in the Unaltered and Seepage Zones. Most but not all of these are destroyed by the geochemical cell and are not present in the altered zones.

Opaque minerals in the altered zones consist primarily of manganese and iron oxides. These account for the increase in opaque heavy mineral content of these zones relative to that of the Unaltered Zone.

DISCUSSION

UNALTERED ZONE

Eh-pH conditions within the Unaltered Zone in the Morton Ranch area require that the ground water be in near equilibrium conditions with minerals which exhibit no corrosion, namely pyrite, magnetite, and organic carbon, as well as with less reactive heavy minerals such as the amphiboles and pyroxenes. Assuming a dissolved CO_2 content of less than 10 moles per liter, the pH of the water in contact with the minerals of this zone must be weakly acidic (in the range 6 to 7) and the Eh must be relatively reducing (in the range

-0.1 to -0.4) (Garrels, 1960; Files, 1972, Wedepohl, 1969). Within these ranges, uraninite and coffinite are stable forms of uranium (Langmuir, 1977). Assuming that no influx of dissolved species has occurred, uranium present in this zone is depositional and not related to the system of uranium roll front formation, called a geochemical cell. This is also true for the other rare elements present in small quantities in the Unaltered Zone.

By definition, the Unaltered Zone has not been affected by geochemical cell migration. This zone, therefore, represents the base for determining the changes that result from the passage of a geochemical cell.

SEEPAGE ZONE

The Seepage Zone is observed in all subsurface cross sections in the Morton Ranch area, The writer has noted Seepage Zone characteristics on the convex side of Mineralized Zones in the Turnercrest area in the Powder River Basin of Wyoming and in Tertiary sediments of northeastern Washington. The Seepage Zone has not been observed by the writer in the Shirley Basin of Wyoming, in the Slick Rock and Uravan Districts of Colorado, in the Laguna District of New Mexico, or elsewhere in Jurassic or Cretaceous uranium host rocks. This is probably due to change in groundwater flow (due to tectonic or ground-water changes) causing oxidation that masks the subtle character of the Seepage Zone.

Initial pyrite corrosion and the production of limonite grain coating are the observed characteristics of the Seepage Zone. A slight increase in the content of uranium may be noted on electrical logs (for example, see MXC 13, Plate 1). Carbon exhibits slight corrosion due to oxidation. These effects are produced by oxygenated and slightly mineralized water that has passed through the Altered and Mineralized Zones without losing all of its dissolved oxygen. This water is therefore out of equilibrium with the minerals in the Unaltered Zone and reacts with them to produce the observed effects. Through this zone the Eh of the water gradually decreases until the water reaches the conditions approximating equilibrium with the minerals of the Unaltered Zone. Rather than a gradual increase in Eh near the Mineralized Zone as shown by Files (1972), the writer postulates a gradual decrease in Eh through the Mineralized and Seepage Zones and into the Unaltered Zone. In the Mineralized Zone the oxygen is depleted to the Eh range below Eh = -0.3, which at pH = 7-8 causes deposition of the uranium in solution (Garrels and Christ, 1964). The Seepage Zone of this study and of Rubin (1970) is characterized by slight oxidizing of minerals in the Unaltered Zone.

MINERALIZED ZONE

The Mineralized Zone is characterized by chemical changes that produce the deposition of uranium and other trace elements. Many authors (Sharp and Gibbons, 1964; Garrels and Christ, 1965; Files, 1972; Harshman, 1962; Brookins, 1975; Goldhaber and Reynolds, 1977; Langmuir, 1977) agree that this deposition is in response to a decrease in Eh across the zone. Data from the present study supports the conclusions of these authors. Files (1972) also noted the "acid wave" which produces a sharp drop in pH within the ore zone. However, the acid wave noted by Files is characteristic of the transition between the Mineralized Zone and the Near-Altered Zone, occurring coincidently with the formation of marcasite and ferroselite in the Near-Altered Zone. Therefore, this pH change is discussed in the section on the Near-Altered Zone.

The Eh of water entering the Mineralized Zone drops sharply, as shown by the abrupt depositional interface of mineralization on the altered side of the zone. This abrupt drop is in response to reactions with organic carbon or sulfide sulfur in the zone. The kinetics of the groundwater flow and the relative reaction rates seem to prevent all precipitation from occurring at the Eh interface — which eliminates the space problem of all precipitants dropping out in one location. Continued deposition occurs down the Eh gradient, giving rise to the characteristic roll front with the amount of mineralization gradually decreasing towards the Unaltered Zone.

Other elements occur in roll fronts, in rolls only partially coincident with uranium rolls. These elements, especially vanadium, molybdenum, and copper, but also possibly nickel, zinc, and lead, occur as discrete roll shapes, superposed on the uranium roll but displaced towards the convex edge of the Mineralized Zone.

The cause of the Eh drop is the withdrawal of oxygen from the solution by organic carbon or sulfide sulfur, producing CO_2, CO, SO_2, $SO_4^{=}$, or $SO_3^{=}$ (Shchetochkin and others, 1975). The low Eh then provides an environment for sulfate-reducing bacteria (Jensen, 1963; Lisitsyn and Kuznetsova, 1968) that sustain the reaction. Progressive oxidation at the concave side of the Mineralized Zone determines the rate of migration of the roll front. Uranium and other elements oxidized and taken into solution at this boundary are soon redeposited in the Mineralized Zone due to the Eh decrease. The entire procedure is repeated as the roll front advances.

The reaction rate of the Mineralized Zone/Near-Altered Zone boundary is therefore determined by the organic carbon-oxygen or sulfide sulfur-oxygen reaction at the concave side of the roll. An absence of organic carbon is noted in some roll front deposits. In the Highland mine, adjacent to the Morton Ranch area, uranium is concentrated with sulfide sulfur, rather than organic carbon (Leventhal and Santos, 1981). There, the controlling reaction must be the oxidation of sulfides (Goldhaber and Reynolds, 1977).

NEAR-ALTERED ZONE

The Near-Altered Zone represents an area of mineral-solution reactions and Eh-pH change. Within this zone, limonite is formed at the expense of pyrite and other iron-bearing minerals such as magnetite; marcasite is formed at the expense of pyrite; and selenium is both deposited and removed. Amphiboles and pyroxenes are highly corroded or destroyed.

Selenium occurs in the native form near the Mineralized Zone interface and in ferroselite associated with marcasite in Wyoming rolls (Files, 1972). Although no selenium minerals were observed in the Morton Ranch area in this study, a similar occurrence is possible since the distribution of elemental selenium occurs in the predicted zones.

Mineral changes in the Near-Altered Zone occur in response to the oxidation of mineralized-zone phases by oxygenated groundwater. Reactions within this zone are the controlling reactions of the deposit (Files, 1972). Three major reactions are summarized below:

1. $FeS_2 + 7/2\ O_2 = FE^{+2} + 2H^{+} + 2SO_4^{=}$

This reaction produces H^{+}, decreasing the pH of the water, and results in the deposition of marcasite, ferroselite, and native selenium. The following reactions,

2. $CaCO_3 + H^+ - Ca^{++} = HCO_3^-$

and

3. $HCO_3^- + H^+ = H_2CO_3$

raise and buffer the pH of the water as calcite is encountered in the Mineralized Zone.

Reaction 1 may be promoted (catalyzed) by bacteria (Jensen, 1963; Lisitsyn and Kuznetsova, 1968), aiding the production of the hydrogen ions and lowering the pH.

Because reaction 1 uses oxygen dissolved in the water migrating into the Mineralized Zone, the Eh drops abruptly at the zonal interface. However, not all of the oxygen is consumed.

Observed physical changes resulting from these chemical changes include the formation of limonite from pyrite with the addition of water and oxygen, the deposition of selenium phases as previously noted, and the oxygenation and subsequent solution of reduced phases at the roll front interface. As previously noted, these reduced phases are redeposited in the Mineralized Zone as Eh is decreased and pH in increased. Amphiboles and pyroxenes are removed, and iron and other cations from them form limonite and hematite. The silica is available for the formation of coffinite (a uranium silicate).

It is particularly noteworthy that neither organic carbon nor the economic minerals, particularly uraninite or coffinite, are necessary for the formation of a roll front. The presence of sulfide sulfur and calcite in the unaltered sediment is required since they react with an influx of dissolved oxygen, thereby initiating and sustaining a roll front. The presence of other elements in a roll front is in response to the conditions produced by reactions 1, 2, and 3.

REMOTE-ALTERED ZONE

The Remote-Altered Zone represents an area in which oxygenated, sulfate-bearing, mildly alkaline water is in near equilibrium with the atmosphere. Hematite and manganese oxides are stable in this zone. Other elements may be adsorbed onto hematite and manganese oxides, producing the relatively high but erratically occurring copper, cobalt, and nickel concentrations observed in Tables 1 and 2 (Jenne, 1968). Uranium and other trace elements are transported through this zone. In oxidizing, slightly alkaline waters, as found in this zone (Langmuir and Chatham, 1980), several uranium complexes are stable, including oxides, hydroxides, chlorides, sulfates, carbonates, and fluorides (Hostetler and Garrels, 1962; Kyuregyan and Kocharyan, 1969). Work by Langmuir (1977) shows that stable dissolved uranium species are:

$UO_2(HPO)_2^{2-}$ at pH = 4-7.5,

and

$UO_2(CO_3)_2^{2-}$ or $UO_2(CO_3)_3^{4-}$ at pH > 7.5

at a PO_4^{3-} concentration of 0.1 ppm. The carbonate complexes predominate below pH=7.5 if the phosphate concentration is less. Molybdenum (Brookins, 1978), copper, silver (Garrels, 1960), vanadium (Evans and Garrels, 1958), nickel, zinc, cobalt (Jenne, 1968), and selenium (Howard, 1977) may be transported through the Remote-Altered Zone. Some elements, such as thorium (Langmuir and Herman, 1980), zirconium, platinum group elements, tin, and antimony (Brookins, 1978) are not soluble and do not migrate under these conditions. These elements do not occur with geochemical cell mineralization.

Anomalous concentrations of copper and cobalt from this zone are associated with both manganese and iron concentrations,

often in concretionary form. Manganese oxides in particular scavenge trace elements from solution through adsorption (Hem, 1978). Hydrous iron oxides also adsorb certain trace elements (to produce anomalous concentrations in this zone) (Jenne, 1968).

These effects may be useful in determining the passage of a geochemical cell. Unfortunately, uranium and other associated elements such as vanadium and selenium do not form concentrations on iron and manganese oxides. These cannot be used as a tracer of a uranium-mineralized geochemical cell.

SUMMARY

Uranium mineralization occurs in the Morton Ranch area in the form of roll fronts. A roll front is the boundary of a geochemical cell, which is the boundary of an influx of oxygenated water into a permeable sandstone unit containing reductants, particularly sulfide, sulfur, and calcite. These sandstones are bounded by confining shale layers. The migration of the geochemical cell results in the formation and migration of a zone at the redox boundary which may contain anomalous amounts of uranium, copper, silver, vanadium, selenium, arsenic, molybdenum, zinc, lead, or other valuable elements.

Zones of alteration, if recognized, can guide exploration geologists in the search for geochemical cell ore bodies. Four subzones in the Remote-Altered Zone indicate both in outcrop and subsurface studies that a geochemical cell has passed through the sandstone. Nearer the Mineralized Zone, recognition of the Seepage Zone and Near-Altered Zone serves as a guide to the proximity of a cell and its direction of migration. On a large scale, the recognition of unaltered and altered zones brackets ore bodies between them.

Criteria for the recognition of the Remote-Altered Zone include the presence of limonite, hematite, and manganese oxides and the absence of magnetite, pyrite, carbon, amphiboles, pyroxenes, and biotite.

Criteria for the recognition of the Near-Altered Zone include the presence of limonite, marcasite, anomalous amounts of selenium and arsenic, and highly corroded relict amphiboles and pyroxenes and the absence of fresh pyrite, carbon, and magnetite.

Criteria for the recognition of the Mineralized Zone include the presence of pyritohedral and octahedral pyrite, carbon as mobilized grain coatings or interstitial material, marcasite, and anomalous amounts of uranium, vanadium, molybdenum, copper, lead, zinc, and iron.

Criteria for the recognition of the Seepage Zone include the presence of pale yellow limonite grain coatings, abundant calcite, slightly corroded irregular and octahedral pyrite, and carbon.

Criteria for the recognition of the Unaltered Zone include the presence of carbon, calcite, and irregular masses and octahedrons of uncorroded pyrite and the absence of oxidized forms of iron.

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