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Environment of Wyoming Tertiary Uranium Deposits[1]

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Abstract Four major uranium districts in Tertiary rocks of central Wyoming are in fluvial sandstones derived from the granitic rock of the ancestral Sweetwater arch and deposited in adjacent intermontane basins. Sediment transported southward into the Great Divide basin was deposited on an apron of alluvial fans. Sedimentation in the Gas Hills area of the Wind River basin was on an alluvial fan in which ridges of older rock disrupted the normal development of the fan. Sediment in west Shirley basin was deposited on an alluvial fan, but in east Shirley basin and in the Powder River basin sedimentation was channel and flood-basin deposits of a meandering stream. The sandstones are subarkosic to arkosic, medium grained to conglomeratic, angular and poorly sorted. Sandstones intertongue with green or carbonaceous shales. Sedimentation was in a warm, humid climate with abundant vegetation. Decay of the organic material created reducing conditions in the sediment which caused partial carbonization of some of the plant debris, formation of pyrite, and precipitation of uranium minerals.

Following burial, uplift-induced changes in the hydrodynamic system caused an invasion of the reduced sediment by oxygenated water far below the static water table. This caused destruction of carbonaceous material, oxidation of pyrite, and accumulation of uranium and other susceptible metals in a wave or front just ahead of the invading oxidizing environment. The invading oxidation was a dynamic, expanding process which moved through the permeable zones of the fluvial sequence until its dimensions measured miles in areal extent and hundreds of feet in thickness. This geochemical cell had a sharply defined boundary produced by biochemically controlled changes in physical and chemical conditions. Oxygenated waters, aided by *Thiobacillus ferrooxidans,* oxidized pyrite to produce sulfuric acid and ferric sulfate, a strong oxidizer, which leached uranium and other susceptible elements. In the reducing part of the cell, anaerobic bacteria, including the sulfate reducer *Desulfovibrio,* consumed the organic material in the sediments and the sulfates from the oxidizing area, to produce hydrogen, hydrogen sulfide, and a mildly alkaline, strongly reducing environment which precipitated pyrite, uranium, and other metals on the front. Migration of the cell was controlled by the permeability of the sandstone and by availability of carbon and pyrite. The cell advanced faster in the more permeable zones and was retarded in zones of reduced permeability and areas of greater pyrite and carbon content. The position of the mineral front was a function of the initial sedimentary pattern. Sedimentation, alteration, and mineralization in the Gas Hills and Shirley basin districts illustrate these conditions and processes.

INTRODUCTION

Several features are common to most major sandstone-type uranium deposits and their host rocks. The function of each in the origin of the uranium deposits has generated much speculation and discussion. These features are (1) sandstones of fluvial origin; (2) common association with arkosic or micaceous sediment; (3) siltstones and mudstones interbedded with sandstones; (4) association with organic materials; (5) presence of pyrite in unweathered deposits; (6) gray color of the sandstones and light-gray or green color of the mudstones in unweathered deposits; (7) association with volcanic debris in the host formation or in overlying formations; (8) the peculiar discordant roll features or solution fronts; and (9) the sharp contact between mineralized zones and adjacent carbonaceous-free or oxidized zones. The first seven of these features are related directly to the source rock, sedimentation, and the sedimentary environment; only two are products of the mineralizing process. Regardless of the apparent importance of sedimentary environment and sedimentation, these facets of uranium geology have been grossly neglected.

In Wyoming there are four major uranium districts in sediments of early Tertiary age. The dominant source of sediment for all four districts was Precambrian granitic rock of the Sweetwater arch. Each district is in a different basin and has a different relation to the source area. Each basin possessed some special structural, tectonic, and terranal differences which affected the sedimentary pattern and hence the localization of mineralization. When differences of scale, particularly bed thickness and size of clastic material, are ignored, a restricted set of conditions is common to all the mineralized areas. These common conditions are the product of the sedimentary environment. Subsequent accumulation of the ore bodies is also a product of the sedimentary environment, because the mineralizing process is de-

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The writer is indebted to many co-workers and professional friends for their observations, criticisms, and stimulating discussions.

pendent on these initial conditions for its inception, energy, shape, and mineral content.

Source Area

The Sweetwater arch is a large mass of granitic rock 85 mi (137 km) long, with a maximum width of 30 mi (48 km). The rock is dominantly granite with basalt dikes and local areas of amphibolite making up less than 1 percent of the source rock. All these igneous rocks were emplaced and exposed to erosion prior to the deposition of Cambrian sediment. Quartz or metalliferous veins are notably absent. The uranium content of some parts of the source area is 20-30 ppm (Masursky, 1962, p. B95), five to seven times the average content of igneous rock.

Uplift of the arch began to affect sedimentation in Late Cretaceous time. By the end of the Paleocene elevation probably had reached 2,000 ft (610 m) above sea level, with much of the sedimentary cover removed. Under warm, humid conditions weathering was rapid and deep in the fractured granite. The weathering broke down the feldspar but also produced large amounts of disaggregated granite from sand-size to boulders. The crest of the Sweetwater arch rose at least 5,000-6,500 ft (1,524-1,981 m) above the Gas Hills (Soister, 1968, p. A42) and may have been 9,000 ft (2,743 m) above sea level.

Geologic History and Paleogeography

Great Divide Basin

The southwestern part of the Sweetwater arch thrust southwesterly over the north margin of the Great Divide basin along the Emigrant Trail thrust fault. Stratigraphic displacement exceeds 20,000 ft (6,100 m), and structural relief on the Precambrian basement with respect to the Great Divide basin trough probably exceeds 30,000 ft (9,100m) (Keefer, 1970, p. D20-D22). Half or more of this displacement may have taken place before the end of the Paleocene. Figure 1 shows the relation of the arch and basins. With renewed uplift in early Eocene time the weathered and disaggregated rock was eroded easily, and an apron of alluvial fans spread southward into the Great Divide basin along a 30-40-mi (48-64 km) mountain front. One of the major fans is centered near the Crooks Gap mining district, and another is northwest of Lost Soldier anticline. The anticline probably was rising at the time sediment was being deposited, because the sandstones silt out against the anticline through an interval of several hundred feet. Mineralization is present in the sandstones of this interval west of the anticline.

Lower Eocene sediment, the Battle Spring Formation, reached a thickness of approximately 4,000 ft (1,200 m). Sedimentation probably was continuous throughout the early Eocene but may have been greater at times. The lower Battle Spring is folded slightly more than the upper Battle Spring.

Wind River Basin

The Wind River basin is north and west of the Sweetwater arch. For much of the length of the arch its north flank and the south flank of the basin are identical. Tectonically both have acted as though they had been part of the same crustal block since Late Cretaceous time, the basin subsiding and the arch rising as the block tilted. Sediment filled the basin as the Sweetwater arch and other positive areas supplied detritus. The Gas Hills area remained structurally and topographically above the level of deposition during most of the period when the Wind River basin was being filled. Near the end of this period red, green, and gray silt and mud were deposited in the Gas Hills area. A period of renewed movement about the end of the early Eocene caused partial erosion of the siltstones and mudstones, followed by rapid deposition of the coarse arkose which is host to the Gas Hills uranium. This arkose is the Puddle Springs Arkose Member of the Wind River Formation.

The Puddle Springs has a maximum thickness of approximately 500 ft (150 m). The arkose sequence is predominantly the alluvial fan of one major stream. Two minor streams, one on either side of the major fan, may have contributed to the sequence. Streams were controlled by the preexisting valleys through the Paleozoic and Mesozoic formations on the north flank of the arch. Ridges on resistant strata of anticlinal noses (Figs. 1, 5) protruded through the fan and controlled the movement of the streams and their pattern of deposition.

Shirley Basin

Shirley basin is east of the Sweetwater arch. This area apparently remained in the zone of erosion through the early part of the early Eocene. In late early Eocene an alluvial fan built eastward across the undulating topography of the Cretaceous marine shales from the east end of the Sweetwater arch. The fan did not extend entirely across the basin but merged with deposits of channel and floodplain sediments on the east. The arkosic sediment lapped onto the dip slopes of the ridge-forming strata on the east flank of the basin. These ridges had a major influence on sedimentation and the localization of mineraliza-

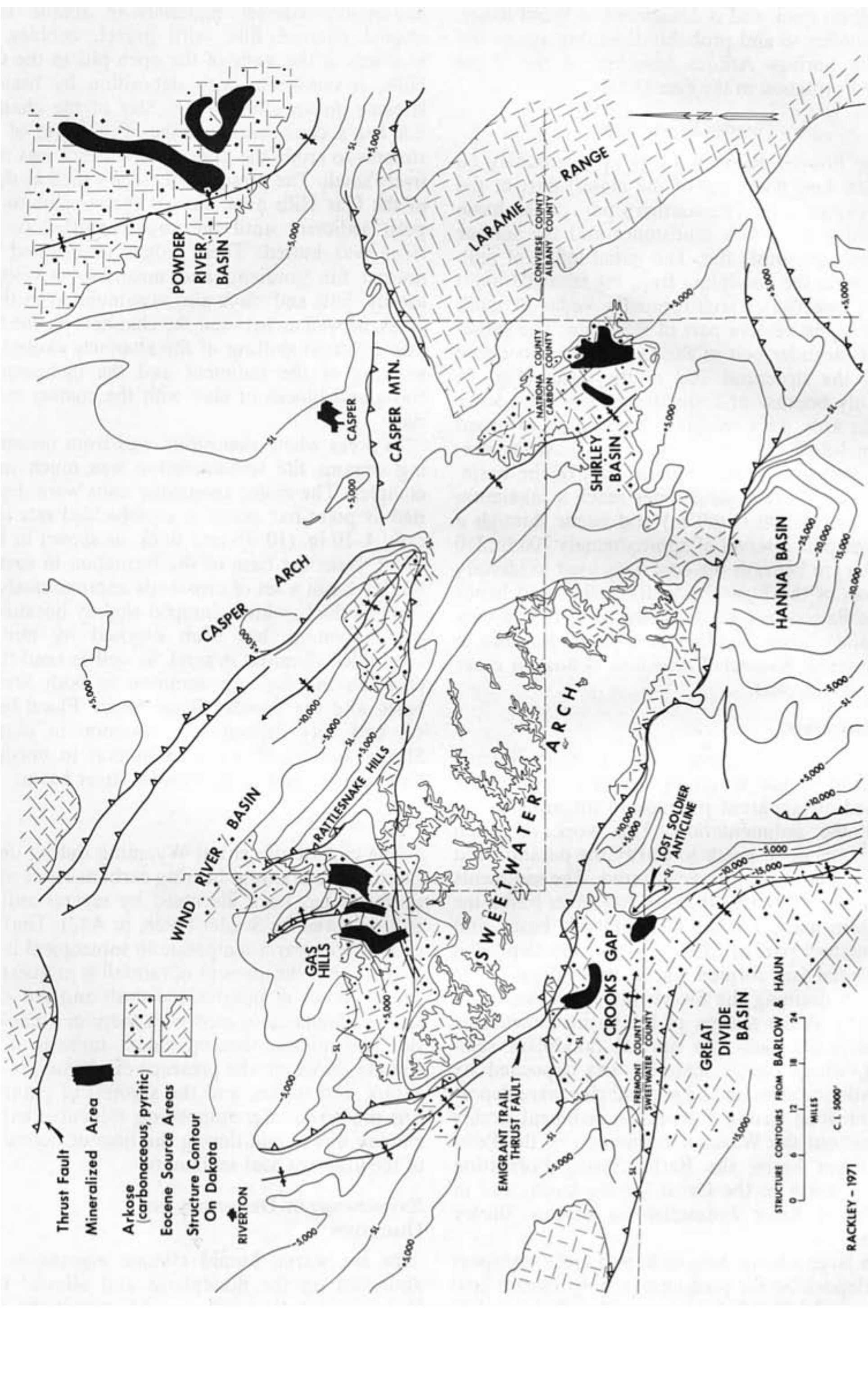

FIG. 1—Index and structure map of central Wyoming uranium province showing relation of Sweetwater arch, major source of sediment, and adjacent basins; distribution of favorable arkosic, carbonaceous facies; and mineralized areas.

tion. This arkose sequence is approximately 450 ft (140 m) thick and is designated as Wind River. It is similar to and probably the same age as the Puddle Springs Arkose Member of the Wind River Formation in the Gas Hills.

Powder River Basin

The Powder River basin is approximately 60 mi (100 km) northeast of the closest part of the Sweetwater arch. The southern part of the basin was filled with dark mudstones and the surface was monotonously flat. The initial influx of sediment onto the floodplain from the renewed uplift of the Sweetwater arch formed a wedge of sandstone in the western part of the basin. The subsequent meander belt of the streams was localized along the structural axis of the basin (Fig. 1), possibly because of a slightly greater subsidence in that area. This produced a sequence of broad channel-deposited sandstones, that host the uranium deposits in the southern part of the basin. These mineralized sandstones reach a maximum thickness of 200 ft (60 m) and occur through a stratigraphic interval of approximately 700 ft (210 m). All are beneath the coal beds used to identify the top of the Fort Union formation and hence are of Paleocene age. A higher series of channel-deposited sandstones farther north in the basin in the Eocene Wasatch Formation is host to other uranium deposits.

SEDIMENTATION

Depositional features in the uranium-bearing sediment of the Wyoming Tertiary basins have created an apparent paradox in attempts to explain the sedimentation. The work of Allen (1970) has done much to clarify the paradox and put these features into perspective. The sediments of the Gas Hills area of the Wind River basin, the northern margin of the Great Divide basin, and the western part of Shirley basin were deposited as alluvial fans formed where the gradient of the streams draining the Sweetwater arch decreased abruptly at the margin of the basin. Downslope the deposits pass into normal floodplain sediment, where coarse material was deposited by meandering streams and silt and clay were deposited in flood-basins. Floodplain sediment occurs throughout the Wasatch Formation of the Powder River basin, the Battle Spring Formation farther south in the Great Divide basin, and in the Wind River Formation in eastern Shirley basin.

On large alluvial fans in humid areas transport and deposition are predominantly by stream flow in powerful braided streams. The streams shift about on the fan, adding sediment in radial bands (Allen, 1970, p. 144). The presence of predominantly coarser materials in simple lens-shaped channel fills, with gravel, cobbles, or boulders in the walls of the open pits in the Gas Hills, is consistent with deposition by braided streams on an alluvial fan. Size of the channel fills has a considerable range. The power of the streams to erode the preexisting surface was relatively small. The presence of ridges, such as those of the Gas Hills area, caused the streams to deposit sediment until the stream shifted or the ridge was buried. These ridges interrupted the normal fan gradient, and meanders developed locally. Silts and clays also accumulated in these areas, as well as between the channels on the fan. The constant shifting of the channels caused reworking of the sediment and the inclusion of clasts and blocks of clay with the coarser material.

In areas where deposition was from meandering streams the sedimentation was much more complex. The major sandstone units were deposited as point-bar sands in crossbedded sets typically 4–10 in. (10–25 cm) thick, as shown in Figure 2. Near the base of the formation in eastern Shirley basin a set of crossbeds approximately 20 ft (6 m) thick, which slumped slightly because of oversteepening, has been exposed by mining. Clay-filled channels in sand, as well as sand-filled channels in clay, are common in both Shirley basin and the Powder River basin. Flood-basin silt and clay deposits are common in eastern Shirley basin and are predominant in northern Shirley basin and in the Powder River basin.

PALEOCLIMATE

The climate of central Wyoming during deposition of the uranium-bearing carbonaceous arkosic facies has been discussed by several authors and reviewed by Soister (1968, p. A42). That the climate was warm-temperate to subtropical is not disputed but the amount of rainfall is in question. The presence of interbedded drab and red clays and the fauna associated with them in areas outside the uranium-bearing facies indicate a dry climate; however, the presence of crocodiles, alligators, and turtles, and the amount of plant debris preserved offer compelling evidence that the climate was humid during the time of deposition of the uranium host sediments.

ENVIRONMENT OF DEPOSITION AND DIAGENESIS

In the warm, humid climate vegetation was abundant on the floodplains and alluvial fans. Vegetation on the surface and buried in the sediment, with warm, oxygen-deficient, organic-rich

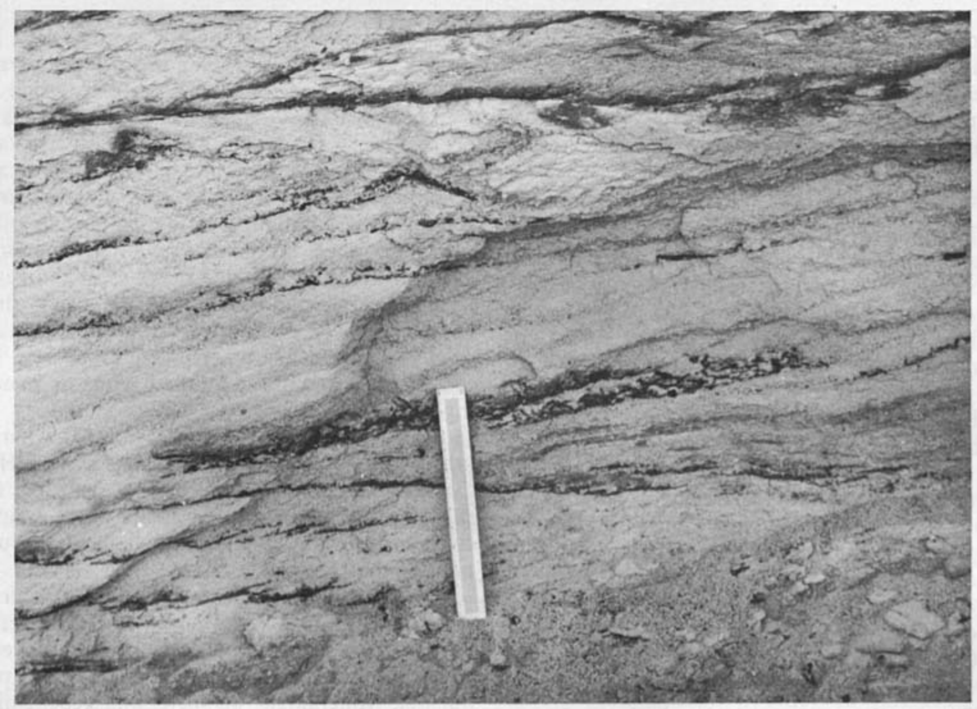

FIG. 2—Cross stratified arkose in sets 4-10 in. (10-25 cm) thick, with plant debris on cross-stratification surfaces, Shirley basin; scale is 12 in. (30.5 cm).

surface water, permitted anaerobic conditions to exist to the sediment interface. The partial decay of the plant debris and other organic matter in the sediment created carbon dioxide and hydrogen sulfide. Iron in the sediment reacted with the hydrogen sulfide to precipitate pyrite. This reaction may have taken place within 1 ft (30 cm) of the surface of saturated sediment, much as pyrite forms in the decaying rootlets of living cypress in the Mississippi delta (Coleman, 1971). Excess hydrogen sulfide may escape to the surface water or atmosphere, where it is oxidized to sulfate and may contribute to the supply of gypsum (Hem, 1970, p. 162). The carbon dioxide increased the solubility of calcium carbonate and essentially prohibited its formation. It is possible to conclude that the environment at the time of deposition or shortly thereafter had a slightly alkaline pH and a strongly reducing Eh, conditions favorable for the accumulation of uranium and the other metals stable in a reducing environment.

The roots of plants growing on floodplains and alluvial fans burrowed the silt and clay and destroyed all stratification. Some sandy zones also are extensively root-burrowed or bioturbated. These zones commonly contain abundant pyrite and carbonized roots in place and have a mottled medium-gray appearance. The silt and clay beds are typically light gray to light green and commonly contain very small euhedral pyrite crystals and carbonized leaves. The color of sandstones ranges from very light gray, indicating reducing conditions but little carbon content, to medium or dark gray with 1-5 percent carbonaceous debris. The carbonaceous material normally consists of flakes and small fragments of carbonized woody materials well disseminated through the sandstones, except for a greater concentration on cross-stratification surfaces (Fig. 2). The detrital character of much of the carbonaceous debris suggests that the woody material was at least partially carbonized before final burial. Lignite beds and carbonaceous shales are present in the floodplain deposits.

The general absence of oxidized zones indicates that the surface of the area was poorly drained and well supplied with moisture to maintain the reducing environment revealed by the sediment. Oxidized zones exposed in mining are thin and discontinuous beds or oxidized clay pebbles in the sandstones.

The distinction between sedimentation and diagenesis is difficult because some of the conditions normally considered diagenetic probably are present prior to final deposition. The only characteristic of the sediment that can be related directly to diagenesis is compaction. The term "sandstone" is used in this paper, although there is very little lithification of the sands. Most of the sediments are not cemented except by the mineralizing process adjacent to the ore bodies.

Lithology

The host rock of the uranium deposits is arkose except in the Powder River basin, where it is an arkosic cherty sandstone. The grain size is typically coarse sand to fine grit, but ranges up to boulders 10 ft (3 m) in diameter. The grains are angular to subangular. There has been little sorting, with the result that gross formation permeability is not determined by the size and packing of the sand grains but by the amount of matrix of silt and clay sizes. The coarsest sandstone and even the boulder beds have a matrix containing a sizeable fraction of clay sizes. Carbon and pyrite are present in amounts up to 5 percent.

Large boulders are present in thick beds in eastern Gas Hills, western Shirley basin, and Crooks Gap, with thinner boulder beds in the western Gas Hills, and small boulders and cobbles as channel lag in most areas of arkose deposition.

Origin of Ore Deposits

Early Ideas

Ideas concerning the mode of deposition of uranium in sandstone-type deposits have undergone wide swings in the last 50 years and now approach full circle return to early interpretations. Workers prior to 1930 considered the uranium to have been deposited with, or introduced into, the sands at the time of their deposition. Hess (1933, p. 477-479) postulated that distinct metalliferous provinces, containing a particular suite of metals, weathered and contributed those metals in a soluble form into local basins where subtropical vegetation was decaying slowly in warm, wet sediment. The metals were deposited in and around the plant remains by reduction of soluble ions to stable minerals as a result of reducing conditions caused by decaying vegetation.

In a review of the geology of uranium deposits exploited for nuclear weapons, Everhart (1951a, p. 13-17) described three types of uranium deposits in sandstone: carnotite, copper-uranium, and uranium-bearing asphalt. All deposits were similar structurally and lithologically, and were in sandstone channels. Everhart (1951b, p. 6-7) concluded that the carnotite ore bodies were deposited by slight chemical change in the groundwater moving through the channel sandstone shortly after sedimentation. He attributed the other two types of deposits, with sulfide minerals, to hydrothermal solutions moving through the permeable channel sandstones. Exploration outside the Colorado Plateau resulted in discoveries of large ore bodies in Wyoming and New Mexico, and significant discoveries were made in North and South Dakota, all within the same environmental setting. This broadening of geographic distribution diminished the credibility of hydrothermal solutions from deep-seated magmas as sources of uranium, and many geologists dismissed them completely. The swing away from hydrothermal origin did not mean an agreement on source. The tuffaceous sediments deposited with, or overlying, the host sand had been proposed as the source of uranium by Love (1952, p. 17), whereas others concurred with the earlier ideas of Hess that the metals were derived from the same terrane that supplied the sediments. Both sources contained several times more than all the uranium in the known deposits.

Gruner (1956) summarized his thinking from knowledge at that time. Most of the presently known uranium districts had been discovered and were partly explored, if not actually in production. Mineralogic, geologic, and geochemical observations and experiments were considered to establish a conceptual model of sandstone-type uranium deposits. Notwithstanding the amount and value of the information presented, this probably has become the most misquoted reference in uranium geology. Gruner's (1956, p. 515) multiple migration-accretion hypothesis called for the accumulation of uranium and other metals in a swamp or peat bog by drainage from higher ground. Each swamp or bog accumulated any metals present in its drainage basin. After burial and renewed erosion, the metals were oxidized and remobilized as the swamp or bog was destroyed by erosion. The metals were accumulated in another swamp from the destruction of this and perhaps other swamps, and from igneous and tuffaceous rocks within its drainage basin. "Each oxidation-solution-migration-precipitation cycle adds to the enrichment of the last stage of accretion" (Gruner, 1956, p. 515). Although this description of the process of ore accumulation initially was directed to the lignite-uranium deposits, he applied the same idea to other sediments.

Neither the rapid erosion of the source area with deposition by braided and meandering streams, nor the accumulation of ores on solution fronts in Wyoming districts is consistent with this concept, although the solution fronts are considered to be accretionary features. The statement, "Now, one can be fairly certain that they (U and

V) may even be dissolved together from some earlier deposit carried through the same underground passages and reprecipitated together in a new site" (Gruner, 1956, p. 514), may be the primary cause of the confusion and misquotes.

Geochemical Cell Concept

During a drilling program in Shirley basin in 1960, Phillip N. Shockey recognized that uranium ore bodies were on the margin of an extensive body of sandstone which was oxidized in varying degrees, yet the ore bodies and the adjacent and equivalent sandstones were carbonaceous and pyritic. The oxidized sandstone body had anomalous radioactivity at its upper and lower surfaces. The sandstone thinned and pinched out against a pre-Tertiary ridge nearby. The oxidized zone occupied most of the sandstone except an area about 800 ft (250 m) wide adjacent to the ore body, where it thinned at a greater rate than did the enclosing sandstone, forming a blunt, wedge-shaped body which was strongly mineralized on its lateral margin and moderately to well mineralized on irregularities of its upper and lower surfaces. The implication that the "roll" or solution front, long known to uranium producers, had a genetic relation to the epigenetically oxidized sandstones within a reduced fluvial sequence provides an important guide for exploration and mining. Shockey, in collaboration with Robert E. Melin, Robert V. Bailey, and the writer, developed this observation into a working genetic concept that was used successfully in mining and exploration. E. N. Harshman of the U. S. Geological Survey participated in many interesting discussions during the development of the concept.

Shockey introduced the term "geochemical cell" for the processes occurring as oxygenated water invaded the reduced, carbonaceous, and pyritiferous sandstones and for the resulting alteration and ore bodies (Shockey *et al.*, 1968, p. 3-4). This term is very applicable to the dynamic system with advancing oxidizing zones or fronts and their marked changes in Eh, pH, mineralogy, chemistry, and microorganisms. The term has gained wide acceptance in the profession, particularly for the Wyoming deposits. The geochemical cell originates essentially at a point and expands to form a continuous, three-dimensional, finite body. The shape of the cell and related ore bodies is determined chiefly by gross permeability and by the availability of pyrite and carbonaceous material. A well-developed geochemical cell is tongue-shaped with the tongue pointed down the hydrostatic gradient. In distinctly channeled sandstone, the tongue-like cell may be elongated parallel with the channel. Ideally, the fronts are convex outward in vertical section with the overall edge of the cell in the shape of a compressed crescent, the shape expected from the velocity of flow through a uniform sandstone layer (Germanov, 1960, p. 69). Geochemical cells may have transverse and longitudinal dimensions measured in miles and thicknesses of hundreds of feet. Where small-scale irregularities such as crosscutting channels, clay zones, and other small-scale sedimentary features are present, complex shapes develop. The size of the cell is very large compared with the size of the mineralized fronts along the edges and on irregularities on the upper and lower surfaces. The contrast between the character of the rock inside the cell and rocks outside are important guides in exploration for the mineralized fronts.

The process of uranium migration or its oxidation, dissolution, precipitation, and reduction is described in geologic literature of the last 5 years in terms ranging from broad generalities to detailed evidence. Krauskopf (1967, p. 528-529) in discussing the geochemistry of uranium and the process of migration, stated that primary uranium minerals are oxidized to the hexavalent uranyl ion, which is somewhat mobile in weakly acidic solutions, and also in neutral and alkaline solutions if carbonate ion is present. From such solutions uranium may be reduced by any one of several reducing agents, notably by organic matter, forming uraninite or a hydrate.

Granger and Warren (1969) have proposed a process whereby the partial oxidation of sulfide minerals produces unstable soluble sulfur species at the front. These are moved promptly into the reducing environment, where they spontaneously undergo decomposition by disproportionation, a reaction in which part is oxidized and part is reduced. The end products are an inert oxidizing agent and active reducing agents. The laboratory experiments have produced some very interesting results, and it is hoped they ultimately will produce some definitive answers. The principal purpose of this work was to establish a process that could produce a well-defined reduction barrier without assistance from bacteria. Although the results may prove useful, the basic assumptions are not necessarily valid, particularly the assumption that the scattered organic fragments could not provide nutrients uniformly along the roll front. This assumption is especially surprising from an author who has called on the mobilization of organic material to account for Ambrosia Lake ore deposits (Granger, 1968, p. B65).

Harshman made an extensive study of the ore bodies and the ore-forming process in Shirley basin. His latest and most comprehensive review of the problem gave much evidence to support his ideas (Harshman, 1970). He discounted the arkose as a source of uranium and substituted granitic rock of mountains which flank the basin (and contributed the arkose), in addition to the volcanic ash which once overlay the basins, as the source of metals. The transporting solution was alkaline and oxidizing, and not acidic, although Harshman advocated a drop in pH (of undetermined extent) from the oxidation of pyrite in the ore body. The deposition of the ore is a result of a reduction in the Eh of the transporting fluid. The reductant is probably hydrogen sulfide.

A large part of the difficulty in determining the character of the mineralizing fluid and ore-forming process stems from artificially imposed restrictions. First of these is the requirement that the solution must be able to travel for miles through the formation in equilibrium with the rocks, because very little change was produced by the passage of mineralizing fluids (Harshman, 1970, p. 228; Gruner, 1956, p. 498). However, there is little evidence that the solutions actually transporting uranium moved more than several feet. The second restriction is the range of Eh and pH conditions which reasonably can be expected in natural environments (Harshman, 1966, p. C171). An orebody is the product of uncommon conditions, and it is illogical to regard as unattainable rigorous conditions which are present in nature, such as acid water from coal mines, from the oxidation of sulfide bodies in supergene enrichment, or from the weathering of waste dumps containing disseminated sulfides.

Most workers in Wyoming uranium geology agree on one point—geochemical cells are a dynamic migrating phenomenon. Because the cell migrates and carries metals with it, remobilization and precipitation of metals become necessary. If the formation were invaded by an oxidizing fluid without mineralization, and mineralizing solutions were introduced and ore bodies precipitated at the static border of the oxidized zone, an external source such as tuffaceous sediments would present no problem. Because the ore bodies have moved and possibly are moving to a limited degree at present, leaching of the sediments as the cell migrates through them is the preferred source of metals. However, if the process by which the cell migrates is capable of dissolution of the metals, those reaching the front from external sources would supplement the accumulation of metal and, in the case of metal-deficient sediment, could supply it all. Either source contains an adequate supply for all the known ore bodies in the Wyoming districts. The key to the source probably will be found as a better understanding of the mineralizing process is achieved.

Geochemical Cell Reactions

From observations in several uranium-producing districts, detailed knowledge of several ore bodies, and a thorough review of the geologic and microbiologic literature, a hypothesis was developed to relate the known associations of geochemical cells and uranium deposits (Rackley *et al.*, 1968, p. 120). Reactions that take place in a geochemical cell are biochemically controlled changes in physical and chemical conditions. Many reactions probably take place in the advancing edge of the cell, but those that can be identified as important are shown in Figure 3. The right side of the figure, inside the curved line, is the oxidizing zone, and the left side is the reducing zone. The arrows indicate products or conditions created by one reaction affecting or entering some other reaction. The pyrite and the reduced ore minerals are not mobile; the cell advances to them.

The bacteria discussed hereafter have not been identified from a geochemical cell by the writer. Bacteria of these types have been identified by Lisitsyn and Kuznetsova (1967, Fig. 1, Table 3) in a study of the bacterial population from flowing water-well samples taken from the recharge area of the mineralized zones across the front (reduction barrier) in a Russian basin. The U. S. Atomic Energy Commission had studies made of the bacterial populations in which some of these bacteria were identified (Douros, 1967, p. 43-49). However, in geology we can use the techniques followed in bacteriology and medicine, where bacteria are identified by their effects or their symptoms in patients.

Reducing environment—In the leading edge of the geochemical cell (left part of Figure 3, outside the oxidizing zone) there is a zone of increased activity within the initially reduced sediments. The amount of organic material and pyrite may be substantially greater than in the sediments beyond the influence of the cell (King and Austin, 1965, p. 32; Rubin, 1970, p. 5-8). Several reactions occur in this area. Most obvious is the change in the carbonaceous material from bright, carbonized plant fragments retaining much of their woody character in the area just outside the influence of the cell, to sooty, incoherent but distinct masses near the interface with the oxidized zone, and finally complete obliteration of these distinct masses into a dark sooty, commonly sticky, coating on the grains. This change indicates that the carbonaceous material is mobi-

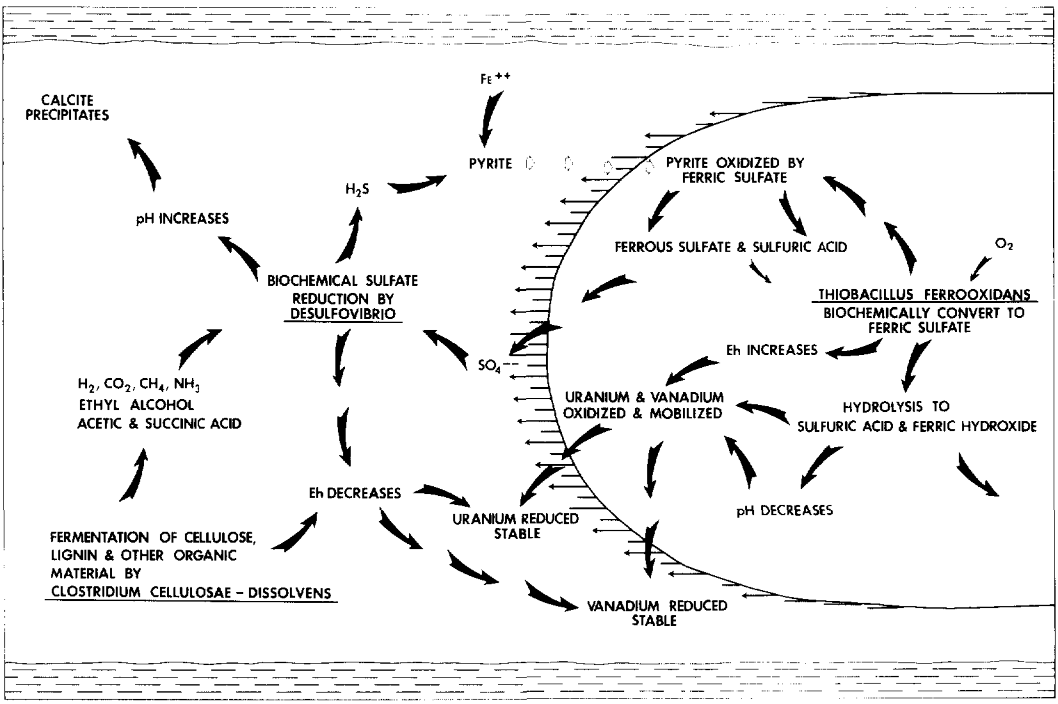

FIG. 3—Some probable reactions in advancing geochemical cell. Cell moves from right to left. Left side is reducing, right side is oxidizing. Vertical and horizontal scales are relative to each other. Thickness range is 3-40 ft (1-12 m).

lized and utilized by the bacterial population as the cell encroaches.

The fermentation of the cellulose and other organic material by the anaerobic spore-formers, *Clostridium cellulosae-dissolvens* (Stanier *et al.*, 1963, p. 446) produces several products required by other bacteria. The ubiquitous sulfate-reducing microbes also are active, and almost any form of organic matter—*e.g.*, cellulose, lignin—will support growth of one or more of the microbes in this group (Zajic, 1969, p. 79). The sulfate-reducing genus, *Desulfovibrio*, through anaerobic respiration, utilizes the inorganic sulfates, carbon dioxide, succinic acid, and sometimes gaseous hydrogen to produce hydrogen sulfide (Stanier *et al.*, p. 423). These bacteria are extremely strict anaerobes and create an environment of pH 7.8-8.4 (Jones and Starkey, 1962, p. 65) and a low Eh because of the hydrogen sulfide they generate and the free hydrogen in the environment produced by *Clostridium*. These two bacteria and others of the same group provide an environment which physically reduces and precipitates the uranium and other ions associated with uranium. Sulfate-reducing microbes normally do not select and precipitate specific metals, but they act as generators of hydrogen sulfide which reacts with metals to precipitate sulfide minerals (Zajic, 1969, p. 85). Under certain conditions other sulfate-reducing microorganisms produce a bituminous oil-like substance (Zajic, 1969, p. 83) which may be the source of the asphaltic material in some uranium districts.

Oxidizing environment—In the Gas Hills, Shirley basin, and Crooks Gap areas the oxidized or altered zone has a sharp contact with the ore and reducing zone, but in the Powder River basin there is a zone of incomplete oxidation of varied thickness and width, but generally less than the size of the ore body, between the completely oxidized and the mineralized reduced zones (Davis, 1969, Plate 4; Rubin, 1970, p. 8). This incompletely oxidized zone is a pale yellowish green and contains some remnants of carbonaceous debris, pyrite, and minor limonite and hematite stains. This difference is probably the result of a lower Eh gradient across the Powder River basin fronts than across the fronts in the other Wyoming districts. In the reducing side of the cell the lower Eh gradient causes somewhat broader and thicker but lower-grade mineralized zones.

In all the Wyoming districts there is a substantial contrast in environments in close proximity in the same permeable host; the contact zone separating these environments is commonly 1-8 cm wide. In the altered oxidizing part of the cell (shown inside the curving line on the right of Fig. 3) *Thiobacillus ferrooxidans* and related bacteria are the most active populations (Lisitsyn and Kuznetsova, 1967, p. 1181). *Thiobacillus ferrooxidans* is found in nature wherever sulfides are found in an oxidizing environment (Kuznetsov *et al.*, 1963, p. 134). Not only does this species thrive in an oxidizing environment but it creates pH as low as 1.8 and can survive in a pH of zero. The optimum pH is from 2 to 4, but with a pH of over 4.5, activity is greatly reduced (Kuznetsov *et al.*, 1963, p. 131). These bacteria are the cause of the extreme acidity of coal-mine waters and are used in the recovery of copper from waste piles. The oxidation of pyrite by the *Thiobacillus* is approximately 200 times faster than by atmospheric oxygen alone (Kuznetsov *et al.*, 1963, p. 128). Together with the oxidation of pyrite, sulfuric acid is produced in greater quantities than it is consumed.

There are three basic reactions in the *Thiobacillus* zone. One is chemical and uses pyrite, ferric sulfate, and water to produce ferrous sulfate and sulfuric acid. In the biochemical reaction, the ferrous sulfate is used by the bacteria to produce more ferric sulfate, which can be further used in the oxidation of other pyrite (Silverman, 1967, p. 1047). The third reaction is hydrolysis of the ferric sulfate to produce sulfuric acid and iron hydroxides. The principal addition to the *Thiobacillus* zone from external sources is carbon dioxide from the unaltered side of the cell and oxygen from the altered side. Iron minerals present in the altered area as a result of the geochemical cell are largely dependent on the amount of oxygen supplied and the Eh which results. Therefore, pyrite can be formed if oxygen is relatively deficient, and hematite and limonite if the oxygen is abundant.

Not only does the *Thiobacillus* create an extremely acidic environment, but it also creates an extremely oxidizing environment. Eh values up to plus 760 mv have been reported (Kuznetsov *et al.*, 1963, p. 133). There are extreme conditions of both pH and Eh in very close proximity on the leading edge of a geochemical cell. The two zones are incompatible to a large degree, in that the *Desulfovibrio* is a strict anaerobe, whereas the *Thiobacillus* requires low pH and high Eh for its activity. A band of decreased activity separates the two zones.

Normal constituents of groundwater enter the *Thiobacillus* zone where the bacteria create a strongly oxidizing and acidic condition. This zone is a mobile environment a few centimeters to a few meters in cross-section width, controlled by the availability of nutrients and by unfavorable conditions for bacterial activity. Metals oxidized from this zone are moved into the reducing side of the cell and are precipitated by the moderate to highly reducing alkaline conditions.

Metal zoning—Peculiarities of the geochemical cell are the metals concentrated by it and the order in which they occur. Cells in the Tertiary sediments are very simple, containing principally uranium with minor amounts of molybdenum and minor to moderate amounts of selenium. In some parts of the Powder River basin vanadium is a significant constituent. A knowledge of these relations can be very useful in determining detailed configurations of the ore bodies and in identifying alteration in questionable areas.

In the simple cells of the Wyoming Tertiary deposits, uranium is on the reduced side of the contact, with the greatest concentrations adjacent to the contact, as shown by the cross-hachured area of Figure 4A. The uranium concentration gradually diminishes away from the contact, as shown by the diagonally hachured area. Vanadium has not been important in these deposits and is present in recoverable quantities only in the Powder River basin. Where vanadium does occur, it is associated with the highest concentrations of uranium, generally adjacent to the oxidized contact.

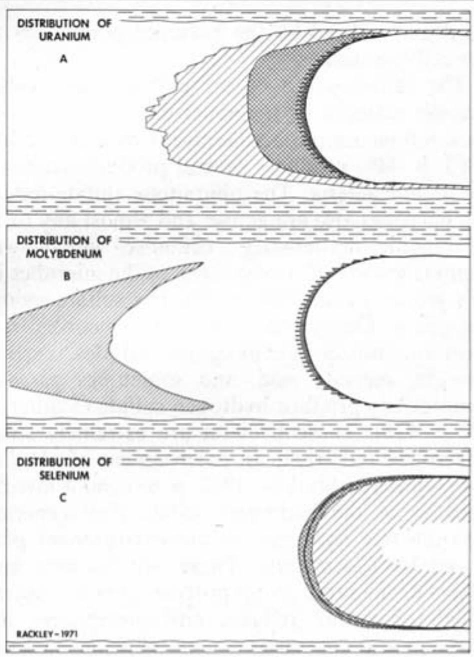

FIG. 4—Characteristic zoning of (A) uranium, (B) molybdenum, and (C) selenium in leading edge of geochemical cell. Intensity of hachuring is relative indication of concentrations which may range from traces to a few percent on same front.

Molybdenum is farthest from the contact and may be separated completely from the uranium zone, as shown in the diagonally hachured area of Figure 4B. Molybdenum typically forms a halo around the uranium zone, but may be at a distance one to three times the width of the mineralized zone from the uranium. The amount of molybdenum ranges from traces to 0.5 percent, but generally is in the lower end of the range.

Selenium is present in trace amounts in the oxidized zone, increasing in concentration toward the border with the unoxidized. The greatest concentration is in a narrow band straddling the contact, as indicated by the cross-hachured band at the contact in Figure 4C.

Calcite-cemented lenses and concretions are present in the outer margins of the reaction zones. The calcite is resistant and in places the contact partly moves past a calcite-rich zone but does not completely envelope it in alteration.

The cause of the metal zoning is unknown, but Kashirtseva (1964, p. 44) has suggested that redox-potential gradient is important in the metal accumulation.

Gas Hills Case

Sedimentation

The Gas Hills uranium district was affected directly by two obvious controls in the sedimentary pattern: (1) the topography of the depositional area, and (2) the large drainage basin building an alluvial fan around and over the significant topographic features. The Gas Hills are the topographic expression of the Dutton Basin anticline, the entire area being known as the Gas Hills uranium district. Figure 5 is an artist's sketch of the Gas Hills immediately preceding the deposition of the arkosic facies of the Wind River Formation. The escarpments of the Mesozoic and Paleozoic formations in the southwestern part of the area, T32N, R90-91W, were structurally and topographically higher than the equivalent zone on the north flank of the Dutton Basin anticline. With this situation, the stream originating on the Sweetwater arch on the south would crosscut the resistant strata until a thick, nonresistant formation was encountered, then follow it to the lower Dutton Basin anticline, T33N, R89-90W. The redbeds of the Triassic Chugwater are the first major nonresistant formation. The Rattlesnake Hills, the easternmost anticline, T33N, R88W, and Black Mountain in the southeast corner of T33N, R89W, acted as barriers to deposition of coarse sediments on the north and east throughout the period of arkose deposition.

As the Sweetwater arch began to rise south of the Gas Hills, erosion of the earlier Wind River sediment ended and deposition began. Until the time represented by Figure 6, sediment deposited in the central part of the district was dominantly fine grained and carbonaceous facies with coaly beds (Soister, 1968, p. A18). This initial phase of sedimentation was floodplain sediment deposited before the formation of the alluvial fan or downstream from the initial slope of the fan. As the rate of sedimentation and the thickness of the arkosic facies increased, shifting of the streams on the fan caused the fan to build westward through the gaps in the escarpments and onto the plain west of the Dutton Basin anticline. Figure 7 is a sketch of the area near the middle of the deposition of the arkosic facies. The escarpments in T32N, R90W, particularly the siliceous Mowry Shale ridge, were conspicuous topographic features. These ridges were barriers to the westward shifting of the streams on the fan. The Dutton Basin anticline protruded through the fan and provided control for streams flowing west of it and for those flowing across it on the southeast. The Paleozoic escarpments and Black Mountain, the resistant core of the Dutton Basin anticline, were limiting factors on the southeast edge of the fan. The mineralized interval of the Wind River Formation, approximately 300 ft (92 m) thick, coincides well with the sediment deposited between the times represented by Figures 6 and 7. Coarse material is the predominant sediment of an alluvial fan, but when the stream shifts against a ridge higher than the fan, silt, clay, and lignite accumulate locally in the low-lying areas between the stream and the ridge. Thus, areas of intertonguing arkose and finer sediment are present against the flanks of the ridges.

These three sketches portray the development of the arkosic sequence from channel and floodplain deposits of an initial meandering stream to a broad alluvial fan. The limits of the coarse permeable zones are initially the dimensions of the valley, but successively higher sedimentary zones cover increasingly broad areas. This progressively greater freedom for lateral movement of the streams also increases the variety of conditions of sedimentation, but at the same time it results in a tendency to homogenize thick extensive units within the formation. Onlap onto older formations makes the margins of these units less susceptible to homogenization, and the overall result is a thick sequence which has relatively high permeability in its central section but reduced permeabilities along its margins.

The approximate limit of the arkosic facies of the Wind River Formation is shown in Figure 8.

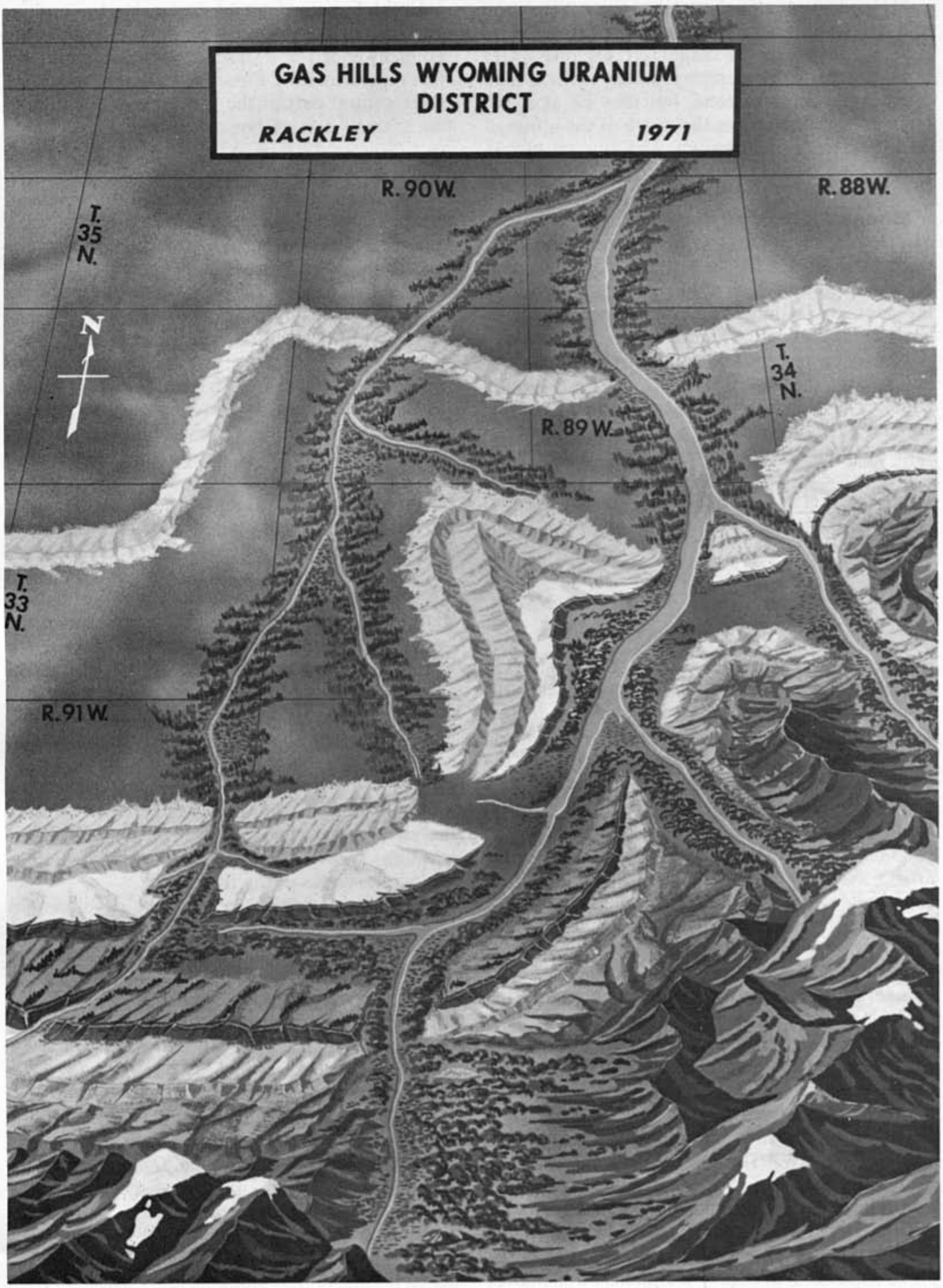

FIG. 5—Gas Hills area before beginning of sedimentation of arkosic facies of Wind River Formation.

The Gas Hills, as well as the hills on the southwest, were completely covered. Part of Black Mountain and much of the Rattlesnake Hills were still exposed.

Alteration and Mineralization

After the end of Wind River sedimentation the area was covered by a sequence of silt, fine sand, and volcanic tuff and debris. Prior to the deposition of the Oligocene White River Formation, the area was subjected to extensive erosion. Probably this erosion removed most of the sediments overlying the apex of the fan of the Wind River arkose and some of the arkose as well. Erosion also opened an avenue for the introduction of oxygenated waters which penetrated far below the water table into the reduced sediments of the Wind River Formation. The exact timing of this introduction is not known, but it could have started with initial removal of the cover. The final emplacement of the presently known ore bodies may have been much later.

The alteration and mineralization of the Gas Hills began with the introduction of oxygenated water, which initiated the growth of a geochemical cell. The cell expanded as the front migrated slowly down the fan. Small discontinuous clay and silty zones were enveloped by the cell, but beds of low permeability adjacent to the pre-Tertiary ridges divided the cell into lobes which may have been superimposed or have taken separate directions as the local permeability conditions dictated. The cell ultimately formed a continuous, three-dimensional, finite body of alteration similar to that shown in Figure 8. In this sketch, sediments overlying the Wind River have been ignored, and the surface is shown as it would have appeared at the end of Wind River deposition. The strata overlying the geochemical cell are shown as having been removed in the shape of the uppermost extent of the cell. Two lower levels of the cell also are shown as they would have conformed to the sedimentary pattern at those levels (*cf.* Fig. 6). The distribution of alteration is generalized from the distribution of known ore bodies on the lateral margins of the cell. The position of the cell west of the Gas Hills is a projection based entirely on the probable sedimentary pattern, because that area has been removed by erosion. Little is known about the southeast part of the cell, and it is projected on the basis of known limits to sedimentation.

The known ore bodies are on the lateral edge of alteration in the west and central ore trends, but significant ore bodies also are present on the lower surface of the altered zone in the east Gas Hills. Present distribution of the host formation and known mineralized areas are shown in Figure 9. Simple ore bodies have been implied, but the ore bodies and associated alteration may be in exceedingly complex shapes as the fluvial origin of the host sediment might suggest.

The visual, chemical, and mineralogic character of the Gas Hills alteration and mineralization has been described by King and Austin (1965). For additional information the reader is directed to Soister (1967, 1968) and Anderson (1969).

Shirley Basin Case

Although Shirley basin is an intermontane basin with granitic rocks exposed on both the east and west, the sediments were derived from the eastern flank of the Sweetwater arch on the west. The sediment was dumped into the basin as an alluvial fan which spread eastward across the western half of the basin. The coarse sediment in the eastern part of Shirley basin was deposited as point bars in the channel of meandering streams. The silt and clay were deposited in flood basins adjacent to the streams. The erosion surface of the basin prior to the deposition of the arkose was gently rolling hills because of the nonresistant nature of the marine shales on which it was developed. The Wall Creek sandstones of the Frontier Formation formed discontinuous ridges at the foot of the Laramie Range, and successively higher ridges developed on the older resistant beds to form the eastern limit of the basin. The Wall Creek ridge, trending northwesterly from the southern part of T28N, R78W, reached a height of 300 ft (91 m) above the lowlands on the south and west. The broad flat south of the ridge probably was the low point of the basin, and the sediment transported to the basin by meandering streams accumulated rapidly in this area. As sedimentation continued, the ridges acted as barriers to the migration of the streams and served to control the distribution of the coarse sediments. Abundant coarse material is present south and west of the Wall Creek ridge, but there is very little on the east.

The configuration of the present pre-Wind River surface and the mineralized and altered areas are shown in Figure 10. There has been post-Wind River tilting toward the northwest, which is demonstrated to a limited degree by the northwest tilt of the Wind River onlap. This tilt, combined with the increase in coarse sediments in the southeast, suggests that the drainage from Shirley basin was toward the southeast. The tilting probably was responsible for the introduction of the geochemical cell, because the cell appar-

FIG. 6—Early sedimentary pattern of arkosic deposition, Gas Hills.

FIG. 7—Intermediate sedimentary pattern of arkosic deposition, Gas Hills.

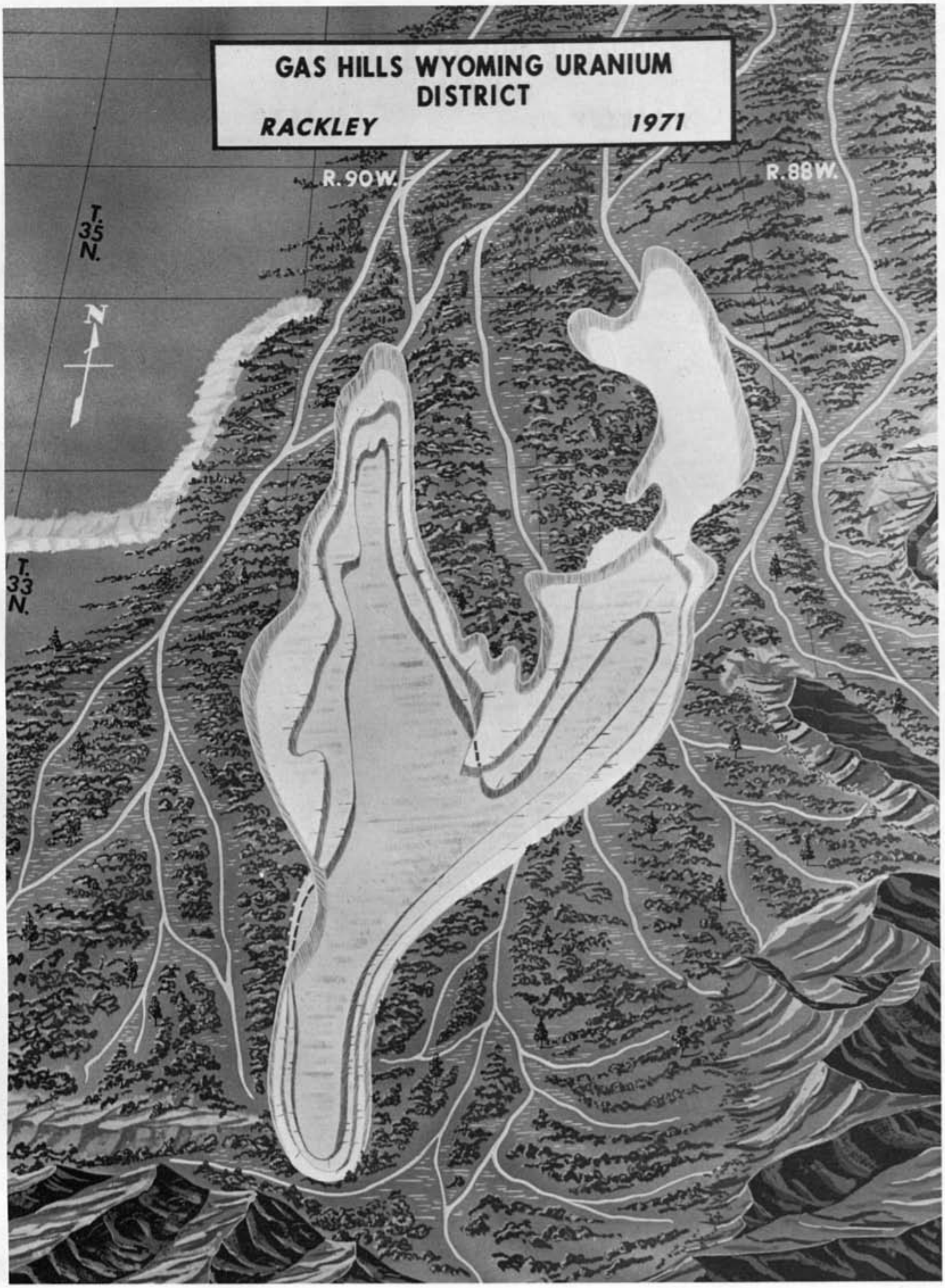

FIG. 8—Final sedimentary pattern of arkosic deposition with altered area and strata overlying uppermost alteration shown as having been removed. Mineralized areas are along margins of altered area.

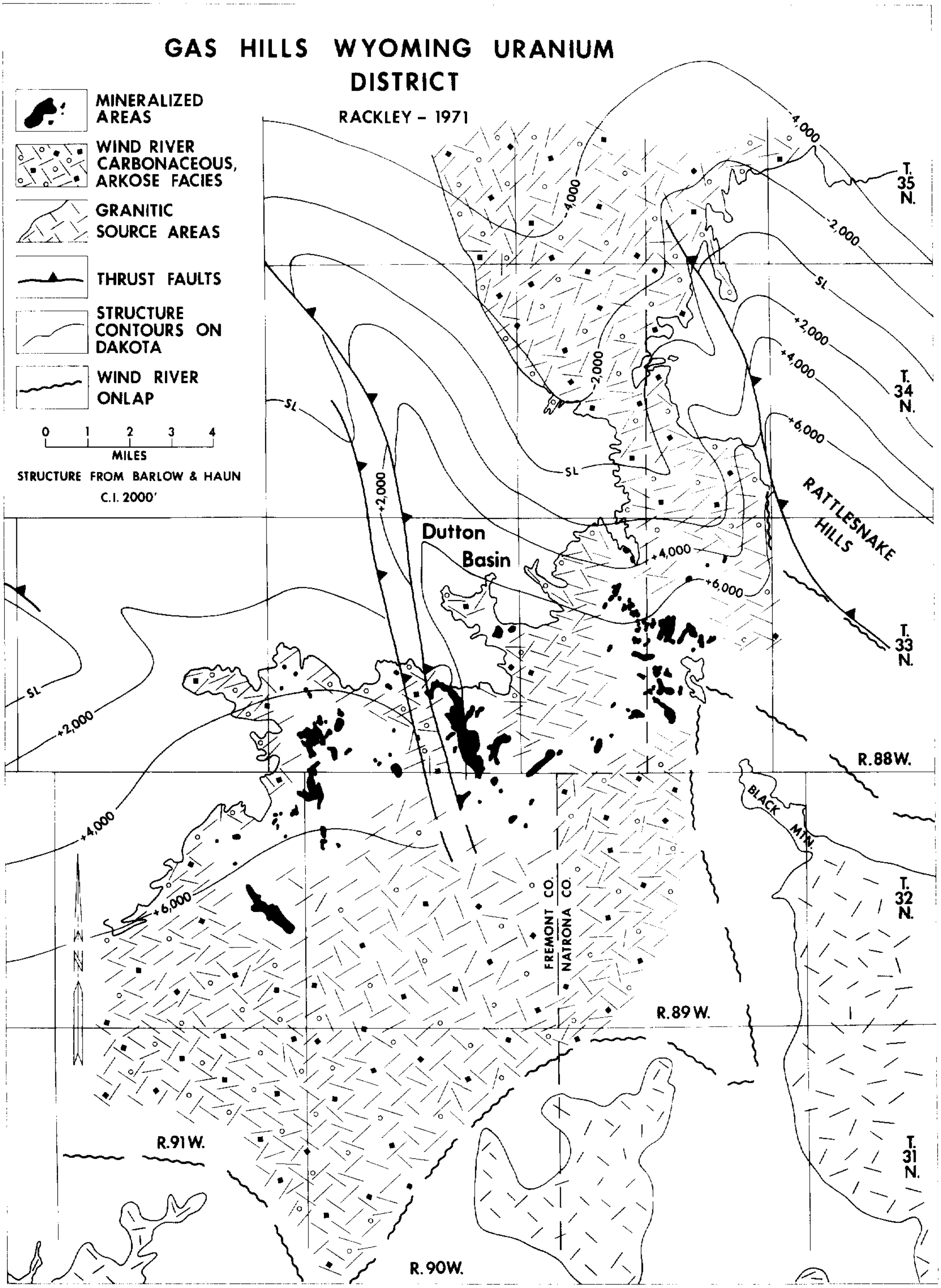

Fig. 9—Distribution of arkose facies and mineralized areas as presently known, shown on generalized structure map.

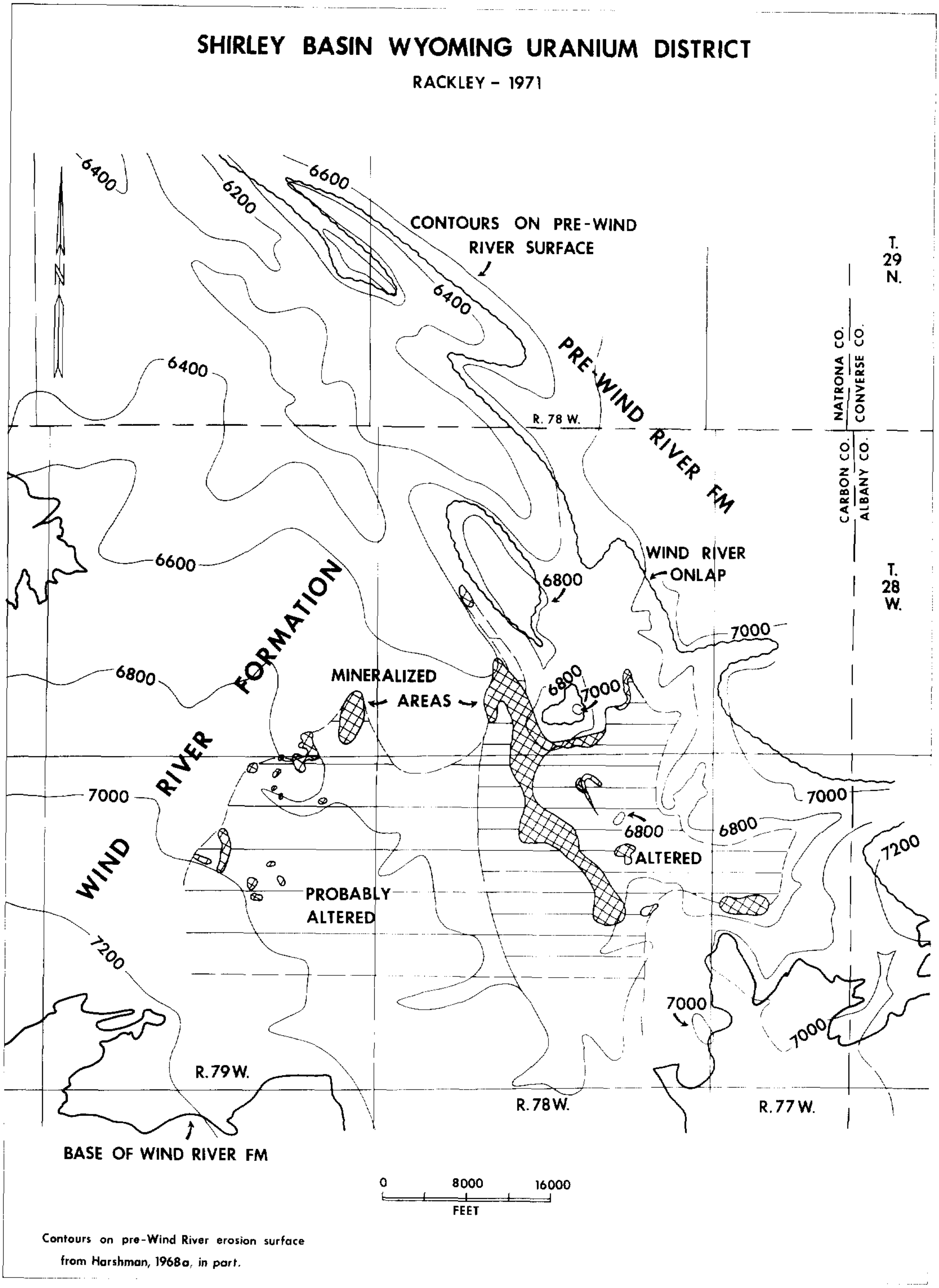

Fig. 10—Present configuration of pre-Wind River surface in Shirley basin showing relation of mineralization and alteration.

ently moved from south to north and not down the depositional slope from west to east. The shape of the alteration and mineralization indicates the importance of topography in sedimentation and in the distribution of ore bodies.

For additional information on the geology, alteration and mineralization of Shirley basin, the reader is directed to Harshman (1961, 1962, 1966, 1968, 1970), Bailey (1965), Melin (1964, 1969). For other Wyoming Tertiary deposits, consult Davis (1969) and Rubin (1970) for the Powder River basin, and Bailey (1969) for the Crooks Gap area.

Conclusions

In the long series of events from the degradation of a source area to the accumulation of a sandstone-type ore body, the single most critical process is sedimentation in a suitable environment. The critical combination of permeability, carbonaceous material, and pyrite can be achieved only under restricted conditions of climate, flow regime and, to a limited extent, the composition of the sediment. When these sediments are preserved by burial, and uplift causes movement of groundwater through an aquifer carrying oxygenated water well below the static water table, a geochemical cell develops. The distribution of alteration and mineralization or the shape of the cell will be controlled indirectly by those factors which influenced the sedimentary pattern, *i.e.*, tectonic elements and paleotopography. Many factors have direct control of the shape of the cell; however, most of them can be determined only after extensive work, and probably after mineralization has been discovered. Paramount among these factors is the detailed shape of the sandstone bodies and of the silt and clay beds and lenses which intertongue with them.

Application of the concepts of the geochemical cell to uranium exploration can significantly reduce costs and improve success. The typical geochemical-cell ore bodies have geometric relations which permit a numerical evaluation of the favorability of the cell or one of its zones for uranium production with a relatively small number of drillholes that penetrate the cell in areas other than the front. Many more holes are required to define the ore body for production. This evaluation is based on the generalizations that: (1) thicker sandstone units contain thicker and wider ore bodies; (2) the grade of mineralization on the top and bottom surfaces of the cell is directly related to the grade of mineralization on the front; and (3) the thinning of the cell at a greater rate than the thinning, if any, of the sandstone indicates that the strength of reaction in the cell is great enough to produce a significant front at some distance from the physical limits of the sandstone. Conversely, those sandstones that are altered all the way to their limits invariably are poorly mineralized. The thickness of the cell is normally 40-80 percent of the thickness of the sandstone at the front. This relation lends itself to computerization if the basic information is properly correlated and identified. This may be expressed:

$$\text{favorability} = \frac{t \times R}{r}$$

Where t is thickness of cell or zone host sandstone unit; R is radioactivity on an arbitrary scale from 1 to 10 to cover radioactivity above normal background to ore grades, or the grade times thickness of the anomalous zones multiplied by a constant to convert them to whole numbers; and r is the ratio obtained by dividing thickness of cell by thickness of host sandstone (t) which always will be less than 1 and normally greater than 0.4. It cannot be zero because the drillhole must penetrate the cell in this evaluation technique.

Larger numbers are more favorable than smaller numbers. The favorability of the cell or zone is the average value of the points that penetrate the cell. The points which fortuitously might be in the front are useful in confirming the favorability but should be eliminated from the calculations because of a probable bias produced by one point. If the results are contoured, the more favorable areas and their general shape can be determined.

The habits of uranium ore bodies and their associated alteration are variable from district to district and even within districts, so the most important tool in exploration is a competent geologist who makes good observations and applies that knowledge to detailed execution of the exploration program.

Use of patterns of sedimentation as a guide to exploration should improve the odds and reduce the cost in the search for uranium ore bodies in new districts. In initial evaluation of a new prospective area, indirect evidence which may be available from outcrop patterns and structure maps may be useful. Structure maps are valuable for predicting the paleotopography of inclined or faulted strata and locations of subsiding or rising tectonic features and their effects on sedimentation. From the sedimentary pattern, the margins of zones of greatest permeability can be predicted and should be the highest priority exploration targets.

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