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Chapter 3

ORIGIN OF WESTERN-STATES TYPE URANIUM MINERALIZATION

RUFFIN I. RACKLEY

INTRODUCTION

The Colorado Plateau is the "home" of the uranium industry in the United States. Many uranium–vanadium deposits in sandstone occur there and these occurrences constitute a geologic type of ore deposit recognized in other areas of the world. The uranium deposits in the Wyoming basins are geologically similar to those of the Colorado Plateau in tectonic history and source-rock type, sedimentation, sedimentary environment, paleoclimate, mineralization, and alteration. This type of uranium deposit has been referred to as carnotite type, sandstone type, or western-states type. Because the bulk of reserves are non-carnotite and other types of uranium occurrences can also occur in sandstone, the use of the term western-states type is preferred for area and type recognition. The uranium occurrences in Cretaceous formations of the Black Hills of Wyoming and South Dakota are of this type (Renfro, 1969). Uranium occurrences in the Permian sandstones of Europe also demonstrate many similarities (Barthel, 1974). The Texas uranium deposits are similar in ore-body configuration and in some of the elements present, but differ in sedimentary environment and in some aspects of uranium source (Eargle and Weeks, 1973).

While there is and probably will continue to be differences of opinion concerning the similarities and differences, there is an increasing awareness that the similarities in the sedimentology and ore-forming processes far outweigh the differences in details of shape, size and elements present (Gruner, 1956a and Fischer, 1970 and 1974). These deposits have provided over 90% of the United States domestic production of uranium and vanadium and will continue to be the principal source of domestic uranium for some time to come. The importance of this type in the U.S. production and reserve picture indicates it constitutes approximately one fourth of the free-world reserves. This type of deposit possibly contributes a much higher portion of the total world supply, depending on the east-European and USSR reserves. No major uranium deposits of other types are known in the United States. Fig. 1 is a location map of the principal uranium-producing districts. Grutt (1972) provides an excellent review of the U.S. uranium occurrences.

The uranium deposits are epigenetic in the sense that they were formed in their present position after the enclosing sediment was deposited. How much later than the

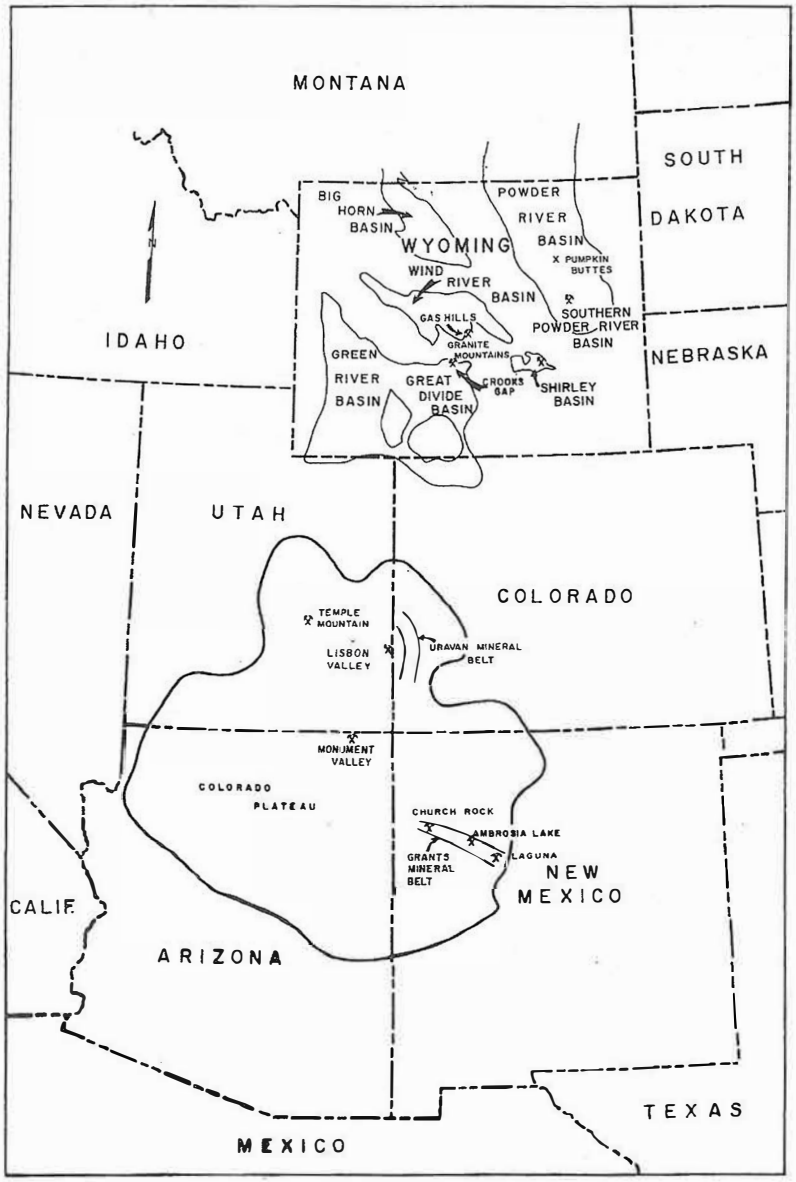


Fig. 1. Location map of Colorado Plateau and Wyoming basin uranium districts.

deposition of the host is one question yet to be answered. The deposits are also epigenetic in the sense used by Perel'man (1967) to indicate geological processes originating at or near the surface of the earth at low temperatures and pressures. In many respects, the ore deposits are similar to strata-bound supergene enrichments but have horizontal scales

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measured in miles. This implies that the metals were present in the sediment in small quantities, but in readily leachable form. Some geologists will not admit this possibility and some contradictory evidence has been presented. While more knowledge is being accumulated, this intrinsic source should be considered at least as a possible alternative because it requires the simplest process. These uranium deposits are considered to be the product of a physical–chemical trap, such as the hydrogen sulfide, reducing geochemical barrier for V, Fe, Cu, Co, As, Se, Ag, Ni, Zn, Cd, Hg, Pb, and U (Perel'man, 1967), which precipitates ore minerals from solutions on the basis of their concentration in solution, their sensitivity to changes in Eh and pH and their affinity for sulfur.

The most significant fact in the geological mobilization, transportation and deposition of uranium is that uranium has two naturally occurring valence states. In the hexavalent oxidized state, uranium can be taken into solution by acidic, neutral or basic water and transported infinitely. In the tetravalent reduced state uranium is practically insoluble. Therefore, the uplift and erosion of any provenance will take place under conditions favorable for the oxidation and mobilization of its uranium content. The accumulation of uranium from this or any other source can only take place in sediment in an environment in which reducing conditions are sufficiently developed to reduce it to the tetravalent state and precipitate it.

The typical ore body represents an addition of less than 1%, which is accommodated in the pore space. The physical habit of ore minerals in deposits of this type is thin coatings on detrital grains which may fill the pore spaces in high-grade deposits. The dissemination and microscopic size of the minerals increases the susceptibility to subsequent oxidation and remobilization by both alteration and weathering. The end result is an ore body formed by a mineralizing process which has little effect on the host rock, other than the addition of or an increase in the epigenetic minerals. The ore bodies are adjacent to moderately to strongly oxidized zones, which may show marked changes in color and epigenetic mineral content.

The metals known to occur in these deposits in significant quantities are: uranium, vanadium, copper, silver, selenium, and molybdenum. Other metals also known to be present include chromium, lead, zinc, arsenic, cobalt, and nickel, none of which are known to be commercially important. A deposit may be composed of any one or more metals in almost any combination, except copper and vanadium, which tend to be mutually exclusive. The reason for the latter phenomenon is not definitely known, but vanadium is deposited on the basis of reduction while copper is precipitated by hydrogen sulfide regardless of its redox state (Perel'man, 1967). The metals present always have a definite relationship to each other and to the overall geometry of the deposit. These minerals provide the principal limitations on the character of the process. Throughout this chapter the deposits will be referred to as uranium deposits although other metals may be commercially important.

Like "beauty is in the eye of the beholder", the "differences" between the Colorado Plateau and the Wyoming uranium deposits with respect to host rock depositional envi-

ronment, diagenesis, epigenetic alteration, and mineralization are largely in the eyes of the observer and in the observer's interpretation. The present cycle of erosion with the attendant oxidation of outcrops has caused confusion concerning the initial conditions of deposition and diagenesis. This, in turn, further adds to the confusion concerning the nature of the alteration and mineralizing process (Fischer, 1970 and 1974 and Adler, 1970 and 1974).

The present state of knowledge is conclusive that sedimentation and syndiagenesis of fluvial pyritic carbonaceous green, gray or black sand and mud produce these colors in the sediment almost immediately on entering the depositional basin, where vegetation is abundant in waterlogged sediment. The iron-oxide minerals staining the oxidized sediments are quickly converted to the reduced state and, if hydrogen sulfide is being generated, pyrite forms as discussed by Love (1964) and Berner (1973). Coleman (1971) reports pyrite forming on rootlets of living cypress trees along the lower Mississippi River at depths of 30 cm. Perel'man (1967) describes a reduced sediment (gley) at the bottom of streams and rivers in the USSR. One only has to venture into any marsh or swamp to examine the reduction of sediment taking place at the surface. It is possible to oxidize these sediments and thereby convert them to a red color but it is not possible to emplace carbonized logs, detrital carbonaceous material or bacterial residue into sediment deposited and brought into equilibrium as red beds.

The occurrence of uranium in sequences containing red beds is similar in some respects to the copper occurrences in fluvial sediment. References have been made to these red-bed copper deposits of the southwest United States, but from the author's examination of many of these deposits, it can be safely stated that none of these "red-bed" copper occurrences are actually in red sediment (Fischer, 1937; Soule, 1956; Ham and Johnson, 1964 and Woodward et al., 1974). The copper mineralization occurs in local bleached reduction centers within the red beds or in light-green or gray, white or medium-gray siltstone or claystone beds or sandstone channel deposits interbedded with or in the case of channels cut into red sediments. There is undoubtedly a genetic connection between the oxidizing environment in which copper and uranium are mobile and the reduced sediments in which hydrogen sulfide precipitates the copper as sulfide minerals, principally chalcocite, and uranium is precipitated by reduction, principally as uraninite.

The adoption of terminology for forms of an entire ore deposit or for geometrically similar segments has emphasized unnecessarily the "differences" between deposits in the various districts of the Colorado Plateau and Wyoming basins (Shawe et al., 1959; Fischer, 1960 and Gould et al., 1963). The variation of metals present from district to district also tend to emphasize the "differences", especially when weathered deposits are included. However, a roll, trend, wing, solution front, roll front, stack, limb, tube, or blanket can all be produced by a common process described below. The sizes, forms, or the metals present in the system, are not critical to the development or explanation of the process but are of primary economic concern.

There is a tendency to classify or characterize uranium deposits and the sediment in

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TABLE I

Common features of western-s

Tectonic conditions
1. Host rock is part of a thick
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5. Burial and preservation
Sedimentation
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Sedimentary environment, pal
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2. Gypsum crystals in mudsto
3. Reptilian fauna
4. Bioturbation
5. Vegetal carbonaceous mat residue and/or asphaltic m
Mineralization and alteration
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3. Mineralization occurs in sh
4. Epigenetic minerals occur
5. Mineralization is most co 20–50% of the sequence

which they occur by some of their properties. Unless these characteristics are based on interpretations of the basic sciences and observations of modern processes, there can be little progress toward unraveling the mysteries of their origin. The true differences reflect local variations, which are understandable and predictable if the overall process is known.

Although the uranium deposits of the Colorado Plateau and Wyoming occur in sediment ranging in age from Triasssic to Eocene, there are a number of features common to most, if not all, of the deposits. These features, listed in Table I, fall into four major divisions: (a) tectonic conditions; (b) sedimentation; (c) sedimentary environment, paleoclimate and diagenesis; and (d) mineralization and alteration. A discussion of these features could become a discussion of the origin of the uranium deposits, but since these are largely products of a series of conditions which occurred in each district, the conditions will be discussed rather than the products.

TABLE I

Common features of western-states type uranium deposits

Tectonic conditions

1. Host rock is part of a thick, extensive continental sequence, much of which may be red beds
2. Host rock is feldspathic to arkosic, micaceous or cherty sandstone
3. Volcanic material is present in or overlying the host rock
4. Upstream erosion of host rock
5. Burial and preservation

Sedimentation

1. Sedimentation by stream flow of braided or meandering streams on local or regional unconformities
2. Sandstones and conglomerates tend to be lenticular and relatively restricted
3. Siltstone and mudstone are interbedded with and in erosional relationship to sandstones and conglomerates
4. Mudstone clasts are common constituents of sandstone and conglomerates

Sedimentary environment, paleoclimate and diagenesis

1. Light gray or green to dark gray sandstones with gray and green mudstone, all commonly pyritic; pink or red mudstones present but minor in amount
2. Gypsum crystals in mudstones
3. Reptilian fauna
4. Bioturbation
5. Vegetal carbonaceous material from logs, stumps and roots in place, detrital fragments to bacterial residue and/or asphaltic material

Mineralization and alteration

1. Uraninite and coffinite are principal uranium minerals, in non-weathered deposits
2. Mineralization is both discordant and concordant with sedimentation
3. Mineralization occurs in sharp contact with carbonaceous-free or oxidized zones
4. Epigenetic minerals occur in same relative spatial positions when present
5. Mineralization is most common in thicker sandstone-facies belts where mudstone facies make up 20–50% of the sequence

TABLE II

Development phases of western-states type uranium deposits

Source area	Depositional area
1. Strong positive, erosion removes sedimentary cover, sediment supply very large and easily eroded, stream volume low to moderate; volcanic centers develop	weak positive to neutral, extensive accumulation of continental sediments; alluvial fans-bajadas, sand dunes, vegetation sparse to moderate, sediment dominantly oxidized; red beds and gypsum
2. Moderate positive, erosion of mountain cores; rainfall increases, sediment supply large and easily eroded, stream volume moderate to high; volcanic centers active	relatively limited accumulation of sand on alluvial fans or meanderbelts; rainfall increases or natural irrigation, vegetation abundant, swamps; sand – organic rich, pyritic, light to dark gray; clay – light- to medium-gray or green, pyritic, some carbonaceous clay or lignite; local high areas subaerially oxidized
3. Weak positive, erosion; stream gradient lowered, sediment supply moderate but difficult to erode, stream volume moderate; volcanic center inactive	sediment increasingly clay, sand deposited as point and braid bars, organic rich, light- to dark-gray; clay·light- to medium-gray or green, swamps increase, vegetation very abundant, lignite and carbonaceous clay form
4. Weak positive, erosion; stream gradient low, stream volume moderate, sediment supply moderate but difficult to erode	sedimentation ceases, extensive basin erosion or erosion of basin margin, geochemical cells develop if oxygenated water invades host rock
5. Weak positive to neutral, erosion	host rock buried by new depositonal environment, geochemical cells expand if oxygen supply continues
6. Collapse	basin uplifted, faulted, erosion of basin begins; geochemical cell develops and reaches maximum expansion if not initiated previously
7.	weathering and erosion of host rock, oxidation of ore bodies, some loss with erosion, some enrichment of unoxidized ores

In the series of events from the initial uplift of a positive area to the accumulation of a uranium ore body, the sequence is rather consistently repeated in the Triassic and Jurassic of the Colorado Plateau and the Tertiary of the Wyoming basins. All of the producing districts have been subjected to seven more or less distinct episodes or phases in the development of their present conditions. All phases in all districts are not developed to the same degree, but all are recognizable in every district. The seven development phases are outlined in Table II. These phases have unique combinations of tectonic conditions,

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erosion, sedimentation, sedimentary environment, paleoclimate, diagenesis and hydraulics, which have produced uranium concentrations of commercial importance.

The host formations of the uranium deposits discussed in this chapter contain or have produced approximately 90% of the known United States uranium (U.S. A.E.C., 1974). Since the United States has approximately 29% of the uranium reserves of the free world, these deposits constitute over 26% of the free-world reserves (Nininger, 1973). In the Triassic, the Chinle Formation is the principal uranium host formation. The Jurassic Morrison Formation is the host of the largest known uranium deposits in the United States. In the Wyoming basins the Paleocene Fort Union Formation and the Eocene Wasatch Formation, or equivalent formations, are host to the important uranium deposits.

TECTONIC CONDITIONS

The Wyoming basins are all intermountain basins developed on the platform well removed from the continental margin. These basins developed in Paleocene time as a result of the Laramide orogeny, ending Cretaceous sedimentation in the Wyoming area. The entire area was uplifted, but the Granite Mountains area was thrust up into a prominent range of mountains in Paleocene and Early Eocene time. From the Granite Mountains coarse sediment spread into the adjacent basins (lower areas on and between mountains) in a series of pulses.

The Colorado Plateau is also on the platform well removed from the continental margin. The entire Paleozoic and Mesozoic sedimentary section is of shallow water or continental clastic sediment with very small amounts of volcanics. The area can be considered a miogeosyncline filled with molasses-type sediment (Mitchell and Reading, 1969). The sediment was derived from the ancestral Rockies east of the Colorado Plateau from Permian through Early Triassic, but from Late Triassic through Jurassic the primary source of sediment was to the west. The development of this new source area reflects the westward movement of the North American plate and the development of the Mesocordilleran geanticline with its attendant acidic intrusive bodies near the continental margin (Dietz and Holden, 1970).

The sequence which produced each of the uranium provinces began with the uplift of a positive area from which large quantities of detritus was supplied to adjacent negative, or at least less positive areas. At the end of the first phase the erosion of the positive area and the filling of the depositional basin approach equilibrium. While the source area remains moderately positive, the relationship of sediment supply, stream volume, and gradient to the depositional area reaches a condition where sedimentation is greatly reduced.

The tectonic conditions of the source and depositional area are shown in Fig. 2 in graphic form for the seven development phases. Figs. 3, 4, and 5 should be referred to for

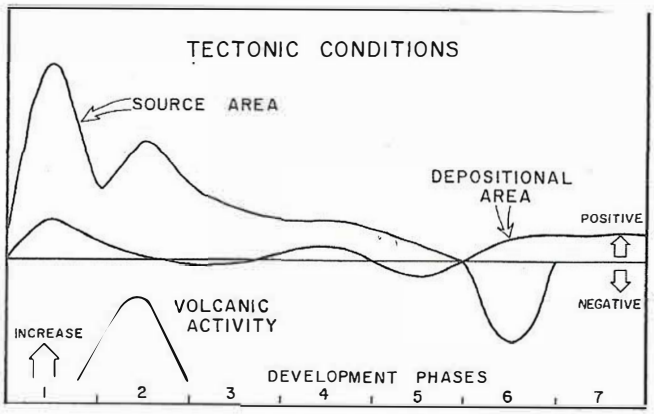


Fig. 2. Tectonic conditions in the principal source area and in the depositional area in which uranium deposits occur in sandstone during the seven development phases of uranium deposits.

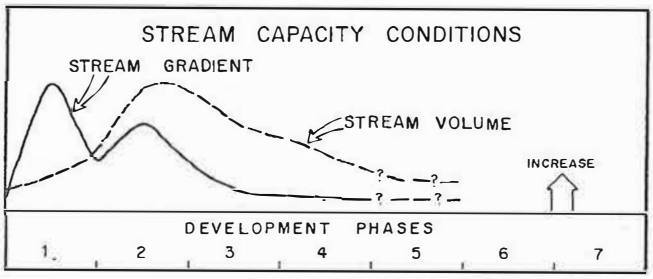


Fig. 3. Stream capacity conditions from the source area into the depositional basin during the first four development phases.

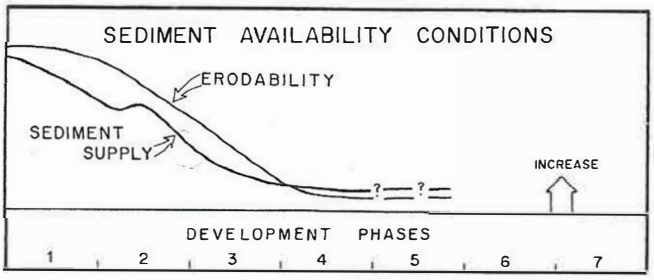


Fig. 4. Sediment availability conditions in the source area during the first four development phases.

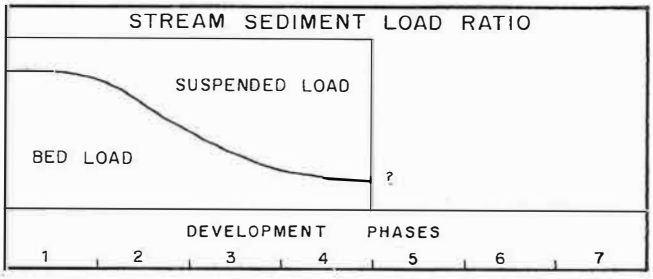


Fig. 5. Stream sediment load ratio of the stream during the first four development phases.

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the complementing conditions of sediment availability, erodability, stream capacity and bed-load/suspended-load ratio. Since the sediment of interest is a product of phases 2 and 3, interpretation of conditions other than tectonics are limited to about the end of phase 4.

The initiation of the second phase can be produced by renewed uplift of the source area or an increase in precipitation or most likely a combination of both. With the mountain core exposed, the sediment is largely derived from granitic rock which may have an anomalous uranium content. In contrast to the thick accumulations of red or variegated sediment of the first phase, the second phase produces a relatively limited amount of sediment deposited under conditions which give rise to a reducing environment. The increase in water supply causes the growth of abundant vegetation in the depositional area. The decay of vegetation growing in and buried with the sediment consumes the available oxygen and permits the development of a reducing environment in which sulfides might form. Weathering conditions in the source area would permit the oxidation and solution of uranium present. The reducing conditions in the depositional area would permit the reduction of hexavalent uranium carried in solution and cause its deposition in a tetravalent form. Volcanic centers become active and may contribute to the depositional basin directly through ash-fall or indirectly through stream-transported detritus.

The third phase may simply be a tectonically stable time during which the erosion and deposition during the second phase caused a reduction in the gradient of the streams. There is also the probability that the orographic rainfall may diminish as the mountains are reduced in height. Weathering of the source area becomes more intense and deeper, which increases the breakdown of both rocks and minerals and increases the availability of metals mobilized by an oxidizing environment. In the depositional area, the lower gradient reduced the rate of sedimentation and increased the residence time of water and contained metals and the probability of those metals being reduced and deposited.

The fourth phase is a critical stage, because the depositional area in continental sedimentation may become subject to erosion as slowly reduced stream gradients cut into sediment deposited by high energy, steeper-gradient streams. If erosion continues, the potential host may be partially or completely destroyed, and the probabilities are great that more have been destroyed than preserved. In the Jurassic and Tertiary host rock a few tens to a few hundreds of meters of sediment were deposited over the favorable host sandstone to provide a confining as well as a protective cover before the basin was subjected to erosion. Preservation of the favorable host during this phase is paramount, but the subjection of the basin or at least the basin margins to erosion may be almost as important. During this period of erosion, the surface water would tend to retain its oxygen because the reducing environments have been destroyed or restricted in size. The introduction of oxygenated water into the favorable host rock during this period would begin to destroy the carbonaceous material and the reducing conditions in the sediment. When conditions of oxygen input are adequate an invading oxidizing zone or geochemical

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cell is initiated. The period between the beginning of erosion and the final burial may be sufficient to initiate and complete the mineralizing process or the process may be initiated during this time but completed much later. This period of erosion presents the first opportunity for the initiation of geochemical cells and possibly the only opportunity for the mineralization of some of the erosional remnants of channels enclosed by fine-grained sediment.

After the sediment, deposited during the second and third phases, has successfully survived the erosion of the fourth phase, negative tectonic conditions of the depositional area cause renewed sedimentation to bury the potential host rock in the fifth phase. The sedimentary environment of the covering sediment may be considerably different than that of the host rock. The role of the source area becomes less important as its positive tectonic condition continues to diminish in the fifth phase.

The time the host rock remains buried varies with the age of the enclosing sediment, because all of the districts under consideration in this chapter entered the sixth phase of uplift and erosion at about the same general period of time.

The search for uranium deposits has been directed to those areas which have been subjected to the fifth and sixth and most commonly seventh phases of development. The search for uranium deposits presently in the process of formation could be most easily identified in the second, third or fourth phases. The fifth phase may be very long compared to the length of the others. Much of the earth's uranium resources may be in deposits which have reached this fifth phase but which have no surface expression. These deposits can be identified through evaluation of tectonic history and the processes of sedimentation.

The character of the streams, the supply of sediment and the sediment load are shown in Figs. 3, 4, and 5. The stream gradient was high in phase 1, but the stream volume was low and the sediment supply was dominantly older sediment on the uplift. As the second positive tectonic pulse began in phase 2, increased stream volume combined with increased stream gradient from renewed uplift to produce a flood of sediment from the erosion of the weathered mountain core. The sediment supply and erodability were both high in phases 1 and 2, but diminished thereafter. Stream volume decreased from its peak in the second phase. Sediment load diminished from the peak in phase 2 and the bed-load/suspended-load ratio decreased, resulting in a progressively higher percentage of silt and clay deposition as the end of phase 3 approached.

SEDIMENTATION

Sedimentation of the formations containing uranium has been largely, if not exclusively, by the process of stream flow. No debris flow is known to be present, but mud flows have been suspected in two Wyoming uranium districts close to the source area. The basic physics of fluids and sediment movement govern the process of stream-flow erosion,

transport and deposition. Wolman and Miller (1960) Rust (1969) and Allen (19 reader is directed for mo erosion and dispersal of se require some comment.

Streams draining the ri large supply of debris ava stream volume to transpo depositional area is relative mining the capacity of the early phases of the develop tion of a deeply weathered as indicated by Fig. 4. The decreases as the gradient o suspended load may decrea suspended load as the ene adjacent depositional areas. bajadas develop. If the stre apex of the fan, gravel and fine sand and silt will be de deposited if the water reac streams on alluvial fans will the upper fan is easily en stream tends to be shallow over its banks and disperse takes place on the braid b stream volume causes succ itself to reducing volumes.

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transport and deposition, a discussion of which is beyond the scope of this chapter. Wolman and Miller (1960), Doeglas (1962), Ore (1963), Coleman (1969), Williams and Rust (1969) and Allen (1970) have presented excellent work on this subject to which the reader is directed for more information. However, those factors which influence the erosion and dispersal of sediment as a part of the process which forms uranium deposits require some comment.

Streams draining the rising positive area at the beginning of a tectonic cycle have a large supply of debris available in the source area. However, unless there is sufficient stream volume to transport the sediment, the amount of sediment deposited in the depositional area is relatively small. The gradient of the streams is also a factor in determining the capacity of the streams to transport sediment. The conditions prevailing in the early phases of the development of a uranium host rock are shown in Fig. 3. Disaggregation of a deeply weathered granite mass provides a large supply of easily eroded material, as indicated by Fig. 4. The amount of bed load is high in the early phases, but gradually decreases as the gradient of the stream decreases, as indicated in Fig. 5. The amount of suspended load may decrease as well as the bed load, but the ratio will shift to a higher suspended load as the energy of the stream decreases. Where these streams enter the adjacent depositional areas, the gradients abruptly decrease and alluvial fans and aprons or bajadas develop. If the streams have sufficient volume, boulders will be deposited on the apex of the fan, gravel and sand will be deposited on a lower gradient further down slope, fine sand and silt will be deposited on the lower flatter parts of the fan, and mud will be deposited if the water reaches flats or lakes where settling can take place. Permanent streams on alluvial fans will have a braided pattern, because the cohesionless sediment of the upper fan is easily eroded with increase in stream volume. An aggrading braided stream tends to be shallow, further increases in stream volume cause the stream to spread over its banks and disperse sediment over much of the fan. The accretion of sediment takes place on the braid bars as the stream volume diminishes. Further diminution of stream volume causes successive levels of bars to form or emerge as the stream adjusts itself to reducing volumes.

Meandering stream patterns develop in areas where the bank material is cohesive and the bank is eroded by undercutting and slumping. The principal deposit in meandering streams is point-bar accretion. Clay clasts and blocks of considerable size accumulate with the point-bar sand from the slumping-bank material. Because of the decrease in gradients on alluvial fans and the increase of cohesive bank materials at the lower edge of fans, braided streams may change to meander patterns as the streams leave the fan. Both types of aggrading streams will be influenced by pre-existing topography, but neither have power to erode an obstacle and remove it. An easier alternative is to deposit the bed load and bury the obstacle or change directions.

From the preceding discussion of the development phases of uranium deposits, the changes in tectonic setting and climate interact to produce changes in stream volume and gradient, sediment supply and erodability which in turn determines the sediment load.

Fluvial systems, like other complex systems, are affected by changes in the variables. Since a wide variety of conditions are possible, it is necessary to relate to the genetic factors of process and environment for proper interpretation. The genetic approach provides a means whereby the complex variables can be estimated. Stratigraphic models based on process and environment of the fluvial systems have recently been synthesized by Fisher and Brown (1972), from work by Ore (1963), Bernard and Major (1963), Smith (1970). McGown and Garner (1970), Bernard et al. (1970), and excellent diagrams presented in Brown (1973). The terrigenous clastic fluvial depositional systems have three end members of the spectrum which are important in the sedimentation of the known uranium-producing districts. These are the braided system, the coarse-grained meanderbelt system and the fine-grained meanderbelt system. These systems are summarized briefly below from the above authors with comments relating the depositional models to the uranium-producing areas.

Braided-stream fluvial system

The braided-stream deposits are composites and remnants of lens-shaped channel fills and braid-bar accretions. The composition and texture of higher-energy streams are a mixture of grain sizes from cobbles to coarse sand and from pebbles to medium sand in moderate-energy streams. Silt or clay beds are normally not present, although clay clasts are present in the sand and conglomerate. Internal structures become increasingly less conspicuous as the grain size increases and the sorting decreases. Coleman (1969) found internal structures to be abundant in the fine sand of the Brahmaputra River where large-scale bed forms have been observed (by sonar) to migrate rapidly when the river is at flood stage. The beds of braided-stream deposits range from a fraction of a meter to a few meters in thickness, but the aggregate thickness of braided-stream sediment may reach hundreds of meters (Allen, 1970). Fig. 6 is a block diagram of an idealized fluvial system developed by Brown (1973).

The characteristics of the braided-stream system have been described by Fisher and Brown (1972) from which the following summary is largely taken. Braided streams are best developed where slope is relatively high and bed load is very high. These streams deposit under low flash–discharge conditions and dominate sedimentation on humid area alluvial fans. Geometry of the channel units are essentially flatbedded, discontinuous, tabular and lenticular bodies deposited as longitudinal and transverse bars. Structures are predominantly parallel bedding and tabular cross-beds with minor trough cross-beds and ripple cross-lamination. Composition is invariably coarse-grained with few fines or top-stratum deposits. Texture is poorly to moderately sorted, except longitudinal bar deposits fine and become better sorted downstream. Scouring is slight and commonly marginal to longitudinal bar as it becomes emergent. Individual channels can be delineated only by textural differences or discontinuities in structural trends. The braided streams produce multilateral sand facies as shown in Fig. 6. Braided streams have no levees and no in situ organics accumulate with the sediment.

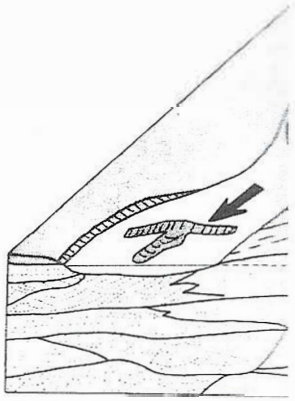


Fig. 6. Block diagram of an id
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The distribution of brai
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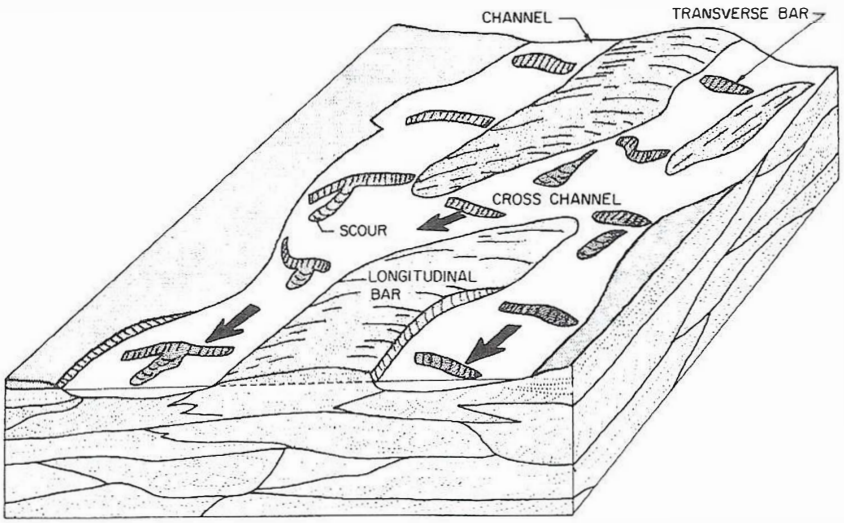


Fig. 6. Block diagram of an idealized braided fluvial system showing bed forms, sedimentary structure, and multilateral sand geometry. Brown (1973), with permission, modified from Ore (1963, 1965), Smith (1970); described by Fisher and Brown (1972).

The distribution of braided-stream sediment in typical aggradational periods is that of an alluvial fan. Figs. 11 and 12 (pp. 109, 110) show a simplified example from the Morrison of the Colorado Plateau. In the beginning of tectonic cycles, such as the early development phases of uranium deposits, the alluvial fan may be modified by prominent topographic features. The Gas Hills uranium deposits (Wyoming) occur in an alluvial fan, which was deposited over and around topographic features high enough to protrude through the fan during the period when the host sand was deposited, as shown in Fig. 7. The known ore bodies are along the margin of the fan where the sediment onlaps the preexisting topography (Rackley, 1972). The central Gas Hills trend is on the south extension of the west flank of the Dutton basin anticline near the center of the figure. Other ore trends are present on the opposite side of the fan from the central trend and on the margins of the fan segment east of the Gas Hills topographic features (Dutton basin anticline). The northern portion of the Crooks Gap area of central Wyoming is braided-stream facies on alluvial fans. The western portion of the Grants mineral belt of northwest New Mexico is also in the braided-stream facies. In the vicinity of Ambrosia Lake near the center of the Grants mineral belt the structure and geometry of the stream deposits indicate deposition under slightly different conditions (those found in a coarse-grained meanderbelt). Still further downstream in the Grants mineral belt (southeast) conditions change more to those of a fine-grained meanderbelt. The uranium deposits at Laguna are in the remnant of channel sands deposited in a fine-grained meanderbelt.

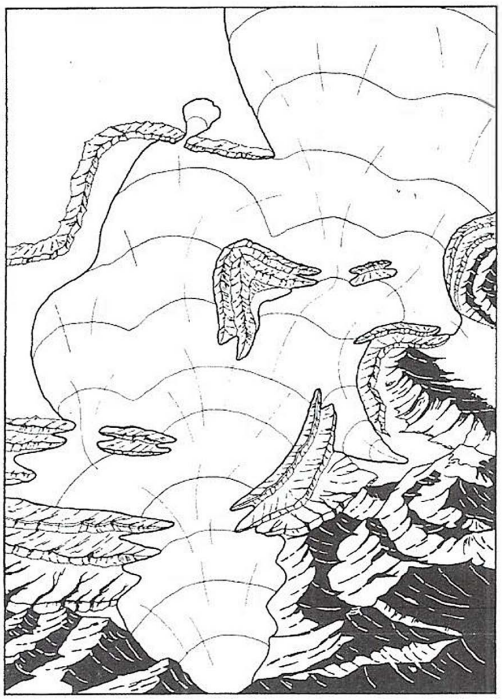
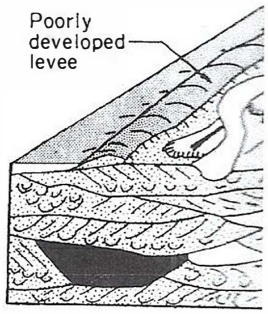


Fig. 7. Pattern of braided-stream sediment distribution on alluvial fan in Gas Hills, Wyoming. Modified from Rackley (1972).

Coarse-grained meanderbelt

Since the most important uranium deposits of the western-states type are in sandstones deposited in a coarse-grained meanderbelt fluvial system, a summary of this system is appropriate here. Fig. 8 is a depositional model of this system from Brown (1973). The block diagram in Fig. 8A shows the bedforms, sedimentary structures, and multilateral-sand geometry. Fig. 8B is a cross-section of a point-bar deposit of this system. The characteristics of the coarse-grained meanderbelt fluvial system have been described by Fisher and Brown (1972) and Brown (1973) from which the following summary is largely taken. These systems occur in the lower part of moderate to high bed-load streams under lower to moderate discharge and intermediate gradient. Sand bodies are a multilateral complex of partly preserved channel and other meanderbelt units. Larger sand units are built up of superposed and adjacent meanderbelt sand bodies. Internal structures include moderate- to large-scale trough cross-beds and wedge sets, some tabular cross-beds, and small-scale trough cross-beds, and few horizontal or ripple cross-laminations. Composition is mainly fine to dominantly coarse-grained sand with common granule to fine-pebble gravel. Mud and silt are minor constituents. Depositional units are laterally accreting



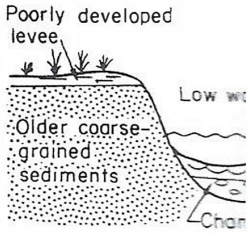


Fig. 8. Depositional model
showing bed forms, sedimen
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Fine-grained meanderbel

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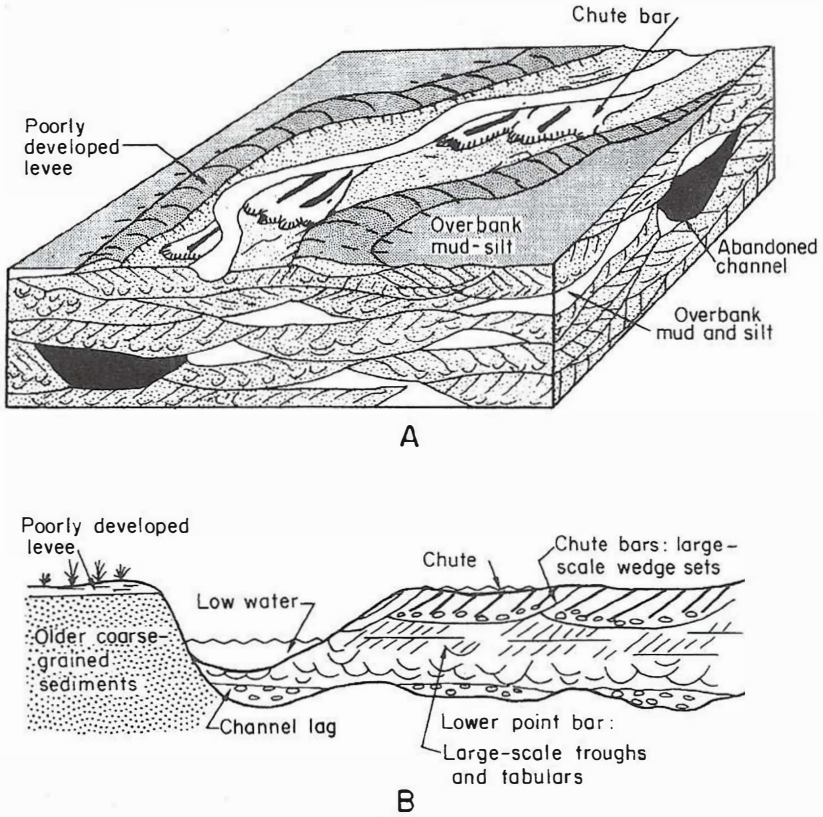


Fig. 8. Depositional model of an idealized coarse-grained meanderbelt fluvial system. A. Block diagram showing bed forms, sedimentary structures, and multilateral sand geometry. B. Schematic cross-section of coarse-grained point-bar deposits. Brown (1973), with permission, after McGowen and Garner; described by Fisher and Brown (1972).

coarse-grained point bars and vertically accreting chute channel-lag gravels and chute bars that develop on point bars during floods.

Fine-grained meanderbelt

The fine-grained meanderbelt system was active in the deposition of host-rock sequences of the Shirley basin and Powder River basin uranium districts of Wyoming as well as the Laguna district of the Grants mineral belt, New Mexico. This depositional system occurs under conditions of low gradient, moderately high discharge, mixed-load streams on aggrading alluvial plains (Fisher and Brown, 1972). Fig. 9 is a depositional model of an idealized fine-grained meanderbelt fluvial system from Brown (1973).

Fig. 9A is a block diagram showing bedforms, sedimentary structures and the multistory geometry of the channel sands. Included with the overbank mud in this diagram are

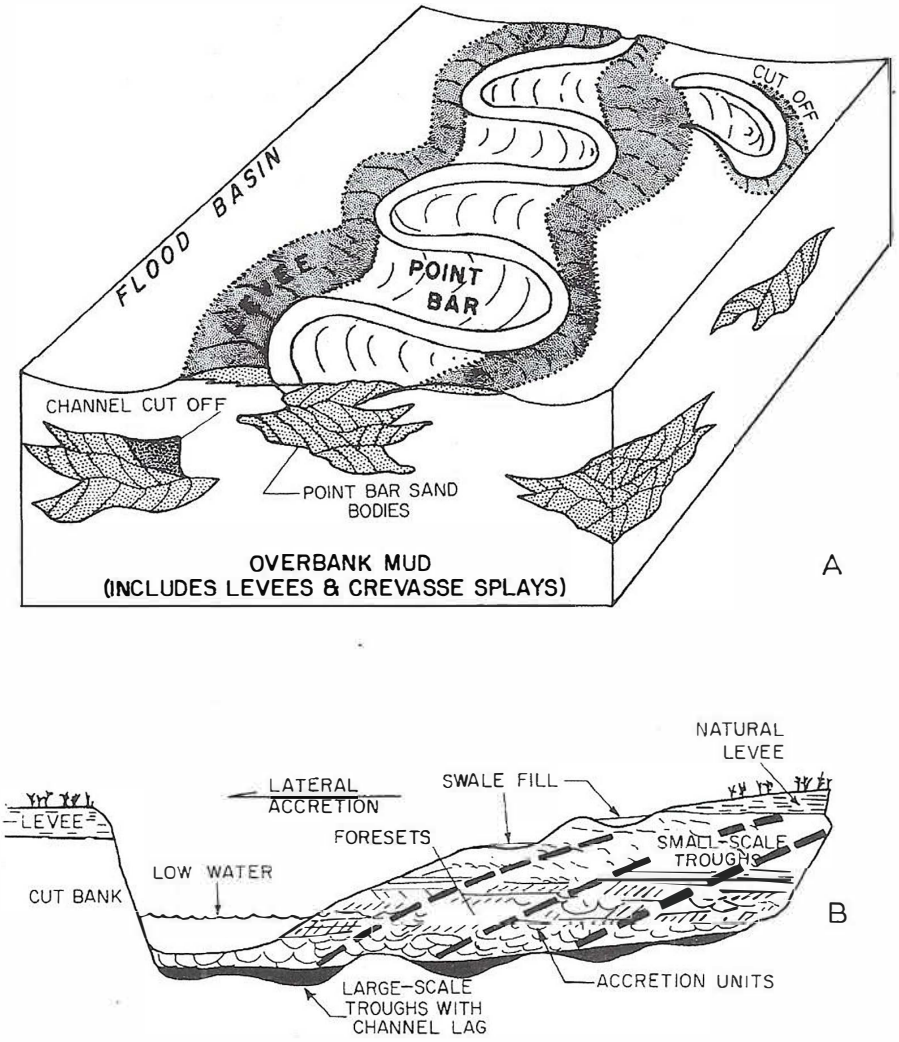


Fig. 9. Depositional model of an idealized fine-grained meanderbelt fluvial system. A. Block diagram showing bedforms, sedimentary structures, and multistory geometry. B. Schematic cross section of fine-grained point-bar deposits. From Brown (1973), with permission, after Bernard and others (1963); described by Fisher and Brown (1972).

sand bodies deposited as levees and crevasse splays and there may also be deposits of other smaller streams which are commonly present on the flood basin of the larger stream. Fig. 9B is a schematic cross-section of fine-grained point-bar deposits which are the typical host to the uranium deposits in contrast to the levee, crevasse splay and small flood basin stream sand bodies which are not normally mineralized except in proximity to the larger point-bar sand bodies. The geometry of the channel units are multistoried

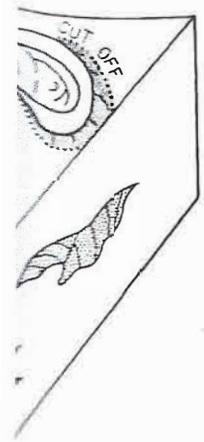
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and asymmetric. The base and cut-bank side of the channel are erosively bounded. Point-bar deposits of the channel are transitional at the top with levee and overbank deposits. Moderate- to large-scale trough cross-beds, a few tabular cross-beds, some small-scale trough and tabular cross-beds and a variety of ripple cross-laminations are the sedimentary structures. The deposits of this system are chiefly fine-grained sand, ranging from gravel at the base to mud at the top in an upward fining of textures. Clay-pellets and plant debris are prominent in the upper point bar. Deposition of point bars is by accretion on the sedimentation side during flood stage. The meanderbelt sand body is enclosed in topstratum or overbank muds in well-developed systems (Fisher and Brown, 1972).

When streams shift by avulsion to more advantageous gradients, multistorying of meanderbelt sands occur. The Fort Union Formation, host to the uranium deposits of the southern Powder River basin, has three fairly distinct stories of meanderbelt sands in a stratigraphic interval of 360 m. Each of the stories occupies significantly different portions of the basin overlapping only locally. Equally important from an exploration standpoint are the areas in which none of the meanderbelt sands are present. The entire interval is topstratum or overbank mud with coal and carbonaceous shale.

In addition to silt and mud accumulations on flood plains, carbonaceous shales and lignites are common if the climate is temperate to warm and humid (Allen, 1970). In contrast to the thick sand wedges deposited by braided streams, the sand bodies of meandering streams tend to be linear bodies. Soft-sediment deformation occurs when uneven sand loading above clay causes the clay to deform resulting in spectacular contemporary faulting and folding.

In Wyoming the sediment of the Gas Hills area of the Wind River basin, the northern margin of the Great Divide basin which includes the Crooks Gap area, and the western part of the Shirley basin, were deposited as alluvial fans formed where the gradient of the streams entering the basins decreased abruptly. Downstream the deposits pass into normal flood-plain sediment where coarse material was deposited by meandering streams, and silt and clay were deposited in flood basins. Flood-plain deposits occur throughout the Fort Union and Wasatch Formations of the Powder River basin, the Battle Spring Formation farther south in the Great Divide basin, and the Wind River Formation in the eastern Shirley basin (Rackley, 1972, p. 758). The Morrison Formation of the Colorado Plateau is dominated by an alluvial fan with its apex in the southwest portion of the plateau. From the apex braided streams fanned out across the plateau eventually reaching gradients where the fan merged with flood-plain deposits and the stream pattern changed from braided to meandering in a manner similar to that shown in Fig. 13 (see p. 111) and described by Brown (1973) in the series of depositional models which change from a braided system to a coarse-grained system and, finally, to a fine-grained system laterally down the slope of the fan and vertically upward as the gradient diminished.

Streams supplying sediment to all the uranium-bearing basins of Wyoming headed in the Sweetwater arch. The headwater of the stream, building the alluvial fan of the Morrison Formation of the Colorado Plateau, was in the vicinity of western Arizona. The

evidence suggests the size of the stream at normal flow was no greater than about 100 m wide; however, flood stages were an entirely different matter.

From a regional study of the transmissive character of the sedimentary rocks of the Colorado Plateau, Jobin (1962) found the uranium deposits to occur in formations of intermediate transmissivity between the thick porous eolian sequences and the thick low permeable shales. This general statement still holds true on a formation basis, but on the basis of the fluvial systems within a formation, the uranium ore bodies occur on the lateral margins of a moderate to highly transmissive central zone of alluvial fans and meanderbelts where the central zone intertongues with finer flood-plain sediment or other fluvial or eolian systems.

SEDIMENTARY ENVIRONMENT, PALEOCLIMATE AND DIAGENESIS

Sedimentation of a sequence of fluvial conglomerates, sandstones and shales is, like most other sedimentary sequences, a process which acts on the sediment many times between the time a particle is torn from its parent rock and deposited in the new sequence.

This repetitive process may bring the sediment closely into equilibrium with its environment well before it reaches its final position. The sorting of grain sizes by running water is offset by slumping of the banks as mud is remixed with sand. The freshly buried plant material begins to decay and is partially carbonized, when it is eroded and disaggregated, only to be redeposited with new plant material and clastic particles. Consequently, diagenesis may begin as soon as the sediment enters the depositional basin and may be almost completed by the time the sediment reaches its final position. Climate, environment of deposition, sedimentation, and diagenesis are so intimately related in the formation of fluvial deposits that it is impractical to consider them as separate steps in the development of a sedimentary rock.

The paleoclimate of the areas in which the host sediment of the uranium deposits accumulated was warm subtropical to tropical. The amount and distribution of the precipitation is not so easily determined. Crocodiles, alligators and turtles were common in the Wyoming basins, and terrestrial reptiles were near their peak in Morrison time on the Colorado Plateau. These cold-blooded reptiles would suggest year round frost-free conditions.

In the Mesozoic breakup of Pangaea, the position of the North American continental plate during Late Triassic Chinle time would have placed the Colorado Plateau in the vicinity of 15°N (Seyfert and Sirkin, 1973, p. 328). The Pacific Ocean was present on the southwest margin of the Colorado Plateau, where its influence would dominate the climate during the summer when the equatorial maritime air mass migrates northward producing a hot wet season. The dry season is characterized by dry dusty northeasterly tradewinds. The paleoclimate was similar to the present Nigeria climate. Alternatively, the

proximity of the ocean its typical hot, wet su wind belt migrates so precipitation. As the N Jurassic Period the Co 50–60°W, a position n 108). By Morrison tim wind belt and to come wind belt, which migra wet winters. The clima ran geanticline immedi orographic rainfall to n dry summers (Seyfert a

The depositional en example of the conditi host rock occur. The te continental stability an progressive change in gressive development o facies units. The terrige Morrison on the Colo deposition of sediment Jurassic. Mixed with th Glennie (1970) as wadi rado Plateau by the T overlying Entrada. Blu was a low-energy fluvia deposited in the basin slopes of the fan as a system is best represe though the system pro ended as the basin onc tion of the depositional of the Morrison Forma Plateau was emphasized tent streams covered th the southwest margin o deflation of the alluvial became increasingly hu of green silty zones wi sedimentation during

proximity of the ocean and a large land mass may have produced a monsoon climate with its typical hot, wet summers and dry winters. In the winter, when the northeast trade-wind belt migrates southward, hot dry winds from the continent would produce no precipitation. As the North American plate continued to drift northwestward during the Jurassic Period the Colorado Plateau occupied an area in the vicinity of 20–30°N and 50–60°W, a position north and east of modern Puerto Rico (Dietz and Holden, 1970, p. 108). By Morrison time, the area began to leave the dominating influence of the trade-wind belt and to come under the seasonal influence of the cyclonic storms of the westerly wind belt, which migrate southward during the winter. This produced dry summers and wet winters. The climate of the Colorado Plateau was also effected by the Mesocordillcran geanticline immediately to the west, which supplied sediment and probably caused orographic rainfall to naturally irrigate the depositional area of the Morrison during the dry summers (Seyfert and Sirkin, 1973, pp. 326–332).

The depositional environment and systems of the Morrison Formation are used as an example of the conditions in which sediments favorable to the deposition of uranium host rock occur. The terrigenous clastic depositional systems evolved in an area of relative continental stability and include eolian, fluvial and lake systems which evolved through a progressive change in climate from arid to seasonally moist. Figs. 10–13 show the progressive development of the Morrison and attempt to show the distribution of the major facies units. The terrigenous depositional systems of the Morrison are not unique to the Morrison on the Colorado Plateau. The eolian system has been a dominant factor in deposition of sediment on the Colorado Plateau throughout the Late Triassic and Early Jurassic. Mixed with the eolian sand dunes are interbeds of fluvial sediments described by Glennie (1970) as wadi environment. The eolian system is best represented on the Colorado Plateau by the Triassic Navajo Sandstone, but the system continues through the overlying Entrada, Bluff, and Cow Springs. Contemporaneously with the eolian system was a low-energy fluvial system dominated by fine sands, silts and clay. This sediment was deposited in the basin during the early arid phase and was gradually restricted to higher slopes of the fan as a more plentiful supply of water irrigated its lower portions. This system is best represented by the Recapture Member of the Morrison Formation, although the system prograded into the basin as the Todilto Limestone and gypsum system ended as the basin once again rose above the level of the sea. Fig. 10 shows the distribution of the depositional systems at the maximum development of the Recapture Member of the Morrison Formation. The positive nature of the southwestern part of the Colorado Plateau was emphasized by the retreat of the Todilto Sea as alluvial fans fed by intermittent streams covered the depositional area. The preexisting eolian system continued along the southwest margin of the basin and new eolian systems may have developed from the deflation of the alluvial fans. Towards the end of this depositional period, as the climate became increasingly humid, small lakes developed as evidenced by the local distribution of green silty zones with sparse lime nodules. With the exception of the lakes deposition, sedimentation during this period was in a strongly oxidizing subaerial environment in

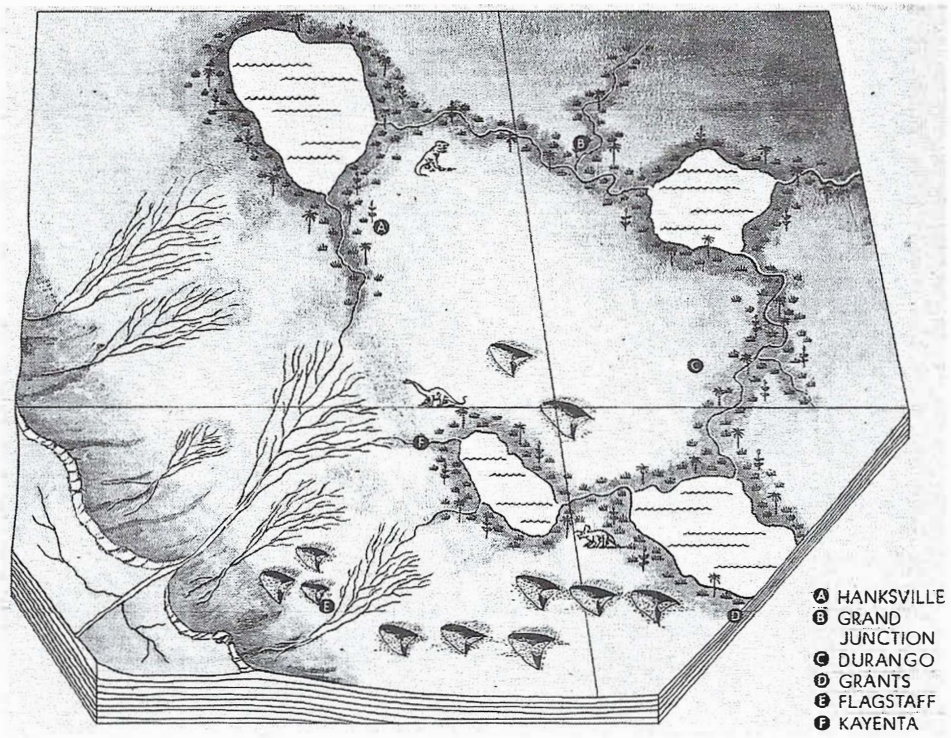


Fig. 10. Summerville–recapture depositional environment.

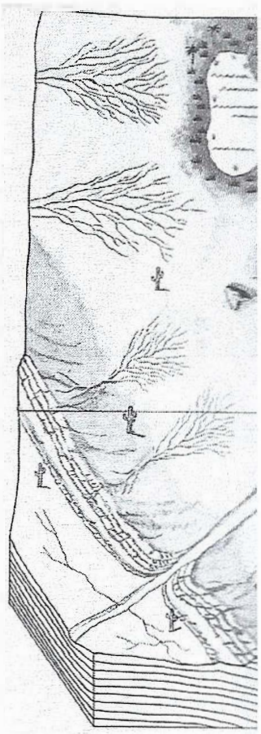


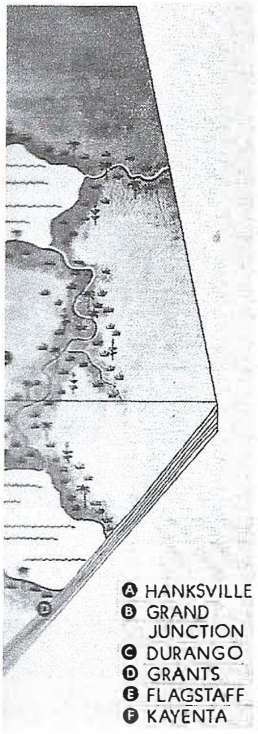
Fig. 11. Salt Wash Member o

which dark-red is the dominant color. The major exception to the dark-red color is the white gypsiferous zones which occur in the lower part of the sequence (Summerville Formation).

Continued uplift to the southwest of the depositional basin, in combination with an increase in precipitation, caused the development of a major fluvial system fed by perennial streams, as shown in Fig. 11. Sand dunes continued to be prominent in this scene. Local intermittent streams continued to deposit under the same conditions as before, but the addition of significantly greater amounts of water produced some major changes in the environment of deposition. Fig. 11 represents the facies distribution of the fluvial system which deposited the Salt Wash Formation, the lower of the two important uranium-bearing members of the Morrison Formation. Along with the development of permanent streams came the substantial increase in vegetation. As the water spread over the previous red mud flats, vegetation developed these flats into marshes with shallow temporary lakes. The combination of waterlogged sediment and abundant vegetation created reducing conditions in the sand facies, as well as in the mud in the extensive marshes. The overbank flood stage deposits higher on and between the Salt Wash alluvial fans remained in an oxidizing environment to cause the Summerville–Recapture environment

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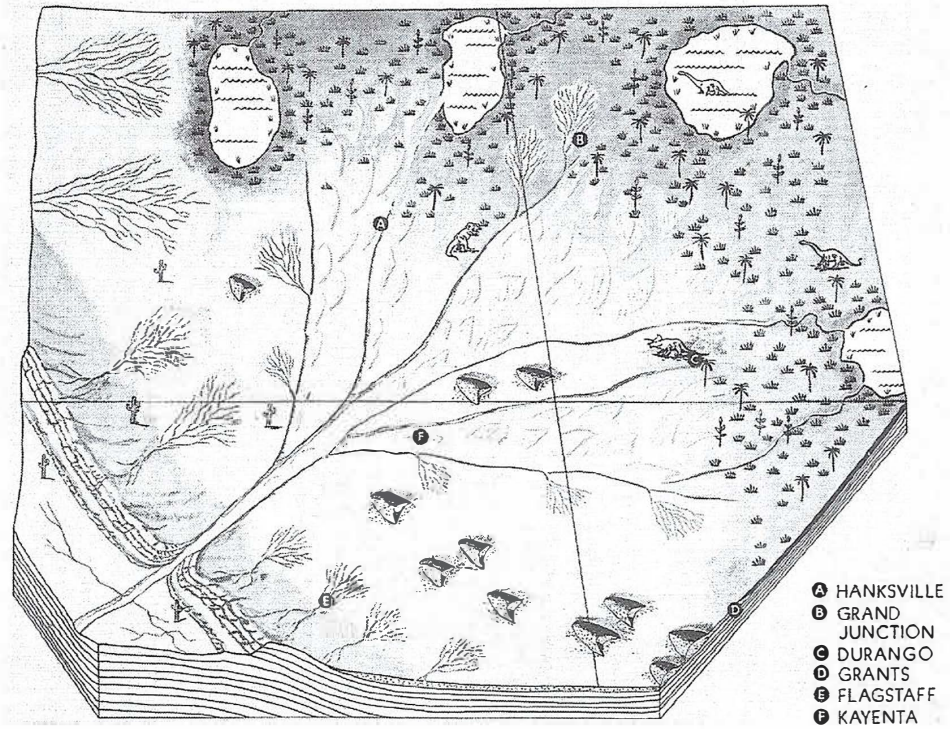


Fig. 11. Salt Wash Member of Morrison Formation distribution and depositional environment.

to persist contemporaneously with the development of blue-green mud and silt, commonly referred to as the Brushy Basin Member of the Morrison. From the period represented by Fig. 11 throughout the remainder of Morrison time, the Recapture diminishes as the Brushy Basin environment increases. In the development of the Salt Wash alluvial fans came an increase in the amount of vegetation and the rise of the water table to permit the preservation of the organic material in the sands. These reducing conditions probably developed earliest on the mud flats and gradually moved up the fan as the water table intersected the surface of the fan at progressively higher levels. Thus, conditions favorable for the deposition of uranium could occur in the lower portions of the fan while conditions higher in the system may not have been permissive.

In the further development of the coarse fluvial system of the Morrison, the major stream draining the rising source area to the southwest shifted from a northeasterly course to a southeasterly course at the apex of the fan, as shown in Fig. 12. This diagram represents the early phases of deposition of the Westwater Member of the Morrison, the uppermost and most significant of the uranium-producing members. The reason for this southeasterly shift may have been a simple avulsion or it may have been a slight shifting of the basin axis. The cause may also have been the result of the addition of large

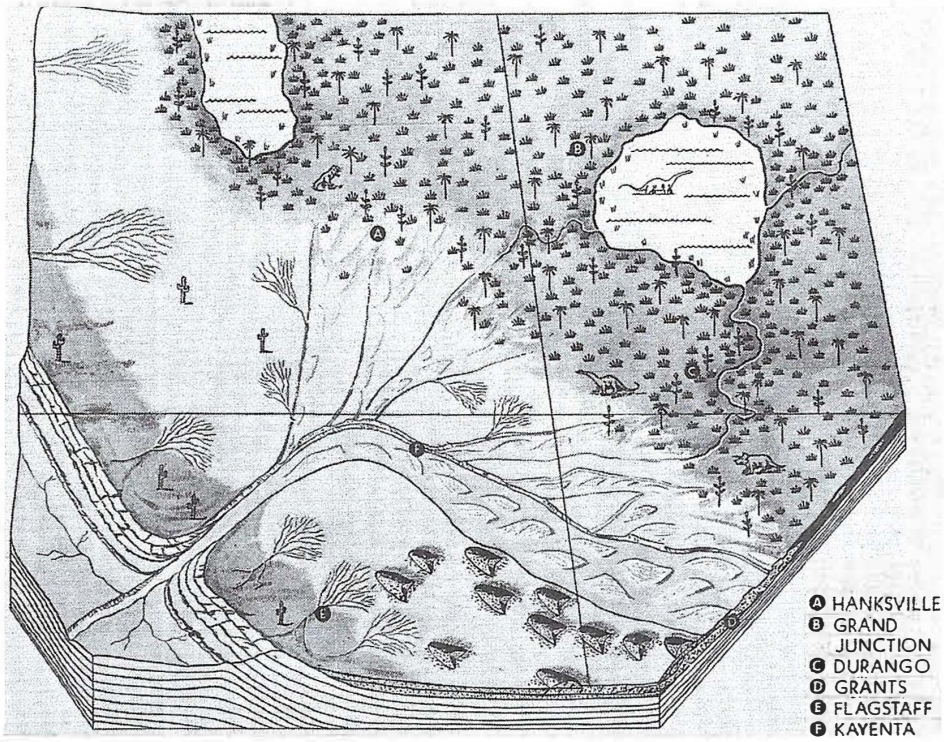


Fig. 12. Early Westwater and Brushy Basin Members of Morrison Formation distribution and depositional environments.

quantities of fine-grained material in the center of the basin, possibly as a result of an ash fall. In this case, the fluvial system could best accommodate itself by lapping against the eolian system which bordered it on the southwest. Thus, we have the coarse fluvial facies intertonguing with the fine-grained, blue-green sediment of the mud flat on one side and onlapping onto the eolian system on the other.

The final phase of the coarse fluvial Morrison sand deposition is represented in Fig. 13. The blue-green mud flat environment encroaches higher onto the alluvial fan causing the stream to adapt to a meandering pattern as it encounters the difficult-to-erode cohesive banks of the mud-flat environment. As the major stream meanders across thick sequences of the waterlogged blue-green mud, differential loading causes the sand to subside into the mud to produce trough-shaped bodies of sands similar to that in the Laguna area to the east of this diagram. In both Figs. 12 and 13, vegetation was extensive over the coarse fluvial facies of the Morrison, as well as on the adjacent mud flats.

An environmental analysis of the Morrison Formation of the Colorado Plateau has not been published prior to this oversimplified version and is a subject which is deserving of considerably more study.

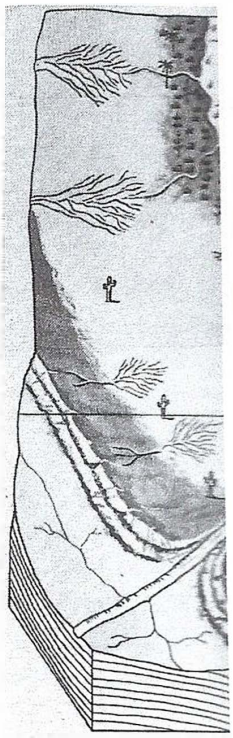
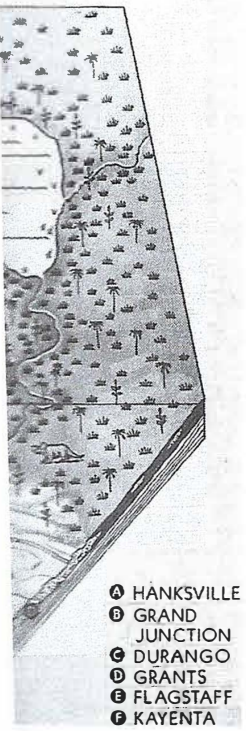


Fig. 13. Late Westwater
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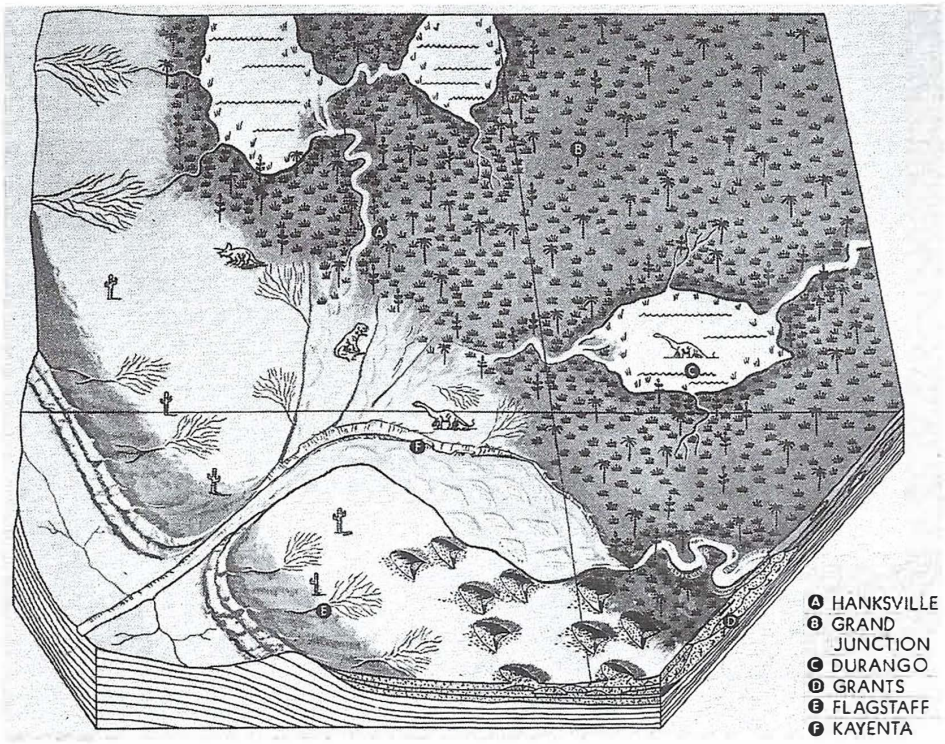


Fig. 13. Late Westwater and Brushy Basin Members of Morrison Formation distribution and depositional environments.

The climate of the Wyoming basins was warm enough to permit alligators, crocodiles and turtles to survive even though the drift of the North American plate was near its present latitude in Paleocene and Eocene time (Dietz and Holden, 1970, p. 109). The elevation was lower than at present and a warming trend between the Paleocene and Eocene interrupted the worldwide cooling that began in the Late Cretaceous (Seyfert and Sirkin, 1973, p. 418). Orographic rainfall on the rising Sweetwater arch provided ample water, either directly as rainfall or indirectly as natural irrigation, to maintain abundant vegetation and a high groundwater level in the uranium host sediment similar to the conditions in Figs. 12 and 13.

The combination of warm temperatures, rainy seasons and natural irrigation during dry seasons is adequate to support abundant vegetation. However, vegetation is abundant under other climatic conditions, particularly in tropical rain forest and humid continental climates which indicates the amount of vegetation growing on the surface is not critical, once a certain minimum level is reached. The critical factor in the development of a favorable uranium host rock is the mixing of the vegetation with the sediment in large enough quantities to shift the decay of the vegetation from aerobic to anaerobic condi-

tions. Decay of vegetation begins under aerobic environments through the oxidation by bacteria and fungi, but if the oxygen available is insufficient to complete the process, an anaerobic environment develops. In anaerobic environments, the vegetation is initially decomposed by fermentation, and the organic products of fermentation are further oxidized by anaerobic respiration, provided nitrate, sulfate or CO_2 are present as hydrogen acceptors in a manner similar to that shown on the left side of Fig. 16 (see p. 116; see also Stanier et al., 1963 and Chapter 6 of Vol. 3 by Trudinger). Vegetation decaying on the surface and buried or burrowed in the sediment combined with warm, organic-rich oxygen-deficient surface water would permit anaerobic conditions to exist near the surface of the sediment. The decomposition begins almost as soon as life ends and continues at a rate dependent on availability of suitable nutrients. The rate of decomposition of organic matter is greatest in the earliest stages, because a greater variety of decomposable materials are available to a broader spectrum of organisms. It can be reasonably concluded that reducing conditions are established in a sedimentary environment while sedimentation is still in progress and not at some later time (Love, 1964 and 1967; Perel'man, 1967 and Coleman, 1971). This is demonstrated by the common occurrence of plant debris in the sediment which has been partially carbonized or decomposed, then reworked with the sediment, disaggregated into segments, blocks and flakes to be redeposited with the clastic sediment, typically concentrating on cross-stratification surfaces. Fig. 14 shows carbonized wood flakes and blocks up to 1 cm long deposited with coarse

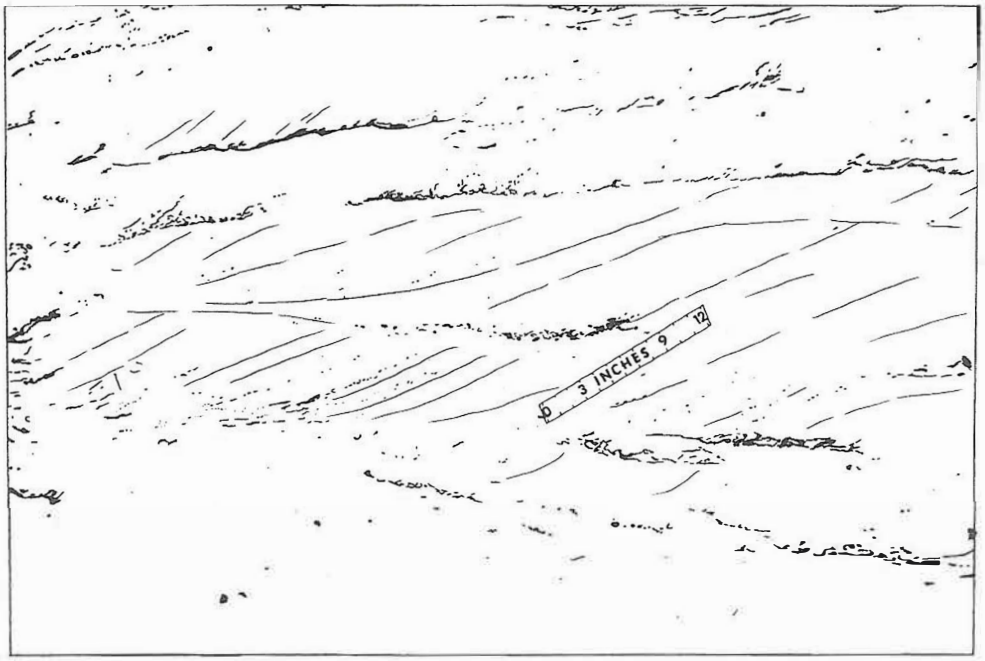


Fig. 14. Detrital carbonized wood flakes in coarse cross-bedded arkose (sketch from photograph).

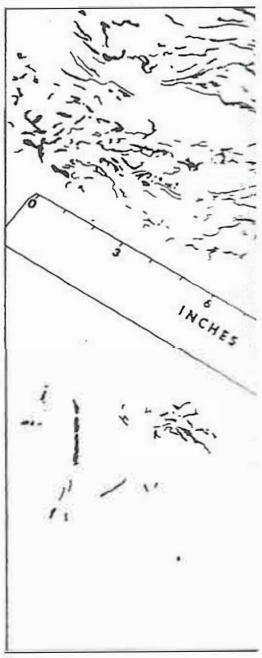


Fig. 15. Water-worn carbo leaves not disturbed after i

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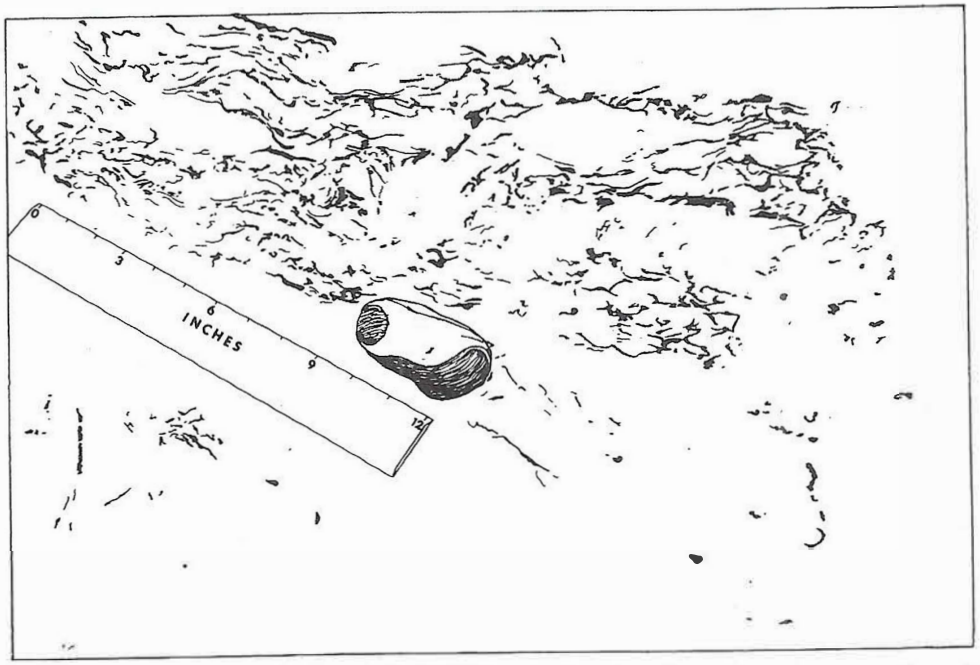


Fig. 15. Water-worn carbonized wood "cobble" 5 cm in diameter adjacent to carbonaceous films of leaves not disturbed after initial burial in coarse unstratified arkose (sketch from photograph).

arkose. Fig. 15 illustrates contorted carbonaceous films of leaves and related plant fragments "rolled" into the sediment with the inorganic detrital components and a water-worn "cobble" of carbonized wood. The carbonized films have not been disturbed since initial burial as recently fallen or living leaves.

Among the by-products of the anaerobic decomposition of the vegetation are carbon dioxide, methane, hydrogen, and hydrogen sulfide. Iron in the system reacts with the hydrogen sulfide to form pyrite and marcasite. Excess hydrogen sulfide may escape to the surface water or atmosphere, where it oxidizes to sulfate and may contribute to gypsum formation (Hem, 1970, p. 162). Gypsum may also accumulate from evaporation and transpiration of plants during dry seasons. Carbon dioxide increases the solubility of calcium carbonate and essentially prohibits its formation in this environment.

The environment at the time of deposition had a slightly alkaline pH and a strongly reducing Eh. These conditions are favorable for the reduction and deposition of uranium which enters the system. Uranium, released in the weathering of the granitic terrane of the source area and moved into the depositional area in solution, has a reasonable probability of entering the system where reduction and deposition would occur. Other metals stable in a reducing environment and those with an affinity for sulfur may also accumulate.

Coexisting with the abundant vegetation, which produces a reducing environment, is bioturbation caused by root-burrowing, animal burrows and the trampling of the sediment by large animals. This bioturbation destroys the stratification in the silt and clay which are typically light-gray to light-green in color and commonly contain very small euhedral pyrite crystals. Leaf impressions are present in some clays. Carbonaceous clays and lignite are also present. Some mottled medium-gray sandy zones are extensively root-burrowed and commonly contain abundant pyrite and carbonized roots in place. The color of reduced sandstones ranges from very light-gray, indicating reducing conditions but little carbon content, to medium- or dark-gray with 1–5% carbonaceous matter. The carbonaceous material normally consists of flakes and small fragments of carbonized wood well disseminated through the sandstone, except for a greater concentration on cross-stratification surfaces. Large segments of logs and stumps are present, but quantitatively are less important than the disseminated carbon. These large woody pieces commonly have major pyrite replacements, typically at the core. The detrital character of much of the carbonaceous debris and the content of bacterial residue indicates the woody material can be partially carbonized before final deposition. Undoubtedly, some continuation of the carbonization of the organic material takes place after burial, but it is essentially complete within weeks or months and in the case of large trees and stumps within a century or two.

The general absence of oxidized zones within the fluvial system indicates that the surface was poorly drained and well supplied with moisture to maintain the reducing environment. Oxidized zones that are present are thin and discontinuous beds or oxidized clay pebbles in the sandstones.

The process described above produces most of the conditions present in the uranium host rock. The major exceptions are compaction and those changes related to mineralization which will be described below. The changes which convert sediment entering a depositional basin into a uranium host rock begin while the sediment is still in transit and are almost complete when it reaches its final resting place; hence, the term most fitting to the process is syndiagenesis. The principal post-depositional change in the sediment is compaction of the sand and dewatering of the clays. The relative lack of cementing typical of uranium host rock, causes poor mining conditions. The clays are normally moderately to strongly sensitive to water which causes sloughing of the clays in mining and in drilling. In general, uranium host rock has greater lithification with age, but rock deposited under other conditions younger than the youngest uranium host may be more lithified than the oldest uranium-bearing rock.

MINERALIZATION AND ALTERATION

Uraninite, UO_2, and coffinite $U(SiO_4)_{1-x}(OH)_{4x}$, are the principal uranium minerals in non-weathered deposits of the Colorado Plateau and Wyoming. These minerals are of

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exceedingly low solubilities, yet they are clearly epigenetic in that they have been introduced into their present location since the deposition of the sediment. The host rocks show no evidence of alteration by hydrothermal solutions, nor do they show evidence of the extreme pH conditions necessary to mobilize and transport the reduced uranium minerals. It was stated in the "Introduction" that uranium has two naturally occurring valence states which is most significant in its geological mobilization, transportation, and deposition. In the reduced or tetravalent state, uranium minerals are practically insoluble, while in the oxidized or hexavalent state uranium minerals can be taken into solution at low temperature by acidic, neutral, or basic water and transported infinitely. The basic problems concerning the origin of uranium deposits are: (1) what are the processes which mobilize uranium, transport it for distances of miles and redeposit it with little change in the rock through which it passes; (2) what is the source of uranium; (3) when was it deposited; and (4) why do the ore bodies commonly have both discordant and concordant relationships to the enclosing sediments.

The kinds of processes were identified by Gruner (1956b) as oxidation–solution–migration–precipitation and reduction. The manner in which these processes operated, however, and the source of their energy was not well defined. The mineralizing processes have minor effects on the host rock, namely, principally the destruction of the carbonaceous material and the conversion of iron sulfides to iron oxides.

The source of uranium is difficult to identify.* There are two popular ideas regarding the source: (1) the granite from which the sediment is derived is considered by many to be the source either directly or indirectly through transfer to the sediment, followed by remobilization and then concentration into ore bodies; and (2) the second popular idea concerning the source is the volcanic debris which overlies the host sandstone or is interbedded with it.

The time of ore-body emplacement has received considerable attention through age dating. The age dates have not been conclusive, partially because the deposits may have migrated either intermittently or continuously over a long period of time. It is not unreasonable that some of the deposits are migrating now. The relationship of the ore-body shape and position within the sediment is the result of an invasion of the sediment by oxidizing and mineralizing water along zones of greatest permeability. The ore bodies conform to the external configuration of the invading zone.

Vickers (1957) recognized that the small ore bodies of the northern Black Hills, South Dakota, were at the margin of altered pink (oxidized) sandstones in buff to gray carbonaceous–pyritic sandstones within the same stratigraphic unit. He also recognized there was a genetic relationship between the oxidized zones and the ores in the adjacent reduced, laterally equivalent zones. These relationships were not tested in other areas, and since these deposits were not commercially important, the significance of Vicker's findings were not immediately recognized by the industry.

* Editor's note: see the chapter on conceptual models, Vol. 1, Chapter 2.

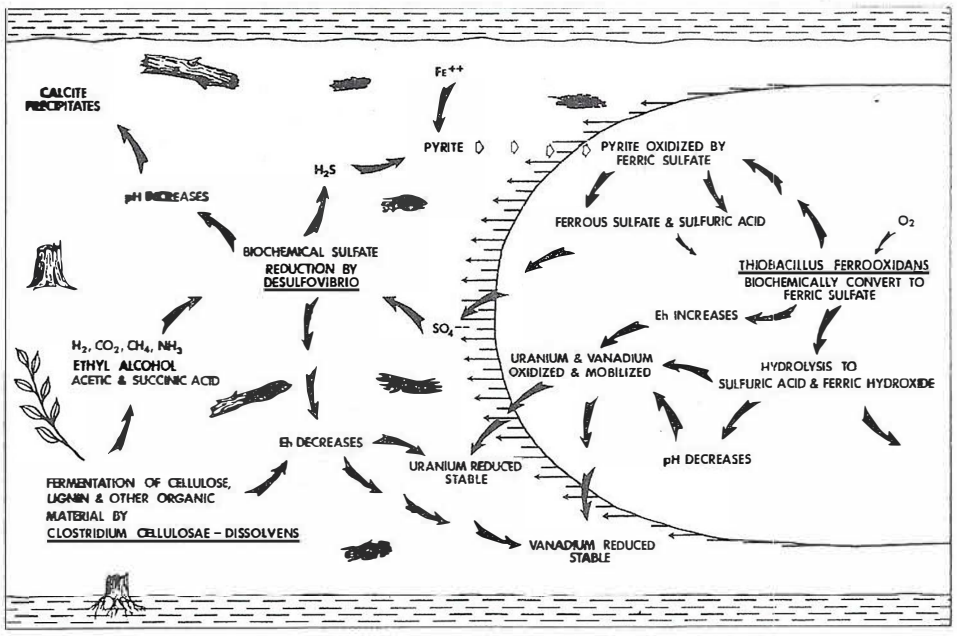


Fig. 16. Probable reactions in advancing geochemical cell.

In 1960 Philip N. Shockey independently recognized that uranium ore bodies in the Shirley Basin district of Wyoming were on the margin of an extensive body of sandstone which was oxidized in varying degrees, but the ore bodies and the adjacent and equivalent sandstone were carbonaceous and pyritic, a situation illustrated in Fig. 16 and described by Germanov (1960), Kashirtseva (1964), Lisitsyn and Kuznetsova (1967), Rackley et al. (1968) and Shockey et al. (1968). The oxidized sandstone had anomalous radioactivity at its upper and lower surfaces and occupied most of the sandstone, except an area adjacent to the ore body where the sandstone onlapped a paleoridge. The oxidized zone thinned at a greater rate than 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 uranium "roll" has long been known to uranium producers, but this was the first recognition that the "roll" had a genetic relation to the epigenetically oxidized sandstones within a reduced fluvial sequence (Rackley, 1972, p. 761). This provided an important guide for exploration and mining in the Shirley Basin and its validity was soon successfully tested in the Gas Hills mines. The successful use of this relationship did not provide answers to the questions of origin, but it did provide an empirically based concept or framework on which to build a hypothesis for the origin of the uranium deposits. Shockey et al. (1968, pp. 3–4) introduced the term "geochemical cell" for the processes occurring as oxygenated water invaded the reduced, carbonaceous, and pyritic sandstones, the resulting alteration of the sandstones, and the ore bodies on the margins of the altered zones.

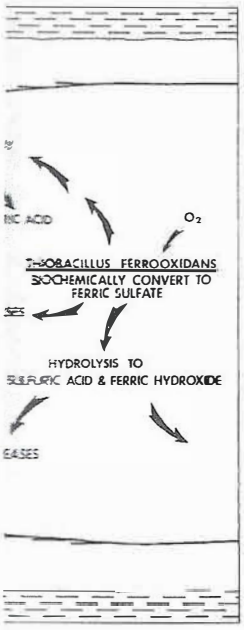
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Geochemical-cell concept

The geochemical cell originates at the outcrop or at any place where oxygenated water has access to the previously reduced sediment and expands to form a continuous, three-dimensional, finite body. The cell is a dynamic system of advancing oxidizing fronts which causes changes in Eh, pH, mineralogy, chemistry and microorganisms. The shape of the cell and the position of the related ore bodies is determined chiefly by gross permeability and by the concentration of oxidizable constituents. A geochemical cell in sediment deposited in the meander belt of a meandering stream is an elongated tongue-shaped body pointing down the hydrostatic gradient, typically downstream and/or downdip. The lateral edges of the cell are irregular due to the physical variations in sand deposition along the margins of the sand body and the chemical variations due to organic carbon and pyrite accumulations associated with the physical environment. 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). Fig. 16 is a typical shape of a roll, but the overall wedge shape of the margin of a geochemical cell has been vertically expanded for drafting considerations. Figs. 21B–21E and 22B–22D (pp. 132–135) are more realistic shapes.[1]

The cells have dimensions comparable to those of the sand bodies in which they occur. Known lateral dimensions are measured in miles and thicknesses in hundreds of feet. Irregularities in sedimentation cause the cell to take complex shapes which are reflected in the size and shapes of related ore bodies. The size of the cell is very large compared with the size of the mineralized fronts along the edge and on the irregularities on the upper and lower surfaces. The contrast between the character of the original reduced sediment and the altered sediment inside the cell are important guides in exploration for the mineralized margins.

Since the recognition of the genetic relation between the mineralized margins of the geochemical cell — the "rolls" — and the altered interior of the cell, research has been directed toward a knowledge of the processes which take place at the margins of the cell. This research has demonstrated that the processes are very complex and difficult to identify. The close spatial location of some reactions, such as oxidation and dissolution, to the opposite reactions of reduction and deposition along with the transitory nature of those reaction zones, increases the difficulty in identifying the processes. The process of uranium migration, oxidation, dissolution, transportation, reduction and deposition, involve both physical and chemical reactions all of which may be taking place within an overall distance of a few centimeters. The proximity of the reactions suggests that there are additional factors which exert controlling influences to produce microenvironments. The intimate association of these reactions with organic carbon further suggests that the reactions and the microenvironments are controlled by biological processes. Some of the

[1] See Notes added in proof, (1), p. 151.

biologically important elements undergo cyclic changes in their state of oxidation (valence) as a result of the activities of living organisms. These cyclic changes are characteristic of carbon, oxygen, nitrogen, sulfur and, on a minor scale, hydrogen and iron (Stanier et al., 1963). All of these elements are present in the margins of geochemical cells and some of these cyclic changes in states of oxidation could produce conditions for the oxidation and dissolution of uranium and for its reduction and deposition on either micro- or macro-scales.

No natural sedimentary process can take place in a sterile environment because some microorganisms will be active. Only those that are favored by the local and temporary environment reproduce, and their growth ceases when they have changed their environment. However, a few cells of each type of microorganism persist to initiate a new burst of growth when conditions again become favorable for their development. The importance of microorganisms in the mineralization process, i.e., conversion of living organisms into inorganic forms, is caused by their ubiquity, their high rates of growth and metabolism, and their ability to attack all naturally occurring organic compounds (Stanier et al., 1963).

The role of microorganisms in the formation of uranium deposits has been investigated through traditional bacteriological methods by Lisitsyn and Kuznetsova (1967) and by Douros (1967; see also Chapter 6, Vol. 2). Both investigations revealed the presence of a wide variety of bacteria. Douros worked with rock samples from the mineralized areas while Lisitsyn and Kuznetsova worked with water samples from artesian wells which produce from the mineralized strata covering a broad area from the vicinity of the recharge area across the mineralized reduction barrier into the center of the artesian basin. Another line of investigation had been the work on sulfur isotopes as a measure of bacteria fractionation by sulfate reducing bacteria (Jensen, 1958; Jones and Starkey, 1962; Jensen, 1963 and Cheney and Jensen, 1966). A general concensus has developed that bacteria are important in the development of the environment in which uranium deposits occur. There is much less agreement on the role of bacteria in the actual formation of the ore deposits. Rackley et al. (1968) proposed that bacteria control the chemical and physical conditions which form the ore deposits. Austin (1970) presented a status report on the distribution of sulfur isotopes in uranium deposits and concluded that the roll structure contained a population of bacteria which reduced and fractionated sulfur to produce H_2S, with the process culminating at or near the solution front. Grutt (1972) also supports the thesis that bacteria played a part in the formation of the uranium deposits. Granger and Warren (1969 and 1974) and Warren (1971) proposed an abiological chemical process to produce a reduction barrier to which Cheney and Trammel (1973) and Dahl and Hagmaier (1974) lend their support. This is a subject deserving of much additional research in both the laboratory and in the field where actual ore occurrences can be related to the laboratory and theoretical findings. There is further treatment of the conflicting views on this subject in the "Discussion" section of this chapter.

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reasonably well established in the Shirley Basin and in the Gas Hills by the late 1960's. By this time continued mining and exploration had also produced much detailed information on some of the ore bodies in both districts. The association of carbonaceous material with uranium and vanadium deposits has been a common thread in the geologic literature from the early workers like Coffin (1921), Hess (1933), and Fischer (1937, 1942) continuing through the period of intensive research by the U.S. Atomic Energy Commission (Everhart, 1951a and b; McKelvey et al., 1955; Wright, 1955; Shawe et al., 1959; Gruner, 1956a and b; Laverty et al., 1963 and Young, 1964) to recent papers (Grutt, 1972; Haji-Vassilious and Kerr, 1973; Adler, 1974; Barthel, 1974; Mittempergher, 1974 and Woodward et al., 1974). The work of Jensen (1958 and 1963) and Cheney and Jensen (1966) on bacterial fractionation of sulfur isotopes combined with the finding of Lisitsyn and Kuznetsova (1967) and Douros (1967) on the bacterial populations associated with mineralized areas, suggested a direct relationship between the ore deposits, the bacteria and carbonaceous material which serves as an energy source for the bacteria. Further study on the activities of microorganisms (Stanier et al., 1963) and their relationship to geologic processes (Kuznetsov et al., 1963 and Silverman, 1967) provided a basis for numerous discussions of the possible role of bacteria in the ore-forming process with biologist Dr. Gail Zimmerman. From these seemingly diverse lines of evidence, a hypothesis was developed to relate the known associations of geochemical cells and uranium deposits with probable reactions and conditions (Rackley et al., 1968, p. 120).

Geochemical-cell reaction

Many reactions probably take place in the advancing edge of a cell, but those that can be identified as important are shown in Fig. 16. The reactions shown in this figure and discussed more fully below, are biologic activities and biochemically controlled changes in physical and chemical conditions. 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 product or conditions created by one reaction affecting or entering some other reaction. Pyrite and reduced ore minerals are not mobile; the cell migrates from right to left bringing a previously reduced area under the influence of the encroaching oxidizing environment.

The bacteria discussed in the following processes have not been identified by the writer, but 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 a Russian basin. The samples were taken from the recharge area of a mineralized formation basinward across the edge of the geochemical cell (reduction barrier). The U.S. Atomic Energy Commission had studies made in which some of these bacteria were identified (Douros, 1967, pp. 43–49). In geology, however, we are more compelled than most investigators to use the extrapolative technique of identifying bacteria by their effects, a method used in bacteriology and medicine.

Reducing environment. Several reactions occur in the reducing side of the cell just ahead of the oxidizing zone. The increases in the amount of organic material and pyrite compared to the sediment beyond the influence of the cell (King and Austin, 1965, p. 32 and Rubin, 1970, pp. 5–8) indicate an increase in activity in that area. Other evidence of increased reactions in this zone is the change in the carbonaceous material from vitreous, carbonized plant fragments retaining much of their original 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 masses. These changes indicate the carbonaceous material is being acted upon and utilized by the bacterial population as the cell encroaches.

The microorganisms present in the reducing environment of a geochemical cell are characterized by a group of organisms, the strict anaerobes, to which oxygen is harmful. Oxygen-free conditions in nature are best developed in media of low oxidation–reduction potential. In this anaerobic environment, organic compounds are initially decomposed by fermentation. The organic products of fermentation are then further oxidized by other bacteria in anaerobic respiration if nitrate, sulfate or carbon dioxide are present (Stanier et al., 1963).

The fermentation of the cellulose and other organic material by the anaerobic spore-formers, *Clostridium cellulosae–dissolvens* and similar bacteria produce ethyl alcohol, acetic and succinic acids, carbon dioxide, and hydrogen as the principal end products (Stanier et al., 1963). The hydrogen tends to lower the oxidation–reduction potential and the other products of fermentation are utilized by other bacteria such as the sulfate-reducing genus, *Desulfovibrio,* in anaerobic respiration. Almost any form of organic-matter cellulose, lignin, or sewage can be utilized by ubiquitous sulfate-reducing microbes (Zajic, 1969; see also Chapter 6 by Trudinger, Vol. 2).

The sulfate-reducing genus, *Desulfovibrio,* utilizes the inorganic sulfate and carbon dioxide with decomposable organic matter in the following types of reactions (Berner, 1973):

For carbohydrates: $2CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO_3^-$

For amino acid: $4CH_2NH_4COOH + 4H_2O + 3SO_3^{2-} \rightarrow H_2S + 2HS^- + 8HCO_3^- + 4NH_4^+$.

Methane-forming bacteria are present in the reducing environment of a geochemical cell (Cheney and Jensen, 1966 and Lisitsyn and Kuznetsova, 1967). They are strict anaerobes and obtain the energy for growth by anaerobic oxidation of specific inorganic or simple organic compounds coupled with a reduction of CO_2 to methane (CH_4), a reaction which requires relatively large amounts of CO_2 (Stanier et al., 1963).

All these bacteria are extremely strict anaerobes in that oxygen is toxic to them and their activity is inhibited by selenates (Baas Becking and Moore, 1961, p. 263). *Desulfovibrio* create an environment of pH = 7.8–8.4 (Jones and Starkey, 1962, p. 65) and $E_h \approx -200$ mV (Germanov, 1958), but are capable of an Eh = −500 mV (Baas Becking and

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$$Fe_3S_4 + H_2S \rightarrow 3FeS_2 + 4$$

$$FeS + S^0 \rightarrow FeS_2$$

$$Fe_3S_4 + 2S \rightarrow 3FeS_2$$

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Moore, 1961, p. 262). These bacteria convert the organic constituents of the original sediment into energy-producing products and create an environment which physically reduces and precipitates the uranium and associated minerals. Sulfate-reducing bacteria normally do not select and precipitate specific metals, but they act as generators of H_2S which reacts with metals to precipitate sulfide minerals (Zajic, 1969, p. 85). The formation of pyrite in uranium deposits, as well as most reduced sediment, is not a direct one-step process. At neutral pH and low temperatures, the first formed iron sulfides resulting from the reaction of H_2S with either iron minerals or dissolved Fe^{2+} or Fe^{3+}, are always iron monosulfides such as mackinawite (FeS) and greigite (Fe_3S_4) and never pyrite (Berner, 1973). Iron is reduced and monosulfides formed by the following reactions:

$$2HFeO_2 + 3H_2S \rightarrow 2FeS + S^0 + 4H_2O$$

$$2Fe_2O_3 \cdot H_2O + 6H_2S \rightarrow FeS + Fe_3S_4 + S^0 + 8H_2O$$

The transformation reactions from monosulfides to pyrite entails oxidation and the addition of sulfur by the following reactions (Berner, 1973):

$$FeS + H_2S \rightarrow FeS_2 + 2H^+ + 2e$$

$$Fe_3S_4 + H_2S \rightarrow 3FeS_2 + 4H^+ + 4e$$

$$FeS + S^0 \rightarrow FeS_2$$

$$Fe_3S_4 + 2S \rightarrow 3FeS_2$$

Pyrite, FeS_2, is stable and can form only at low oxidation–reduction potentials in the absence of dissolved oxygen. In addition, the anaerobic waters must be sufficiently high in dissolved H_2S so that pyrite is stabilized relative to other reduced iron compounds. If total dissolved sulfide is too low, siderite, magnetite, pyrrhotite, hematite and probably glauconite are stable relative to pyrite (Berner, 1973). The fact that pyrite is stable relative to other reduced iron minerals in high concentrations of dissolved H_2S probably accounts for the general low magnetite content of most uranium host rock and the leaching of iron from ilmenite in the New Mexico deposits, as described by Adams et al. (1974). Because sulfate is mobile and able to diffuse into sediment undergoing sulfate reduction, the limiting factor in sulfate reduction is usable organic matter while the limiting factor on pyrite formation may be the concentration of reactive iron (Berner, 1973).

The iron monosulfides are black and this coloration combined with the carbonized organic material is responsible for the gray to black color of reduced sediment.

Under certain conditions, some 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 altered, oxidizing part of the cell, shown inside the curving line on the right of Fig. 16, a distinctly different group of bacteria and conditions are present. The contact zone separating the oxidizing environment from the reducing environment is commonly 1–8 cm wide. In the oxidizing environment *Thiobacillus ferrooxidans* and related bacteria are the most active populations (Lisitsyn and Kuznetsova, 1967). *Thiobacillus ferrooxidans* belong to a group of bacteria that can use CO_2 as their sole source of carbon and can develop in environments that are entirely free of organic matter. This group of bacteria are able to use molecular hydrogen, nitrogen compounds, sulfur compounds and iron as their only and specific source of energy and are unable to utilize organic compounds (Stanier et al., 1963).

Thiobacillus can oxidize several reduced forms of sulfur (H_2S, S, thiosulfate) with the formation of sulfate as the end product and are adapted to growth in an acid environment. In well-aerated laboratory conditions, the oxidation–reduction potential increased to +715 mV with increasing oxidation of ferrous iron and accumulation of ferric iron (Kuznetsov et al., 1963). While this level of Eh is not likely to be achieved in the oxidizing portion of a geochemical cell, it does indicate the potential for geochemical change of these microorganisms. They create pH as low as 1.8 and can survive in a pH of zero. The optimum pH is from 2 to 4 and with a pH of over 4.5 activity is greatly reduced (Kuznetsov et al., 1963).

Thiobacillus ferrooxidans are found in nature wherever sulfides are found in an oxidizing environment (Kuznetsov et al., 1963). These bacteria are the cause of the acidity of coal-mine waters and are used in the recovery of copper from mine dumps. The oxidation of pyrite by *Thiobacillus* is approximately 200 times faster than by atmospheric oxygen alone. Along with the oxidation of pyrite, sulfuric acid is produced. The work of Silverman (1967) indicated that ferric iron is a participant in the bacterial oxidation of pyrite which is also a product of *Thiobacillus ferrooxidans* (Kuznetsov et al., 1963) by the following reaction:

$$4FeSO_4 + 2H_2SO_4 + O_2 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O$$

Silverman (1967) indicates that the bacterial oxidation of pyrite with the participation of ferric iron follows the following pattern:

$$FeS_2 + Fe_2(SO_4)_3 \rightarrow 3FeSO_4 + 2S$$

$$2S + 6Fe_2(SO_4)_3 + 8H_2O \rightarrow 12FeSO_4 + 8H_2SO_4$$

$$FeS_2 + 7Fe_2(SO_4)_3 + 8H_2O \rightarrow 15\,FeSO_4 + 8H_2SO_4$$

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The ferrous sulfate may be recycled by the bacteria or pass into the reducing area of the cell where the anaerobic bacteria utilize it to produce H_2S to form new pyrite. The ferric sulfate may hydrolize according to the following reaction and be removed from the system, but produce more sulfuric acid (Kuznetsov et al., 1963):

$$2Fe_2(SO_4)_3 + 12H_2O \rightarrow 2Fe_2(OH)_6 + 6H_2SO_4$$

The addition of carbon dioxide from the reduced portion of the cell and oxygen from the invading water are all that are required to carry forward the oxidizing reactions. The addition of sulfate from the oxidizing zone may be the only requirement to carry forward the reducing reactions.

Physical and chemical conditions

There are large contrasts in both pH and Eh on the leading edge of a geochemical cell. The mildly alkaline but strongly reducing environment of *Clostridium* and *Desulfovibrio,* both strict anaerobes, is hostile for the growth of *Thiobacillus* while the low pH and high Eh of *Thiobacillus* aerobic environment in incompatible for the growth of the other two bacteria. The oxidizing *Thiobacillus* zone is a mobile environment a few centimeters to a few meters in cross-section width, controlled by the availability of nutrients and by conditions unfavorable for this bacteria. This mobile zone of oxidizing acidic conditions created temporary conditions favorable for the oxidation and mobilization of uranium, vanadium and other elements unstable under these conditions. Once mobilized these metals move, in solution, into the reducing part of the cell where they again encounter conditions favorable for their precipitation by reduction or reaction with hydrogen sulfide. The reducing conditions are inherent in the sediment from the time of sedimentation and diagenesis, but the bacteria are inactive until the advance of the oxidizing zone begins to contribute nutrients for their activation and growth. The two bacterial populations have a dependent relation initiated or terminated by the introduction or discontinuation of a supply of oxygenated water.

The amount of pyrite and carbonaceous material appears to be the controlling factor in determining the nature of the reaction zones and the gradients in pH and Eh between them. Typically, there are sharp contacts between the altered and mineralized zones, but in the Powder River basin of Wyoming there is a zone of incomplete oxidation of varied thickness and width between the completely oxidized and the mineralized zones (Davis, 1969, pl. 4 and Rubin, 1970, p. 8). This incompletely oxidized zone is a pale yellowish-green and contains some remnants of carbonaceous debris, pyrite, minor limonite and hematite stains, and some uranium. This appears to be the result of a lower Eh gradient across the front which is also reflected in somewhat broader and thicker but lower-grade mineralized zones.

Character of alteration

Although alteration has a different connotation to almost everyone, it is a good term for the alteration in the interior of a geochemical cell. While the general processes of geochemical cells are essentially the same, the differences in alteration are considerable from district to district, particularly as reflected in color. Some of these colors are characteristic of sediments which are unrelated to uranium mineralization or secondary alteration, and therefore it is essential to determine that the suspected alteration is in fact in the same sandstone body as unaltered carbonaceous pyritic sediment. Oxidation--reduction potentials of an environment can be evaluated by means of mineral-indicators. Because of their bright coloring, iron minerals are the most diagnostic. The trivalent iron minerals hematite, goethite and limonite are red, yellow, and brown while bivalent iron minerals siderite, vivianite, or the high-iron clay mineral, nontronite, are white, blue or greenish (Perel'man, 1967). The bivalent ferrous monosulfides, i.e., mackinawite and greigite, produce a black coloration but pyrite adds no color to the sediment. However, the monosulfides are not likely to be present in alteration zones. In addition to the oxidation–reduction potential, the pH and the concentration of dissolved sulfide determines the iron minerals present in a particular environment (Berner, 1973). Any of the iron minerals in the altered zone are subject to further oxidation and maturation. The color changes associated with alteration described in Adler (1970) are not those found in actual conditions except in limited areas, a situation he partially corrected in subsequent work (Adler, 1974).

Some areas have readily recognizable alteration while others have very subtle differences between the altered and unaltered portions of the geochemical cell. There are some criteria which can be used to verify areas that are altered. The altered zone is invariably more oxidized than the unaltered. This can be identified by the absence of carbonaceous material if good samples are available. Pyrite may be present in areas of alteration, but it is much less abundant than in the unaltered portions of the host sandstone. Yellowish-green, buff or pink from iron-staining of the clay and thin coatings on larger clastic grains make alteration easily recognizable to the careful observer. The pink to brick-red hematite staining is so obvious that untrained observers can see the change, even if they do not appreciate its meaning.

Recognition of alteration in outcrop may be especially difficult if not impossible. Weathering of altered sediment has little effect on the color of the outcrop but weathering of pyritic carbonaceous, unaltered strata tends toward the yellow and brown colors on and near the outcrops and along major fault zones. This subject is worthy of more investigation.

There is generally very little cementation in the host rock of uranium deposits and this is especially true of the altered zone. In the vicinity of ore, the alteration will have low radioactivity but the upper and lower margins of the altered zone are commonly accompanied by thin sharp radioactive anomalies.

Mineral zoning

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Mineral zoning

The Eh and pH gradients at the edge of a geochemical cell determine which minerals are deposited and their positions in the cell. One of the peculiarities of the geochemical cell is the minerals which are concentrated by it and the characteristic order in which they occur. The cells in the Tertiary sediments are very simple, containing principally uranium with minor amounts of molybdenum and minor to moderate amounts of selenium, but vanadium is present in some areas. In cells in other districts of the Rocky Mountains, the metals copper, silver, chromium and lead occur in significant amounts. It normally is not possible to identify minerals directly by their characteristics because of the low concentrations and extremely small size of the mineral grains or coatings. Color of the minerals will indicate their presence, particularly the oxidation products. The zones are best identified by detailed analysis and actually show the distribution of the elements which can be related to the mineralogy of the geochemical cell. Since selenium, silver and copper are the only elements concentrated by geochemical cells which are likely to occur in the metallic state, mineral zoning is the preferred term rather than metal or element zoning.

Mineral zones like roll fronts, have been known for several years. Shawe (1956) showed the mineral zoning in figures of ore bodies in the Salt Wash Member of the Morrison Formation of the Colorado Plateau. Garrels et al. (1959) reported on detailed analysis of the suite of samples taken across a roll front of the Mineral Joe Mine in the Uravan mineral belt. Botinelly and Fischer (1959) and Fischer (1960) described the mineral zones in the Rifle Mine. Harshman (1966, 1970 and 1972) reported the zoning of the Shirley basin roll fronts and recently extended this phase of roll-front studies to other districts (Harshman, 1974). Granger et al. (1961) showed the mineral zoning in the Ambrosia Lake area of New Mexico. Rosholt et al. (1964) described an isotopic fractionation between ^{234}U and ^{235}U and ^{238}U across roll features in the Shirley Basin, and Dooley et al. (1966) reported similar fractionation across ore boundaries in Ambrosia Lake. King and Austin (1965) did considerable work on the mineral zones of the Gas Hills, Wyoming. Kashirtseva (1964) reported mineral zones in uranium deposits of the USSR. Typically these studies have been restricted to a single linear suite of samples which goes from the interior altered zone across the ore body into the barren fresh or unaltered. Rackley and Johnson (1971) reported detailed analysis of a cored profile across the nose of a Powder River basin roll front to emphasize the three-dimensional nature of the mineral zoning.

Figs. 17 and 18 show the characteristic positions or uranium, vanadium, selenium, molybdenum and calcite. Fig. 19 shows the uranium-grade distribution and the distribution of radiometric disequilibrium. In these figures, the limits of uranium and the calcite cemented areas are shown for reference for the other elements.

Since the knowledge of these three-dimensional relationships can be very useful in exploration and exploitation of these ore bodies, Figs. 17, 18 and 19 are shown as block

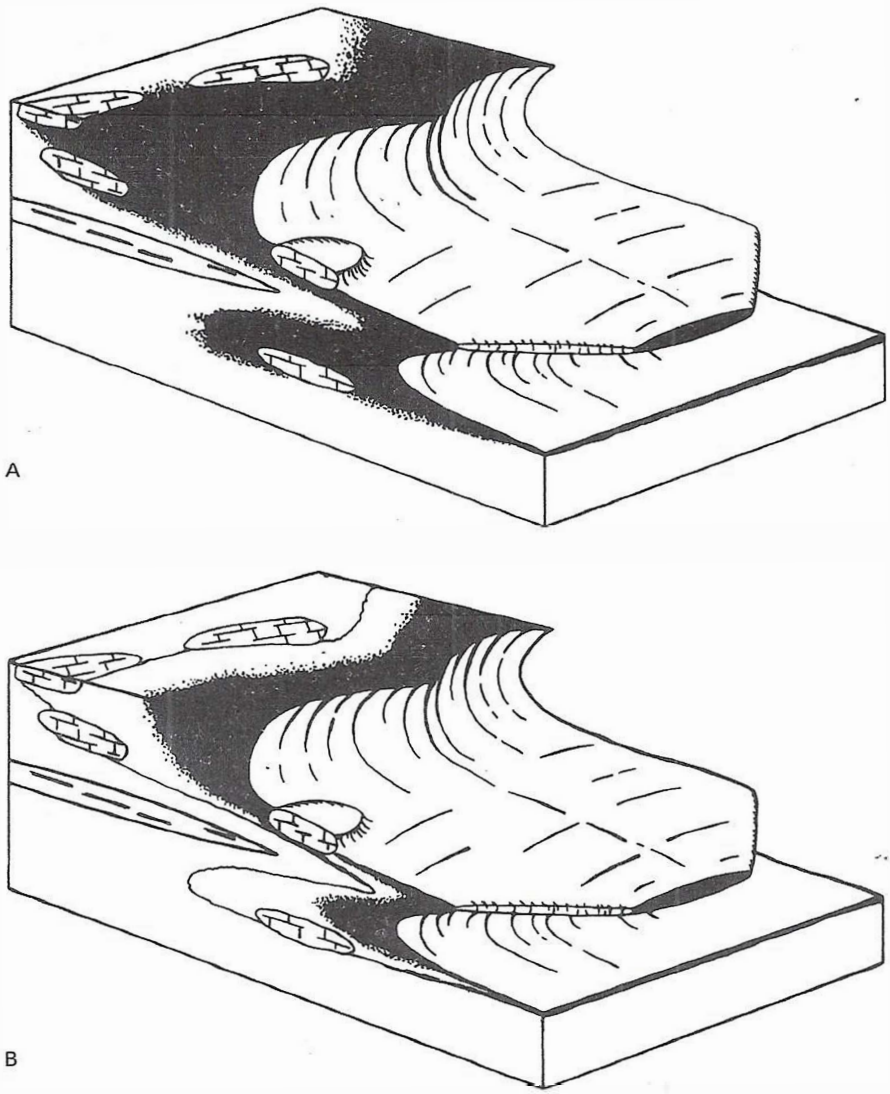


Fig. 17. Geochemical-cell zoning. A. Of uranium and calcite. B. Of vanadium.

diagrams of the lower portion of a segment of a geochemical cell. Since a roll front is commonly much more complex than the typical C-shape, a small incomplete or subsidiary roll is shown on the lower limb of the major roll to further emphasize the three-dimensional nature of the mineral zoning. While the mineral zoning is generally best developed across the nose of a front where it may be many meters wide, it also occurs above and below the altered zone commonly compressed to a few centimeters in thickness. This compressed zoning may extend from a few meters to as much as a kilometer on

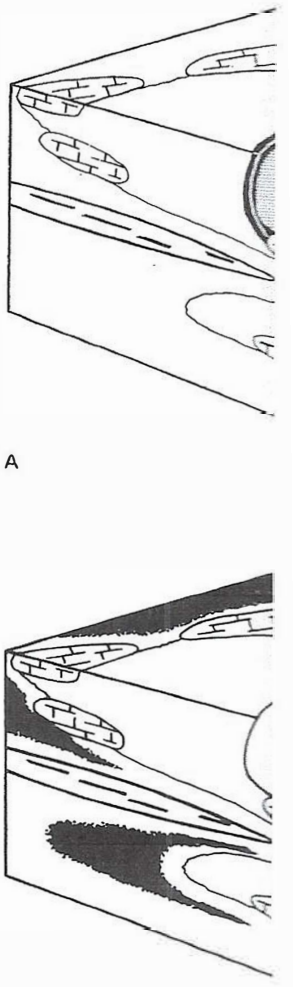


Fig. 18. Geochemical-cell zon

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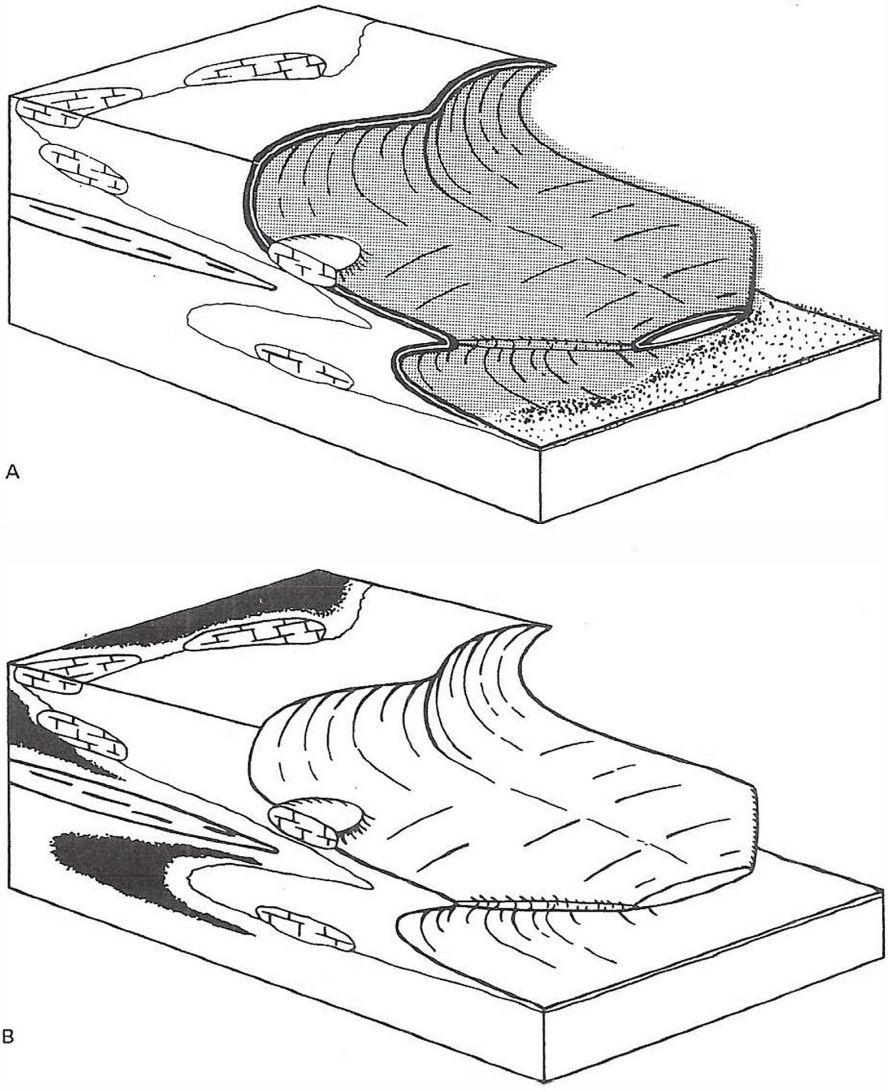


Fig. 18. Geochemical-cell zoning. A. Of selenium. B. Of molybdenium.

the upper and lower surfaces of the altered zone from the roll front. This zone of residual minerals, commonly at the contact between a mineralized sand and the bounding shales above and below, produce weak radioactive anomalies at these points which is commonly characteristic of the altered sands. The incomplete upper limb of the lower or subsidiary roll in the block diagram is a common and significant feature. If it is caused by a finer-grained carbonaceous zone, which is commonly the case, this kind of feature may extend a considerable distance into the altered zone. With alteration both above and

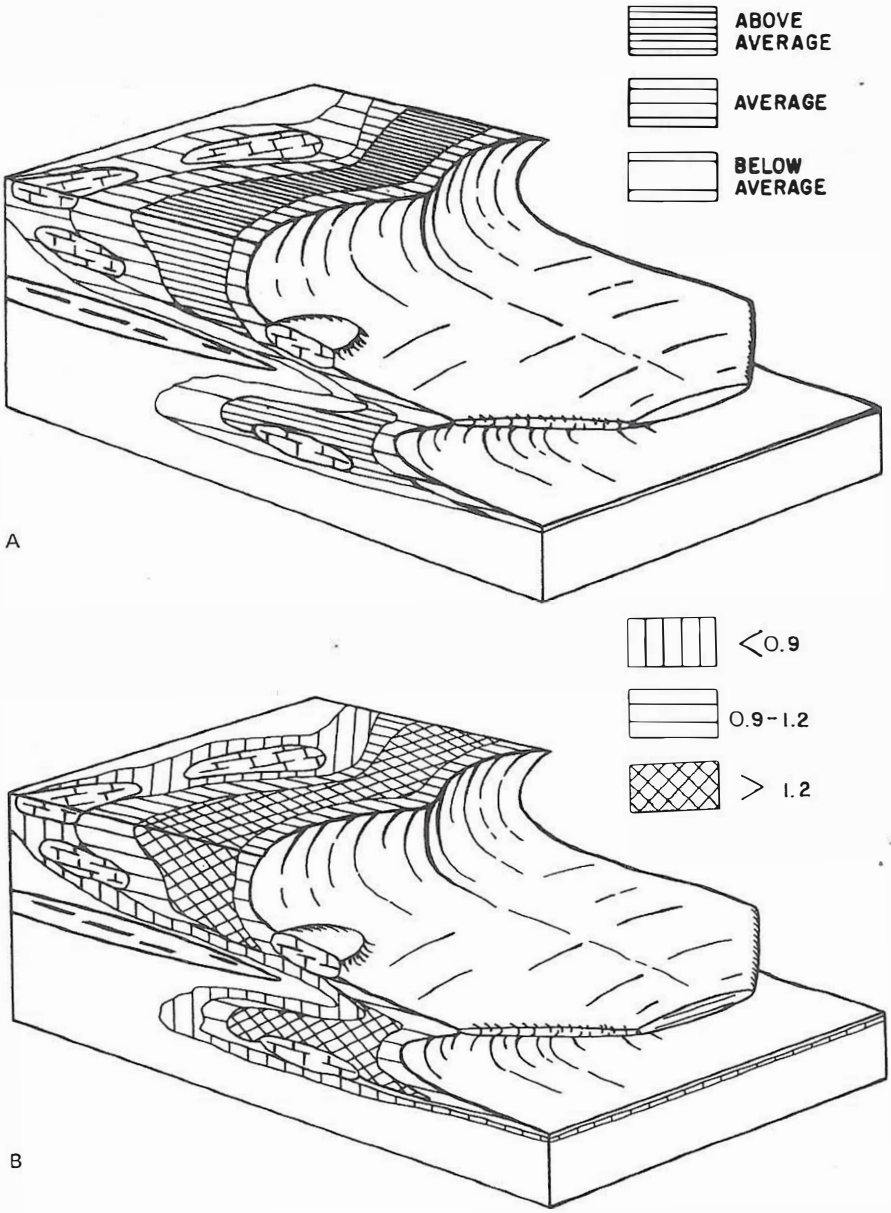


Fig. 19. Geochemical cell. A. Zoning of uranium grade distribution. B. Radiometric disequilibrium ratio of a geochemical cell.

below, the mineral zoning will be symmetrical in an otherwise asymmetrical zoning pattern. Granger et al. (1961), by sampling of the trend ore bodies in New Mexico, demonstrated this symmetrical pattern in which selenium and lead, followed by uranium

were symmetrical from th interior.

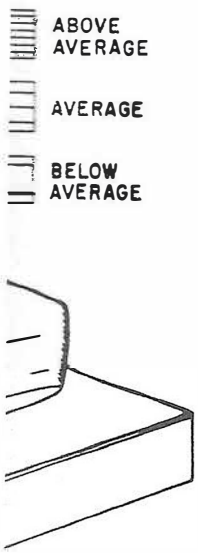
In the simple cells uran 17A, diminishing gradual altered zone adjacent to leached (Harshman, 1966 minerals will occur adjace may not contain uranium occurs at the contact and u

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Uranium and its gamm within an ore body. Part of cell and part is related to t uranium. The equivalent ur which uranium and all th deposits, there is a tendenc of less than one, while grade increases as the grade increa five. The typical distributio Fig. 19B. When uranium c surface, the disequilibrium uranium is oxidized and lea uranium is redeposited belo and hence a very high disequ



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In the simple cells uranium occurs on the reduced side of the contact, as shown in Fig. 17A, diminishing gradually away from it. Uranium also occurs in the margin of the altered zone adjacent to the contact, but this uranium is actively being oxidized and leached (Harshman, 1966, p. C172). However, if vanadium is also present, vanadium minerals will occur adjacent to the contact, as shown in Fig. 17B, and this zone may or may not contain uranium. If the uranium is separated from the vanadium, vanadium occurs at the contact and uranium occurs adjacent to the vanadium.

Selenium occurs in trace amounts in the altered zone, increasing in concentration towards the contact with the unaltered zone. The visible presence of selenium has been noted only at the contact zone with the selenium on both sides of the contact, as shown in Fig. 18A. Lead occurs with selenium in the contact zone of some districts. Molybdenum occurs furthest form the contact as indicated in Fig. 18B and may be completely separate from the uranium zone. The oxidation of the molybdenum to ilsemannite causes a deep-blue bloom to form as a halo around the dark uranium ore.

Calcite-cemented lenses and concretions occur in the outer margins of the reaction zones approximately in the outer margins of the uranium zone, as shown in Fig. 17A. The calcite is resistant and commonly the contact moves past a calcite-rich zone and uncommonly forms a ghost roll in the altered zone.

The distribution of uranium values within the uranium zone is illustrated in Fig. 19A. The highest values are commonly a few centimeters to as much as a meter from the altered contact. Carbonaceous debris within the zone shown as above-average grade may be enriched in uranium five to twenty times the average. From this zone of the above average grade, the values diminish further into the unaltered until the typical host-rock values are reached. The actual grades are relative with the high-grade zone ranging from 0.20% to 2.00% U_3O_8. The size is also relative, a zone such as Fig. 19A may be as little as two meters or more than 100 m across.

Uranium and its gamma-ray emitting daughter products tend to become separated within an ore body. Part of this separation appears to be related to the movement of the cell and part is related to the grade. The disequilibrium ratio is uranium over equivalent uranium. The equivalent uranium is the amount of gamma-ray emissions from a sample in which uranium and all the daughter products are in equilibrium. In the unoxidized deposits, there is a tendency for grades of less than 0.08% to have a disequilibrium ratio of less than one, while grades above 0.08% tend to have a ratio greater than one. The ratio increases as the grade increases, with very high-grade samples attaining ratios of three to five. The typical distribution of disequilibrium ratios in a geochemical cell is shown in Fig. 19B. When uranium deposits of this type are subjected to weathering near the surface, the disequilibrium ratios attain ranges from almost zero to near infinity as the uranium is oxidized and leached leaving the gamma-ray emitting products behind. If the uranium is redeposited below the oxidizing zone, it may have little gamma-ray emissions and hence a very high disequilibrium ratio.

Cell growth and shape

The cells originate at the basin margins or on a structure which permits groundwater recharge of the host sediment with oxygenated water. The water is capable of transporting hexavalent uranium and probably has a uranium content ranging from a few tens parts per billion to a few parts per million. The water also has the capacity to initiate the biological reactions to leach and concentrate the very low concentration of uranium (5–50 ppm) already in the host rock. The uranium introduced into the cell by the groundwater recharge is held in solution until it reaches the roll front, where it accumulates by accretion from both sources. From the points of origin in the recharge area the small oxidized areas expand down the hydrostatic gradient, growing like smouldering fires and ultimately coalescing to occupy the more permeable portion of the recharge area. With passage of time, erosion of the overlying formations would enlarge the surface area exposed to recharge and accelerate growth of the cell. Within the deposits of a specific paleo-stream system the cell originates essentially at a point and expands to form a continuous three-dimensional, finite body.

Referring again to the Colorado Plateau as an example, Fig. 20 illustrates the distribution of altered zones of the Morrison Formation based on Fig. 11 which illustrates the distribution of the Salt Wash Member and Fig. 13 which refers to the Westwater Member. This figure is a very simplified example and is not intended to encompass all the altered and mineralized areas of Colorado Plateau. The Salt Wash fan, extending northeastward into the basin, was deposited during a period of gradually increasing rainfall on the fan and in the drainage basin (headwaters) of the Salt Wash streams. Consequently, the upper segment of the fan, which consists of very thick sandstone units, did not accumulate sufficient organic material to lower the oxidation–reduction potential to a reducing environment. On the lower-gradient portions of the fan, surface or near-surface water would increase the vegetation and also permit the development of reducing environments. In the case of the Salt Wash sandstones, the geochemical cell(s) may not have developed except in the lower portions of the fan. Fig. 20 depicts in a simple way the alteration (stippling) and mineralization distribution, the thickened areas on the margin of the alteration, of the Uravan mineral belt, the Green River district (Utah); the Henry Mountain district (Utah); the Lukachucki district (Arizona); and projects undiscovered districts in the San Juan basin of northwest New Mexico.

The Westwater Member was deposited to the east and southeast of the apex of the fan (Figs. 12 and 13) along the southwest margin of the basin. In this instance, the alteration in the Westwater originated in two areas. One altered area is in the Arizona portion of the Westwater facies, which was essentially a downdip development from the apex of the fan. This alteration extends into the structural low between the Fort Defiance uplift in eastern Arizona and the Zuni uplift east of Gallup, New Mexico. The Westwater is removed by erosion from most of its initial depositional distribution in eastern Arizona, but the well-developed facies extends into the San Juan basin of northwest New Mexico from the

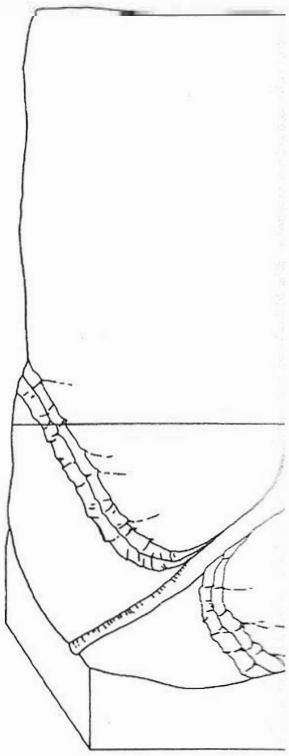


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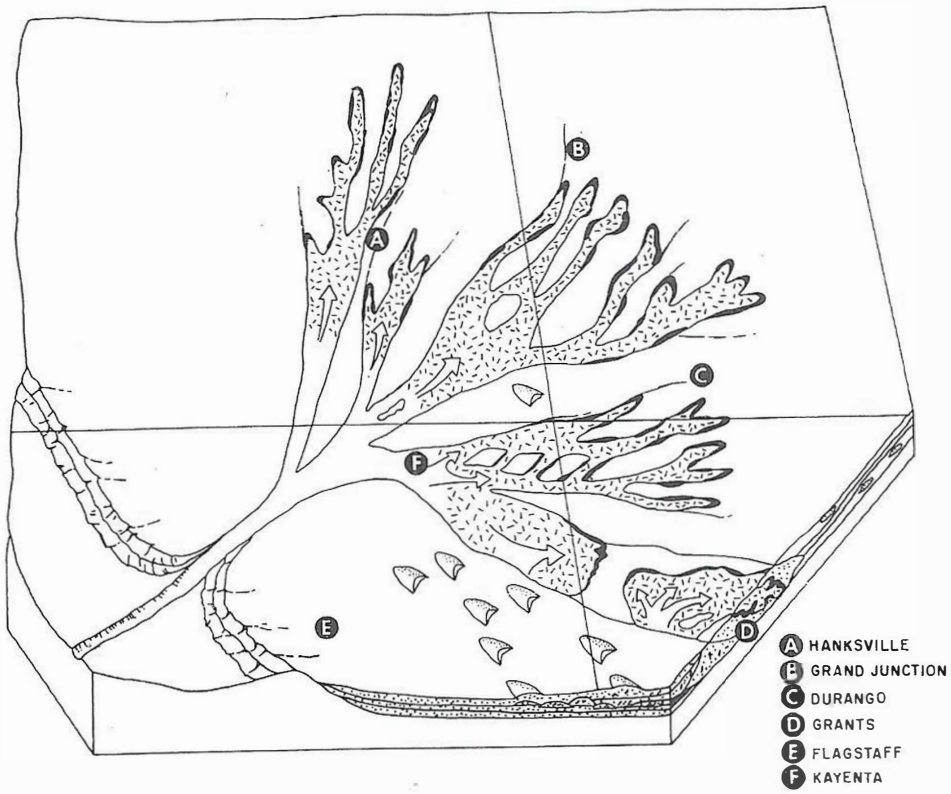
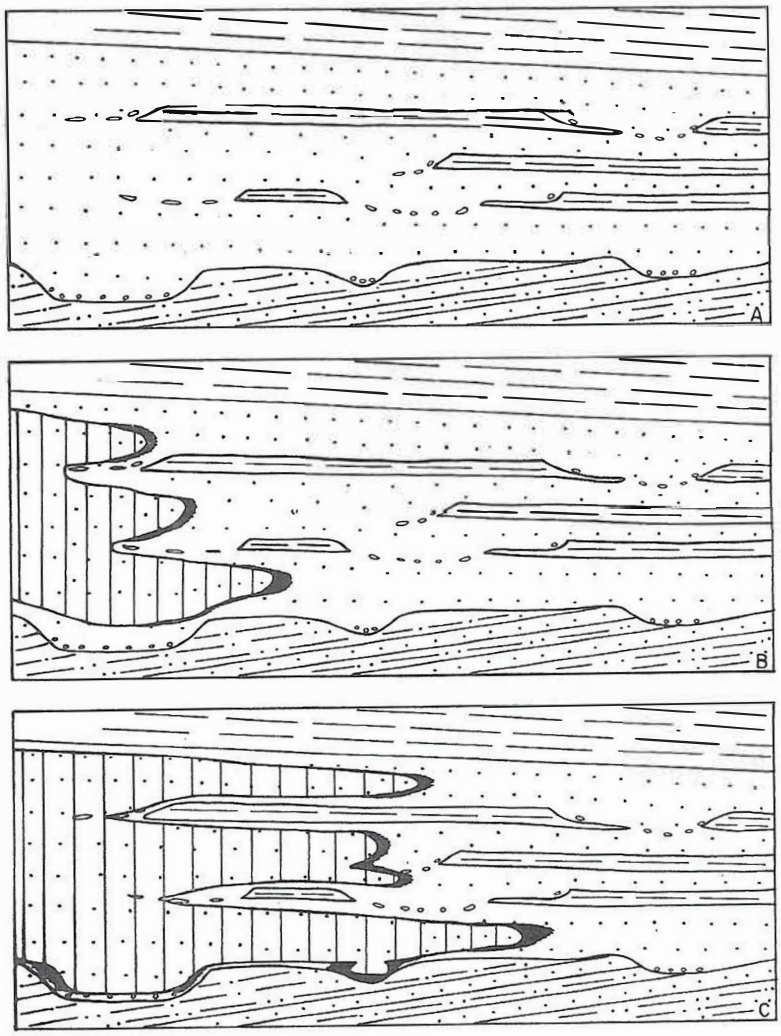


Fig. 20. Idealized distribution of alteration and mineralization in the Salt Wash and Westwater Members of the Morrison Formation of the Colorado Plateau.

well-altered outcrops on the west margin of the basin. The extent of the facies and the associated alteration is unknown. The other altered area encompasses the Grants mineral belt from Grants to a point northeast of Gallup. The alteration of this area has unusual access to the favorable Westwater facies in that the hydraulic gradient was developed on the Zuni uplift and the oxygenated water migrated through the eolian system into the fluvial Westwater system. In the area from the north end of the Zuni uplift eastward for about 20 miles (about 32 km) the Westwater sands are in direct contact with the eolian Cow Springs sands. Eastward from this point the hydraulic continuity is partially or completely interrupted by silts and clay of the Recapture facies. From the area of access on the north of the Zuni uplift alteration spread, as indicated by the arrows in Fig. 20, northward to the Church Rock mineralized area and southeastward into the Ambrosia Lake area (how much further to the southeast is still not fully known). Parts of the Grants mineral belt alteration and its associated mineralization is poorly known, because depths from the surface to the Westwater targets range from 2,000 to 4,000 ft (about 300–600 m). The next few years will see these areas explored and hopefully many new ore bodies will be defined on this important geochemical cell.

Returning to the model of the growth and shape of a geochemical cell, once oxygenated water establishes oxidizing conditions in the host sediment the cell continues to grow as long as oxygen is supplied. As the cell moves through the host, the ore bodies on its margin increase in size and grade. It migrates around shale partings which intertongue with the main sand system and divide the cell into lobes, still maintaining its finite, three-dimensional shape.

A series of five drawings is shown in Fig. 21 to show in a simple manner the growth and shape of a generalized geochemical cell in an average fluvial sequence. This sequence was deposited by a meandering stream on a regional unconformity. Downstream and downdip are perpendicular to the figure and the central portion of its meander belt is on the left with the right side of the belt beyond the right side of the drawings. Fig. 21A is



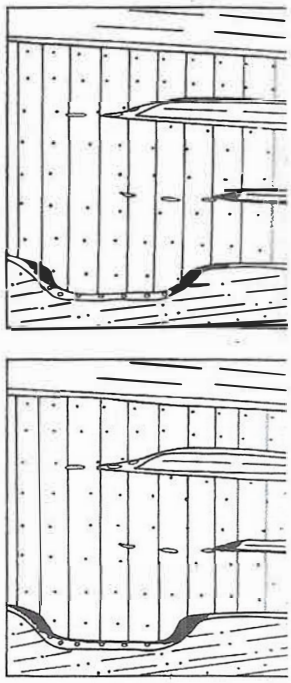


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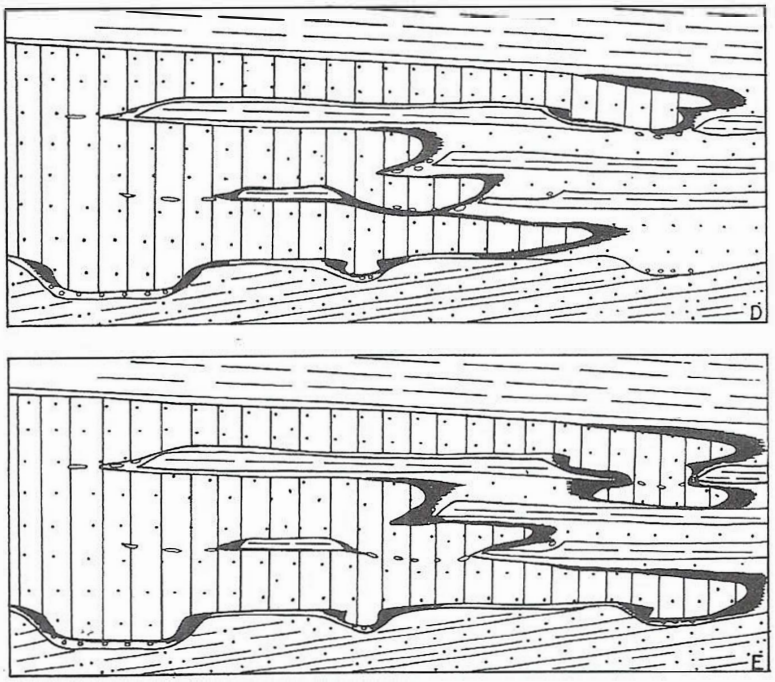


Fig. 21. Growth of a geochemical cell. A. Prior to invasion the sands are gray carbonaceous and pyritic interbedded with green to gray shale resting on a regional unconformity. B–E. Successive periods of advance. The oxidized area is indicated by vertical lines and the mineralization is indicated by the shading on the margin of the oxidized zone.

prior to invasion by the cell and the sediment contains the disseminated pyrite and carbon originally present when the sediment reached diagenetic equilibrium shortly after deposition. In Fig. 21B, the cell has invaded from the left occupying the central portion of the sand because of the greater gross permeability in that area and mineralization accumulates on the margins. The invaded or altered area is indicated by vertical lines. The shale has a retarding effect and tends to divide the cell into lobes. Further invasion in Fig. 21C had divided the cell into three distinct lobes and has produced ore bodies adjacent to the cut banks on the old erosion surface. The middle lobe is beginning to divide into an upper and lower lobe because of the influence of the shale to the right. In Fig. 21D the altered zone on the left side continues to expand against the margins of the sand, ultimately reaching the shale. The cell continues to migrate to the right and the size of the ore bodies also increases. The shale lag blocks are completely enveloped by alteration.

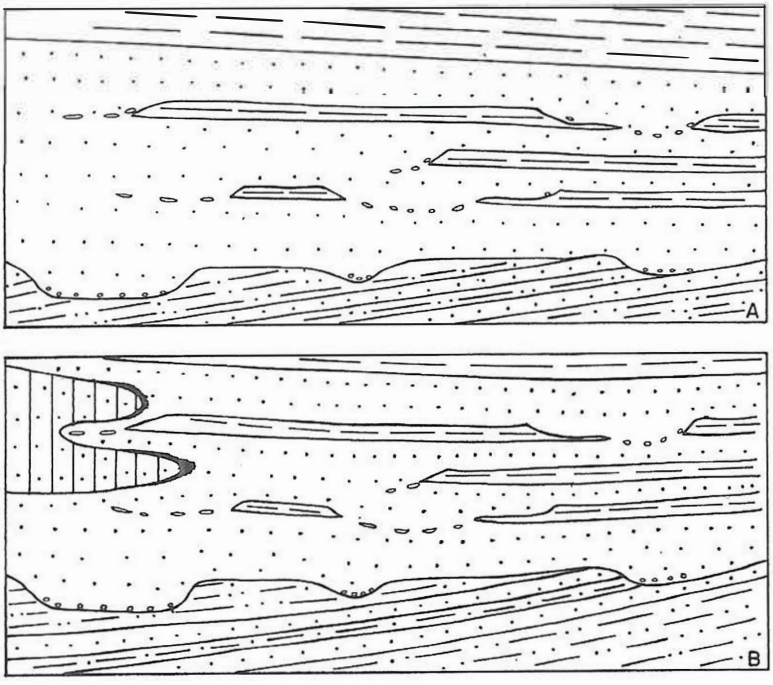
In Fig. 21E the cell has reached a typical development in which the central sand of the meander belt is completely altered while the ore bodies accumulate in the thinner sands along the margins and on irregularities on the erosion surface. These conditions satisfy the

statistical determination that ore bodies most commonly occur in areas where shales make up 20–50% of the host rock. The observation that ore bodies most commonly occur where the sand bodies thin to less than 10 m in thickness is also related to the growth pattern of a geochemical cell (Wright, 1955).

The expansion of the upper lobe through an erosional perforation in the underlying shale into the sand below is a common occurrence. These situations produce donut-shaped ore bodies below and around small perforations. Moderate-size perforations tend to have altered areas comparable in shape to that of the perforation. Vertical migration of the cell through major areas of erosion or shale pinch-out are common. The cell can also migrate downward into deeply eroded areas or into areas of subsidence due to displacement of soft mud by differential loading of channel sand.

Modification of geochemical-cell development

Ore bodies, such as those in the Laguna district at the southeast end of the Grants mineral belt, New Mexico, and many in the Chinle of Arizona and Utah, have conditions common to those of geochemical-cell ore bodies but have other conditions which prohibit the development of a geochemical cell in the conventional manner, namely isolation of the host sand into discrete bodies not connected hydraulically to each other or to an outcrop from the time of burial until the present cycle of erosion. With slight modifications of cell shape, manner of development, and a precise fixing of the time of mineralization these ore bodies conform to the overall geochemical-cell concept.



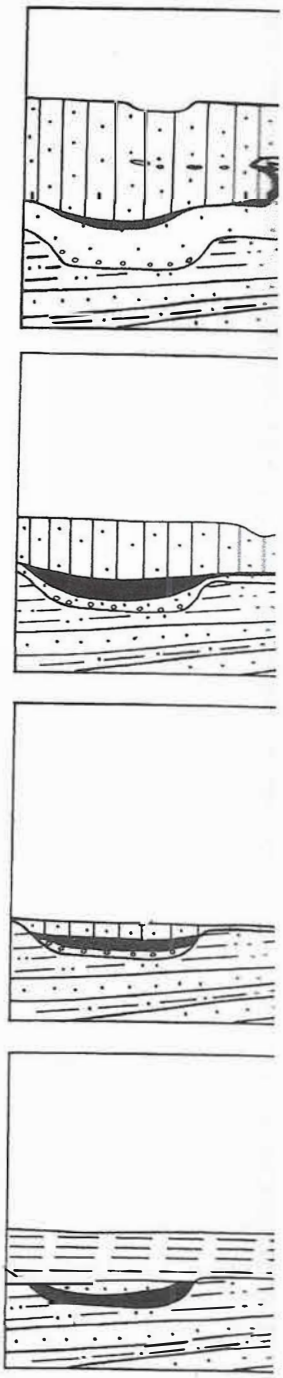


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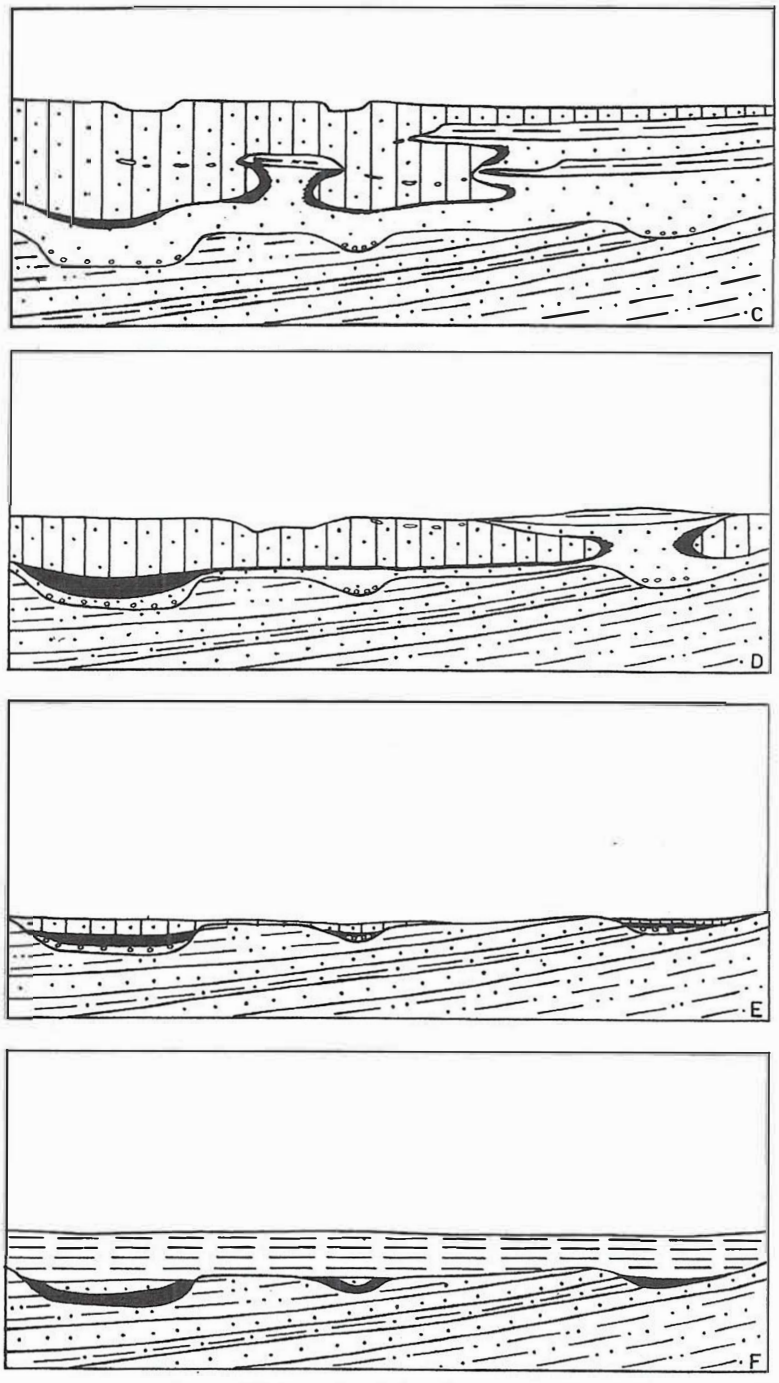


Fig. 22. Growth of a modified geochemical cell. A. It begins with the same conditions as Fig. 21, but B–E moves principally vertically rather than horizontally. F. Remnants of the cell are covered and preserved. The oxidized area is indicated by vertical lines and the mineralization is indicated by the shading on the margin of the oxidized zone.

The modifications of a cell to produce ore bodies in discrete sand bodies are shown in the series of drawings in Fig. 22. The series begins with the same condition as the beginning of a conventional cell in Fig. 21, which was formed by horizontally flowing fluids, and its initial development may be essentially the same as indicated by Figs. 21A and 22A. There is one major difference in the two cases: the protective cover is stripped away by wide-spread erosion as shown in Fig. 22C. This allows the direct (i.e., vertical) access of rainfall into the host formation, as well as other oxygenated surface water. This period of erosion occurs in the fourth development phase, as discussed under tectonic conditions. Although there are no known cases where both the conventional and the modified cells have developed in the same basin, there is no reason why both could not occur simultaneously, either in separate horizons or in separate areas. The depositional areas may have a weak positive tectonic tendency to cause the erosion or they may simply be the result of a stream which slowly reduces its gradient headward and cuts into the sediment it deposited under higher-energy, steeper-gradient conditions. Figs. 3, 4, and 5 indicate this phase would be characterized by moderate stream volume, but the erodability and sediment supply from the source area were low and the load was dominantly suspended sediment. These conditions combine to enhance the probability of erosion rather than continued sedimentation in the depositional area. The development of oxidizing conditions on the surface would occur quickly in the hot seasonally dry areas once the water table is lowered by the down-cutting of the streams. Seasonal rains would accelerate the leaching and oxidation process once the water table subsided, the amount of vegetation decreased, and aerobic decomposition of organic material became dominant again. The geochemical-cell reactions, once initiated, should continue without regard to direction as long as the supply of nutrients (oxygen and carbonaceous material) were available. The leachable minerals in the near-surface sediment would be available for concentration in the reducing zone below. Possibly more important is deep leaching of the source area and the best opportunity during the entire cycle to introduce the metal content from that leaching directly into the geochemical cell.

Fig. 22D shows a continuation of erosion and advance of the cell. Since remnants of the uranium host rock survive this period of erosion, the rate of downward migration of the cell and the rate of erosion diminish as indicated in Fig. 22E. As the conditions for the deposition of reduced sediment over the remnants of the host formation are being developed, the altered portion of the cell may be bleached. Fig. 22F shows the final stage in which clay and silt cover the remnants and their contained ore, isolating them from other opportunities for subsequent mineralization.

There are two other possible interpretations. One is that the cell developed in the conventional manner and was eroded subsequently and destroyed, the other that the host sediment was exposed at the surface, similar to Fig. 22C, when erosion began and oxidation migrated downward over the entire depositional area.[1]

[1] See Notes added in proof, (2), p. 152.

Time of mineralization

A knowledge of the time of mineralization in either absolute age or in relative terms in relation to other geologic conditions would assist immeasurably in establishing limiting conditions for theories of origin of the ores. There has been a reasonable amount of work concerned with determining the absolute age of uranium deposits (Miller and Kulp, 1963; Harshman, 1972 and Dooley et al., 1974). Their results have shown wide ranges of age for samples in the same formation and within the same deposit. The success (?) of each worker tends to be determined by the assumption and techniques used to obtain the results. Harshman (1972, p. 73) used selected high-grade samples to date the Shirley Basin deposits (Wyoming) obtaining a range just over 10 million years to nearly 40 million years in sediment considered to be 50 million years old. He concluded 18 million years, Late Miocene, is a reasonable age. More recent work by Dooley et al. (1974) on massive uraninite samples from Gas Hills and Shirley Basin ores indicates an age of 22 million years, plus or minus 3 million years, for both deposits to establish an Early Miocene age. Miller and Kulp (1963) used polished sections, when necessary to obtain pure minerals, from which they obtained mineralization-age ranges from Triassic rock of 22 to 220 million years and from Jurassic rock of 65 to 175 million years. They concluded from their work that there were two periods of mineralization, one about 110 million years ago and one about 210 million years ago for ore of the Colorado Plateau, but recognized that remobilization and redeposition could have occurred throughout the history of the Colorado Plateau. Miller and Kulp (1963, p. 621) also concluded that initial uranium deposition may have occurred soon after or during the formation of the sedimentary rock at temperatures less than 90°C in the presence of biogenic hydrogen sulfide (reducing condition).

There is one inherent problem in age-dating using either the isotopic or total lead/uranium ratios. Lead and uranium have different chemical characteristics. Lead has only one valence state and is less affected by oxidation–reduction potential than it is by the concentration of selenate or sulfides in solution in the media, while uranium is strongly dependent upon oxidation–reduction potential for its activity or stability. Therefore, it is unlikely they will be mobilized, transported and redeposited together. Some spatial separation is, consequently, likely to occur if all the lead and uranium migrate with the cell. Rosholt et al. (1964) found there was even a fractionation of the ^{234}U isotope from the ^{235}U and ^{238}U isotopes across the contact from the altered to the unaltered, i.e., ore-bearing, areas of the roll in the Shirley Basin, and Dooley et al. (1966) found a similar relationship on the contacts of Ambrosia Lake ores.

It is even more likely that one will be more completely leached than the other. The concept of uranium–lead age dating is that radiogenic lead accumulates at a fixed rate from the time of uranium deposition until the present. The ratio of uranium/lead should indicate the length of time since the formation of the uranium minerals. Translated into typical uranium ore concentrations a 10 million year old uranium deposit of 0.20% U_3O_8

would have a radiogenic lead content of 0.00025% or 2.5 ppm Pb provided there were no losses or additions of uranium daughter products or of lead. It is hardly conceivable that uranium at 2,000 ppm would be leached, transported, and redeposited with the same efficiency as lead at 2.5 ppm.

When lead has been identified as either galena (PbS) or clausthalite (PbSe) in geochemical-cell occurrences, it is concentrated at the alteration boundary with selenium. This would indicate that lead and uranium both migrate in a geochemical cell and also that a geochemical cell can concentrate lead, crustal as well as radiogenic. They do not concentrate in the same zones of the cell, which makes this method of age-dating highly suspect. A large bulk sample representative of the entire ore body might come closest to giving the correct age since the commencement of mineralization. A sample taken from the zone of highest uranium values a short distance from the front may be sufficiently separated from the lead–selenium zone to permit the initial formation of uranium minerals without contamination by radiogenic lead. This may be the case with the samples collected by Dooley et al. (1974), and would represent the true age of the mineral or the minimum age of the geochemical cell. Evidence indicates the geochemical-cell ore bodies, or segments of them, have changed or moved in the recent past and may be moving at present. Any sample can be expected to indicate the time of its formation only if no lead has been added to that sample from external sources before, during, or after uranium precipitation. True age dates are most likely to come from deposits, such as the Triassic Chinle areas, which probably were formed in one mineralizing episode and immediately isolated from conditions which would cause subsequent migration.

As discussed under "Tectonic conditions", all the western-states type uranium districts were subjected to either basin margin or basin-wide erosion in the fourth phase of development soon after sedimentation of the host rocks. The Chinle was subjected to basin-wide erosion which removed an unknown thickness of sediment before accumulation of the Upper Chinle halted the erosion and buried the remnants of channels under a blanket of mud and silt. For the Chinle uranium occurrences, this period of erosion offered the only opportunity for mineralization from non-hydrothermal sources.

The Morrison was subjected to a period of erosion prior to the advance of the Cretaceous sea depositing the Dakota Formation. The latter rests directly on the Jackpile eroding it to a level which isolates this sand body from other channel sands of the Morrison. The Dakota rests directly on the Westwater on the north end of the Zuni uplift where the Cow Springs and Westwater also have good hydraulic continuity. The apex of the Salt Wash fan was truncated by this period of erosion. Since some or all of the Grants mineral belt host sediment was derived from a stream emanating from the vicinity of the apex of the Salt Wash fans, this pre-Dakota erosional truncation also removed the upstream portion of the Westwater.

In the Wyoming basins, moderate folding and erosion took place between the Fort Union and Wasatch in the Powder River basin and between the Lower and Upper Battle Springs on the northern margin of the Great Divide basin. The Gas Hills and Shirley Basin

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[1] See Notes added in proof.
[*] Editor's note: see the chap

districts were deeply eroded between the end of Upper Eocene sedimentation and prior to the deposition, in Oligocene, of the White River. The Wasatch in the Powder River basin also had some upstream erosion prior to White River time.

These periods of erosion soon after sedimentation of the host formation offer the best opportunity for the introduction of oxygenated water into the formation and for the introduction of elements from external sources into the cell, because the formations are exposed. The reason for the erosion could be either an increase or a decrease in stream-load capacity. In the event of an increase due to renewed uplift, the host sediment most likely would not survive. The decrease in stream-load capacity is most probable and further suggests a period of slow physical degradation and deep chemical weathering. The weathering of the granitic provenance would ultimately make the uranium and other elements mobile in an oxidizing environment available to water draining from it. The position of the recharge area of the host rock would provide direct access for the oxygenated mineral-bearing water into the geochemical cell. Under these conditions, it is unlikely that reducing conditions along the stream would be extensive or persist for long. Rainfall on the exposed host rock would supplement oxygenated water from the streams to initiate an invading oxidizing zone or geochemical cell. Harshman's (1972) genetic model of the mechanism and timing of mineralization in the Shirley Basin is similar to the ideas presented here with the major difference in time from Miocene to pre-Oligocene and thickness of cover difference of 600–100 m.[1]

From the evidence and reasoning above, it has been concluded that the period of ore-body formation was associated with the period of erosion shortly after deposition of the host rock. For some ore bodies, such as those in the Chinle and in the Laguna area, this was the only opportunity for mineralization because they were sealed from further access of oxygenated or mineralizing water and the means of further migration and ore accumulation ended until the present cycle or erosion. For most other deposits of the Colorado Plateau and Wyoming, subsequent periods of ore concentrations and migration have occurred. It can be reasonably expected that when hydrodynamic conditions permitted oxygenated water to be supplied to the geochemical cells, they responded with the redevelopment of the original processes. The present cycle of erosion is the latest period of cell migration and certainly some has taken place in recent time.

Source of mineralization

Clear identification of the source of the uranium and other metals associated with it in sandstone occurrences in Wyoming and the Colorado Plateau remains elusive.* From the uranium mining industry's experience of the last twenty years, it can be reasonably concluded that the oxidized uranium minerals are remnants of previously reduced minerals. It can also be extrapolated that no significant uranium occurrence in fluvial sandstone

[1] See Notes added in proof, (3), p. 152.

* Editor's note: see the chapter on conceptual models, Vol. 1, Chapter 2.

originated in the oxidized hexavalent state. These deposits are in the process of being destroyed. From this experience, it has also been learned that uranium is mobilized quite readily under the present weathering conditions. No extraordinary conditions are needed on a macroscale to accomplish the oxidation and remobilization of uranium minerals. The reprecipitation of the mobilized uranium is quite readily accomplished by reduction to the tetravalent state which can be accomplished by the reducing environment so characteristic of uranium host rock. With the exception of a period around 1950, most thought concerning the deposition of uranium has been based on these simple basic facts.

Workers prior to 1930 considered the uranium to have been precipitated with, or introduced into, the sands at the time of sedimentation. Hess (1933) 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 accumulated in and around the plant remains by reduction of soluble ions to stable minerals as a result of reducing conditions caused by decaying vegetation.

The possibility of hydrothermal sources is ever present, but this possibility is relied upon less and less since the early 1950's. The geochemistry of uranium was so poorly known that D'Arcy George (1949) stated that uranous oxide (UO_2) is the stable oxide under high-temperature reducing conditions and uranous salts are highly unstable, being rapidly oxidized to the uranyl form and consequently not found in nature. He also stated UO_2 was an original constituent in all hypogene uranium minerals, although, as now found, most of the uranium in these minerals has been oxidized.

In a review of the geology of uranium, Everhart (1951a) described three types of uranium occurrences in sandstone: carnotite, copper–uranium, and uranium-bearing asphalt. All deposits were similar structurally and lithologically, and were in sandstone channels. Everhart (1951b) concluded that the carnotite ore bodies were formed by slight chemical change in the groundwater moving through the channel sandstone shortly after sedimentation. He attributed the other two types of occurrences, with sulfide minerals, to igneous hydrothermal solutions moving through the permeable channel sandstones.

Kerr's (1958) extensive study of mineral associations, relationships of uranium ore bodies and volcanic or other igneous activity and the alteration of the sediment, led him to the conclusion that temperatures were above those attributed to even deeply buried groundwater (hence hydrothermal solutions were the source of the uranium). The reasoning that, because a group of elements are associated in a vein or clearly igneous-related deposit, they are hypogene when found in any deposit, is not necessarily acceptable today. The alteration of bright-colored sediment to gray is now fairly well accepted as being a product of the sedimentary environment. Not even the vertical bleaching along faults and fractures is necessarily hydrothermal, because hydrogen sulfide and other natural gas can produce the bleaching. Kerr's recent work (Haji-Vassilious and Kerr, 1973) indicated that he no longer holds to the hydrothermal source for the extensive bedded deposits of the Colorado Plateau. Instead, the deposits are attributed to low-temperature (groundwater) solutions whose migration was dominantly lateral.

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Gabelman (1970) considers the mineralizing fluids to be connate or groundwater or water of crystallization. This water has been heated by deformation and mobilized by differential tectonic pressures in addition to temperature gradients. The increase in temperature increases the corrosive power and ability of the water to leach mobile elements. If compression is sufficiently intense the water enters the magmatic–hydrothermal cycle, but if there is no magmatism the fluids may be termed tectonic–hydrothermal. The elements are mobilized in reverse paragenetic sequence and move down the metallo-tectonic temperatures gradients to new zones of stability. The more mobile, lower-temperature elements, such as sandstone uranium, copper, and vanadium, are flushed from the hinterland (Gabelman, 1970). Gabelman (1971) also considers the ore occurrences of the Colorado Plateau and Wyoming to be unrelated to regional paleogeographic, sedimentational, and tectonic features present at the time of sedimentation. This conclusion is diametrically opposed to the thesis of this chapter. While tectonic features may generate some or all of the conditions he proposes, these same features can generate other conditions which bear more directly on the formation of ore deposits. These other possible conditions produced by tectonic features are: increased stream gradient; increased stream volume due to orographic rainfall; changes in climate in the provenance and depositional area. The principal reason why uranium deposits are zoned about tectonic features is that the climate and depositional conditions conducive to producing a favorable uranium host rock are most likely to occur simultaneously in adjacent areas or reoccur more frequently in areas where they have previously occurred. In which case preservation of the favorable host-rock sequence commonly preserves several of these potential host rocks rather than all being eroded and destroyed together, which is the more common fate of continental sediment.

A non-hydrothermal source was proposed for the uranium in the lignites of the Dakotas. Love (1952) indicates that Denson, Bachman, and Zeller originated the theory that the uranium in the South Dakota lignites migrated downward from radioactive tuffs in the overlying White River and Arikaree Formations. Love also believes that the Powder River basin uranium deposits were formed in a similar manner. Since these tuffaceous sediments covered most of Wyoming, as well as the northern great plains, they were a potential source for the uranium deposits in the Wyoming basins. Waters and Granger (1953) determined that volcanic debris was also present in the Morrison and Chinle sediment of the Colorado Plateau. They concluded that the simple leaching of ash and precipitation of the leached uranium and vanadium by organic matter is inadequate to explain the genesis of the sandstone-type ores of the Colorado Plateau. They suggested the possibility that some and possibly most of the uranium and vanadium may have been supplied by the devitrification of volcanic ash, then reconcentrated into ore bodies by groundwater circulation caused by igneous invasion, hydrothermal activity or uplift.

Davis (1969) suggests that the bulk of the uranium in the Powder River basin deposits was derived from tuffaceous sediment with some enrichment from the arkosic host sediment as the solution passed through them in the formation of the ore deposits. Davis

offers the evidence that the analysis of cores ahead of the front are only 2 ppm U, while those in altered rock several thousand feet back of the front are 6 ppm U. He also questioned the adequacy of the arkosic sediment actually traversed by the solutions (geochemical cell) to supply the known uranium.

The granitic provenance supplying the clastic material which accumulated as arkose, feldspathic, or micaceous sandstone uranium host rock is considered by some to be the source of the uranium. There is no doubt that the average granite contains sufficient uranium to provide an adequate source. The average granite contains 4 ppm uranium, which is equivalent to 40,000 tons of uranium metal (Gruner, 1956b) or 96,000,000 pounds of U_3O_8 per cubic mile. Some granites contain several times the average abundance of uranium and one of those granites is in the Granite Mountains or Sweetwater arch of central Wyoming. Masursky (1962) found 20–30 ppm uranium in these granites. Harshman (1972) indicated the eastern end of the Sweetwater arch, which supplied sediment to the Shirley Basin, contains granites with a uranium content of several ppm. Rosholt and Bartel (1969) found uranium concentrations in Granite Mountain samples ranged from 2.4 to 7.09 ppm for seven of eight samples and the eighth had 402 ppm U.

The availability of the uranium in the granites to leaching solutions is well established. Gruner (1956b) indicated that the uranium in granite was readily leachable and Harshman (1972) demonstrated that almost 1% of the uranium in granite samples was leached in a ten-hour period by a leach solvent similar to present-day Shirley Basin groundwater. The work by Szalay and Samsoni (1973) found the uranium content of granite and rhyolite is far more leachable than that of gabbro, andesite or basalt. They also found the concentration of uranium in the water attains within four to five hours an equilibrium value, due to an absorption equilibrium between the rock surface and water. Replacement of the leaching water at four-hour intervals produced repeatedly a new equilibrium. The new equilibrium concentration decreased somewhat, but the leachable uranium was not exhausted. The work of Rosholt and Bartel (1969) indicated uranium has been leached from the near-surface rock of the Granite Mountains, thus providing a major source for uranium deposits.

There are two variations of the granite-leach source idea. One is that the uranium was transported along with the sediment, probably in solution, to form a protore (Gruner, 1956b and Shockey et al., 1968). This protore has been described by Shockey as the original granitic source prepared and mixed with the other necessary ingredients (pyrite and carbonaceous material). The other variation is that the uranium was leached from the granite and introduced into the host rock either a little later or much later than the deposition of the sediment. Hess (1933), Wright (1955), Hilpert (1969), and Houston (1969) have indicated their acceptance of the granite as the direct source without being specific as to the time or the means of transportation.

However, Harshman (1972) proposes a much later time when the host rock is buried and subsequent uplift produced a change in hydraulic gradient. This change in gradient was necessary to induce the circulation of the uranium-bearing groundwater downward to

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the host sands where it moved laterally through the permeable zones. Erosion of the uplifted area may have subsequently permitted easier, more direct access for the mineralizing water which may have derived its uranium from both the granite and the overlying tuffaceous sediment.

These two variations constitute the "granite leach" school, but most likely there is a combination of the two variations from almost one extreme to the other. From the standpoint of simplicity, the conversion of uranium-rich granite into a readily leachable sediment (protore) in which the uranium is contained interstitially as uraninite and coffinite or possibly as urano-organic compounds and absorbed on woody or humic substances is the preferred source. Uranium within refractory numerals, such as monazite or detrital grains of arkosic sands, is not considered a potential source. It has not been adequately established that the sediment contains enough uranium to provide the necessary supply. The uranium available within the protore leached by the geochemical cell is the maximum available, if this is considered the only source. The calculations of Gruner (1956b) and Helgeson (1967) for the metals available do not apply to the geochemical-cell situation, because there is a finite, although large, volume of leached protore within the cell at any time.

Davis (1969) and Harshman (1972) present information that the uranium content of the unaltered sediment ahead of the front of a geochemical cell is less than in the altered interior of the cell, a condition which would dissipate rather than accumulate an ore body. There is a relationship between the source of uranium and the time of mineralization for all sources except the protore source. If the host rock is deeply buried and mineralizing solution has limited access, the period of mineralization would be limited to those times when uplift and erosion increases the accessibility from the granitic or volcanic sources. Mineralization from the volcanic sources would be further limited to those periods subsequent to the deposition of the volcanic debris.

The contribution of elements from volcanic sources which were transported in solution into the geochemical cell cannot be denied: however, the mechanics of transportation are more complex. They will be concentrated by a cell if they are introduced with oxygen in a form available for biologic processes. This statement can also be made of elements from any source. Once the epigenetic minerals had been accumulated by the cell, they would continue to migrate with it. Minerals or elements in the host sediment which can be concentrated by the cell would continue to be accumulated as it migrates and expands. With these possibilities there is no way to exclude any of the possible sources. Davis (1969) and Harshman (1972) accept multiple sources: Davis from the volcanics and the arkosic host rock but does not comment on the granite of the mountain range; Harshman's source is the granite of the mountain range supplemented by possible additions from the volcanics overlying the basin, but denies the possibility of the sediment contributing to the ore.

Notwithstanding the problems of producing ore bodies by the leaching of the uranium from the host rock, there is a substantial number of supporters for this source. Melin

(1964), Rackley et al. (1968), Shockey et al. (1968) and Anderson (1969) advocate the leaching of the uranium from the host sediment for the source of Wyoming deposits. Gruner (1956b), Shawe (1956), and Shawe et al. (1959) advocate the uranium contained within the host rock as a source for the uranium deposits of the Uravan mineral belt and possibly other areas of the Colorado Plateau. Rapaport (1963) indicated the uranium deposits in the Ambrosia Lake area, New Mexico, were derived from the host sediment, and a similar view is held by Moench and Schlee (1967) for the deposits at Laguna, New Mexico. Rackley et al. (1968) calculated that the volume of the geochemical cell of the Gas Hills could have accumulated 400 million pounds of U_3O_8, if 2 ppm were leached and concentrated by the cell, an amount of only half the average crustal abundance and possibly only 10% of the uranium in the granite from which the arkose is derived. They also calculated on the same basis that the Grants mineral belt could contain over two billion pounds of U_3O_8 on the margins of the geochemical cell.

The source of uranium is one of the facets of the formation of uranium deposits that obviously needs much more research. If the tuffaceous sediment is considered the source, then the search for new deposits must be limited to areas of volcanic activity. If the granites are considered to be the source, then the search can be broadened to include any arkose or feldspathic sandstone. The condition of weathering and erosion may play an important role in making the uranium available for the development of ore bodies and some comments on this subject are given below.

There is one essential ingredient of all the significant uranium occurrences, and that is "ground preparation" of the host rock. This "ground preparation" is the development of a reducing environment, with carbonaceous material and pyrite, strong enough to resist the invasion of oxidizing solutions in a manner which permits the maintenance of reasonably sharp boundaries between the two environments. Poorly developed reducing conditions permit massive invasion by oxidizing conditions in which local reduction centers may accumulate minerals for a short period before they are destroyed by the same solutions that mineralized them.

The study of the tectonic and sedimentary history, as outlined earlier, of all the districts leads to the conclusion that mineralization occurred as a result of the development of geochemical cells during the erosion of portions of the depositional basins relatively soon after the deposition of the host rock. This erosion takes place during the fourth phase of development, as described earlier in "Tectonic condition". During this period of erosion, the physical relation between the granite source area and the recharge area of the uranium host sequence was well suited for the direct transportation of uranium-bearing solutions from the source area into the geochemical cell. The erosion within the basin provided the hydrodynamic gradient which permitted the geochemical cell host sequence to accept water from the streams in the recharge area. Weathering and chemical conditions were probably near optimum for the oxidation and dissolution of uranium from the granitic rock, or from any other source of leachable uranium, in the drainage area. This direct transportation of uranium-bearing solutions from the sediment-

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source area into the groundwater recharge area of the host sequence would occur under well oxygenated conditions – conditions under which hexavalent uranium is readily mobile.

This unfortunately does not clearly establish a source because there are three potential sources available in all areas: the granitic rock of the source area; the host sediment; and, some intrabasinal volcanic material.

The behavior of uranium in the weathering and erosion processes of a weathering mantle or crust may play a significant role in the formation of uranium deposits. Samama (1973) states that continental weathering and erosion processes influence the nature of sedimentary supply and the nature and geochemistry of the sediment. Numerous economic concentrations of lead, zinc, copper, vanadium, or uranium are found in formations of continental facies of the "sandstone type". These are characterized by the association of a terrigenous residual phase cemented by a chemical phase, unstable in surface conditions, which contains heavy metals as sulfides or oxides (Samama, 1973). Perel'man (1967) indicates the processes of weathering are: (1) comminution of rocks and minerals; leading to (2) a decrease in density; (3) an increase in porosity; (4) an increased dispersion of the chemical elements; and (5) aquatic migrants are removed. Weathering is relatively slight in water-bearing strata and disappears entirely with depth. However, the processes of leaching, cementation, and recrystallization are common in all water-bearing strata and intensify with depth (Perel'man, 1967).

Because of the difference between the behavior of an element at the crystal level (mobile or immobile) and its behavior on a regional or continental level, Samama (1973) introduces the concept of migrating elements and residual elements. Under some weathering processes an element may be a residual element, but the weathering processes may change with time causing the elements previously accumulated to be eliminated, thus causing the weathering cover to act as a very efficient separating filter. A continental area, both rich in a chemical element and weathered under conditions concentrating that element, can give rise to a really important metalliferous supply to the basin, and induced in appropriate sedimentary conditions, lead to significant ore deposits (Samama, 1973). The possibility that processes of these types have influenced the accumulation of uranium deposits is great enough to warrant further investigations.

Samama's (1973) work on weathering profiles indicates uranium is accumulated by allitization weathering processes and is eliminated by the bisiallitization processes. Perel'man (1967) partially confirms this indirectly by the sorption of uranium by colloidal hydroxides of aluminum and iron which forms under hot humid climates or allitization weathering processes. He also indicates in the weathering of siliceous rocks in temperate climates, that uranium has a strong migrational intensity in an oxidizing environment.

GENETIC MODEL

The preceding review of the literature concerning the various aspects of the origin of the western-states type uranium mineralization may leave the reader with an unclear impression of the central thesis of this chapter. The concept of a series of simple related processes which produce uranium ore bodies is somewhat contrary to traditional ideas of ore formation. To present this concept as concisely as possible, a genetic model is used to summarize and tie together these processes.

The model, of necessity, began with an uplift which uncovered a granitic source area and increased the capacity of the stream, draining the uplift, to transport the granitic debris into an adjacent depositional area. Sediment was transported by braided streams on alluvial fans which merged into flood plains, on which the stream patterns changed to meandering. Climatic conditions were warm to hot and seasonally humid with natural irrigation supplementing the dry-season rainfall. Abundant vegetation grew in the depositional area and the plants and animals burrowed and mixed the sediment. Frequent reworking by the streams incorporated sufficient organic material in the sediment to produce reducing conditions by its decay. The sands deposited under these conditions were organic-rich, pyritic, light- to dark-gray and the clay deposits were light- to medium-gray or green, pyritic and commonly carbonaceous (the pyrite being of diagenetic origin). These conditions provided the "ground preparation" prerequisite for the subsequent mineralization.

In the weathering of the granite, the minute uranium-mineral grains interstitial to the common rock-forming minerals were oxidized and leached well in advance of the development of a soil profile. This supplied uranium to ground- and surface-water well before that specific portion of the granite was physically eroded. Because the supply of granite is typically very large, the granitic mass may continue to supply uranium to the depositional basin when physical erosion is very slow. The uranium released by weathering migrated through the basin and was lost to the sea unless it came into contact with reducing conditions present in the organic-rich sediment a short distance beneath the sediment–water interface, in which case it enriched the sediment.

In the late stage of erosion of the source area, the relative increase in silt and clay caused the host sands to be overlapped by a confining cover of less permeable sediment. When sediment supply to the depositional area was less than stream capacity, erosion began in the depositional area. Exposure of the host sediment to oxidizing conditions at the surface permitted an invasion of the reduced sediment by oxygenated water. This water was derived, in part, from the granitic mountain core and carried trace amounts of uranium and other elements mobile in an oxidizing environment. In some cases this period of erosion almost destroyed the entire favorable host, the remnants of which accumulated uranium from the oxidation and erosion of the overlying sediment.

In other cases, the oxidizing environment invaded the reduced sediment for considerable distances from the eroded basin margins and far below the static water table. This

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caused destruction of carbonaceous material, oxidation of the diagenetic pyrite and accumulation of uranium and other susceptible metals from both the water and from the sediment being invaded. The metals were concentrated 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 until its dimensions measured miles in areal extent and hundreds of feet in thickness. This oxidizing invasion is a geochemical cell which had a sharply defined boundary produced by biochemically controlled changes in physical and chemical conditions. Oxygenated water, aided by the bacteria *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 sediment 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.

The physical development of a geochemical cell began in the upstream area of the fluvial system near the margin of the basin. The area in which the oxygenated water invaded the reduced, organic pyritic sediment and established an oxidizing environment can be considered a point source in the overall scale of the geochemical cell which resulted. From this small beginning, the cell grew by the energy derived from the oxidation of the oxidizable constituents of the reduced sediment. Gradually expanding from the original point of beginning, the cell developed preferentially down the hydrostatic gradient and in general followed the thicker more permeable portions of the fluvial system. The continued growth of the cell caused it to expand further down the hydrostatic gradient and also laterally from the central permeable portion of the host sequence into the thinner fine-grained units along its margins. Carbonaceous material and pyrite tend to be more abundant along these margins, so the cell was retarded by both the decrease in permeability and the increase in reactive material in the sediment.

The development of the mineralization on the margin of the cell began as soon as the cell developed an Eh gradient across the front which would act as a reduction barrier for the elements mobile in an oxidizing environment. The size of the cell may have been as little as a few meters long and probably not more than a few hundred meters long. Once the reduction barrier or Eh gradient was established, the mineralization began to accumulate. A unit of uranium carried by the oxygenated water from the weathering granitic core of the mountain (or any other external source) was added to a unit of uranium intrinsic to the sediment. As the cell continued to grow, other units of external uranium were added to adjacent intrinsic units. However, as the oxidizing environment expands at the expense of the reduced environment, the previous site of uranium deposition was overrun by the oxidizing zone and the uranium was oxidized and remobilized. The remobilized elements were moved across the reduction barrier again and were reprecipitated at a new site where other units from external and intrinsic sources had been previously deposited. Through many repetitions of this process the size of the mineralized body slowly grew from the small beginning to the ore bodies now being produced.

Erosion of the strata covering the host formation tended to accelerate growth of the cell by enlarging the surface area exposed to recharge. It is important to understand that the cell originates essentially at a point and expands to form a continuous, three-dimensional, finite body. As the geochemical cell moved farther through the host, the ore bodies along its margin increased in size and grade. The cell migrated under and around shale parting, but always maintained its continuous finite body. Islands of unaltered sand may be surrounded by the cell just as shales are enveloped by it. The reverse is never true; the cell does not form islands of alteration in the unaltered rock.

The mineralization on the margin of the cell is far from uniform. There is a tendency for the thicker, higher-grade margins of the cell to have preferred orientations. This suggests that there is a direction of groundwater flow or cell movement and those segments of the cell perpendicular to that direction accumulate more mineralization than those segments parallel to it. This is most noticeable in plan view, but the same kind of non-uniformity is also true in cross-section views.

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 geochemical cell and the mineral fronts on its margins was controlled by the initial sedimentary pattern and conditions. When the hydrodynamic system was disrupted and the oxygen supply was cut off, the invasion stopped. If the conditions permitted a renewal of the supply of oxygen to the front, they resumed expansion.

DISCUSSION

In recent years there has been a growing awareness that the uranium deposits described herein as the western-states type have much more in common than originally thought. Although old ideas and terms "die hard", new work and new ideas filter into the professional working knowledge to replace older concepts which cannot meet the test of scientific verification. The mineralization of the roll or geochemical-cell deposits, regardless of their physical shape, has been singled out as the most important process in the series of events leading to the formation of a uranium deposit and some work has been done on the subject. Harshman (1972) made an extensive study of the mineralogy and trace-element distribution of the Shirley basin ore bodies. Harshman (1974) has extended these studies to other uranium-producing areas, including Texas, from which he has established limits on the ore-forming fluids. The transporting solution was alkaline and oxidizing although he advocates a drop in pH, to acidic levels, from the oxidation of pyrite in the ore body in the vicinity of the front. The deposition of the ore is a result of a reduction in the Eh of the transporting fluid. The reductant is probably hydrogen sulfide of biogenic origin (Harshman, 1972).

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* IBG = interior barren ground

and reduced species of the ore and related trace elements of a geochemical cell. This diagram clearly indicates the increasingly lower Eh values required by the various elements from the roll front into the reducing side of the cell. Another equally important aspect of the diagram is the fact that the reverse is also true; that is, the elements are arranged according to their increasing stability in an oxidizing environment. This serves to re-emphasize Harshman's (1972) earlier statement that there are a series of nested and commonly overlapping frontal zones in which each of the elements are concentrated. The front normally indicated in discussions of roll-front geology is the contact between the zone of oxidized iron minerals and the carbonaceous pyrite zone at or near the zone of uranium concentration.

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 a mixture of an inert oxidizing agent and active reducing agents. The laboratory experiments by Granger and Warren (1969) have produced some very interesting results, and it is hoped that they ultimately will produce some definitive answers. The principal purpose of this work was to establish an inorganic 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.

Cheney and Tramell (1973) consider the diagenetic formation of bacterial pyrite as ground preparation for the later and unrelated formation of roll ore bodies. Their "possible" evidence for their support of a non-biogenic origin of the roll ore bodies is the "inference" that the unaltered rock through which the roll is passing has nonpyritic areas. The nonpyritic areas cause the dissipation of the ore as the altered zone moved through it and became juxtaposed on the unaltered nonpyritic area (Cheney and Trammell, 1973). Unfortunately there are no known observations which support the inference that the host rock has major (more than a few meters wide) nonpyritic areas. On the contrary, the uranium host beds are characterized by a consistent minimum amount of pyrite with some locally enriched zones in areas of abundant carbonaceous material.

It cannot be determined just what is meant by the juxtaposition of the altered (IBG)* and unaltered (EBG)* areas, but it is an inherent part of the geochemical-cell concept that it moves at a rate determined by the reactive constituents of the rock so that pyrite and/or carbon-poor areas would be traversed relatively quickly. The geochemical cell does not develop holes in its exterior reaction zone just as inflating balloons do not have holes. Without the nonpyrite areas neither of Cheney and Trammell's (1973) "geologic evidence" are valid. As mentioned heretofore, the weakly or nonmineralized portions of a geochemical cell appear to be related to the direction of cell movement.

* IBG = interior barren ground, EBG = exterior barren ground.

Granger and Warren (1974) have modified their earlier ideas somewhat to explain the generation of the unstable soluble sulfur species and the zonation of the alteration near the ore. They cite Kashirtseva (1964) for evidence of siderite and elemental sulfur in a Russian uranium occurrence as evidence on which to develop their process. Berner (1973) indicates siderite and/or glauconite will be stable if the concentration of sulfide ions is low, which makes the development of a western-states type uranium deposit dissimilar to the deposit Kashirtseva describes. Kashirtseva (1964) shows in his fig. 6 that the distribution of pyrite is restricted to the immediate vicinity of the roll which is overlapped by a much more extensive siderite zone. Furthermore he concludes: "Most likely it is rocks with predominantly sulfide iron that shows the steepest redox-potential gradient, which promotes a considerable uranium accumulation. Conversely, rock with predominantly carbonate iron probably are unfavorable for uranium accumulation" (Kashirtseva, 1964, pp. 44–45).

In the Shirley Basin and in the Powder River basin ore bodies, hematite and calcite are found together, but siderite is not known to be associated with the ore. Granger and Warren (1974) offer no evidence that either siderite or elemental sulfur are present in the districts they describe, and the acceptance of their proposed processes should be withheld until more evidence is offered.

Warren (1971) offers another line of evidence to support the chemical origin of the ore-stage pyrite and uranium accumulation in a roll-type uranium deposit. He proposes that a biogenic origin of the pyrite would cause a much larger volume of pyrite in the ore bodies than is now found, whereas the chemical origin would produce the volume found in the deposits. There is, however, one facet of this reaction which was not considered. The formation of pyrite is dependent upon the availability of reactive iron (Berner, 1973), as well as sulfide in the solution. The geochemical cell throws off iron by the hydrolysis of ferric sulfate to sulfuric acid and the insoluble ferric hydroxide as shown in Fig. 16. Even if the validity of that reaction is questioned, the iron content of the altered area is sufficient to indicate much of the iron is retained there. Warren (1972) repeats the same argument based on sulfur-isotope considerations for chemical disproportionation as the means of ore-body formation and the same limit of available reactive iron also applies to this argument.

Gruner's (1956b) multiple migration–accretion hypothesis has been accepted by many uranium geologists and the evidence he presented has guided much of the thinking leading up to recent, more comprehensive concepts of uranium ore deposition. Gruner summarized his ideas from knowledge of most of the presently known uranium districts which had been discovered and were partly explored or in production at the time. Mineralogic, geologic, and geochemical observations and experiments were considered to establish a conceptual model of sandstone-type uranium deposits. Gruner's hypothesis called for the accumulation of uranium and other metals in a swamp or peat bog by drainage from higher ground. Each swamp accumulated most metals present in its drainage basin. After burial and renewed erosion of the swamp the metals were oxidized and remobilized as the

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swamp was destroyed by erosion, and surface waters transported the metals to enrich the next swamp. 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, 1956b).

If one substitutes the physical erosion of a swamp or bog for the oxidation and alteration in place of sandstones originally deposited in a reducing – and certainly swamp like – environment, Gruner's hypothesis would adequately explain the concentration of disseminated minerals into ore bodies. This has been the interpretation many workers have placed on this hypothesis and perhaps Gruner intended this.

TOPICS FOR FUTURE RESEARCH

Creative research is required to transform the empirical art of uranium geology into the science needed to provide the resources for the future. Since economic geologists and students of ore deposits have lost hydrothermal solutions as a "magic wand" or crutch to explain the origin of many strata-bound ore deposits, it becomes necessary to put genesis in context with the overall sedimentary rock-forming process. Fortunately "giant steps" are being made in the knowledge of the physical processes of sedimentation, but equally large steps are required in the knowledge of the biological and chemical processes which are an inseparable part of the sedimentary rock and strata-bound ore-forming processes.

In this chapter five topics for future research have been suggested. These are:

(1) The role of bacteria in the formation of ore bodies as distinguished from ground preparation.*

(2) The means of recognition of geochemical alteration in outcrop and in subsurface samples.

(3) Further definition of the time of mineralization in relation to other geologic events as well as absolute age.

(4) What is the source or sources of the mineralization?**

(5) What is the behavior of uranium in weathering and erosion in various climates?

NOTES ADDED IN PROOF

(1) Childers (1974) has interpreted the term "geochemical cell" to refer to a geometric shape. It was never been intended to denote a shape but rather a process of alteration and mineralization which can conform to any shape determined by the sediment.

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* Editor's note: see the chapter by Trudinger on bacterial processes, Vol. 2, Chapter 6.

** Editor's note: see the contribution by the editor on conceptual models, Vol. 1, Chapter 2.

(2) Childers (1974) proposes that the alteration and mineralization developed while the host sediment was either exposed at the surface or only slightly buried. He does not consider the question of erosion but the change from a wet to a dry climate almost implies that erosion of the host sediment may take place with the oxidation and mineralization.

(3) Childers (1974) offers the evidence that mineralization of Eocene sediment in the Cyclone Rim area of the Great Divide Basin of Wyoming is probably older than the Middle Oligocene. This evidence is the faulting of mineralization by faults which were active during the deposition of the Oligocene White River formation as determined by differences in thickness of that formation in various faulted segments.

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Chapter 4

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INTRODUCTION

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HANDBOOK OF STRATA-BOUND AND STRATIFORM ORE DEPOSITS

II. REGIONAL STUDIES AND SPECIFIC DEPOSITS

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Volume 7

Au, U, Fe, Mn, Hg, Sb, W, AND P DEPOSITS

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