

# CONCEPTS AND METHODS OF URANIUM EXPLORATION

By

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## INTRODUCTION

A geologic concept which guides exploration for uranium in sandstone-type deposits can succeed only if that concept deals effectively with the major generic questions concerning ore concentrations. These questions concern the source and method of transportation of the uranium, the relationship of the deposits to structurally positive areas, the physical-chemical nature of the host rock, the character of the concentration process and its capabilities to produce the minerals in the quantities observed, the amount and distribution of carbonaceous matter, and the shape of the orebodies.

Exploration guides for sandstone-type uranium deposits were developed empirically by the U.S. Atomic Energy Commission from experience in the early exploration of the late 1940's and early 1950's (Wright, 1955). The exploitation of uranium deposits during the past twelve to fifteen years has added substantially to the knowledge of uranium geology. There are complex relationships in the deposition of a uranium orebody, which are commonly unrecognized and invariably poorly understood.

There has been much written on the association between carbonaceous material or organic matter and sandstone-type uranium deposits (Schmidt-Collerus, 1967; Scott, 1961; Vine; Szalay). Pyrite is also present in amounts which make one think that it too plays a role in the deposition of uranium and again, the part played is not clearly understood. The sulfur isotope studies have indicated that some of the pyrite is biogenic and that there is a relationship of unknown significance between the biogenic sulfides and uranium deposits (Austin, 1968; Jensen, 1962). There have been a number of papers on solution fronts or rolls, some of which attribute the fronts to contrasts in oxidation-reduction potential (Vickers, 1957; Bailey, 1964; Harshman, 1966; Adler, 1964; Young, 1964), while Melin (1964) attributes the front to neutralization of an acidic solution. Some writers think that tuffaceous sediments are the uranium source. Others, including the authors, think that the granitic rocks and sediments derived from them are the uranium source. Still others think that the uranium is from deep seated igneous sources.

While it cannot be denied that all of these possibilities exist, the authors prefer the granitic source because

it eliminates the need for external sources and avoids some problems of transportation.

The key to the source is probably found in the process which produces the deposit, therefore, the events which take place in the leading edges of geochemical cell, or in the solution front, shall be examined. It is easy to say that a solution front is the combined product of chemical, physical and biochemical reactions. To say what these reactions are is an entirely different matter.

The need to combine the available knowledge into a working hypothesis is obvious if the renaissance uranium exploration effort is to fulfill the anticipated demand for nuclear fuel. The concept elucidated here is a genetic hypothesis used to guide exploration for sandstone-type uranium deposits. The hypothesis may be applicable broadly in the search for vanadium, copper, silver and other metaliferous sandstone-type deposits.

This concept has been used successfully to explore for uranium within known districts and in the discovery of new districts, the magnitudes of which are as yet largely undefined. In a more detailed sense, the concept is applicable to mine planning and ore control.

An orebody is a unique geological occurrence in which one or more elements have been concentrated a few times to a few hundred or more times their average abundance. The average abundance of uranium is 4 ppm for all rock (Fleischer, 1953). Orebodies of .20% or 2000 ppm uranium contain 500 times as much uranium as the average rock of the earth's crust. It is interesting to note that 4 ppm is equivalent to more than 40,000 tons of uranium metal per cubic mile (Gruner, 1954) or 96,000,000 pounds of  $U_3O_8$ . Uranium is plentiful but it is concentrated into orebodies only under uncommon conditions. The authors believe that this concept provides a skeleton on which to hang the details of uranium concentration processes yet to be developed. The authors hope to generate thought and discussion leading to more understanding of these processes.

## SOURCE ROCK

The relationship of the sedimentary source rock to the area of deposition is depicted in Figure 1. The scale is omitted so that the diagram may be mentally compared with the area in which the reader is most familiar. In central Wyoming one would think in terms of composite fans and streams ten to twenty miles wide and some twenty to thirty miles long. In the Grants, New Mexico area, the

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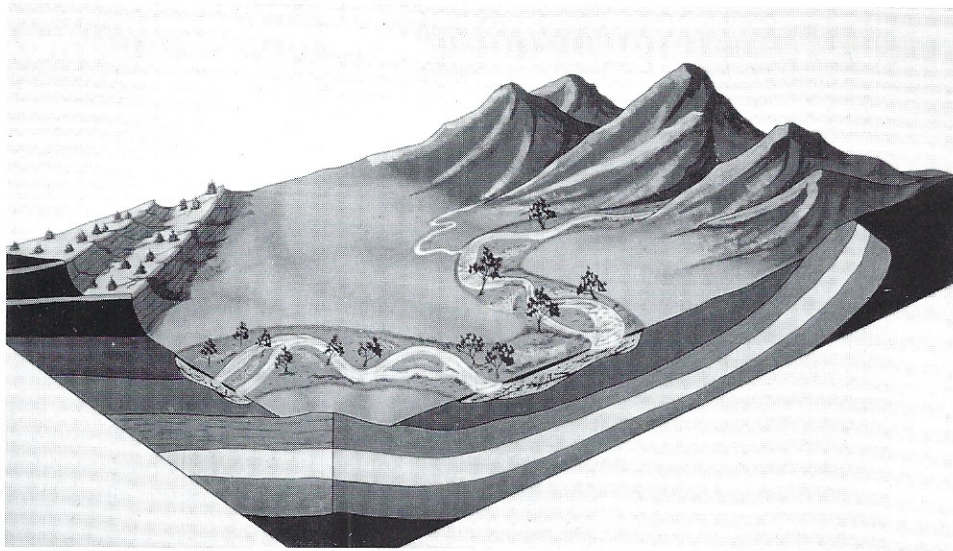


Fig. 1.

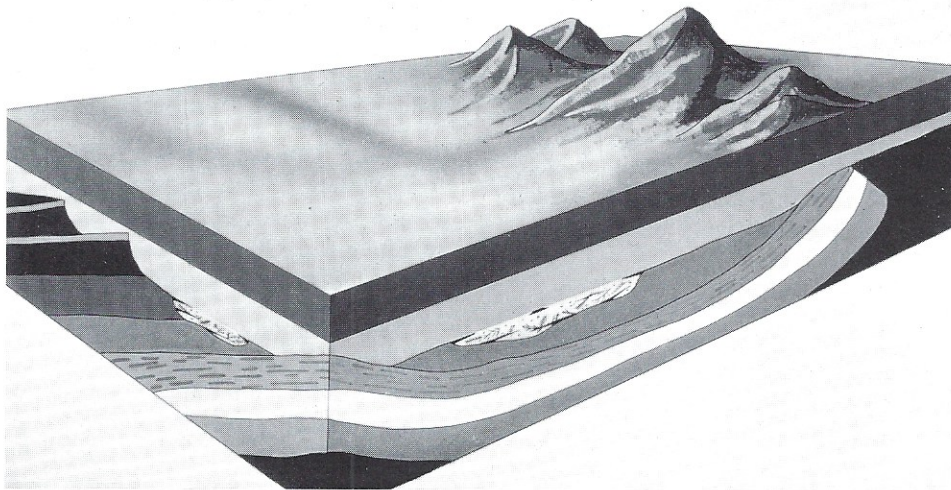


Fig. 2.

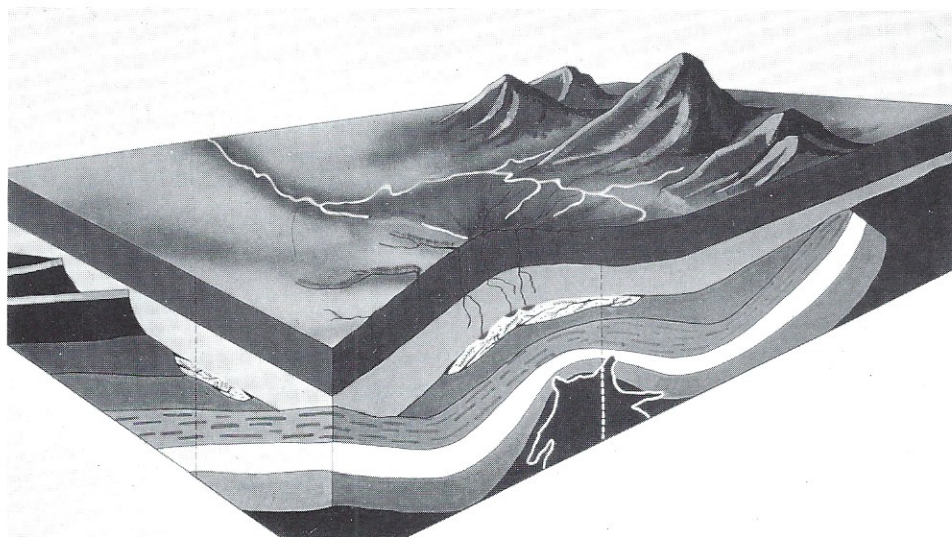


Fig. 3.



stream system is fifteen to twenty miles wide and possibly eighty to 100 miles long. In the Colorado Plateau or the Black Hills of Wyoming, the size diminishes.

The uplift is important in order to bring granitic rocks into the zone of weathering and erosion. (Other rocks may also be sources, i.e. uraniferous chert-phosphatic deposits.) The granitic debris was transported basinward to produce the host rock. The increased stream gradient produced by the uplift was also a necessary factor in producing rapid erosional and favorable depositional conditions. Climatic changes had an effect on the weathering and depositional environments.

The uplift may be accompanied by addition of uranium to the granitic rocks by hydrothermal alteration. Other areas may contain anomalous uranium due to differences in composition at the time of emplacement. Reason for the uranium content within the granites is less important than the fact that subprovinces of anomalously high uranium exists.

It is implied that granites are THE source or at least the principal source of uranium in the major uranium deposits that are being considered. Analyses of samples of granite from the Granite Mountains of central Wyoming show as much as twenty to thirty ppm uranium (Masursky, 1962, p. B95). This is six times the average uranium abundance and certainly sufficient to account for all the known uranium concentrations in the area. The presence of anomalously high uranium content in the Westwater formation, host to the principal deposits in the Grants District, is confirmed by Laverty and co-workers (AEC Uranium Workshop, 1966-1967). They have described a halo, containing twenty ppm, several miles wide which surrounds the Grant ore trend. Relatively uranium-rich sediments are deposited only basinward from uranium-rich source rock. Both are distinctly sub-provincial in otherwise similar terrane.

The exact method of transport of "primary" uranium is not known but it is probable that some was transported in solute and some as particles. If the weathering conditions were not conducive to desolving the uranium, it would have been transported with or in the other solids. Once uranium entered the depositional area, it was effectively precipitated and preserved by the reducing environment. If conditions were favorable in the weathering and erosion area for oxidation and removal of uranium in solution, some of that uranium was subsequently extracted in the depositional area by carbonaceous material and through the precipitation by H<sub>2</sub>S and hydrogen produced by anaerobic bacteria working in the sub-stream sediments.

Deposition of the protore sediments takes place in favorable environment. The favorable environment included incorporation of abundant vegetation into the sediments. Rapid erosion and deposition produces a poorly

sorted 'dirty' sediment which is ideal for the preservation of associated organic material. Sorting during transportation would tend to eliminate much of the organic matter and also tend to make the sediments less amenable to preservation of the little organic material retained.

Events following burial of the sediments included the initial stages of carbonization and fermentation of the plant materials. As a co-product, anaerobic bacteria produced hydrogen sulfide and hydrogen. These in turn precipitated available iron as pyrite and any uranium in solution.

Through this process, the original impermeable, non-amenable granitic uranium source rock has become a permeable, amenable arkosic uranium source bed . . . or true protore. To this has been added carbonaceous material and pyrite, both of which play an important role in the subsequent concentration of this lean protore into substantial orebodies.

### BURIAL

Burial protected the sediments from erosion and provided a cover capable of containing the hydrodynamic system which developed in the "host" following subsequent tectonic adjustments.

### TECTONISM AND INCEPTION OF GEOCHEMICAL CELL

Tectonism subsequent to burial is required in the evolution and development of a uranium district. (See Figure 2.) The event may be igneous folding, as illustrated here, or epirogenic or orogenic folding which resulted in movement of groundwater through the aquifer. As these waters flowed through the "host" sands, a change was initiated in the sediments. A complex physical, chemical, and biochemical reaction caused this change. The zone of reaction is a solution front or roll. The changes which took place in the rock inside the solution front is alteration. The solution front and the alteration it produced is called a geochemical cell. These cells, which began at this early stage, grew like smoldering fires and ultimately coalesced and spread as reactive constituents were fed to and enveloped by the cell.

These beginning cells are shown in red on the illustration for ready recognition and also because many cells produced red hematitic alteration of the otherwise drab host rock.

### CELL GROWTH

Figure 3 is a longitudinal slice of the stream system across the uplift. The time is the same as the previous figure. The geochemical cells have not as yet coalesced. Pyrite is disseminated through the rock in amounts up to one percent. The carbonaceous material originally deposited with the sediments is preserved with only slight addi-



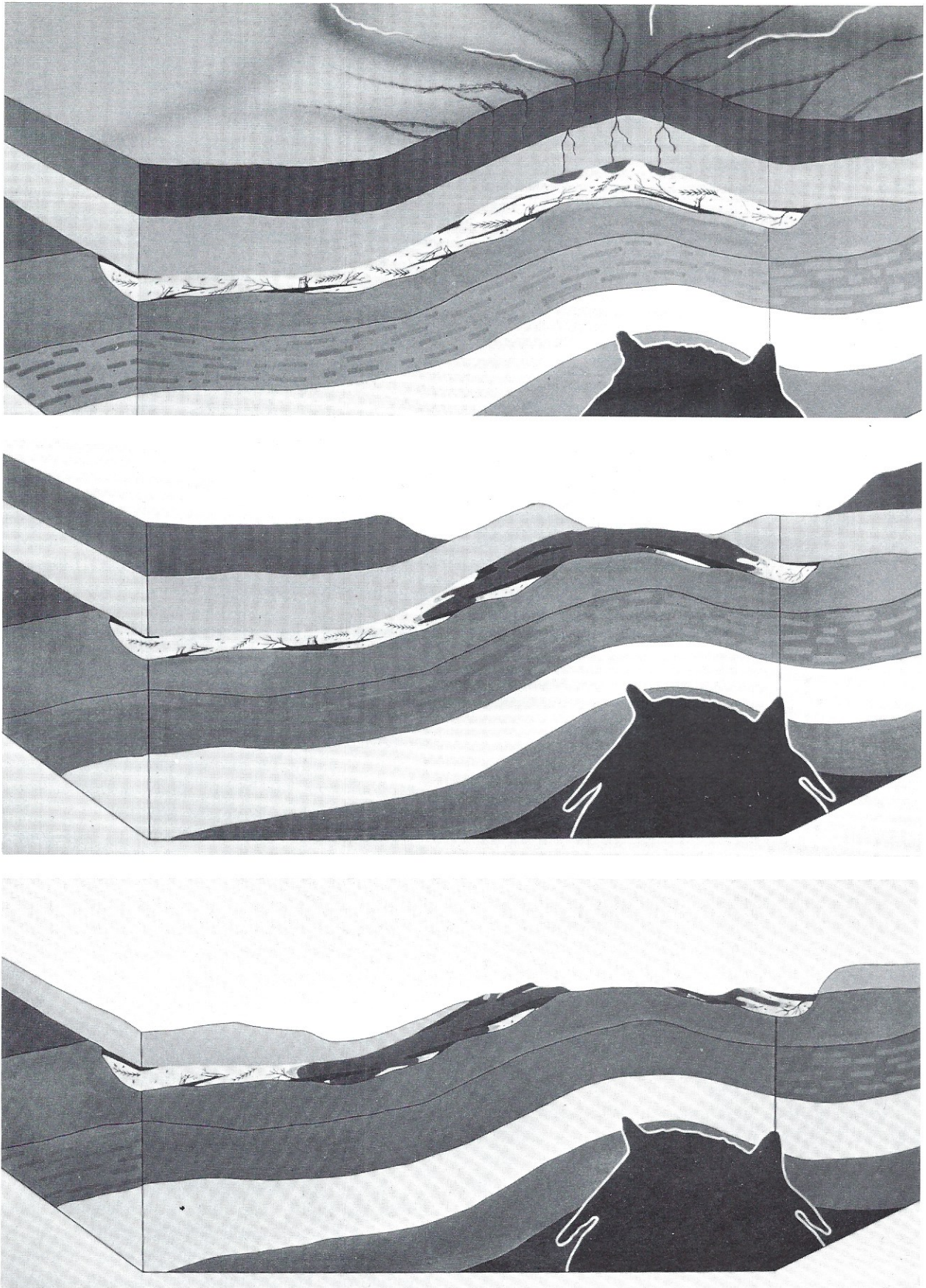


Fig. 4.



tional carbonization. The uranium and other metals, such as vanadium, selenium, molybdenum, silver, copper and chromium, which were present in the source rock, are also present in limited amounts in the host.

Metals concentrated by the cell are those present in the source and subsequently in the host rock in sufficient quantities to enter the reactions of the cell. Some cells are definitely deficient in uranium. Molybdenum, copper and vanadium deposits occur as a product of geochemical cell concentrations with little or no uranium. Conversely, uranium may occur without appreciable amounts of other metals.

With passage of time, the cell continued to grow, as indicated in Figure 4. Erosion of the strata covering the host formation would tend to accelerate growth of the cell by enlarging the surface area exposed to recharge by surface waters. It is important to understand fully that the cell originates essentially at a point and expands to form a continuous, three-dimensional, finite body. The shape of the cell and related orebodies is determined chiefly by gross permeability.

As the geochemical cell has moved farther through the host, the orebodies along its margin increased in size and grade. The cell migrated under and around shale partings, still maintaining its finite, three-dimensional shape. The carbonaceous matter originally present was removed by the solution front and uranium deposits were accumulated at the interface between protore and the geochemical cell.

### BIOCHEMICAL REACTIONS

The principal reactions within the geochemical cell are shown in Figure 5. There are probably a wide variety of biochemical reactions which take place in addition to the three shown but these other reactions may play no direct part in the geochemical cell. The arrows indicate products from one reaction entering other reactions. There are several activities which could feasibly operate in a closed circuit.

The first reaction to consider is the fermentation of the cellulose and other organic material by the anaerobic sporeformers, *Clostridium cellulosae*—*dissolvens* (Stanier, p. 447-553), which produce a number of products required by other bacteria.

These products of fermentation are then further oxidized by the mixed population in anaerobic respiration. The sulfate reducing genus, *Desulfovibrio*, through anaerobic respiration, utilizes the inorganic sulfates,  $\text{CO}_2$ , succinic acid (Stanier, p. 423), and sometimes gaseous hydrogen to produce  $\text{CO}_2$ ,  $\text{H}_2\text{S}$  and water. These bacteria are extremely strict anaerobes and produce an environment of pH 7.8 to 8.4 (Jones & Starkey in Jensen, 1962, p. 65) and an Eh of approximately minus 200 mv (Germanov,

1958), but they are also capable of an Eh of minus 500 mv (Bass, 1961). The *Clostridium* produces hydrogen as a by-product of the fermentation of the cellulose and hydrogen is a strong reducing agent. The environment produced by these two and other bacteria provides an environment which physically reduces and precipitates the uranium and other metallic ions in the order of their solubility. Thus, a definite relationship between the organic materials originally incorporated in the sediments and the deposits of uranium ore is demonstrated.

The *Desulfovibrio* and *Clostridium* both operate in the protore portion of the geochemical cell . . . this is the area in which the uranium is deposited. In the altered side of the cell, *Thiobacillus ferrooxidans* are the principal bacteria. These bacteria require and produce an altogether different environment from those on the protore side of the cell. They are the principal cause of the extreme acidity of coal mine waters. They are used in the recovery of copper from waste piles and are found in nature wherever sulfides are found in an oxidizing environment (Kuznetsov, 1963, p. 134). Not only do they thrive in an oxidizing environment, but create pH's as low as 1.8 and can survive in a pH of zero. The optimum pH is from 2 to 4. With a pH of over 4.5, their activity is greatly reduced (Kuznetsov, 1963). The oxidation of ferrous iron by the *Thiobacillus* is approximately 200 times faster than by atmospheric oxygen (Kuznetsov, 1963). Along with the oxidation of pyrite, sulfuric acid is produced in greater quantities than is consumed by the pyrite oxidation.

There are three basic reactions in the *Thiobacillus* zone. One reaction is chemical which utilizes pyrite, ferric sulfate and water to produce ferrous sulfate and sulfuric acid. The second is a biochemical reaction by which the ferrous sulfate is utilized by the bacteria to produce more ferric sulfate. The ferric sulfate is utilized in the oxidation of other pyrite (Silverman, 1967). The third reaction is the hydrolysis of the ferric sulfate to produce sulfuric acid and iron hydroxides.

The principal addition to the *Thiobacillus* zone from external sources is carbon dioxide from the protore side of the cell and oxygen from the altered side of the cell. Oxygen is not necessarily present as free oxygen but may be in the form of sulfates, carbonates and nitrates. Some free oxygen would greatly assist in the cell development. The iron minerals which are found as a result of the geochemical cell are probably largely dependent on the amount and form of the oxygen supplied. Therefore, it is possible to have pyrite formed if oxygen is relatively deficient and hematites and limonites, if the oxygen is abundant.

Not only do the *Thiobacillus* create an extremely acidic environment but they also create an extremely oxidizing environment. Eh values up to plus 760 mv have been observed (Kuznetsov, 1963, p. 133). Two extreme



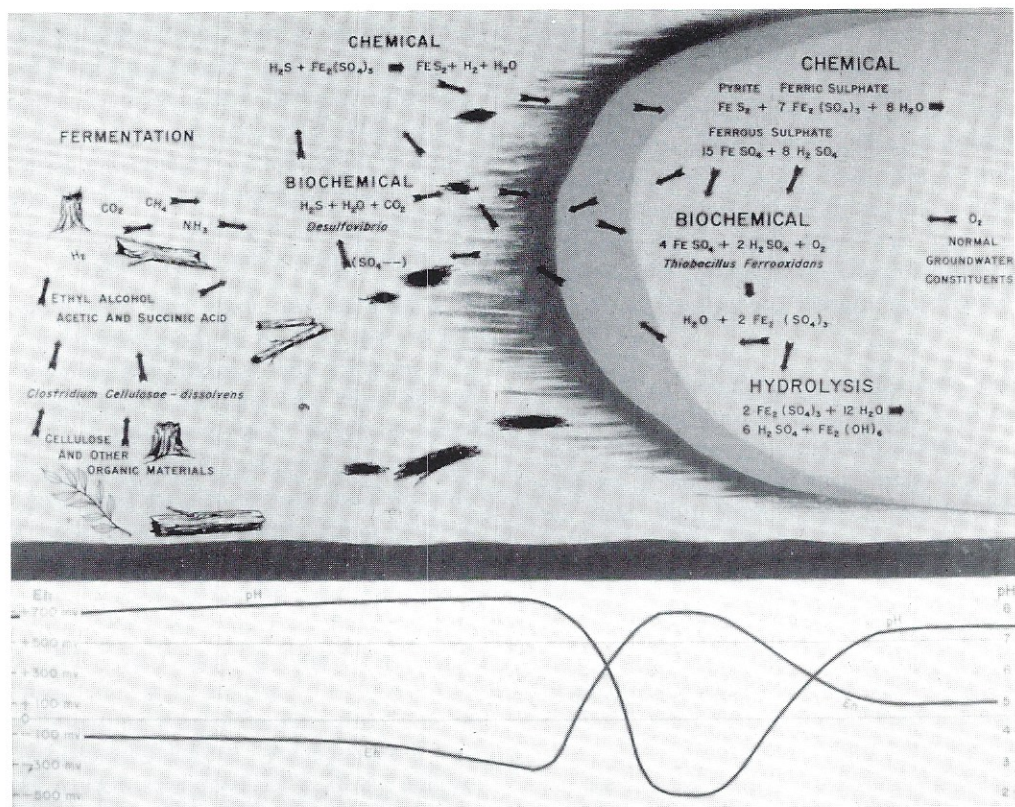


Fig. 5.

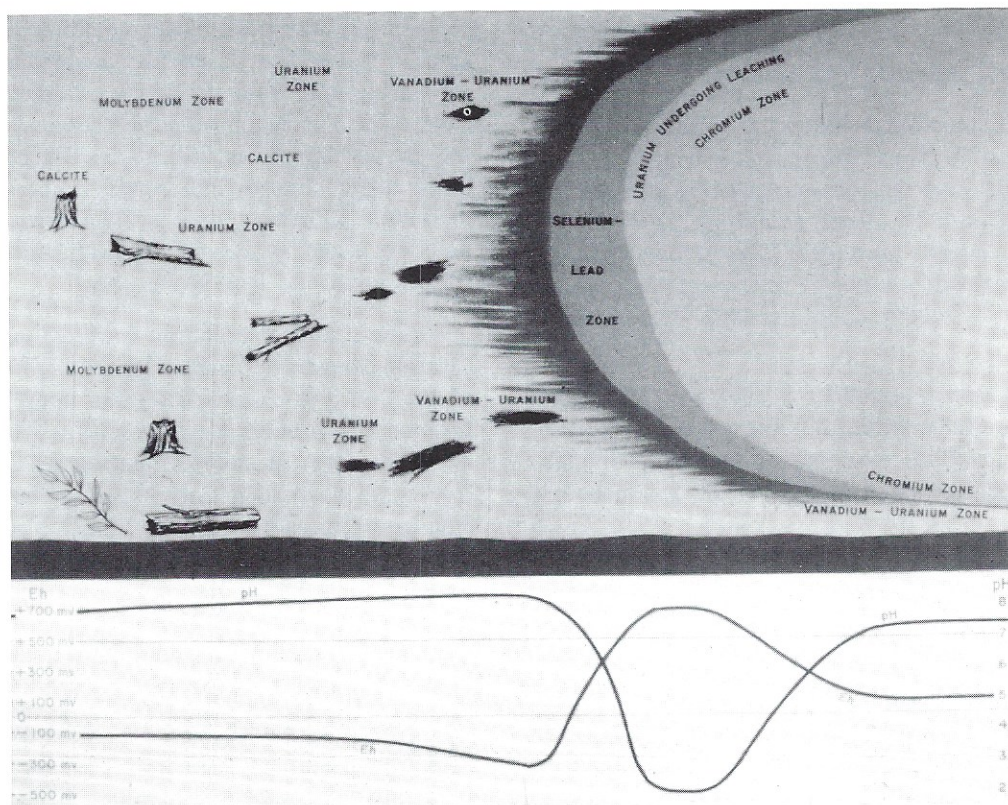


Fig. 6.



conditions of both pH and Eh in very close proximity are present on the leading edge of a geochemical cell. In the oxidizing or *Thiobacillus* zone, an environment is produced which will oxidize and take into solution most of the minerals associated with uranium deposits. On the other side of the cell boundary, a moderate to highly reducing alkaline condition is present which will precipitate these same minerals.

The two zones are incompatible to a large degree in that the *Desulfovibrio* are strict anaerobes while the *Thiobacillus* can tolerate very little organic material. A band of decreased activity separates the two zones.

The presence of *Thiobacillus* in these orebodies has been established by the work of Douros (1967). Nineteen samples from various uranium districts have been inoculated on various culture mediums; thirteen had positive *Thiobacillus* development, four were questionable and only two had no *Thiobacillus* development.

In summary, the normal constituents of groundwater enter the *Thiobacillus* zone where the bacteria create a strongly oxidizing and acidic condition. This zone is a mobile cell controlled on one side by the availability of nutrients and on the other side by unfavorable conditions for its activity. A good analogy is the progress of a grass fire. The metals oxidized from the *Thiobacillus* zone are moved into the protore side of the cell and are precipitated by the changes in Eh and pH.

### METAL ZONING

The activity within the geochemical cell produces a metal zoning within the cell as shown in Figure 6. Along the margin of the *Thiobacillus* zone, adjacent to the protore, uranium is being oxidized and leached (Harshman, 1966). In the zone between the *Thiobacillus* and the *Desulfovibrio*, where the sharp contact which is normally called the roll front is located, selenium and lead are deposited in zones from a fraction of an inch to a few inches wide (Fischer, 1960). The more complex vanadium-uranium minerals form the next zone. As the vanadium is used in the vanadium-uranium minerals, any uranium left over will be deposited in a zone still further into the protore. Molybdenum is deposited in a band outside and farther ahead of the uranium zone. It may be separated completely from any commercial uranium ore. On the altered side of the cell boundary, a chromium zone may be present. As the cell migrates through the host, there is a strong tendency for the vanadium-uranium minerals to be left behind along the bottom and top of the cell while the pure uranium minerals are carried ahead of the main advancing front. The amount of mineralization on the top and bottom of the cell may be insignificant in terms of ore but it is very significant as an exploration guide.

### GEOMETRY OF THE CELL

For the sake of illustration and further discussion as to overall shape and continuity of the geochemical cell, the altered interior of the cell is shown in Figure 7 without its enclosing host rock and ore zones.

This tongue-like body is the authors' concept of the appearance of the cell. Shale and less permeable zones produced indentations and partition the cell into multiple zones. Variations of permeability within the sand units produced other irregularities in shape. The more permeable zones tend to have lobe-like cell shapes.

A well developed geochemical cell is tongue-shaped with the tongue pointed down the hydrostatic gradient. In distinctly channeled sandstone, the tongue-like cell may be elongated parallel to the channel. Ideally, the edges of the cell are convex outward in vertical section. A well developed geochemical cell, like those recognized in Shirley Basin or Gas Hills districts of central Wyoming, may have transverse and longitudinal dimensions of a few to ten or more miles and a thickness of as much as 300 feet. Where small scale irregularities, such as crosscutting channels, clay zones and other small scale sedimentary features are present, complex shapes develop. A good example of small scale irregularities is the illustration by Shawe, Archbold and Simmons (Shawe, 1959, p. 410) of the Cougar Mine in the Slick Rock district.

The degree of mineralization on the cell margin is a function of complex relationships which are partially illustrated in Figure 8, a cut-away view of a leading edge of the cell. Figure 8 is a mold—the reaction zone of the cell—from which the "alteration cast" has been removed. Wherever the cell contacts rock of significantly reduced permeability above or below, a minor solution front is present as a result of the immobilization of the cell at the barrier. In the diagram, the top of the cell is fairly smooth with no major concentration of uranium. The bottom of the cell crosses stratigraphy in a complex manner with significant accumulation of uranium along these irregularities. On the right edge of the lower limb of the solution front, ore has developed in a bench-like shape where permeability changes. The top of the bench is sloped slightly and merges into a typical C-shaped subsidiary roll produced by the permeability restriction caused by the shale zone immediately ahead. The upper limb of the subsidiary roll extends backward into the altered zone where it gradually fades out in both thickness and grade. The upper surface merged with the lower limb of the next higher subsidiary roll which is controlled by a higher clay bed. This feature diminishes laterally into a terrace along its strike. The leading edge of the cell is the typical C-shape and is larger and more richly mineralized than the subsidiary features.

The dimensions of this view may range from as little as five feet from top to bottom and fifty feet from side to



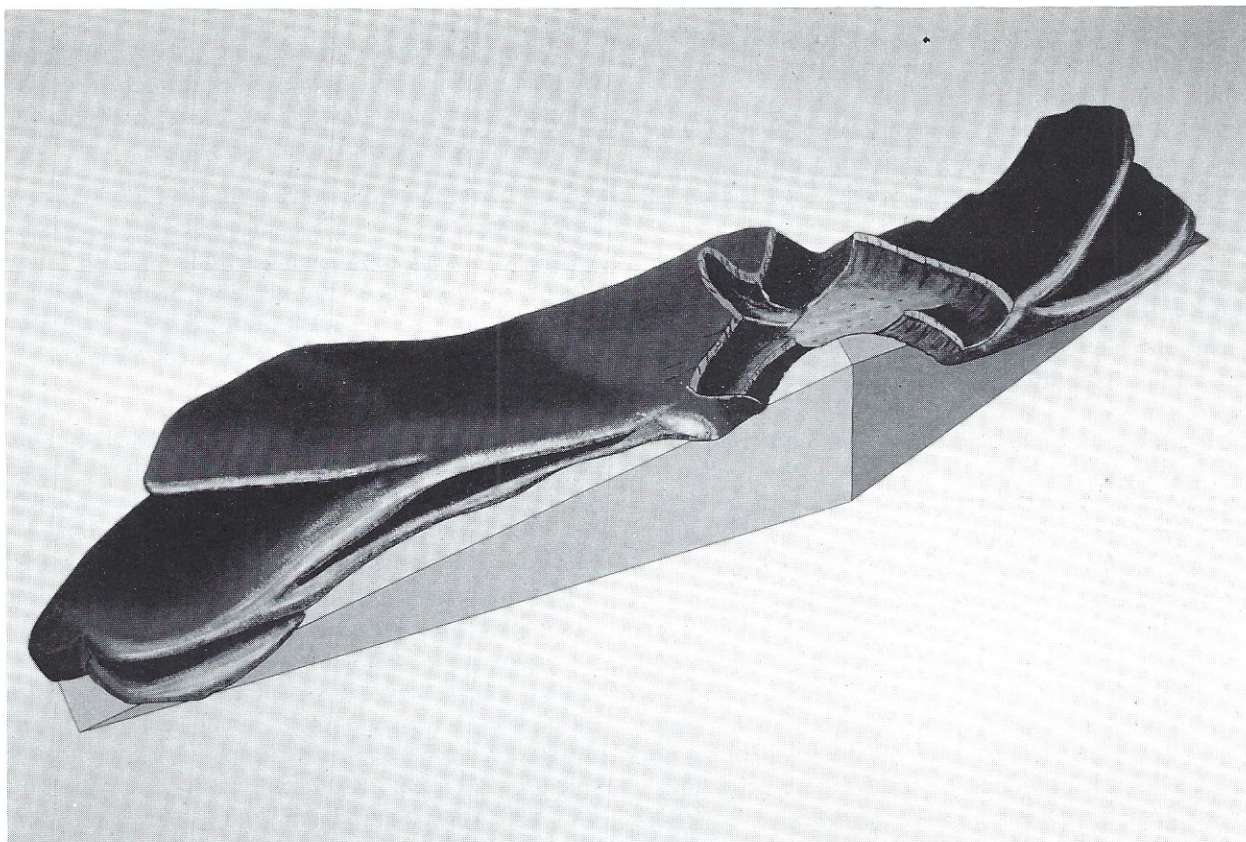


Fig. 7.

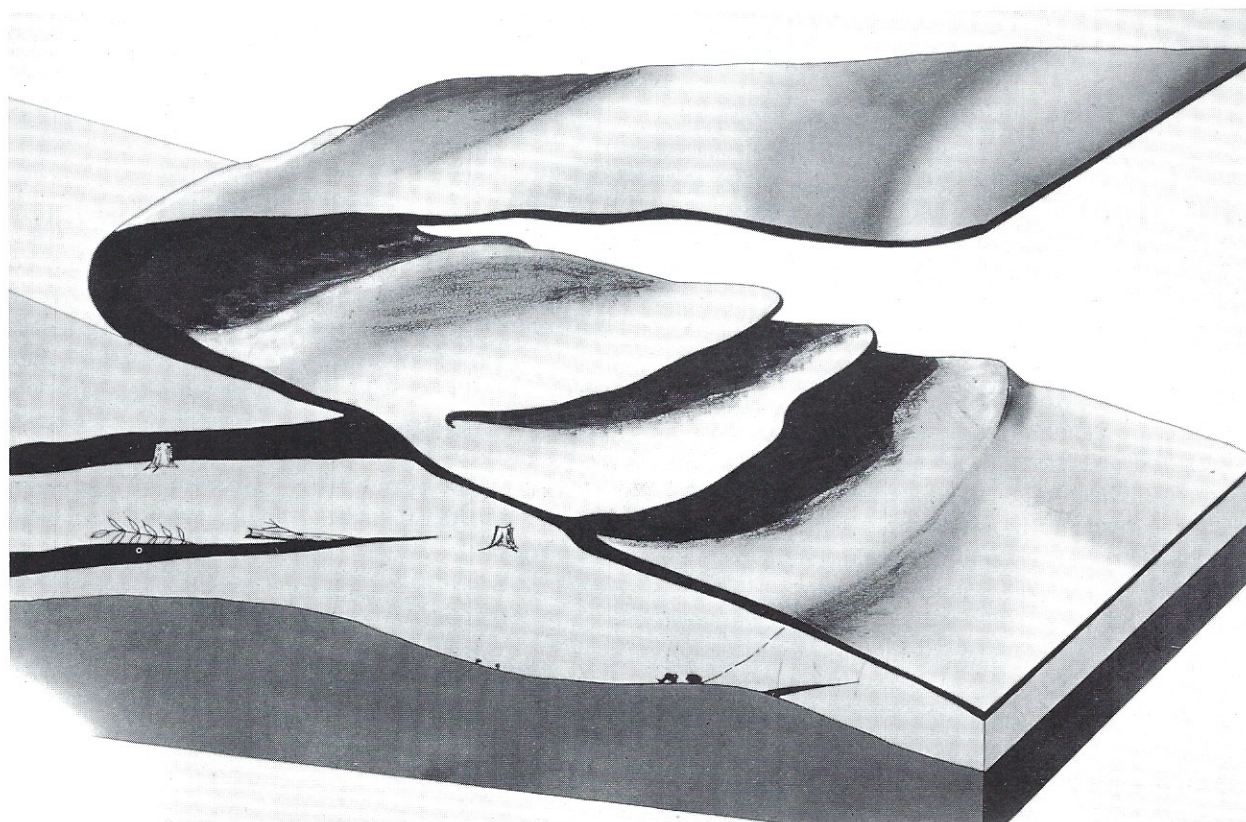


Fig. 8.



side to as much as 300 feet vertically and one-half mile laterally. Granger's (1961) block diagram of Ambrosia Lake ore was modified in the preparation of this idealized section of a solution front.

### SIZE AND CONCENTRATION RATIOS

It was said earlier that the uranium was contained within the host sediments and that it is concentrated by the geochemical cell. Now it must be determined if the uranium present in the sediments can account for the ore-bodies found. The source of the arkose in the Sweetwater rocks between Crooks Gap and Gas Hills of central Wyoming, contains twenty to thirty ppm of uranium which represents over 26 million pounds of  $U_3O_8$  per square mile of area, 300 feet thick. Conservatively speaking, the geochemical cell in the Gas Hills is ten miles wide and fifteen miles long which would contain over four billion pounds of  $U_3O_8$  if these sediments contained twenty ppm. This process cannot be expected to be 100 percent efficient. At ten percent efficiency, the available uranium in the Gas Hills would be on the order of 400 million pounds of  $U_3O_8$ . This is equivalent to two ppm from the leached area and represents only one-half of the average abundance of uranium in the earth's crust. Using the same type calculations for the Grants district, an area eighty by ten miles with a thickness of 300 feet could contain 21 billion pounds. The ten percent efficiency then results in over two billion pounds of ore concentrated by the cell.

All ingredients necessary to make the cell function are present to varying degrees within the host formations of the known uranium districts. A possible exception is the *Thiobacillus*, which actually may be present in an inactive state. The only requirement necessary is the initiation of movement of the waters to carry the nutrients into the cell, all of which are normal constituents of groundwater. Free oxygen has been found to be present in groundwaters to depths of a mile or more (Germanov, 1958).

### EXPLORATION METHODS

Earlier it was stated that this concept works in exploration, in mine planning and in ore control but how well it works depends directly on how much the practitioner works geology. Some areas have readily recognizable alteration while other areas have very subtle differences between the altered and the protore portions of the cells. The principal criteria used are color, pyrite morphology, kaolinization of feldspar, cementation, low gamma ray background of altered zones commonly accompanied by gamma ray anomalies at the upper and lower margins of the altered zone, and tripolitic alteration of chert. Analyses to determine the presence and distribution of trace elements may also be useful. Pyrite morphology is one of the more consistent guides in determining alteration or protore.

In the details of ore control and mine planning, the wedge shape of the overall cell is important, principally

when the upper and lower limbs begin to approach commercial ore. From this point of the edge of the cell, whether it's the leading edge or the lateral edge, the entire thickness of the altered zone can be expected to have ore grade deposits on its surface. An abrupt change in the thickness of the altered zone indicates a possible ore bearing interval which has been missed between drill holes. A good way to assist in the definition of potential ore areas is to isopach the interval between the upper and lower limbs of the cell. A more definitive technique is to contour the upper and lower surfaces of the alteration individually. Ore trends which be commercially significant can be missed by the drill holes themselves but their presence can be predicted on the basis of the contours and further tested to determine their presence.

### ACKNOWLEDGMENTS

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