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Chapter 1

Frontier Areas and Exploration Techniques

Frontier Uranium Exploration in the South-Central United States

ABSTRACT: Selected areas of the South-Central United States outside the known uranium trends of South Texas have a largely untested potential for the occurrence of significant uranium mineralization. These areas, underlain by Tertiary and older sediments, include parts of Texas, Oklahoma, Arkansas, Louisiana, Mississippi and Alabama. The commonly accepted criteria employed in uranium exploration are applicable to these "frontier" areas but special consideration must also be given to the atypical geologic aspects of such areas as they may apply to relatively unique types of uranium mineralization or to the development of special exploration criteria for common types of roll-front and fault-and dome-related uranium mineralization.

The procedures used in evaluating "frontier" areas should be based on comprehensive evaluations involving: 1) location and analysis of potential source rocks (e.g. intrusive igneous rocks, bentonitic sediments, unique complexes, etc.); 2) definition of regional variations in the potential host sediments (e.g. marginal marine to nonmarine environments of deposition); 3) review of all available radiometric data in Tertiary or older rocks; 4) local ground-water sampling (using a specific suite of major and minor elements selected on the basis of the regional ground-water geochemistry; 5) widely-spaced reconnaissance (or stratigraphic) drilling, coring and borehole geophysical logging to define favorable sedimentary facies and to establish the specific lithologic character of the sediments; and 6) detailed petrographic evaluation of all available samples to define the environment of deposition and diagenetic history of "favorable" sediments.

If procedures produce favorable results, suggesting that conditions for the formation of uranium mineralization are present in the area under consideration, an expanded exploration program is justified. Depths up to 3,000 feet should be anticipated if up-dip information is favorable. Selected areas are discussed that have: 1) favorable source and host rocks; 2) favorable age; 3) favorable regional and local structure; and 4) radiometric characteristics favorable for uranium mineralization of potentially economic grade and reserves in the areas.

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INTRODUCTION

The economic advantage of using nuclear energy for the generation of electricity has been well established. However, as indicated previously in this volume, the nuclear industry is presently struggling to deal with three technical and environmental problems critical to the future development of nuclear energy in the United States: 1) reactor safety, 2) reactor-waste handling, and 3) the establishment of sufficient uranium reserves to stock the planned light-water reactors. Failure to resolve these problems will place unnecessary pressure on the development of conventional and other alternate forms of energy. The solution of these problems is mandatory. The first two problems are institution- and engineering-related; the latter problem, however, is strictly geological in nature and therefore dependent upon the ability of that segment of the geologicial profession involved in uranium exploration.

We approach frontier uranium exploration in two ways. First, we will present information concerning the fundamental mechanisms involved in uranium genesis in sedimentary rocks that would interest the inexperienced uranium geologist. In addition, we will introduce information that will be of value to the experienced uranium geologist whose principal responsibility is to locate and evaluate uranium resources. Our emphasis will be on areas in the South-Central United States that have potential for new uranium resources.

Second, we will present information concerning uranium exploration activities and the pertinent features that relate to prospective areas of the South-Central United States. These data will assist in the evaluation of the relative merits of large areas as well as individual prospects.

As the market price for uranium concentrate (yellowcake) increases, serious exploration efforts will be expanded to include frontier areas previously considered as lacking in potential. By definition, frontier exploration is exploration in geologic environments not previously known to be productive to any significant degree. In ERDA terminology, our "frontier" areas are generally equivalent to areas containing "speculative" potential resources. An effect of the increasing market price is that small and/or low-grade ore bodies will become economically feasible to mine and mill. Higher prices will also promote exploration in "trend" areas at depths greater than those explored in the past. "Trend" exploration is exploration in formations or geologic environments known to be significantly productive. This is essentially equivalent to ERDA's "possible" potential resources. The remaining category of uranium exploration is "mine" exploration—areas where ore has previously been mined. Such exploration is designed to demonstrate ore reserves in sufficient tonnages and grade to be mined at a profit. ERDA includes known reserves and reserves from extensions of known deposits in their "probable" potential resource estimates. "Trend" and "mine" exploration in the uranium district of South Texas is discussed by Dickinson and Duval (this volume).

All frontier exploration is based on investigations of individual uranium mines and other significant occurrences of uranium. As discussed later in this chapter, various characteristics of the uranium mineralization and host sediments are used as guides in new formations or geologic environments to locate mineralization. Obviously, as soon as major uranium mineralization is discovered in a new or frontier area, the area's exploration status changes from "trend" to "mine" exploration via development drilling to prove reserves and grades. The areas nearby become "trend" areas.

Exploration guides vary with the numerous types of sedimentary environments known to contain uranium. As noted in the discussion by Dickinson and Duval (this volume), a number of lithologic guides and techniques are helpful in locating new deposits in the adjacent areas and are generally useful in similar formations and environments elsewhere.

It should be noted that the processes involved in uranium genesis are complex and a fully acceptable set of models has yet to be proposed. For certain types of occurrences, empirical models have been used with excellent success. The need for a theoretical understanding of the processes involved is a major challenge to the earth scientists in the academic community. Industrial support for an academic pursuit of such theories remains minimal although past research on the empirical models was stimulated by industry. However, as the need for ore reserves increases, so will industry's need for a better understanding of uranium ore genesis and its distribution in the geologic environment. If the nuclear reactor safety and waste-handling problems are solved soon and breeder-reactor development does not progress as hoped, the emphasis on uranium exploration in the next two decades may be so extensive that industrial, academic and governmental uranium exploration research and development may approach that undertaken by the oil industry today in their search for the remaining oil and gas fields of favorable economic potential. In any case, the next twenty years will be critical to nuclear energy development and will probably be the last period of widespread industrial interest in uranium exploration as we know it today.

URANIUM MINERALIZATION

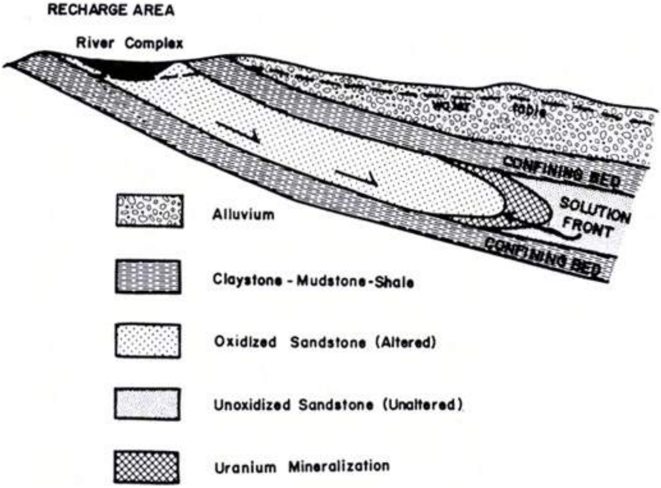
The last fifteen to twenty years have witnessed a proliferation of literature dealing with the origins of sedimentary uranium deposits. Definitive solutions concerning the mode of origin of these accumulations are lacking, although work on Tertiary uranium deposits in Wyoming and Texas suggest possible mechanisms (Rackley, 1972; Dickinson, 1976 and this volume). It is certain, however, that oxidation and reduction of the uranium ion play major (or controlling) roles in the ultimate shape, size, and nature of all sedimentary uranium deposits. The Tertiary deposits serve as examples for most of the mechanisms involved (see Figure 1).

We present a summary of the more important mechanisms and geologic requirements for Cenozoic (Tertiary), Mesozoic and Paleozoic uranium mineralization that may occur in the South-Central United States. This review is not meant to be exhaustive but is presented as a guide to further research by the individual reader on specific aspects of interest in frontier exploration. Publications of a specialized nature that have not been cited in this chapter are listed in Chapter 5—the Selected Uranium Bibliography.

Tertiary Uranium Mineralization

Under the proper physical and chemical conditions, uranium in the oxidized state (U^{+6}) is soluble and may travel in ground water as the uranyl ion UO_2^{+2} or as a soluble uranyl-carbonate complex. If the uranyl ion or complex enters a chemical system that is sufficiently reducing, the uranium is changed to its U^{+4} valence state and precipitates as a uranium mineral (e.g. uraninite). This mineral and other unoxidized uranium minerals are temporarily stable in most reducing environments and are *relatively* immobile. It is probable that uranium is carried by "cold" ground water and is precipitated by the general multiple migration accretion process described by Gruner (1956). However, Rosholt (1961) concluded that the efficiency of the precipitating mechanisms is relatively low. Thus, only a small amount of the total uranium available is fixed in the sandstone, while a larger portion of the uranium moves down dip. In spite of the low efficiency of uranium fixation, substantial quantities of uranium can apparently be extracted from the ground water in relatively short periods of time. Variations in: 1) ground-water flow rates, 2) local flow paths, 3) chemical content of the ground water, 4) paleo-piezometric pressure, and 5) duration of system stability, would have a considerable effect on the rate of uranium accumulation (and dispersal). As long as conditions remained favorable, the uranium content would increase at the specific locality of optimum conditions. As soon as one or more of these conditions changed, the uranium would return to solution and begin to migrate down the hydraulic gradient of the ground-water system.

Garrels (1965) and Hostetler and Garrels (1962) present what theoretical information exists on the chemical behavior of the uranium-carbonate system. Ghosh (1962) reviews the rate of oxidation of iron in "aerated" ground water.



Arrows show direction of groundwater movement.

FIGURE 1a. Typical Tertiary geochemical cell and roll-type uranium occurrence.

URANIUM IN THE GROUND-WATER SYSTEM

Hagmaier (1971) presents an important concept dealing with the regional aspects of Tertiary uranium deposition and their relationship to the ground-water system and associated hydrochemistry. The flow of ground water is generally laminar through permeable materials from an area of high potential (recharge) to an area of low potential (discharge). This may not always be from a high topographic position to a low position because the controlling factor will be the differential pressure that drives ground-water flow. Chebotarev (1955) suggested that along the regional flow path the following hydrochemical facies would theoretically develop for a heterogenous silicate sediment:

$$HCO_3^- \longrightarrow SO_4^- \longrightarrow Cl^-$$

In general, because uranium can easily be carried in solution as a carbonate complex, it would be leached and transported in the bicarbonate ground-water facies (oxidized ground-water facies) and precipitated in the transition zone between the bicarbonate and sulfate facies, where a number of other chemical changes also occur (see Figure 2). Observations by Michel (1965) in western Germany and by Charron (1965) in Canada indicate that the size of the flow system determines the prevailing hydrochemical facies, as much or more than does the mineralogical composition of the host rock, except in special sediment types. For example, in short flow systems most ground water is bicarbonate-rich, in intermediate-length flow systems both the bicarbonate and sulfate-rich facies are likely to develop, and in long, regional flow systems bicarbonate, sulfate and chloride facies are commonly present. The interaquifer transfer of ground water of a different hydrochemical facies, however, is a common phenomenon and may tend to eliminate the possibility of making any clear distinctions in hydrochemical facies type.

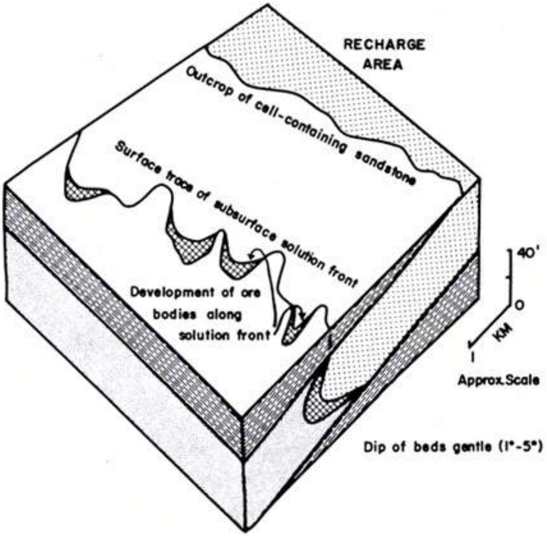


FIGURE 1b. Typical Tertiary solution front with uranium mineralization.

Campbell and Gray (1975) indicate that within many aquifer systems, clays and shales can serve as semipermeable membranes, retarding by varying degrees the passage of dissolved elemental species with respect to water. Hanshaw (1972) and Kharaka and Berry (1974) summarize the principles involved. However, Kharaka (1973) concludes that the retention of ions depends on the physical make-up and related electro-chemical charge configuration of the particular clay or shale membrane and the specific ions involved. He found that the bicarbonate ion was retarded less than was sulphate and the sulphate less than chloride. Therefore, the bicarbonate ion moves more freely through a membrane than sulphate, and sulphate more freely than chloride. It is clear then that membrane effects do not play a major initial role in the development of hydrochemical facies and that a chemical evolution from bicarbonate through sulphate to chloride is involved with increasing maturity of ground water in a large basin. The greater mobility of HCO_3^- and the affinity of uranium for the HCO_3^- ion, however, may be responsible for the migration of a HCO_3^- $(U)^-$ complex well into SO_4^-- and Cl^--dominant facies. If a sufficient reductant is encountered, uranium precipitation may occur. This topic will be discussed further under "Aspects of a Urano-Organic Cell," and under "Favorable Frontier Areas: Texas."

Although the hydrochemical facies concept is a useful exploration tool in determining generally favorable areas, a more precise method is necessary as exploration begins to establish the general location of the solution front, along which significant uranium may or may not occur. The characteristics of alteration also may not be apparent.

In 1970 in the Powder River Basin of Wyoming, ground-water samples were collected from two strategically located water wells, one located in the area of an altered (oxidized) sandstone and the

Table 1

	Well #1 (Altered)	Well #2 (Unaltered)
U_3O_8 (ppb)	175	11
SO_4 (ppm)	186	191
Cu (ppb)	1-9**	66
Co (ppb)	1-9**	ND*
As (ppb)	1-9**	1-9**
Se (ppb)	1-9**	1-9**
Sr (ppb)	1500	450
Fe (total) (ppb)	1-19**	200
pH	6.2	6.7

* Not Detected

** Threshold of Detection

second located down dip in unaltered sandstone. A uranium ore body was known to exist between the two water wells in the same unit from which the ground-water samples were taken.

To minimize contamination and the effects of proximity to the well (Summers and Brandvold, 1967), each well was pumped for fifteen minutes before the first sample was collected. To evaluate these effects and to verify precision of analysis, additional samples were also collected in one-gallon polyethylene bottles at thirty and forty-five minute intervals after pumping began.

The following are the results of the analyses for the sample taken at the forty-five minute interval. Previous samples were also consistent with the results shown in Table 1.

It is clear from the data that dissolved uranium, copper, strontium, and perhaps total iron vary significantly between two water wells on opposite sides of a roll-type ore body. The wells were approximately one mile apart. Until it is established that such variation exists in relation to other ore bodies, it would be premature to speculate on the reasons for these variations. We recognize the potential error in interpreting limited data and that the present ground-water chemistry may not be related to that of the paleoground-water system. However, we also suggest that the relationships are consistent with our view of the mechanisms involved in Tertiary uranium mineralization. The ground water is the aggressor; the host sediment is being acted upon and with time will affect mineralogical changes as the cell moves down gradient. Other features of the relationships are presently under study while additional ground-water data are being collected. Ground-water information, such as that collected for environmental evaluations of uranium mining areas, may be of value in further characterizing the hydrochemical facies and the specific ground-water constituents in uranium-mineralized areas (e.g. Kallus, this volume).

The use of this concept, combined with the use of local ground-water chemistry, will be discussed later in this chapter under "Aspects of a Urano-Organic Cell" and "Favorable Frontier Areas: Texas." Wood (1976) reviews the general features of effective ground-water sampling techniques. Additional information on ground-water chemistry and uranium will be found in Chapter 5—Selected Uranium Bibliography.

GEOCHEMICAL CELL AND ROLE OF BACTERIA

The term geochemical cell, as related to epigenetic uranium, was introduced by Shockey, Rackley, and others (1968) for the processes that occur as epigenetic oxidizing ground water interacts with syngenetically-reduced carbonaceous sandstones and for the lithologic alteration and uranium mineralization formed by the geochemical cell. Reducing conditions can also be created (or enhanced) by gaseous hydrocarbons or hydrogen sulphide, as indicated in some of the South Texas deposits (Eargle and Weeks, 1973; Dickinson and Duval, this volume).

Also, it was suggested that bacteria play an important part in the oxidation-reduction reactions within the cell, the development and continued accretion of which were controlled by the life activities of two ubiquitous genera of bacteria, i.e. the anaerobic, sulfate-reducing species *Desulphovibrio desulfuricans* and *Theobacillus ferroxidans*, an aerobic, sulfide-oxidizing bacterium (Rackley and others, 1968). It is interesting to note that both types of bacteria are not uncommon in the ground-water environment and that they are responsible for much of the corrosion and incrustation affecting metallic well structures (Campbell and Lehr, 1974, p.343). Both are very hardy species. The genus *Pseudomonas* sp., which commonly occurs with *Theobacillus* sp., can alter natural cellulose and can break the chains of many types of hydrocarbons. *Pseudomonas* is especially hardy and can become resistant to the normally toxic quaternary ammonium compounds.

In the past few years, however, isotopic evidence has been used to suggest that the Wyoming Tertiary deposits are the result of inorganic precipitation controlled by an earlier stage of bacterial activity. (For further review of the role of bacteria, see Cheney and Trammell, 1973; Rackley, 1972; and Douros, 1967.) In laboratory research on bacterial identification, Updegraff (1969) could not add materially to the role of the bacteria in uranium mineralization. Sample contamination was a major problem.

Zobell (1964), in work on the microbial modification of carbon compounds, indicates that bacteria

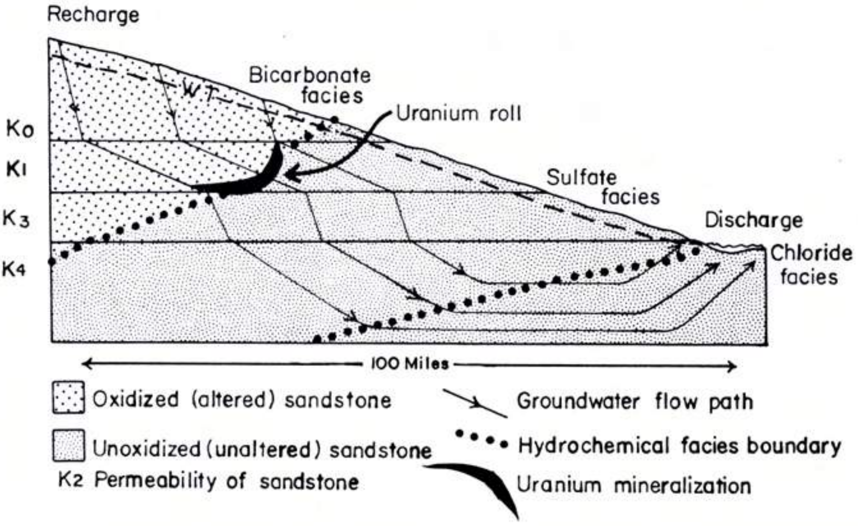


FIGURE 2. Generalized Hagmaier hydrochemical model showing inferred location of uranium materialization (Hagmaier, 1971).

do play an important role in the solution and precipitation of calcium carbonate in the biosphere by producing carbon dioxide and by creating either acidic or alkaline conditions which influence the carbon dioxide/carbonate equilibrium in localized environments. Bacteria would presumably affect the carbon dioxide/carbonate/uranium equilibrium as well. Because of the difficulties involved in working with bacteria, the specific role they play is still in question. However, it is clear that they do produce enzymes, hydrogenase and amino acids. Evans (1960) summarizes laboratory results on adenosine triphosphates (ATP), one of the probable by-products of bacterial activity, and mineral solubilities. Relatively water-insoluble minerals such as carbonates, phosphates, and silicates were brought into solution quickly in the presence of ATP. It was also found that many oxides, particularly hydrated oxides of iron and aluminum, exposed to ATP were essentially insoluble, and were often formed as precipitates from solutions of minerals during the decomposition of the solubilizer, Na-ATP. Such natural solubilizers may also inhibit precipitation by holding salts in solution rather than obeying the apparent Eh-pH relationship suggested earlier by Garrels and Christ (1965) and Hostetler and Garrels (1962).

In effect, the suspected role of ATP and related amino acid groups in uranium precipitation may be significant in terms of supplying bacterial preparation of carbonaceous material to produce an aggressive reductant for inorganic precipitation of the uranium ion. It should be noted that the tests cited were made in a pH environment expected in the shallow subsurface (pH 7-9) and at ambient temperature and pressure. Further research on natural solubilizers and stabilizers is clearly indicated. If ATP is involved in a urano-organic complex, it could prevent re-solution even under pH and Eh conditions that suggest the uranium mineral should break down and return to solution (Akiyama, 1973). The urano-organic complex will be discussed later in this chapter under "Aspects of a Urano-Organic Cell."

SOURCE OF URANIUM

The source of uranium in Tertiary sandstone deposits is generally considered to be acid intrusives, extrusives, or sediments derived therefrom. The only significant prerequisite is that the uranium can be leached from its source and introduced to the ground-water system.

In Wyoming, either distant, weathered, acid intrusives or overlying sedimentary rocks containing tuffs are considered probable sources. In South Texas, the source of the uranium is believed to be the Catahoula Tuff (Eargle and Weeks, 1968). This conclusion is based upon: 1) the discrepancy between the assumed original uranium content of the tuff and the present uranium content, 2) the thorium/uranium ratio, and 3) the lack of other source rocks. Dickinson and Duval (this volume) expand this view in detail. Roberson (1964) examined the petrology of the bentonites of Texas and concluded that those from the Jackson group are generally composed of well-crystallized calcium montmorillonites with very few impurities, whereas the Catahoula bentonites are generally composed of poorly crystallized montmorillonites and contain significant quartz, cristobalite, feldspar and volcanic shards. In addition, he also indicated that the bentonites from the Jackson and Gueydan groups in East and Southwest Texas contain more quartz, feldspar, and clay minerals that do those of Central Texas. He concluded that bentonites formed "in place" contain well crystallized montmorillonite, whereas redeposited [or leached?] bentonitic material is composed of poorly crystallized montmorillonite. These conclusions can be applied to uranium exploration in a number of ways: 1) identification of multiple sources of volcanic activity during Oligocene-Miocene time that may have supplied uranium-bearing tuffaceous material to areas other than South Texas, 2) indication of widespread leaching of the Catahoula Tuff suggesting other areas or rock units may be favorable sources, and 3) establishment of the character of probable sources of uranium which can be useful in evaluating sediments of other ages. The uranium potential for East Texas will be discussed further under "Favorable Frontier Areas: Texas."

Waters and Granger (1952) discuss the relationship of uranium and volcanic tuff; Osmond (1954) investigates a number of bentonites of various ages; and Eaton (1964) reviews windblown volcanic ash, suggesting that Oligocene-Miocene volcanism supplied a considerable volume of tuff to the surrounding Texas region. Spalding and others (1974), in an investigation of cores taken from the Gulf of Mexico, found that sediments of Oligocene-Miocene age, now more than 500 miles southwest of South-Central Texas contain uranium of significantly higher content than the underlying sediments. Winograd (1971) evaluated the hydrogeology of selected silicic pyroclastic sediments and concluded that welded zones can have a very high fracture transmissivity.

CHARACTER OF HOST SANDSTONE

As indicated previously, oxidized ground water, its flow controlled by the permeability and gradient of the host sandstone, is important to the development of the uranium geochemical cell. An optimum permeability may exist indicating that flow rate is significant in controlling the duration of exposure of ground water (with uranium, bicarbonate, and other cations and anions) to precipitating agents, and in determining the rate of down-dip migration of the oxidizing cell. The uranium content within the host rock apparently need only be in the low ppb range. But, if the areas of groundwater recharge contained surface water of relatively high dissolved solids and uranium content, deriving such materials from tuffaceous terrain anomalously high in uranium, the recharged ground water may have been higher in uranium than might be anticipated (low *ppm* range instead of low *ppb* range).

Lithologic prerequisites also exist. Pyrite, formed syndiagenetically (as well as epigenetically) plays an important role, as does carbonaceous material that is commonly deposited in fluvial environments. The fluvial environment as used in uranium exploration terminology probably includes the subenvironments of alluvial fan accumulations, flood plain deposits along mature rivers, delta deposits, and some fluvial-marine or shoreline deposits such as intertidal and supratidal mudflats. All such environments usually contain abundant carbonaceous material, and the sediments, once in the environment, experience pronounced biologic activity via bacterial alteration of the carbonaceous material contained therein. This creates a strongly reducing environment in which marcasite, and later pyrite, is precipitated and remains until that environment is disturbed by erosion and weathering, or until ground water with an oxidizing character invades the sediments.

The sandstones that contain ore bodies in Wyoming and elsewhere are usually described as "arkosic" and are either "ash-bearing" or are overlain by beds containing tuffaceous material. According to Pettijohn (1957) such sandstones range from arkose through feldspathic quartzite to feldspathic graywacke. To date, orthoquartzite or protoquartzites, and lithic graywacke or subgraywacke are not considered important uranium host-rock types. It should be noted that if other favorable factors are present, the host rock-type should not prevent further investigation, especially in rocks older than Tertiary. However, it should also be noted that an optimum range of rock-types may exist which would preclude rock-types with very abundant carbonaceous material. Excess organic material could prohibit oxidation from developing to any appreciable extent because of the relative volumes of oxidant and reductant. Other favorable factors such as radiometric anomalies, epigenetic alteration below effects of surface oxidation, etc. should be investigated before such sediments are excluded from further consideration.

In contrast, clean sandstone may not have sufficient organic material and pyrite to promote cell formation. However, the possibility exists that an introduced reductant (a gaseous hydrocarbon or hydrogen sulfide) may promote cell formation if ground-water chemistry is favorable. (See Dickenson and Duval, this volume.) Both outcrop and subsurface information should be reviewed to establish the potential of the host sandstone, the hydrochemical framework and the proximity of a potential uranium source.

Some of the other important contributions on Tertiary roll-type ore bodies of Wyoming and Texas include: *Powder River Basin*—Rubin (1970), Davis (1969); *Shirley Basin*—Melin (1969), Harshman (1962); *Gas Hills*—Anderson (1969); *Crooks Gap*—Bailey (1969); and *Live Oak District*—Klohn and Pickens (1970) and Dickinson and Duval (this volume). Additional citations can be found in Chapter 5—Selected Uranium Bibliography.

URANIFEROUS LIGNITE

Some of the uranium deposits in Tertiary sediments are associated with minor lignite beds. As discussed by Dickinson and Duval, Wielchowsky and others, and Self and Williamson (all in this volume), the Tertiary Jackson, Wilcox and Claiborne groups all contain potentially economic deposits of lignite from South Texas northeast through Louisiana, Arkansas, and Mississippi into Alabama. In certain of the above areas, fluvial and marginal marine systems are present that are potential source and host sediments for uranium accumulations. Their potential will be discussed in due course but a review of the important characteristics of lignite-associated uranium deposits of the Dakotas and High Plains will be presented here to serve as an introduction to the character of the uranium emplacement mechanisms involved. Breger and Others (1955) demonstrated that uranium can be introduced into and retained by the organic constituents in lignite structures. Denson and others (1959) as part of a comprehensive investigation of uraniferous lignite [0.013% (130ppm) to 00.10% (1000ppm) U_3O_8] of South Dakota and adjacent states, discussed the apparent factors controlling the concentration of uranium in lignite. Those discussed below are believed to be of primary importance:

1. *Stratigraphic proximity of lignite* to the base of ash- or bentonite-bearing sediments (see Figure 3), or to the projected position of its base in areas where such sediments have been removed by erosion (Figures 3A, B). It should be noted that lignite 200 feet (61m) or more below this base is not uraniferous. However, uraniferous lignite is not necessarily restricted to the uppermost lignite bed (King and Young, 1956), and can occur in any interval hydraulically connected to the uranium source rock via joints, faults, or vertically permeable sediments (Figures 3D, E).
2. *Adsorptive properties and permeability* of the organic lignite constituents. Denson and others (1959) believed that soft, porous lignite is a more prospective host material for the adsorption and fixation of uranium than hard, and relatively impervious, semibitumious coal and anthracite, and that the amount of uranium extracted from solution may be directly proportional to the presence of certain specific components of the lignite.
3. *Attitude of lignite beds*: Horizontal or very gently dipping lignite beds (F) contain more uranium than beds having greater dips (G).
4. *The position of both the present and paleowater-table levels* in relation to the position of the lignite will have a significant effect on ground-water flow paths (H). Above the water table, solutions will flow in a downward direction along preferred paths of permeability (Figure 3C); below the water table, flow generally will be lateral.
5. *The amount of uranium originally present* in the overlying source rock and the nature and degree of leaching, dissemination and distribution of uranium may be important. Although it is assumed that source rocks containing tuffaceous material have a uniform uranium content over a wide area, this may not be true and a variation of uranium in tuffs may indicate the expected degree of uranium mineralization in the underlying lignite and other host sediments as well (South Texas?).

Additional information regarding the uranium accumulations in lignite or other organic materials

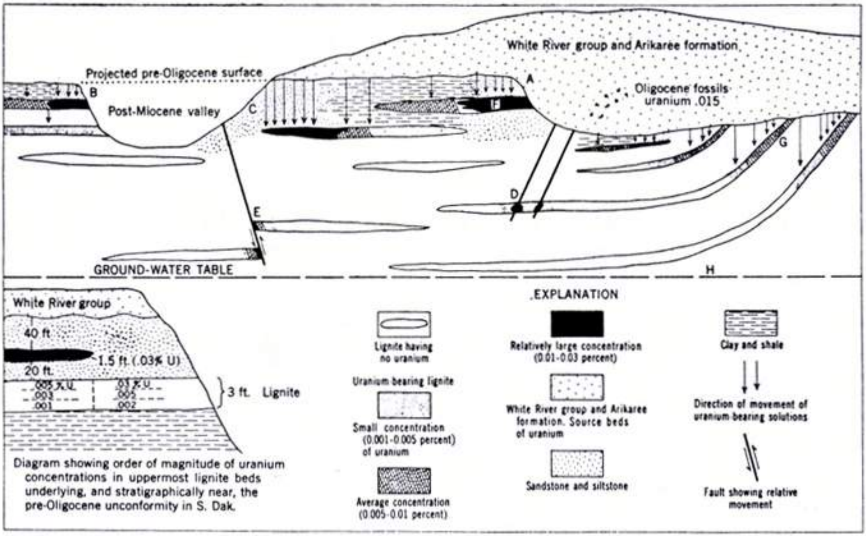


FIGURE 3. Diagram illustrating an interpretation of factors that control the uranium content of lignite (Denson and others, 1959).

include the following: Lisitsin and others (1967), Hail (1957), Zubovic and others (1960), Kim (1970), Pipiringos (1966), Malan (1957), Zeller and Schopf (1959), Gill and others (1959), Moore and others (1959), Gill (1959), Masursky and Pipiringos (1959), Vine (1959), Backman and others (1959), and Haji-Vassiliou and Kerr (1972). Also see Chapter 5—Selected Uranium Bibliography and Chapters 6 and 7 (this volume).

Mesozoic Uranium Mineralization

In addition to the roll-type Tertiary uranium mineralization of Wyoming and Texas, a significant number of so-called tabular ore deposits occur in Mesozoic sediments on the Colorado Plateau. Sediments of similar age and lithology that have frontier potential occur along the West Texas/New Mexico state line.

This type of uranium mineralization generally occurs as ore bodies that are parallel to the host sandstone bedding. The ore zone varies in thickness but averages only a few feet in most places. It is often hundreds of feet across and tends to be irregular in plan view but elongate along the same direction as the long axes of the host sandstone lens (see Figure 4). Ore bodies can occur throughout the host sands (see Figure 5).

Unlike the roll-type ore bodies of Tertiary age that occur intermittently along a sinuous but continuous solution front (in plan view—see Figure 1 B), the tabular bodies tend to be discrete masses. The analogy has been drawn that Tertiary deposits occur like beads on a string, the string being the sinuous solution front marking the boundary between oxidized (altered) and unoxidized (or reduced) sediments. Colorado-type tabular ore bodies are like raisins in a cake. The tabular bodies apparently have no "fronts" or "backs" that have been recognized by mineralogy, grade, or shape as found in the Tertiary roll-type deposits.

Fischer (1974) indicates that below the zone of recent near-surface oxidation, the tabular-type ore bodies are enclosed in sediments of "reduced" geochemical characteristics in the sandstone, are pale gray to white, and contain carbonaceous material and fine, disseminated pyrite. The associated mudstone is usually gray or green and also contains pyrite. This envelope extends laterally in the host sandstone a few hundred feet to a few miles from the ore deposits. It also penetrates a few inches to a few feet into the associated mudstone. In some regions beyond these envelopes of "reduced" rock the sandstone is pale red and the mudstone is red, suggesting an oxidized or epigenetically-altered environment. In other areas of the Colorado Plateau, the host sandstone is gray and the interior of the envelope is brown (see Figure 4). Fischer (1970) cautions that the term "altered" has been applied to the reduced sediments of the Colorado Plateau region and the term "unaltered" to the pale red (oxidized) sandstone beyond the reduced envelopes, whereas the reverse terminology is applied to Tertiary roll-type deposits, e.g. "altered" sandstone is oxidized and "unaltered" sandstone has reduced characteristics. It should be noted that color differences in and near the uranium deposits of the Colorado Plateau may be in part a result of differences in depositional environment rather than effects of epigenetic alteration. Of course, superimposed on such primary characteristics are the effects of the geochemical cell as it migrated through such sediments.

The genesis of the tabular-type mineralization is considered by many to be similar to that of the Tertiary deposits. That is, ground water with a low

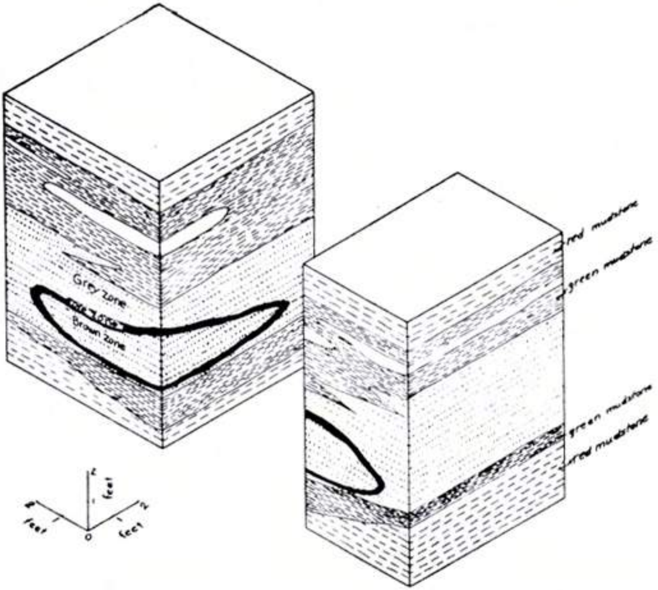
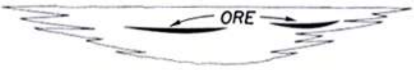


FIGURE 4. Block diagram of "trash pile" type of ore body, Moab uranium claim, upper Montezuma Canyon, San Juan County, Utah. Fossil material lies within the ore which is shown in black (U. S. Atomic Energy TEI-640).



Morrison channel ________ aggradational

Shinarump channel ________ degradational

FIGURE 5. Diagrammatic cross-sections of two channel types: aggradational or Morrison channel above, degradational or Shinarump channel below (Stokes, 1967).

uranium content moved within the host sandstone and upon encountering a reductant precipitated uranium minerals. Possible reducing agents that have been suggested include: 1) locally abundant plant material, 2) humic material derived from the plant material, 3) hydrogen sulphide, generated by bacteria "feeding" on the carbonaceous material, or derived from oil and natural gas. In detail, some tabular ore bodies are remarkably similar in geometric form to Tertiary ore deposits. The difference between them may only have been created by the effects of geologic time, by the differences in depositional environment of the host sand, and by subsequent surficial weathering in the Colorado Plateau area.

Squyres (1970, 1972), in elaborating on the earlier work of Szalay (1964, 1967), has suggested a mechanism controlled by organic matter (humates) for the uranium deposits of the Grants region, New Mexico. In his model, humic substances, produced by the decay of plant material, were molded by flowing ground water into streamlined, lobate, blanket-like geometric forms. The uranium was subsequently concentrated by the adsorption from solution and then fixed by reduction on the organic material. Granger (1968, 1976) suggested a similar involvement of humates (in solution) but emphasized that the humate precipitated at a two level paleo-water table. Robinson and Rosholt (1961) also emphasized the water table. This is difficult, however, to envision as the water table would have had to remain static for a considerable period of time, a behavior not characteristic of a water table since in geologic terms it tends to fluctuate rather rapidly. Further information on humates can be obtained from Shomaker and Hiss (1974) and Griffin (1967).

Important contributions to the tabular-type ore bodies of the Colorado Plateau include: *General* — Rackley (1976); *Grants Mineral Belt*—Kelley, and others (1968), Hilpert (1969), Shawe and Granger (1965); *Monument Valley - White Canyon Mineral Belt*—Stewart and others (1959), Malan (1968), Young (1969); *Big Indian Mineral Belt*—Wood (1968). *Uravan Mineral Belt*—Fischer and Hilpert (1952), Shawe (1962), Motica (1968) and various summary papers presented at the ERDA yearly Uranium Industry Seminars in Grand Junction, Colorado.

Paleozoic Uranium Mineralization

Although only minor uranium production is presently derived from Paleozoic rocks in the United States, production from Paleozoic rocks in Europe and Africa is significant (Barthel, 1974; Lukacs and Florjancic, 1974). The Republic of Niger, for example, ranks fifth in world uranium production and the ore produced occurs predominantly in Late Paleozoic sedimentary rocks. Similar occurrences of uranium in Permian sedimentary rocks of Oklahoma have been reported (Finch, 1956; Beroni, 1956; Shelton and Al-Shaieb, 1976) and in Mississippian and Pennsylvanian sedimentary rocks in Pennsylvania (Klemic, 1954, 1962, and 1963; McCauley, 1961; and recent ERDA reports).

The deposits in Niger are economically significant. A brief review of the occurrences is presented here on the basis that their characteristics may be useful in justifying more intensive exploration of the Paleozoic rocks in the Oklahoma-Texas region.

The Niger uranium occurs in various sedimentary facies; 1) basal, gray Carboniferous sandstone of probable fluvial-deltaic origin, 2) red Permian and Mesozoic fluvial sequences, 3) fluvial-lacustrine, and 4) piedmont. All occurrences are similar to the tabular deposits of the Colorado Plateau (Bigotte and Obellianne, 1968). Some occurrences are apparently fault controlled while others are in proximity to minor unconformities.

Coffinite and uraninite are the reported major uranium minerals, with yellow oxidized uranium minerals occurring in so-called "oxidized" zones. Copper minerals (oxides and sulphides) are reported to occur in inverse proportion to the uranium minerals (Gangloff, 1970).

A granitic source of uranium is postulated for the Carboniferous and Permian ores. A volcanic tuff, with uranium content up to 100 ppm, is suggested to be the principle source of uranium for the Mesozoic ores (Robertson, 1970). In Oklahoma, uranium occurs in Permian red-bed sequences although the copper and uranium-bearing beds are light-colored lenses. The small and scattered uranium deposits known to date are in fine-grained sandstone and siltstone or associated with "asphaltic" arkosic sandstone. The major minerals are torbernite, autunite, uranophane, malachite and azurite in heavily iron- and manganese-stained sandstone. Replacement of woody fragments is common. Shelton and Al-Shajeb (1976) review the stratigraphy, sedimentology and mineralogy of Pennsylvanian and Permian rocks in relation to their uranium potential in Oklahoma. Deposits of similar age and character near the West Texas border in New Mexico were discussed by Finch (1972), and Flawn and Anderson (1955).

It should be stressed here that Shockey, Renfro and others (1974) noted that other metals of significance can be formed by processes similar to those cited earlier for uranium. They have suggested the possibility of a copper-silver solution front, a feature possibly developing at a late stage of cell development in relatively old sediments. Renfro (1974) has also developed a model for stratiform metaliferous deposits that involves a sabkha process.

Aspects of a Urano-Organic Cell

An assumption is made here that the uranium contained in the tabular-type Mesozoic ore bodies of the Colorado Plateau was once initially concentrated by the mechanisms cited previously for the Tertiary roll-type ore bodies (Rackley and others, 1968; Rackley, 1972) at either their present positions or at a previous updip position. As one or more of the sensitive, optimum physiochemical conditions changed, the uranium, still in a concentrated form in a solution complex with a maturing, humate-like material (containing solubility-altering ATP-like components), migrated *en mass* down the hydraulic gradient. The oxidizing cell would move at a greater rate than the organic cell, oxidizing iron and other syngenetically-reduced minerals. The oxidizing cell, although not sufficiently aggressive to either break the urano-organic association or oxidize the contained uraninite and associated minerals, would alter (or oxidize) surrounding sediments.

The tabular or blanket shape of the typical ore zone could be a result of extensive migration along preferred zones of permeability. Rackley (personal communication, 1977) views the tabular deposits as "limbs" hung up well behind the solution front in silty zones that have not been remobilized because of 1) their contained vanadium, 2) their reduced permeability, and 3) their contained organic matter. In addition, roll configurations in the urano-organic cell could develop, as indicated by Squyres (1972). Relatively recent rolls could also develop in "post-fault" or "stacked" ores (Shawe and Granger, 1965, p. 243) according to the specific mechanisms of ore precipitation suggested by Rackley (1972). There is little doubt that the tabular ore bodies develop over extensive periods of time and time affects the maturing urano-organic complex, although conclusive evidence is lacking. However, such an "urano-organic" cell mechanism could also offer a plausible explanation for the significant concentration of other metals (copper, lead, zinc, vanadium, silver, etc.) that are contained in most of the tabular ore bodies but are not present in similar quantities in Tertiary, roll-type deposits (Fischer and Stewart, 1961). On the basis that the urano-organic cell could move more slowly down the hydraulic gradient than the preceding oxidizing ground water, such metals contained in the ground water in the "normal" low-ppb (or abnormal ppm) range would be continuously captured by the urano-organic cell and precipitated as sulphides by reduction within the cell. The variations in metal content would depend on the initial hydrochemical content of the ground water, as well as on the efficiency of the concentrating mechanisms. The continuous replenishment of sulphate to the urano-organic cell would supply all the necessary sulphur for conversion to sulphide, provided bacteria are present to reduce it. The ores in similar sediment types of the Paleozoic (Oklahoma, Pennsylvania, Niger, etc.) would be expected to contain an even higher metal content than the ores of the Tertiary, which they may (Butler, 1938; Klemic, 1954, 1962 and 1963).

As a variation of the simple Hagmaier hydrochemical facies concept, we would expect the tabular ore bodies to have stabilized in either the sulphate or chloride facies. As mentioned earlier, interaquifer transfer can mix hydrochemical facies. Bowles (1968) suggests that with such transfer the sulphate-dominant facies can also be brought into a favorable environment to precipitate uranium in Tertiary host rocks. Dissolved oxygen in the sulphate facies, however, would be especially low, but an oxidation-reduction cell may only require carrier HCO_3^- $(U)^-$ ions and the necessary bacteria to create the proper initial environment for uranium precipitation. The chloride facies, therefore, may also be a favorable site for uranium mineralization, if sufficient HCO_3^- were present during earlier stages of uranium precipitation.

It is interesting to note that research on subsurface waste injection and water flooding of oilfields suggests a strong similarity between the geochemical models of such subsurface migration and uranium-cell migration-accretion—e.g. Leenheer and Malcolm (1973) among many other works. We are presently pursuing this apparent similarity and the mechanisms involved in waste migration.

FRONTIER EXPLORATION

The U. S. Energy Research and Development Administration (ERDA), Uranium Research Division in Grand Junction, Colorado and the U. S. Geological Survey, Uranium-Thorium Branch in Denver, Colorado are very active in assisting the uranium exploration industry, especially in frontier exploration. ERDA is presently conducting a major investigation of domestic uranium resources [designated as the National Uranium Resource Evaluation (NURE) Program] and a comprehensive report should be available in 1981. In the interim, ERDA publishes annual estimates of reserves and potential uranium resources.

During 1976, ERDA efforts were directed toward three types of areas: 1) the uranium-producing areas, 2) areas where geologic favorability studies have been completed by ERDA's on-site contractor, Bendix Field Engineering Corporation, or by subcontractors (geological consultants, universities and other governmental agencies), and 3) areas identified as favorable, but not yet fully assessed.

Campbell (1974a) recommended a comprehensive hydrogeochemical reconnaissance survey of the United States. In 1975, ERDA announced plans for a similar but expanded program with a budget through 1976 fiscal year of approximately $5 million (Carter, 1975).

The hydrogeochemical survey program, which includes ground water, surface water and stream-sediment sampling, is being conducted by four ERDA Laboratories: the Lawrence Livermore Laboratory, California (Pacific Coast and Basin and Range States); the Los Alamos Scientific Laboratory, New Mexico (Rocky Mountain States and Alaska); the Oak Ridge Gaseous Diffusion Plant, Tennessee (Central U. S.); and the

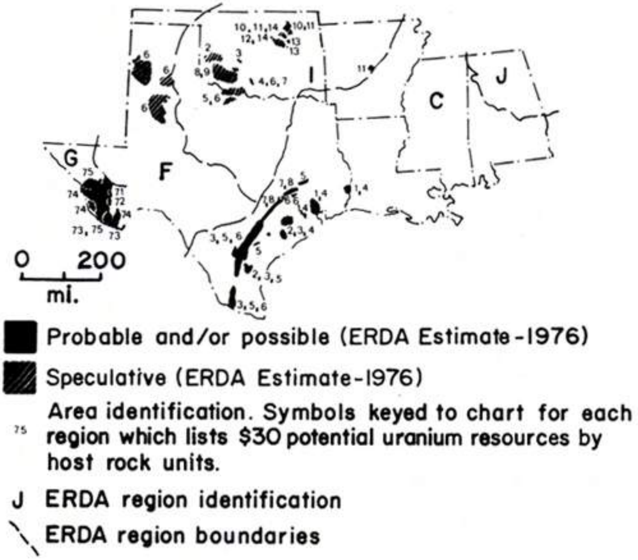


FIGURE 6. Areas in which potential uranium resources have been estimated.

Savannah River Laboratory, Aiken, South Carolina (Eastern U. S., including the Appalachians, New England and Southeastern States). The latter two locations will produce information related to the South-Central U. S. and the areas and principles under review in this presentation. The general survey is part of the NURE program presently in progress. Another ERDA project of particular interest is currently under way at the University of Arizona. Statistical principles are being evaluated for use in expressing projections for probable discovery rates of deposits for a give exploration effort. A broad range of similar projects are currently being conducted. Reports and additional information on these projects are available from ERDA in Grand Junction, Colorado. Reports presently available, bearing on the areas under discussion in this chapter, will either be cited within this chapter or in Chapter 5—Selected Uranium Bibliography.

The role of the U. S. Geological Survey is to generate specific geological data in various areas of uranium potential rather than to estimate resources. In 1975, the U. S. Geological Survey awarded eight grants to state geological surveys and universities for field and laboratory investigations on uranium, three of which concentrate on selected areas of the South-Central United States.

The Geological Survey of Alabama is evaulating the uranium potential of the Pottsville Formation and the sandstones of the Tuscaloosa Group in Central Alabama by geologic mapping, radiometric surveys and hydrogeologic studies. The initial evaluation will be followed by geochemical and geophysical examinations of the most favorable areas, and, if warranted, by reconnaissance drilling as previously conducted by the state for lignite. The Colorado State University is investigating the carbonaceous material associated with most uranium deposits in sandstone. In addition, CSU

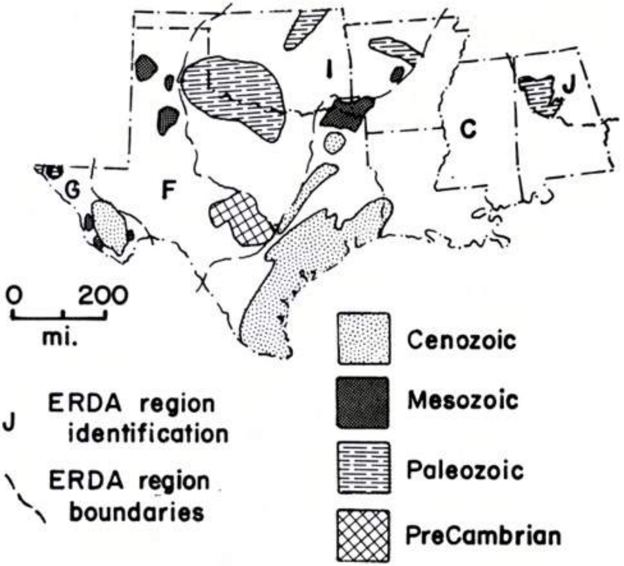


FIGURE 7a. Age distribution of favorable host rock (ERDA Estimate, 1976).

will conduct a statistical evaluation of borehole geophysical measurements in the Gulf Coastal Plain area of Texas. The University of Texas is conducting a study of the uranium potential of the so-called "red-bed" sandstones in the Texas Panhandle. It would be prudent to monitor the progress of such projects via the U. S. Geological Survey in Denver.

Favorable Frontier Areas

The Preliminary Report on the National Uranium Resource Evaluation Program (U. S. ERDA, 1976) indicated 14 million pounds of *in-situ* ore (7,000 tons) of "probable" potential resources in the East Texas area; 6 million pounds (3,000 tons) of "possible" resources; and 62 million pounds (31,000 tons) of "speculative" potential resources. Areas downdip from those discussed by Dickinson and Duval (this volume) were assigned "probable" and "possible" potential resources but not "speculative" (see Figure 6). It should be emphasized that in order to assess the yellowcake equivalent of ERDA's potential *in-situ* resources, the ore grade and the mine and mill recovery factors must be considered. For example, ERDA conservatively estimates that 14 million pounds of *in-situ* ore will probably be located in East Texas. Assuming the uranium ore found averages 0.10% U_3O_8, and mine and mill recoveries are 85% and 95% respectively, the 14 million pounds of ore is equivalent to 11,305 pounds of produced concentrate. Adding ERDA's "possible" and "speculative" estimates of *in-situ* ore to their "probable," the total estimated potential for East Texas is only approximately 66,000 pounds of uranium concentrate. Although ERDA estimates are conservative, they are also based on very limited data. If one significant discovery is made in East Texas in the near future, the area's overall potential will increase drastically. At the present time, ERDA estimates that the Texas Coastal Plain contains approximately 102 million pounds U_3O_8 (51,000 tons) of defined reserves.

Figure 7 is a summary of ERDA data showing: a) age distribution of favorable host rock, b) types of geologic occurrences in favorable areas, and c) average depth to favorable host rock. It should be noted that the data are based on $30/pound ore. The Preliminary ERDA Report should be consulted for detailed information on the general areas shown and geologic units involved.

Certain areas will be discussed in some detail to emphasize the specific types of uranium occurrences considered to be important targets for frontier exploration in the South-Central U. S. In the discussion to follow, some of the areas treated have been emphasized by ERDA (1976), while others have not.

TEXAS

Fisher (1970) indicates that the uranium mineralization in the Jackson Group (Tertiary) occurs in two distinct trends: 1) a strand plain-lagoonal trend of South Texas (discussed by Dickinson and Duval, this volume) and 2) a delta trend north of the Colorado River, which will be considered here. Figure 8 is a strike profile of the principal depositional systems of the Jackson Group from East Texas to South Texas.

The Fayette delta system of the Jackson Group outcrops from central Fayette County eastward to western Angelina County. Figure 9 shows the principal depositional systems involved. Radiometric anomalies are common in the lignite-bearing delta plain facies of these systems; the principal anomalous units are: 1) lignite, 2) carbonaceous

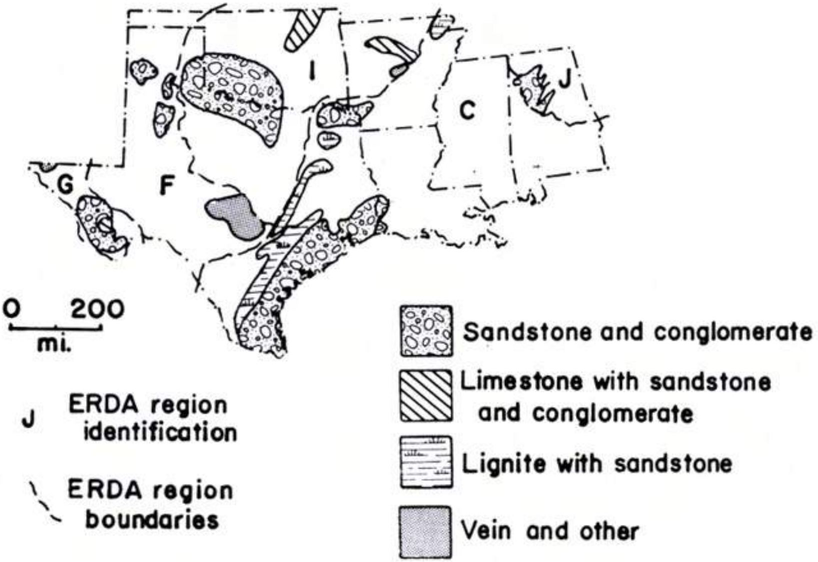


FIGURE 7b. Type of geologic occurrences in favorable areas (ERDA Estimate, 1976).

muds, and 3) thin, poorly sorted sands. These units are adjacent and marginal to the axes of the major thick, massive deltaic channel sand units. Figure 10 compares the depositional systems of West and East Texas and indicates areas of favorable uranium occurrences. Fisher (1970) suggested that a number of features favor uranium mineralization in the South Texas area over the East Texas area. These include: 1) presence of lagoonal facies, 2) presence of calichification, a guide to arid or semi-arid climate in recent history, 3) type and extent of leaching of overlying sediments, 4) topographic position, and 5) overlap of the Catahoula tuffs.

Fisher's principal limiting factor, however, for supporting the potential of East Texas is the apparent absence of an arid or semi-arid climate in recent history. However, two aspects concerning climate should be considered. Climate plays a role in this type of uranium occurrence only by conditioning the hydrochemical character of the ground water at the recharge area. An arid climate may increase the amount of dissolved solids in the rivers which in turn recharges the ground water system with relatively high quantities of dissolved uranium. This is possible if fluvial systems flowed through tuffaceous country rock with an anomalously high uranium content. Further, Katayama (1960) suggests that of the nineteen major sedimentary uranium deposits in the world, sixteen could be related to past or present arid environments, including all of those deposits in rocks of Triassic age or younger.

Dickinson (personal communication, 1967) suggests that a promising source of uranium in East Texas is not known. As mentioned previously in "Source of Uranium," tuffaceous material has been reported from both the Catahoula Tuff and Jackson Group sediments in East Texas, but there is much less there than in South Texas (Renick, 1936). Darton and others (1937) have mapped the Catahoula as a tuff in South Texas and as a

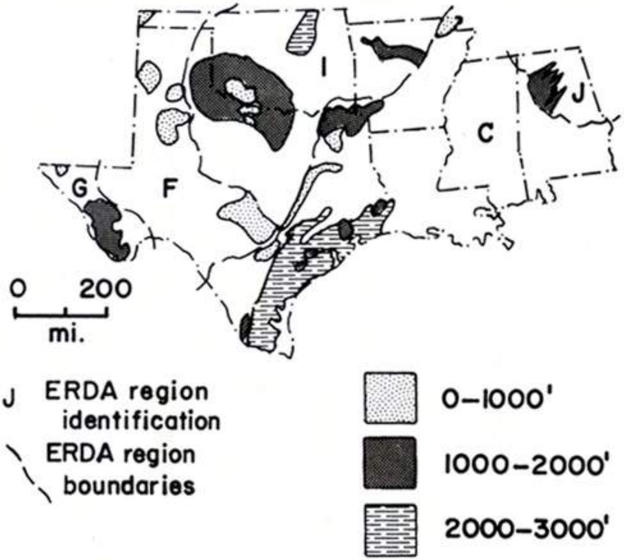


FIGURE 7c. Average depth to favorable host rock (ERDA Estimate, 1976).

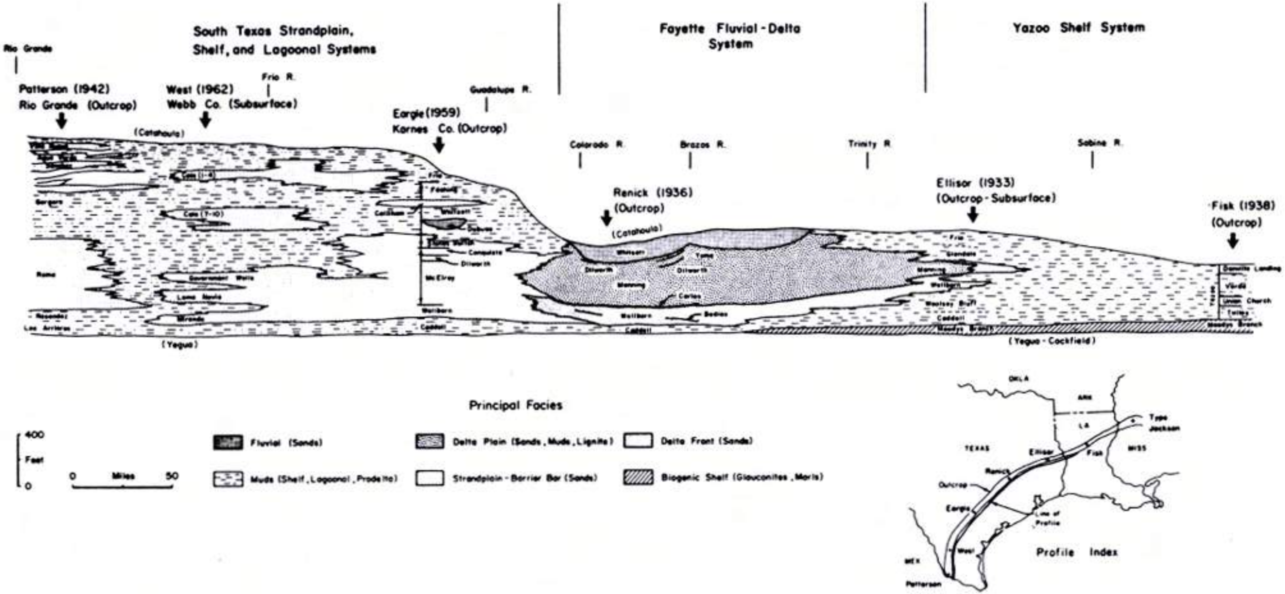


FIGURE 8. Strike profile of principal depositional systems, Jackson Group, Texas and Louisiana, compared to local formally defined stratigraphic units (Fisher, 1970).

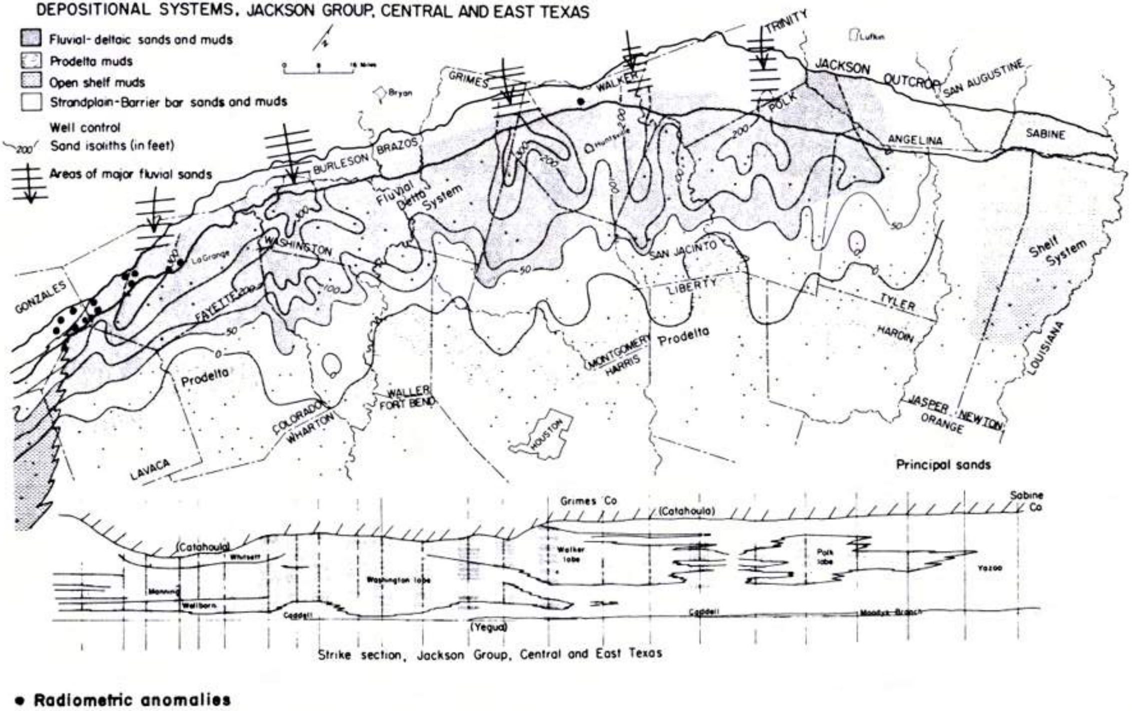


FIGURE 9. Principal depositional systems and strike profile, Jackson Group, central and eastern Texas Gulf Basin. Strike profile drawn along axis of maximum sand thickness (after Fisher, 1970).

sandstone in East Texas. Further, Bailey (1926) gave the Catahoula of South Texas a separate name, the Gueydan Formation, based on its content of volcanic rock fragments.

According to Thomas (1960) fragments of volcanic rock, common in the Catahoula in the uranium areas of South Texas, are lacking in East Texas. He reports that these fragments are not present in the Catahoula east of Karnes County and that the Catahoula sediments in East Texas had a different source than those in South Texas (Bailey, 1926; McBride and others, 1968; Eargle and Weeks, 1973).

Thomas (1960) cites several lines of evidence showing that the climate was more humid in East Texas during deposition of the Catahoula than it was in South Texas. However, most of the evidence could be attributed to epigenetic alteration. The climate prevailing in the recharge area of the subject sediments some 280,000 years ago may indeed have been arid or sub-arid in the East Texas area. The age of the ground water in the ore-bearing sediments of the ore itself in South Texas has considerable impact on the uranium potential for East Texas. If the climate was arid or semi-arid in East Texas prior to 250,000 years b.p. (the suggested time of formation of most of the South Texas uranium—Rosholt, 1963) the host aquifer may have been recharged with ground water relatively high in uranium that was derived from either fluvial systems in tuffaceous rocks or from tuffaceous rocks that overlie the host aquifer. The age of the ground water presently associated with ore should therefore be considerably younger than the ore (approximately 30,000 years b.p. since it entered the recharge area). The ground water facies that initiated the geochemical cell has now migrated considerably downdip, well past the known ore bodies of South Texas. The uranium potential, therefore, should be similar to that of South Texas, although considerably downdip. Pearson and White (1967) and Sultankhodzhayev and others (1971) have demonstrated the feasibility of dating ground water (see Craig, 1961).

Furthermore, an alkaline ground water is generally predetermined by the silicates present in the sediment, especially in the bicarbonate hydrochemical facies. The major interaquifer recharge would be from the thick and permeable channel sands of the fluvial facies and would tend to flush or dilute the effect of relatively low pH ground water supplied by organic sands and associated muds. This would also alter the hydrochemical content. Even if a relatively humid climate existed earlier than 250,000 years b.p., as it does today, the effect would have been to drive the uranium geochemical cells deeper into the formation until conditions were encountered that favored precipitation, such as "normal" cell, fault-trapped or salt dome conditions.

We suggest that the radiometric anomalies indicated by Fisher in Figure 10 are updip remnants of a geochemical cell that has migrated downdip; whether significant uranium mineralization has occurred depends on many factors. The fluvial-deltaic transition to strand plain-barrier bar, in similar position to the major areas of fluvial input, as in South Texas, appears to meet the specific requirements for uranium mineralization. As long as the hydrochemical facies contained sufficient uranium and the sediments contained the proper bacteria and reductants (or the reductants were introduced), the uranium geochemical cell could form, either in the normal roll-type or in response to faulting or domal structures where introduced reductants probably played an important role.

Klohn and Pickens (1970) suggest that structural conditions may be a major controlling factor in the uranium mineralization of South Texas. Areas of faulting in favorable Tertiary sediments are also present in East Texas. Figure 11 is a diagrammatic representation of this type of occurrence. This type is not restricted to Tertiary sediments. Powell (1975) investigated radiometric anomalies in Late Cretaceous sediments of the Woodbine and Tokio Formations in Northeast Texas and Southwest Arkansas. We consider that the down-dip areas are candidates for fault-related and normal roll-type uranium occurrences, especially along the northern margin of the Tyler Basin.

Salt domes are also known to contain significant uranium mineralization. Shumlyanskii (1967) reviews the characteristics of epigenetic reduction

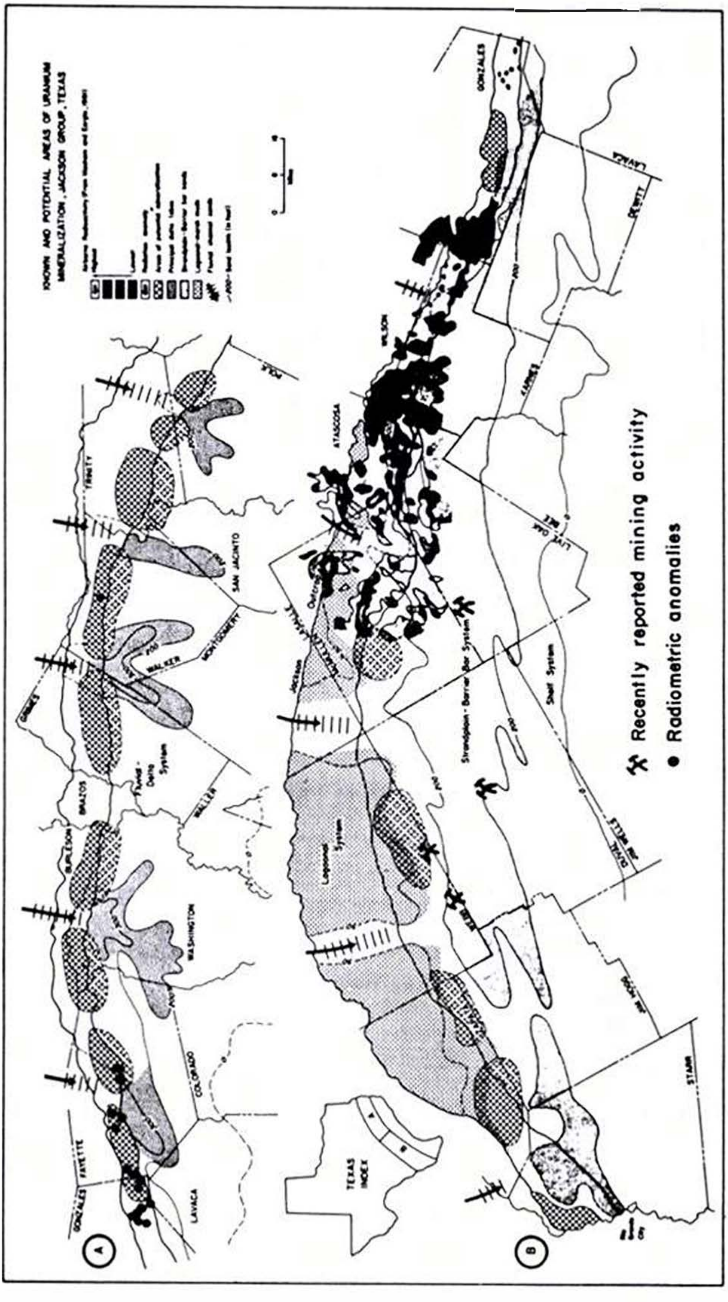


FIGURE 10. Distribution of known and potential areas of uranium mineralization, Jackson Group, Texas (after Fisher, 1970).

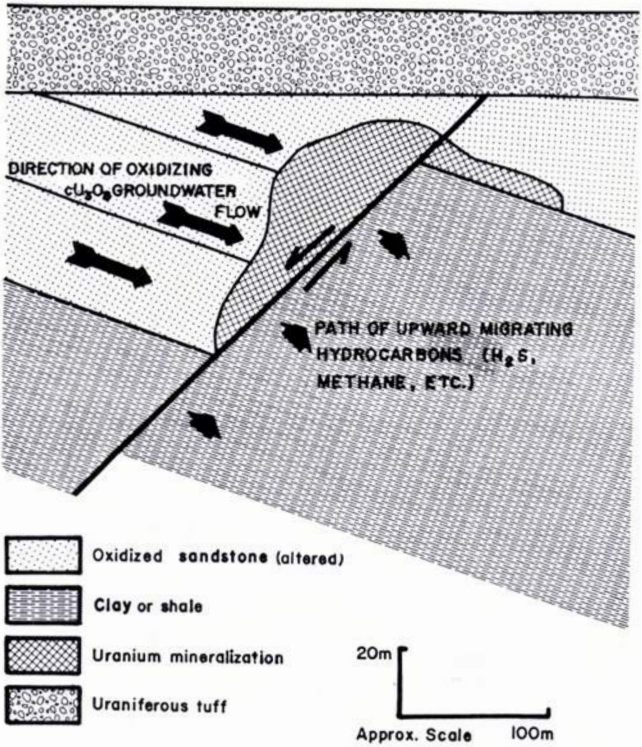


FIGURE 11. Typical fault-type uranium occurrence (after Eargle and Weeks, 1973).

of sediments above oil- and gas-bearing structures. Figure 12 is a generalization of the relationships involved and the type of uranium occurrence (Eargle and Weeks, 1973). Uranium is also known to be associated with other salt domes, one located near Houston. Areas above some domes can contain rather complicated structural features. Figure 13 is typical of such structures in Louisiana (Dinnean, 1958). Because many domes are responsible for oil and gas traps, an introduced source of reductant would be present. The necessary data are available to evaluate the general prospective nature of all domes in the Texas-Louisiana-Mississippi region. (See Figure 14). Data from investigations on geopressured geothermal energy exploration may be useful in evaluating the potential of deep host rocks. (See Jones, Bebout, and Gustavson and Kreitler, all in this volume.) Ground-water data can also be particularly informative in the areas. Lang (1961) indicates that ground water in the vicinity of the Jackson dome from the deep Wilcox Group is of a bicarbonate type while the shallow Sparta sand (Claiborne Group) is of a sulphate-chloride type.

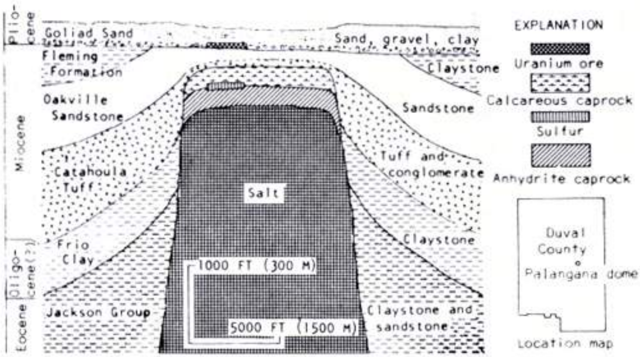


FIGURE 12. Idealized cross-section through Palangana salt dome, Duval County, Texas (Eargle and Weeks, 1973).

The Palangana salt dome contains significant uranium above the cap-rock (see Figure 12). The uranium occurs in a highly calcareous clay-ball conglomerate interbedded with friable fine-to medium-grained sand, locally impregnated with oil. The occurrence is limited to the basal section of the Goliad sand and upper Oakville Sandstone (Weeks and Eargle, 1960). Dickinson and Duval (this volume) discuss the occurrence further.

Another area in Texas that deserves mention—because of the potential importance of the type of occurrence involved—is in the Texas Panhandle, part of the area presently under study by the University of Texas on the "red-bed" occurrences. The Triassic Dockum Group of sediments is generally various shades of red, hence the term "red beds." The Ogallala Formation of late Tertiary age unconformably overlies the Dockum Group in some areas and, based on data derived from water wells and on the few outcrops present, is generally unoxidized. Scattered uranium mineralization has been reported in eastern New Mexico and the western Panhandle of Texas in the Dockum and other beds that underlie the Ogallala (Finch, 1972).

The Ogallala Formation contains pyrite and disseminated carbonaceous material and, under favorable conditions, could serve as a uranium host-rock. Under such conditions, oxidizing bicarbonate or sulfate-dominant ground water with relatively high uranium in solution could be introduced to the basal section of the Ogallala Formation from the underlying Dockum sediments in areas where interaquifer transfer is possible (Figure 15). The ground water in the Dockum would be under sufficient hydraulic pressure to commonly promote such transfer (Campbell, 1974b). Of course, interaquifer transfer could also occur in a downward direction as well although hydraulic pressure will generally promote upward transfer.

An abrupt change in the hydrochemistry of the Ogallala ground water or a surface expression of a fault would be the only indications of this type of uranium occurrence. A local fluctuation in hydrochemical data relative to a "baseline" standard (one that incorporates maturation effects of the paleoground-water system) should be discernable if ground-water sampling is restricted to the Ogallala Formation (Barker and Scott, 1958). As mentioned earlier, Bowes (1968) supports the above possibility in principle.

MISSISSIPPI EMBAYMENT

Although the Mississippi Embayment area has not been emphasized by ERDA as having even a "speculative" potential, except for the known nonmarine Tertiary sediments in northeastern

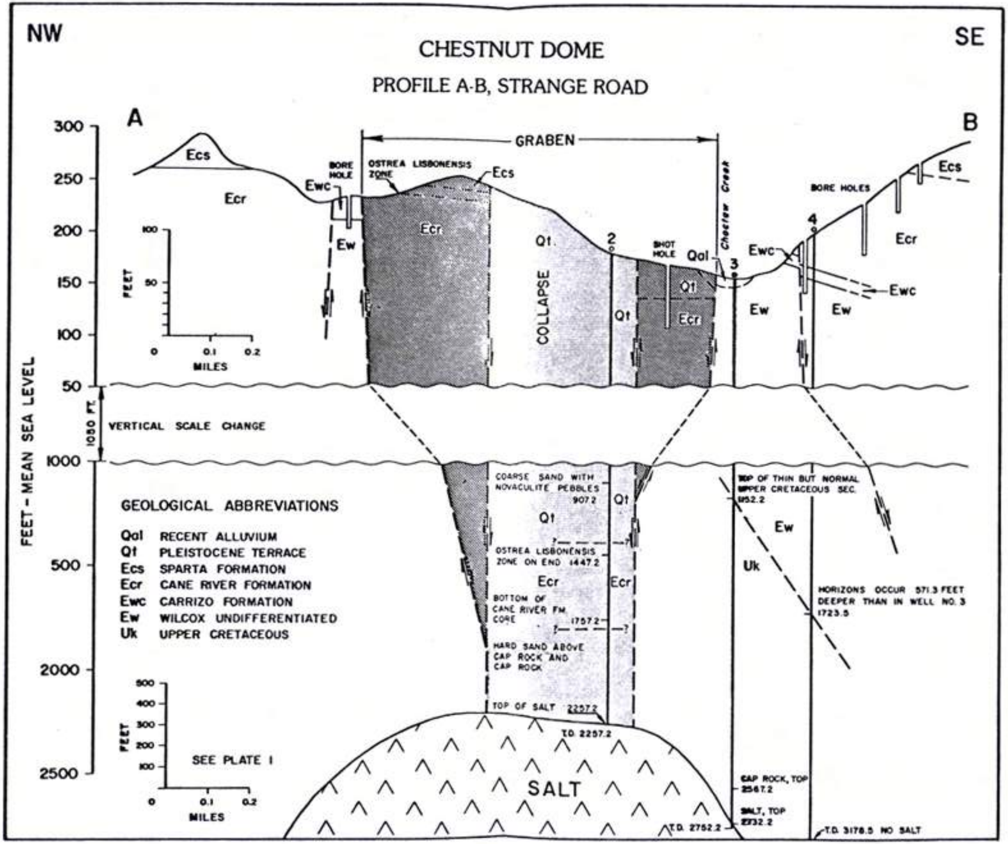


FIGURE 13. Structural features of the Chestnut dome, Louisiana (Dinnean, 1958).

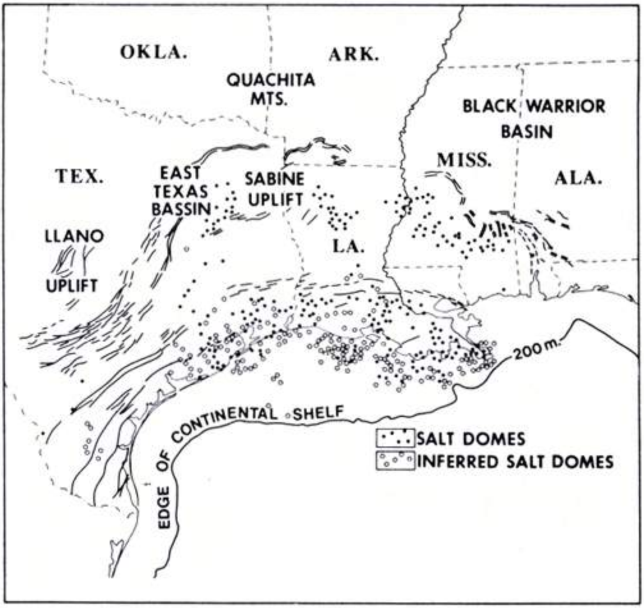


FIGURE 14. Major fault structures and salt domes of the Northern Gulf of Mexico (from Tectonic Map of North America).

Arkansas, many of the mechanisms and processes discussed previously could also promote uranium mineralization in selected areas of the Embayment area involving Tertiary sediments (Wilcox, Claiborne, and Jackson Groups) and Cretaceous sediments in the southwest area of the state of Arkansas.

Potential Source Rock. Numerous airborne and ground radiometric anomalies have been reported in and around the Magnet Cove igneous complex (Anonymous, 1968b; Cooper, 1955; and Arndt and Kuroda, 1953) in Garland County, Arkansas. The area contains a highly-weathered nepheline syenite of Cretaceous age. Tertiary sediments (Wilcox) outcrop a few miles to the east of this complex. Other similar intrusives occur along the outcropping Wilcox in Saline County while others underlie the Wilcox (and Midway) in nearby counties.

The lignite of the general area is known to contain 2-4 ppm uranium on an "as received" basis; a similar content for an "average" granite is considered to be a suitable source rock (Rackley, 1972). Tuffaceous material in the form of bentonite is also known in the Tertiary sediments of the region, although a widespread tuffaceous unit similar to the Catahoula Tuff is probably lacking in some areas due either to erosion or to non-deposition. Such a volcanic unit is known in younger sediments (in the Jackson Group) in Louisiana, Mississippi and Alabama and may be similar to the Catahoula Tuff.

ERDA has emphasized interest in the Paleozoic sedimentary rocks of Arkansas shown in Figure 7 on the basis of favorable host rocks present and the numerous radiometric anomalies reported (Anonymous, 1968b).

Potential Host Sediment. As is noted in the

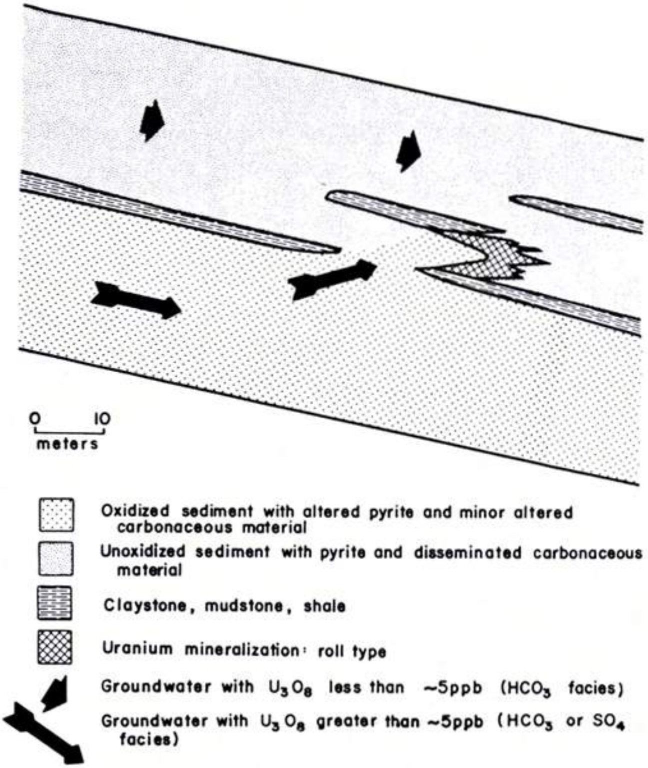


FIGURE 15. Suggested interaquifer transfer-type uranium occurrence (Campbell, 1974b).

discussions on lignite by Wielchowsky and others, and Self and Williamson (both in this volume), the lithologic characteristics of the Tertiary sediments in the Embayment area, relative to those of South-Central Texas, are very similar, such as interbedded arkosic sandstone, siltstone and associated clay beds. The coarse clastics contain pyrite and tuffaceous material in places, and carbonaceous material, both as lignite (hard and soft) and as disseminated fragments. In addition, thin, discontinuous beds of siderite (? altered caliche) are common in some areas.

In the northern region of Arkansas, alteration of a potentially favorable Tertiary host bed was reported but is unconfirmed. The character of alteration (or oxidation) may be very subtle and only an evaluation of many samples will reveal alteration, if present at all. In some uranium areas of Wyoming, alteration is indicated only by the presence of altered biotite (gold rim of plate). Other techniques to identify alteration may involve smoky quartz (Saucier, 1972), radiation damage to albite (McAndrew, 1957), character of calcite cement (Gott, 1956 and Waldschmidt, 1941), alteration of feldspars and heavy mineral suites, etc. It should also be stressed that although most of the major Tertiary deposits are in fluvial host sediments, the Texas deposits and some of the Colorado Plateau deposits occur in so-called marginal-marine sediments (Clinton and Carithers, 1956). This may be significant only because it emphasizes the sedimentary environment in which abundant carbonaceous material was deposited.

Hydrochemical Facies. Although a comprehensive study of the facies types in the Embayment area has not been made (but may be forthcoming from ERDA research), scattered data indicate that the very deep Wilcox and some overlying intervals do contain bicarbonate-type ground water with an inferred alkaline pH in places (Lang, 1961). Ground water data such as that supplied by Tait and others (1953) could be useful, not only in terms of the ground water chemical data such reports contain, but also in terms of the lithologic and structural information they present for use in identifying possible alteration and faulting.

Possible Mechanisms. Any one of four types of mechanisms mentioned previously could be involved in the Embayment area: 1) "normal" Tertiary cell-type, 2) fault-type, 3) dome-type, and 4) interaquifer transfer type. Combinations of the mechanisms would be expected.

With updip lignite or the intrusive complexes serving as a source for down-dip cell development, a broad area would become prospective for uranium mineralization. In considering the Wilcox as a potential host sediment, the maximum depth of interest would be 3,000 feet (915m), occurring from Bradley County in southern Arkansas to Lee County and into northwestern Mississippi.

Fault-type mechanisms are also possible in the general area. Faulting of the lignite beds of present commercial interest is not uncommon (Wielchowsky and others this volume, Figure 21). Dome-type potential can partly be assessed by evaluating the data from previous oil and gas exploration (MacElvain, 1965, Armstrong and Heemstra, 1973). It is interesting to note that the only radiometrically anomalous sediment listed by the AEC (Anonymous, 1968a) for the State of Mississippi is from Tertiary sediments in the Jackson Dome area.

Inter-aquifer transfer can be involved in any of the aforementioned mechanisms. Faulting or jointing of the extensive Midway shale that underlies the Wilcox in central Arkansas could allow a Paleozoic source to supply significant uranium to the ground-water system of the Wilcox and units higher in the section. A Tertiary Wilcox source could also be transferred to units of potentially greater host favorability than the Wilcox.

OTHER AREAS

Limitations of space do not allow us to present additional data on other areas that may exhibit the types of occurrences emphasized previously. We have, however, included pertinent literature on frontier areas in Chapter 5—Selected Uranium Bibliography. If we were to present such information, however, it would focus on West Texas (Finch 1975), Oklahoma (Shelton and Al-Shaieb, 1976) and Alabama (Dennison and Wheeler, 1975) using an approach similar to that taken previously: 1) source-rock identification, 2) host-rock favorability assessment, 3) hydrochemical evaluation of regional and local ground-water systems, 4) consideration of possible mechanisms involved, and 5) selection of areas for follow-up evaluations.

Exploration Techniques

Dickinson and Duval (this volume) summarize some of the important exploration techniques used in South Texas and other uranium districts. We will present information on some of the techniques that are used in frontier exploration.

Radon and helium emanometry or "sniffing" are excellent tools in high priority frontier areas. Although radon sniffing equipment is relatively simple to use, moderately inexpensive, and sensitive (Caneer and Saum, 1974), helium emanometry may be more useful than radon because helium moves more rapidly in the subsurface than radon. Although of significant value in earthquake prediction and in geothermal exploration, helium is more soluble in warm ground-water than in cold, a property that may make radon a more suitable guide element for uranium exploration (Friedman and Denton, 1976). In a field study of the behavior of radon in soil, Bhatnagar (1973) tentatively concluded that unmineralized areas show a single log normal distribution of radon values whereas areas with uranium mineralization appeared to produce two district log normal distributions. One commercial extension of this approach is termed "Track Etch" and, while simple to use, tends to be expensive. This method may not be applicable to frontier areas, but its use may be justifiable in "trend" areas where mineralization is probable.

Drilling Programs

Once a potential host rock has been identified, widely-spaced reconnaissance drilling is undertaken using truck-mounted water-well drilling rigs or small stationary rigs if deep drilling is warranted. During this operational stage, the objective is not necessarily to find ore but to geologically identify areas favorable for mineralization. In Tertiary exploration, "fence" or profile drilling normal to the strike of the potential host rock is usually undertaken. The spacing between holes and between "fences" depends on the size of the property to be evaluated and on whether drilling permits can be obtained from property owners. In frontier areas, this can usually be accomplished for approximately $25 per hole. In some states, county right-of-way drilling is possible; some counties assess a similar fee per hole while other counties do not. It is prudent to insure that good housekeeping is observed not only for general environmental reasons but also for reasons of safety and public relations. When drilling in relatively populated areas, where power lines are common, personnel should be especially cognizant of the potential dangers involved. Electrocution is far too common and rig locations should be selected at least 100 feet (31m) from any overhead lines. Well-site personnel responsible for well locations should also make every effort to please the landowner because his land, or a relative's land, could become important in the development of future mining operations and a mining lease may be required sometime in the future.

Drilling is usually contracted to a local drilling company. Figure 16 is a summary of ERDA data on domestic uranium drilling depths for 1964 and 1975. Depths up to 3,000 (915m) may be common in highly prospective areas in the near future. At present, 1,500 feet (458m) is considered to be maximum for frontier exploration unless sufficient encouragement is encountered to extend the depth.

DEPTH	% 1964	% 1975
0-100'	17	1
101'-200'	38	6
201'-300'	17	12
301'-350'	2	2
351'-400'	6	2
401'-500'	5	12
501'-750'	10	31
751'-1000'	2	8
1001'-1500'	0	5
1501'-2000'	1	6
> 2000'	2	15
	100%	100%

FIGURE 16. Comparison of exploration/development drilling: 1964 and 1975 (Chenoweth, 1976).

Campbell and Lehr (1974) summarize the principles of rotary and other types of shallow drilling and coring and discuss the various features that affect the drilling cuttings obtained. Cuttings are usually sampled on five-foot intervals and laid out at the drill site in rows of ten samples per row. Samples are strained to remove drilling mud before examination. In the lithologic description, a rock color chart (GSA) should be used to assure standardization of color designations by the geological staff. The general color of the potential host sediment is very diagnostic in determining alteration. In addition, on-site descriptions should not be made while the geologist is wearing sunglasses. It should be emphasized here that after the geological descriptions have been made and the necessary samples taken for later study, the rows should be thoroughly "kicked-out" to avoid "midnight" inspection by an impertinent exploration competitor.

Exploration Objectives

The principal objective in early frontier drilling programs is to locate alteration of the potential host sediment, although the type of alteration in Tertiary and older sediments will vary from region to region and from basin to basin. Figure 17 illustrates the "type" geochemical cell in parts of the Powder River Basin of Wyoming and the type of alteration and radiometrics involved (Rubin, 1970). As a general rule, for example, if alteration is detected in Hole #3 (see Figure 18A) of the fence and not detected in the same unit in the next hole (#4) down dip, the solution front has been bracketed. By moving half the distance back up the fence from Hole #4, another hole (#5) is drilled and alteration is sought. If lacking, half the distance between Hole #5 and Hole #3 is drilled, Hole #6, etc. . . . Based on the fence shown in Figure 18A, drilling has established that the solution front (and perhaps uranium mineralization) has been bracketed.

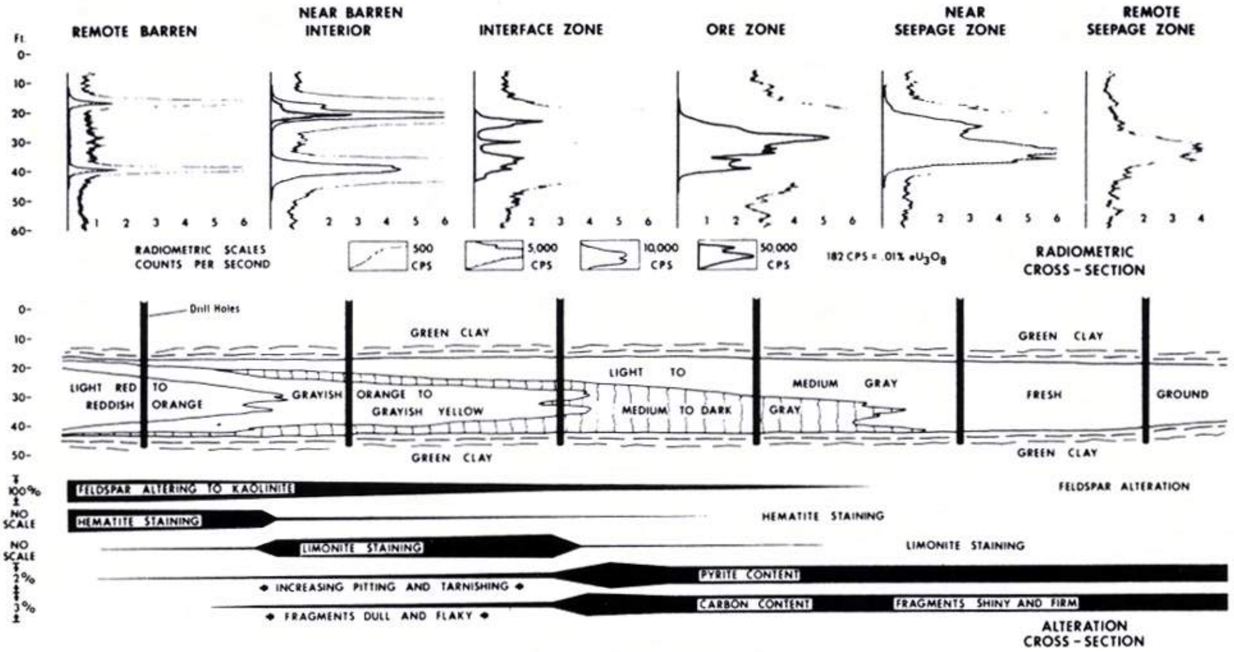
If alteration is established, this feature alone upgrades the area's potential for significant uranium mineralization. Keeping in mind that Tertiary ore bodies are like beads on a string, the primary objective during late frontier exploration is to bracket the sinuous solution front that marks the boundary between oxidized and unoxidized sandstone. Uranium mineralization may or may not occur somewhere along this solution front (see Figures 1A, B and 18A, B). Drilling on 25 foot (~7.6m) centers is required in some instances for use in assessment of reserves.

After the hole has been drilled, geophysical logging is necessary. Commercial or company logging vehicles should be at the well site prior to well completion and should be ready to log as soon as the drilling rig leaves the drill site to avoid hole caving.

Logs such as natural gamma, resistivity and spontaneous-potential (S. P.) are commonly run during frontier exploration. Resistivity and S. P. are used to determine the lithologic character of the potential host rock. Gamma radiation is converted directly to equilibrium-corrected thickness and grade of uranium mineralization, if present, and provides the basic data used in all ore-reserve calculations. A typical correction for converting counts per second of gamma radiation to $\% {}_cU_3O_8$ is 3800CPS = 1%. This correction is valid only under equilibrium conditions where daughter products of the uranium decay series are being formed at the same rate they are decaying. This condition is rare, especially in Tertiary ore bodies; therefore, as soon as mineralization is indicated on the gamma log, the equilibrium conditions must be determined. It should be noted that the gamma radiation is not generated from the uranium sought but from its radioactive daughter products (${}_eU_3O_8$). Chemical assays will determine the content of uranium (${}_cU_3O_8$). Comparisons are made of chemical analyses and the indicated gamma log radiation to determine the equilibrium factor.

When ore is in equilibrium the chemical analysis (${}_cU_3O_8$) will equal the radiometric analysis (${}_eU_3O_8$) from the log, or an equilibrium ratio of 1.0. A ${}_cU_3O_8/\ U_3O_8$ ratio greater than 1.0 indicates a young or enriched ore where time has not been sufficient to produce daughter products, while a ratio of less than 1.0 indicates uranium mineralization that is depleted in ${}_cU_3O_8$, a serious problem in some mining operations in South Texas. Duray (1976) discusses gamma log calibration; Hallenburg (1973) reviews the factors involved in gamma log interpretation; Pirson (1970) discusses logging of host rock environments using redox logging techniques, an approach of significant value in determining altered sediments in unfamiliar potential host rocks.

Frontier drilling for the older Colorado Plateau-type tabular ore bodies presents special problems. At present, there appears to be no systematic pattern of association of the ore mineralization with visually recognizable structures, textures, or mineral associations as exists in Tertiary roll-type mineralizations. There are no obvious up-dip altered and down-dip unaltered zones to use as exploration guides and, aside from limiting detailed exploration to mapping and drilling of point-bar sequences within favorable fluvial sandstone complexes, grid-pattern drilling seems to be the only present alternative (Griffiths and Singer, 1969). However, Rackley (personal communica-



GENERAL ROCK DESCRIPTION

ARKOSIC SAND - COMPACTED BUT NOT CEMENTED
MEDIUM TO COARSE GRAIN
FAIR SORTING

SUB-ANGULAR TO SUB-ROUNDED SHAPES
QUARTZ > 80% FELDSPAR < 15%
CARBON FRAGMENTS < 5% PYRITE ± 1%

BLACK AND GREEN ACCESSORY MINERALS < 1%

FIGURE 17. "Type" geochemical cell, Powder River Basin, Wyoming (Rubin, 1970).

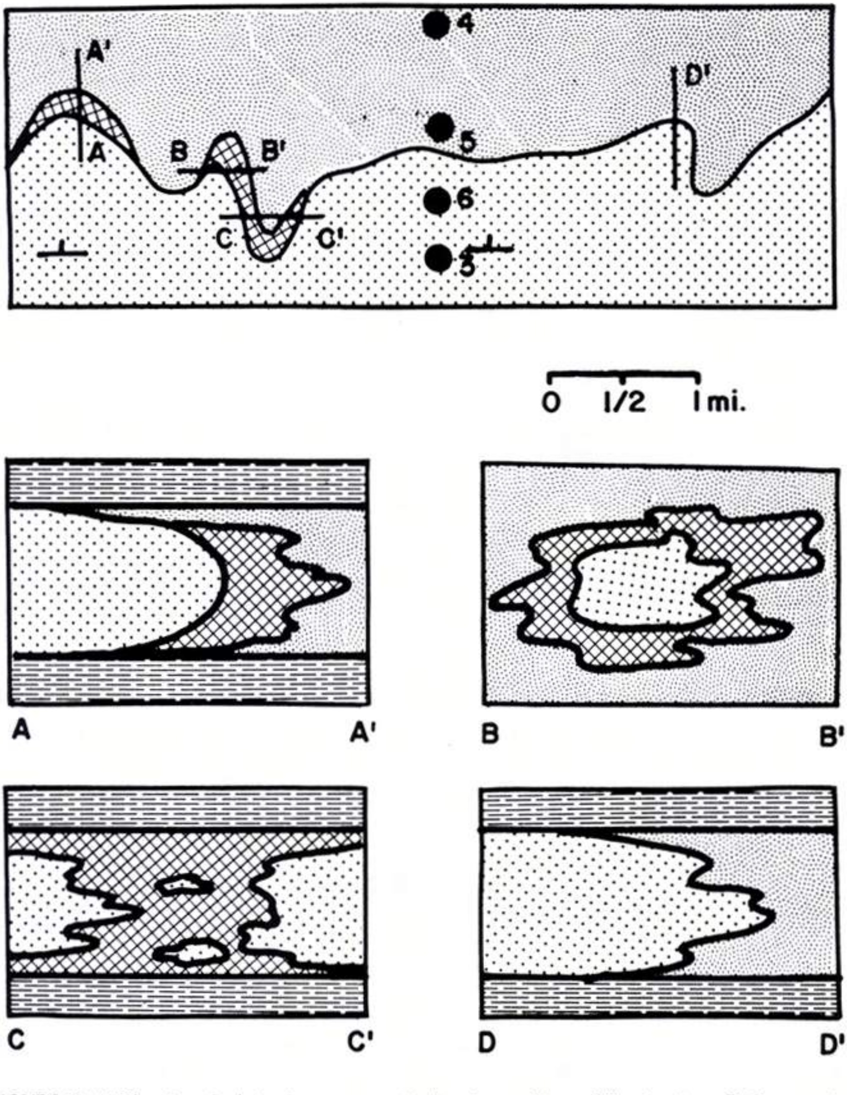


FIGURE 18. (A) Plan view of solution front cross-section locations and fence-drilling locations. (B) Cross-sectional configurations of roll-front deposits along lines AA', BB', CC', and DD' (after Adler and Sharp, 1967).

tion, 1977) suggests that lithologic guides may be discernible if detailed petrographic and sedimentological evaluations are undertaken. Many of the older methods of evaluating such types of occurrences are still widely practiced today. Pitman and others (1956) discuss some of the procedures used in the mid 50's that did find ore. ERDA research, however, should produce some interesting results in the future. Klemenic and Sanders (1976) have made progress incorporating "constant" dollar values in estimations of ore discovery rather than using "current value" as practiced previously. This approach should be more indicative of the quantity of uranium discovered than past estimates.

FRONTIER EXPLORATION PHILOSOPHY AND ECONOMICS

Bailly (1972) has outlined the key requirements for discovery in mineral exploration. Concerning uranium, the first requirement of an exploration company is to have a staff of highly qualified personnel that consider their objective to be one of evaluation and application of known methods of uranium exploration. They must be acquainted with the use, availability, and limitations of all elements of the search. They must also have management support to continuously upgrade their knowledge either through academic course work or through seminars and workshops offered during relatively inactive periods of exploration.

Secondly, the staff must have a knowledge of the principles of geology and must be up-to-date on the new advances in the sub-fields of geology that have practical significance to their objectives, such as in sedimentology, geochemistry, borehole geophysics, etc. In effect, they should endeavor to be at the frontier of the science in terms of their practical knowledge and should have well-developed associations with various university personnel involved in research with particular applications to mineral exploration. They should also have a working knowledge of environmental science, exploration and mining, economics, and law.

Thirdly, the staff must have a broad range of basic equipment and a knowledge of available geological and engineering consultants and contractors. Geological consultants can serve three basic functions: 1) to serve as a source of specialized information, and/or 2) to serve to implement field operations via consultants' staff members in cases where the company does not wish to expand their staff for a particular project, and/or 3) to augment existing company field personnel.

The idealized sequence of frontier exploration is: *Stage I*—1) regional review, 2) local evaluations, 3) field reconnaissance; and *Stage II*—4) reconnaissance drilling, 5) bracket drilling, and 6) ore discovery. The acquisition of mineral rights by staking on public land or by lease of private or public land, options or permits are generally made at the end of local evaluation period of Stage I. In earlier periods it is only necessary to establish that land owners would allow later acquisition. In any event, a value is placed on the land before its true value is known, at a time when an ore body is only a remote possibility. Figure 19 illustrates the typical lead-time for production from any one prospect. Beasley (1970) briefly outlines the procedures involved in staking claims on federal and state lands in Wyoming. Chenoweth (1976) discusses the general features of land acquisition and drilling activities in the U. S. over the past few years.

With time, the potential of discovery diminishes as other companies find new ore bodies. Only the companies that develop new and effective exploration techniques will have a special exploration advantage over the competition. Management should foster and support the development of new exploration techniques and methods. If one out of 100 such attempts is successful in leading to the discovery of a new ore body, the economic rewards would be substantial to the company.

The objective of frontier exploration is, of course, to find new ore bodies. But once "significant" mineralization is encountered, reserves must be calculated and mining feasibility must be assessed. In many instances, personnel, whose prime responsibility is frontier exploration,

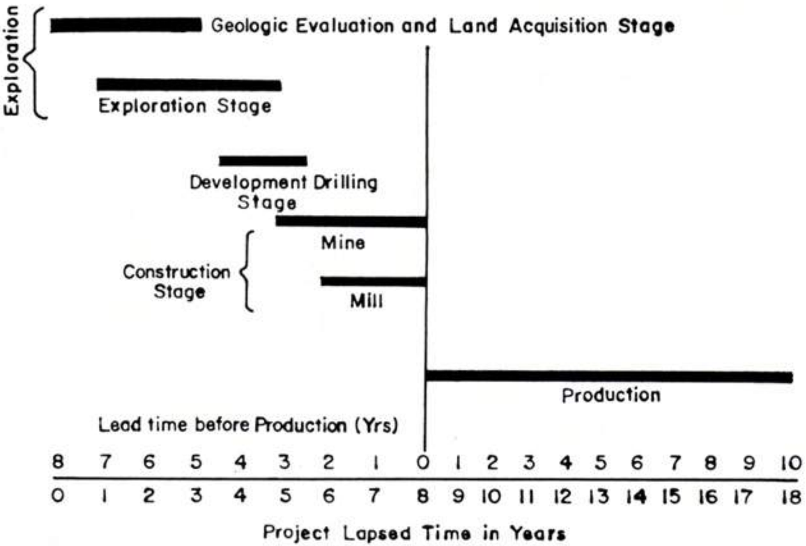


FIGURE 19. Anticipated lead-time for uranium production in single prospect area (after Klemenic, 1976).

will redirect their attention to new areas of potential. However, in many companies, the personnel making the discovery will also be responsible for reserve estimates and preliminary mine planning (Lewis and Bhappu, 1975; Meehan, 1976; and Van Alstine and Curry, 1970). To assist the latter group, we have included in Chapter 5—Selected Uranium Bibliography, a number of citations that will be of assistance to their efforts.

In closing, we might add that the period of open-pit mining of relatively shallow ore bodies has nearly come to an end, not only because of the lack of shallow ore but because the method is less environmentally acceptable than other methods. The emphasis will be on underground mining and subsurface solution mining. Hunkin (this volume) reviews the various aspects of subsurface solution mining. In addition, Kallus (this volume) discusses the potential environmental impact of uranium mining and the present state and federal regulations that affect the uranium industry. Additional citations covering the general topics discussed in this chapter will be found in Chatper 5—Selected Uranium Bibliography.

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