KENDELL A. DICKINSON[1]
JOSEPH S. DUVAL[1]

Trend Areas and Exploration Techniques

South-Texas Uranium: Geologic Controls, Exploration Techniques, and Potential*

ABSTRACT: Host rocks for uranium in the South-Texas Coastal Plain are Tertiary sedimentary rocks that dip gently to the southeast toward the Gulf of Mexico and into the Gulf Coast geosyncline. The uranium host rocks are mainly porous sandstone units found in the upper Eocene Whitsett Formation, the Oligocene (?) Frio Clay, and the Miocene Catahoula Tuff and Oakville Sandstone. The sandstone units are of fluvial origin except for some in the Whitsett that were deposited in a beach environment.

The primary source of uranium in the South Texas deposits was probably the Catahoula Tuff. The uranium was dissolved under mildly alkaline, oxidizing conditions accompanying the semi-arid climate that was apparently predominant throughout the late Tertiary in the South Texas area. The dissolved uranium was transported in streams or underground conduits to an area of strong chemical reduction, where it was precipitated. Carbonized plant fragments in the host rock and H_2S emanating from petroleum deposits may have provided the chemical reductant.

Uranium deposits in South Texas have been found in three principal areas, each characterized by a different host rock. The principal host rocks are the Whitsett Formation in the Karnes County area, the Oakville Sandstone in the Live Oak County area, and the Catahoula Tuff in the Duval County area. Extensive open-pit mining in the Karnes area has allowed detailed studies. In this area the Catahoula Tuff lies unconformably on the Whitsett host rock. Uranium-bearing surface waters draining Catahoula Tuff terrane, or areas where pre-existing uranium deposits were located, were transported in streams or in subsurface paleochannel and beach sandstone units to the sites of deposition. Paleochannels are common in both the Whitsett and in the basal part of the Catahoula.

The ore bodies are generally in the form of rolls that are elongate perpendicular to the direction of ground-water movement and that are crescent-shaped in cross-section. The wings of the crescent point in the direction from which the uranium-bearing ground-water came, which is generally updip to the northwest in the general area under review. The ore minerals in most of the deposits are coffinite and uraninite, except in the ore bodies at or near the surface in the oxidized zone where autunite and tyuyamunite predominate.

Exploration techniques have generally consisted of surface mapping, drilling and logging, and airborne and surface radiometric studies. New exploration tools will become important as the search for new deposits extends deeper into the subsurface. Various airborne, surface, and in-hole

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[1]U. S. Geological Survey, Uranium-Thorium Branch, Denver, Colorado.

techniques are important. Improved radiometric and thermal-infrared surveys may be useful for airborne reconnaissance and intermediate stages of exploration. Important surface methods are gamma-ray spectrometry, radon and helium emanometry, magnetics, very low frequency electromagnetics, and induced polarization. Promising in-hole techniques, which will be especially important in future exploration, are direct uranium measurements using neutron-activation, gamma ray spectrometry, resistivity, spontaneous potential, magnetic susceptibiltiy, and induced polarization. The best potential for large new uranium deposits in South Texas is in the deep subsurface, where the controlling factors for uranium deposition are very similar to those found in the near-surface uranium producing areas.

INTRODUCTION

Texas is playing an important role in supplying uranium for atomic reactor fuel, and its role in the future will be greater. Texas ranks fourth in the United States in current uranium production and third in reserves. So far, essentially all the production and most of the reserves are in the South Texas Coastal Plain. The amount of new uranium to be found in this area depends on (1) the ultimate amount of uranium present in concentrations sufficiently high for economic recovery (potential resources); (2) our knowledge of the geology, especially the factors controlling uranium deposition; and, (3) the effectiveness of new exploration techniques, particularly in the deeper subsurface which offers the best potential for large new deposits. Many of the factors and techniques have also been discussed by Campbell and Biddle (this volume).

The purpose of this chapter is to: (1) describe the geologic setting for uranium producing or "trend" areas in South Texas; (2) present the elements of formation for uranium deposits; (3) describe the uranium-producing areas in South Texas, and the general character of the ore bodies; (4) show in detail the geologic factors that controlled uranium deposition in Karnes County; (5) present possible new exploration techniques; and, (6) give present appraisals of reserves and resources and estimate the potential for large new deposits in South Texas. In this chapter "South Texas" includes that part of the Coastal Plain from Fayette County to the Mexican border, and as such includes the central part of the Coastal Plain.

GEOLOGIC SETTING

Figure 1 shows the rock units that are of interest in the South Texas Coastal Plain. They are Tertiary, mostly nonmarine sedimentary units that grade downdip to the southeast into marine rocks. The rocks consist mostly of sandstone, mudstone, and claystone; and they gently dip into the Gulf Coast geosyncline. Large growth faults, which have low displacement near the surface, together with numerous smaller faults and joints, are closely related to ore bodies. The stratigraphic units of the uranium areas in South Texas are shown on Figure 2. They are the Whitsett Formation (upper Eocene) of the Jackson Group; the Frio Clay (Oligocene?), which crops out only in the southern third of the Coastal Plain area; the Catahoula Tuff (Miocene); the Oakville Sandstone (Miocene), which crops out only in the central part of the Coastal Plain; the Fleming Formation (Miocene), which is combined with the Oakville Sandstone in East Texas (Figure 1); and the Goliad Sand (Pliocene). The Fleming Formation is the approximate equivalent of the Lagarto Clay.

Figure 2 is a diagrammatic cross-section oriented parallel to the dip. This cross-section represents an area such as Karnes County (Figure 1) where the Frio Clay does not crop out and the Catahoula Tuff lies directly on the Whitsett Formation. All the units in this section are uranium host rocks in South Texas except the Manning Clay and the Fleming Formation. The Whitsett Formation contains seven members (see Figure 3). Three members are continental or lagoonal claystone and mudstone units cut in places by

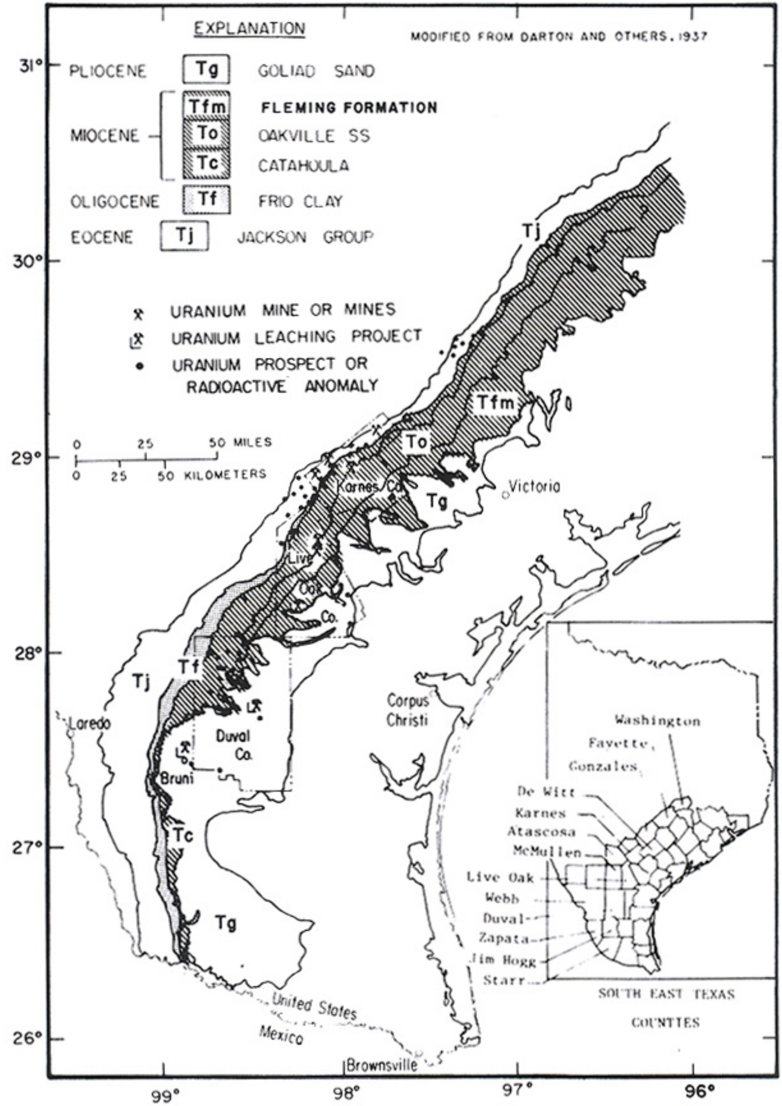

FIGURE 1. Generalized geologic map of South Texas Coastal Plain showing uranium mines, leaching projects, radiometric anomalies and prospects.

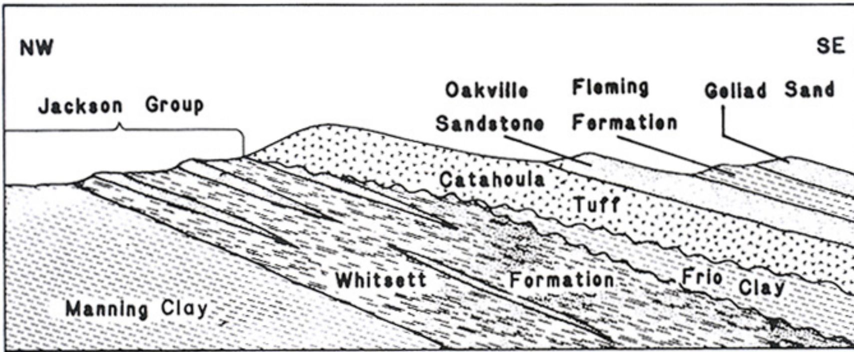

FIGURE 2. Diagrammatic cross-section, South Texas.

sandstone bodies that were deposited in fluvial channels. One of the fluvial channel deposits is the Callihan Sandstone Member. The other three members are beach sandstone units. Both the beach and fluvial sandstone bodies are uranium host rocks in Karnes County (Figure 3).

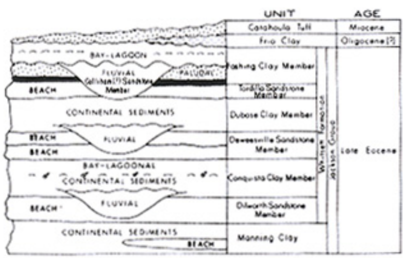

FIGURE 3. Schematic stratigraphic diagram.

GEOLOGIC CONTROLS

The geologic controls believed to be important in the formation of epigenetic uranium deposits are: (1) source rock, (2) leaching, (3) transport, (4) host rock, (5) reductant, and (6) preservation. These controls are evaluated for the South Texas "trend" area and are used as the basis for describing individual deposits in Karnes County, as well as for evaluating "frontier" areas of similar age and lithology (see Campbell and Biddle, this volume).

Source rock. The principal source rock for the uranium in Karnes County and in South Texas in general is believed to be the Miocene Catahoula Tuff (Eargle and Weeks, 1973). This conclusion is based on: (a) the discrepancy between the assumed original uranium content and the present uranium content of the tuff; (b) the thorium-to-uranium ratio; and (c) the lack of other potential source rocks. The present uranium content of the Catahoula is about 3 ppm. Fifteen samples from near the Manka mine (Figure 5), analyzed by the neutron-activation method, average 2.7 ppm uranium. On the basis of 146 radiometric measurements, Duex (1971) found that the Catahoula averaged 3 ppm uranium. According to Adams (1954), the uranium content of acidic volcanic tuffs is about 5.6 ppm, or nearly twice the amount found in the Catahoula. Furthermore. Gottfried and others (1962) reported as much as 45 ppm uranium in alkalic igneous rocks in the Big Bend region of Texas, the supposed source of the South Texas volcanics. Dickinson (1975) reported 10 ppm uranium and 32 ppm thorium from below the depth of soil leaching in a relatively unaltered ash bed in the Fashing Clay Member of the Whitsett Formation. These values are believed to represent the original content of the ash, the source of which was probably similar to that of the Catahoula Tuff. Moxham (1964) suggested, on the basis of total-count airborne radioactivity surveys, that radioelements have been removed from the Catahoula.

A high thorium-to-uranium ratio in the Catahoula may also indicate a loss of uranium. This conclusion is based on the assumption that thorium and uranium are present in alkalic igneous rocks in a ratio of about 3 or 4 to 1 more thorium than uranium (Adams, 1954). Thorium is believed to be more stable, and it tends to remain in the source rock when the uranium is leached. The average Th/U ratio for 15 samples analyzed by neutron-activation of the Catahoula from the Manka mine is 5.6 (Dickinson, 1976). The Th/U calculated from the radiometric date of Deux (1971) is 3.0 and does not indicate preferential uranium leaching.

Another source suggested by Weeks and Eargle (1963) is tuffaceous material in the Jackson Group. Thirty-nine samples of tuffaceous mudstone from the Whitsett Formation that were analyzed by neutron-activation methods averaged 13 ppm uranium, and the Th/U ratio averaged 2.4, suggesting that the tuffaceous material of the Whitsett did not substantially contribute to the uranium deposits.

An oxidized ore trend is parallel to and about 2 km northwest of an unoxidized trend. The weathering of the oxidized trend probably provided uranium-bearing water that fed some of the unoxidized deposits downdip and was an additional uranium source for them. This process may have been similar to Gruner's multiple-migration-accretion hypothesis (Gruner, 1956). The oxidized ores probably represent an earlier unoxidized ore trend that has since been partly destroyed by erosion.

Leaching. The uranium was apparently leached from the Catahoula Tuff by a moderately oxidizing alkaline solution (Weeks and Eargle, 1963). Garrels (1957) described how these conditions developed during diagenetic alteration of volcanic glass, and Eargle and Weeks (1973) suggested that these conditions were enhanced by dry-climate weathering. Arid or semi-arid environments have occurred at least intermittently since the Miocene in South Texas (Eargle and others, 1975). Uranium disequilibrium studies by Rosholt (1959, 1963) indicated that small amounts of uranium have mobilized and were redeposited as recently as 10,000 years ago. Studies of uranium distribution in soils in South Texas by Dickinson (1975) indicate leaching during calichification. Several periods of caliche weathering probably supplied abundant carbonate ions to the system, facilitating uranium leaching.

Transportation. After entering solution, the uranium was transported by surface drainage or underground flow to the depositional site. For near-surface sites this flow may have been largely via streams, and for other sites it may have been primarily or entirely underground. Where underground flow occurred, a permeable rock or a fault acted as a conduit. (See Campbell and Biddle, this volume.) In Karnes County some conduits are beach sandstone units that trend parallel to the strike or fluvial units that trend obliquely to it. The sandstone of the beach facies is fine grained and well sorted; that of the fluvial facies is also well sorted but is medium grained. At other deposits, joints or faults having small displacements may have acted as conduits.

Host Rock. The host rock is the rock in which the oxidation-reduction front is located at the time of ore deposition. The host rock may also have served as a conduit. Typically, the uranium enrichment extends beyond the most permeable rock and may include some siltstone or mudstone. In fact, Weeks and Eargle (1963) have proposed that permeability barriers were important aspects of uranium deposition because they tended to retard migrating ground water to allow time for the uranium to precipitate. Large quantities of water must, nevertheless, have passed through the host rock to bring in the uranium.

Reductant. Reductants may be authigenic, generated from within the host rock, or allogenic, coming from outside the host rock. Both kinds may be important in Karnes County. Carbonized plant material is a common authigenic reductant in the uranium host rocks of both beach and fluvial origin. Weeks and Eargle (1963) have postulated that hydrogen sulfide or some other petrolic gas was an important reductant for the uranium deposits of South Texas. Water-soluble organic carbonaceous material may also have served as a reductant in some deposits. The gaseous and liquid reductants originated outside the host and are classed as allogenic.

Important geological implications surround the distinction between authigenic and allogenic reductants. In the case of authigenic reductants, the reductant is consumed by the continuous entry of oxygenated water and as a result, the oxidation-reduction front migrates. Migration of the fronts produces large oxidized tongues typical, for instance, of the Wyoming deposits. Allogenic reductants, on the other hand, are continuously replenished, and a dynamic equilibrium exists between the entry into the system of oxygen via the uranium-bearing ground water and the entry of reductant from an outside source. With an allogenic reductant, a stationary oxidation-reduction front can form without the development of an extensive oxidized tongue. Such a stationary front seems especially likely where a strong allogenic reductant enters through a stationary geologic feature such as a joint or fault. Most unoxidized deposits in Karnes County are found at about the same depth, about 83 feet (25 m) which is about the depth of the present water table. The depth of the water table at the time of deposition is unknown, but many of the Karnes County deposits are at the same general level, which suggests a relation to an ancestral water table. However, the present water table may merely control the boundary between oxidized and unoxidized ore (Finch, personal communication, 1977; see also Campbell and Biddle, this volume).

Preservation. The uranium deposits were preserved as long as they were not invaded by large quantities of oxidizing water or destroyed by erosion. Weeks and Eargle (1963) have suggested that a dry climate has aided in preserving the South Texas uranium deposits. They further suggested that the caliche cap that covers most of the uranium area helped preserve the deposits by restricting leaching. The caliche cap, which is being destroyed by the present subhumid to semiarid climate, was radiocarbon dated at 18,000 years b.p. If a dry climate is necessary for preservation, then dry climates must have persisted for at least 240,000 years, because many of the deposits are in radioactive equilibrium. These arguments probably apply only to the deposits within 300 to 650 feet (100 to 200 m) of the surface. More deeply buried deposits are probably not affected much by the climate. Campbell and Biddle (this volume) discuss this matter further.

Some of the Karnes County deposits may have been dissolved during wet periods and redeposited farther downdip—perhaps in another sandstone unit—near the water table, where a reducing environment was encountered. This process is similar to the multiple-accretion hypothesis of Gruner (1956). A large, continuous, long-lasting influx of oxidizing meteoric water would tend to completely remove the uranium from the system. The uranium deposits in the central, more permeable parts of some of the large channel deposits, such as the one in the Oakville Sandstone south of Karnes County (Eargle and others, 1975), may have been destroyed by the movement of large quantities of ground water through the deposit. This ground water may also have prevented the formation of deposits in excessively permeable rocks. The oxidation of the deposit in the F. Brysch mine by movement of large amounts of water through a fluvial sandstone conduit may represent incipient destruction of an earlier unoxidized roll-front deposit (Dickinson and Sullivan, 1976).

SOUTH TEXAS URANIUM-MINING AREAS

There are three uranium mining areas in South Texas (Eargle and others, 1975), named for the counties of their principal occurrence: Karnes,

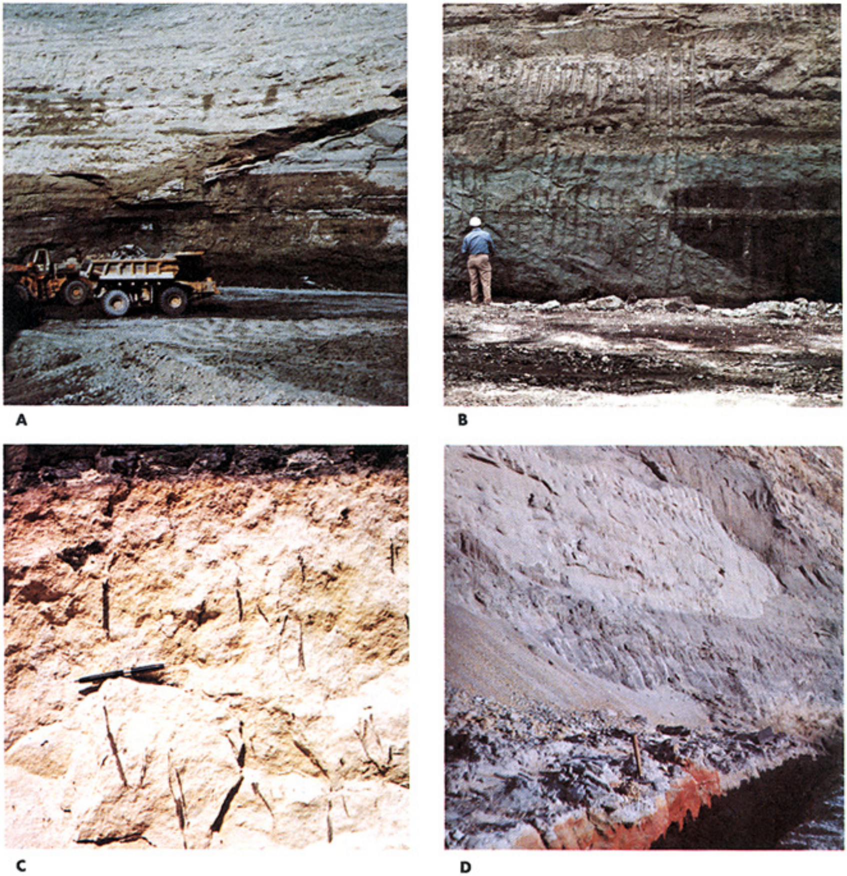

FIGURE 4. Photographs of uranium mine walls in South Texas. A Catahoula Tuff-filled channel eroded into top of Whitsett Formation; ore sand is at level of machinery. The exposure is in the mine on the Brown lease. (B) Leaching by ground water along dipping joints extending through carbonaceous mudstone and lignite of the Fashing Clay Member in the Stoeltje mine (see Figure 5). Man is standing on top of Tordilla Sandstone Member host rock. (C) Carbonized roots at top of Deweesville Sandstone Member uranium host rock in the Searcy mine. Lignite at top of picture is in Dubose Clay Member. Pen is 13 cm long. (D) Ore roll in fluvial Oakville Sandstone near Ray Point in Live Oak County. Oxidized tongue is in upper left (A) and reduced area is upper and lower right (B). Reddish-brown color at base of slope is caused by selenium.

Live Oak, and Duval. They differ primarily in the principal host rock, but also somewhat in the character of the ore. In the Live Oak and Duval areas, the host rock is primarily calcareous fluvial sandstone. Some of the calcareous ores in South Texas are especially amenable to *in-situ* solution mining (Hunkin, this volume), using a weak ammonia-carbonate alkaline reagent. In Karnes County, the host rock is mainly non-calcareous fluvial or marine beach sandstone, although a small amount of uraniferous lignite has been taken from this area as ore. Campbell and Biddle (this volume) discuss uraniferous lignite in some detail.

Karnes Area

The Karnes area includes Karnes County and the southeastern tip of Atascosa County. Areas of high radioactivity have also been found in Gonzales, Fayette, and Washington Counties to the northeast (Figure 1). Campbell and Biddle (this volume) discuss these occurrences.

The host rocks in the Karnes area are mainly beach sandstone beds of the Deweesville and Tordillo Members of the Whitsett Formation; fluvial channel sandstone beds in the Fashing Clay and Dubose Members are also important (Figure 3). One deposit about 2 miles (3km) south of Fashing is in the Catahoula Tuff. The beach units of the Whitsett consist of fine-grained tuffaceous arkosic sandstone. These units, 17 to 100 feet (5 to 30 m) thick, are cross-bedded in the lower part and laminated in the upper part (Dickinson, 1976). They are commonly burrowed by the trace fossil *Ophiomorpha* sp. The beach units are relatively easy to correlate along strike, which trends generally northeastward, but they lense out and change character downdip (Eargle, and others, 1975). The fluvial units, on the other hand, are generally at right angles to the paleoshore, and their exact trend is difficult to predict; they are similar in some ways to the "cross trends" in the Uravan Mineral Belt of the Colorado Plateau. They are difficult to locate on the surface because of poor outcrops. The fluvial sandstone is cross-bedded throughout, is medium grained, and rarely contains *Ophiomorpha*. The fluvial channels apparently had low gradients and were within a few kilometers of the coast. The sand in both channels and beaches originally contained large quantities of volcanic glass, but in some places the glass is altered to one or more of the following minerals: montmorillonite; the zeolite clinoptilolite; alpha-cristobalite; and feldspar. The fluvial sand can generally be differentiated from the beach sand because it is coarse grained (Figure 4). The host rocks dip gently to the southeast and are found in a poorly defined graben formed by the Falls City fault to the northwest and the Fashing fault to the southeast (Figure 5).

The deposition of ore in the Karnes area was controlled, to various degrees, by several geologic factors. One factor was the availability of uranium in water leached from the Catahoula Tuff source rock that unconformably overlay the host rocks. The conduits were commonly the porous beach or fluvial sandstone units that may also have served as host rocks (Figure 4A), but conduits may also have been faults and joints or surface drainage (Figure 4B). Organic matter in the host rocks is an ample source of reductant (Figure 4C), but petrolic gases such as H_2S moving along faults may have been important for some deposits.

Two general types of ore deposits, oxidized and unoxidized, are found in the Karnes area. The oxidized deposits are near the surface and served as the source of first discovery of uranium in South Texas. Principal minerals in the oxidized deposits are the yellow and greenish-yellow autunite and tyuyamunite. These deposits, which were largely mined out during the early 1960's, have been described by Eargle and Weeks (1973), Bunker and MacKallor (1973), and Dickinson and Sullivan (1976). Oxidized ore was taken from the Boso, Bargmann, Hackney, and Luckett deposits (See Figure 5).

More important in both size and number, although generally of lower grade, are the unoxidized deposits that lie at depths of 300 to 650 feet (100 to 200 m) in a northeasterly trend about 1.3 mi. (2 km) south of the oxidized trend. The ore minerals are coffinite and uraninite. These deposits are found primarily in the Tordilla Sandstone Member, but some are found in fluvial channels that existed during deposition of the Fashing Clay Member.

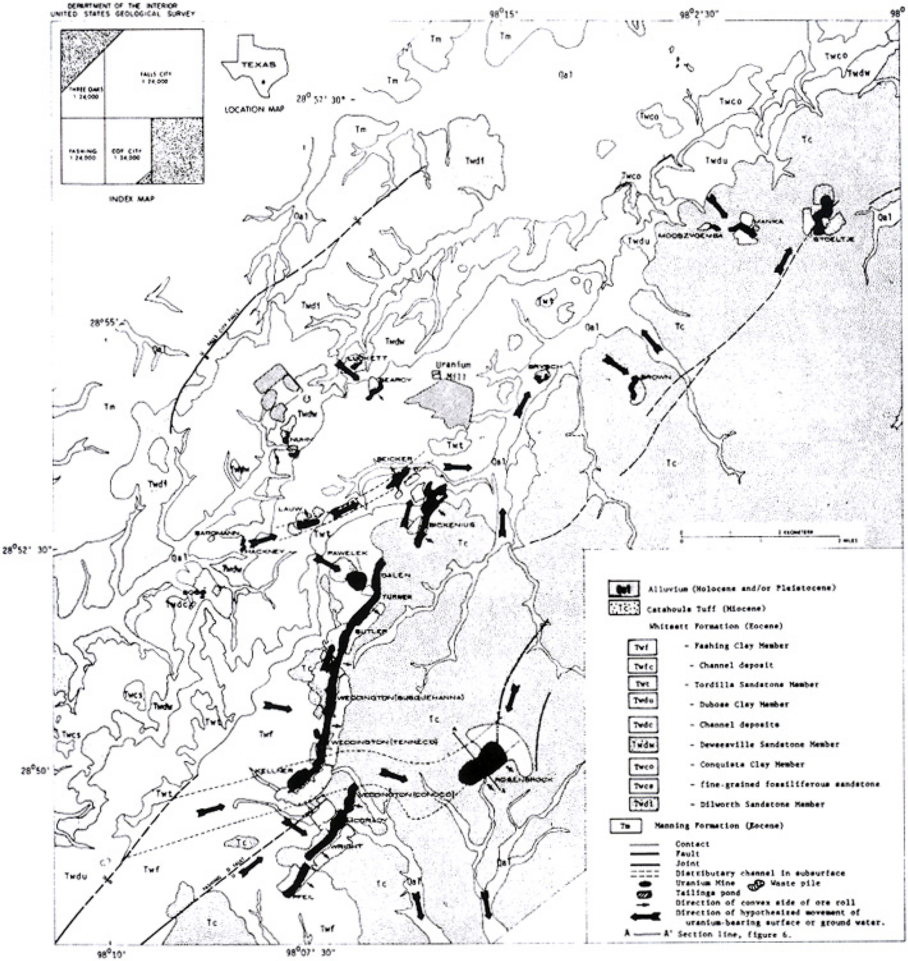

FIGURE 5. Geologic map, Karnes are, showing selected mine location and hypothesized direction of movement of uranium-bearing surface or ground water.

Controls for Individual Deposits in the Karnes Area

The geologic controls for individual deposits in the Karnes area are discussed below; the oxidized deposits along the Deweesville outcrop are not evaluated in this chapter.

Pfeil Mine. The Pfeil deposit extended through the Pfeil, Wright, and McGrady mines and most of the Weddington mine of Continental Oil Company (Figure 5). The uranium-bearing solutions probably entered through the outcropping Tordilla Sandstone Member and through the Kellner channel, which is of Fashing age. The oxidized tongue lies to the northwest and the reduced area lies to the southeast. The convex side of the ore roll points southeastward. The roll-front may have migrated from the outcrop to its present position in response to the downdip movement of uranium-bearing oxygenated ground water within the Tordilla, but the offset between this deposit and the Butler-Galen deposit to the north is a strong indication that the deposition was controlled, at least in part, by the Kellner channel. The Fashing fault was projected into the area (Eargle and others, 1975), but there is no proof that it extends this far or, if it does, where it is located. The reductant for the Pfeil deposit was probably carbonized plant material in or near the host rock. No connection between this deposit and a possible petrolic reductant is apparent, though it cannot be ruled out. The greater downdip migration of this deposit compared to that of the Butler-Galen deposit may have resulted from a weaker reductant in this area.

Butler-Galen Mine. The Butler-Galen deposit was exploited from a series of mines beginning on the southwest with the Tenneco part of the Weddington mining area and extending northeastward through the Susquehanna part of the Weddington, the Butler, the Turner, and the Galen Mines (Figure 5). Uranium leached from the Catahoula entered the deposit via the Kellner channel at the southwest end and through the Tordilla Sandstone Member from the updip outcrop edge. Some uranium may have been dissolved from or passed through the Pawelek deposit (See below). Host rocks are the Tordilla Sandstone Member and the Kellner channel deposit of the Fashing Clay Member. The convex side of the roll lies to the southeast and the oxidized tongue lies to the northwest. In general, the movement of uranium-bearing ground water through the deposit was from northwest to southeast. Water movement was restricted along the northeast end, where porosity was greatly reduced by diagenetic siliceous cement. The reductant was probably carbonized plant material in the host rock and petrolic gases. Oil- and gas-producing holes penetrate the deposit and are found in the area just north of it (Figure 5).

Sickenius Mine. Conquista Creek, which drains a large area of Catahoula terrane and an area of Jackson terrane that contained oxidized uranium ore, crosses the Tordilla outcrop at the northeast end of the deposit (Figure 5). The uranium-bearing Conquista Creek waters apparently entered the host rock at or near this juncture, which would tie the age of the ore emplacement to the modern drainage pattern. This tie is further substantiated by disequilibrium between uranium and its daughter products, which indicates an age less than about a quarter million years for the uranium in this mine. During the early mining on this property, only the near-surface ore from the northeast part of the mine was removed. This ore was mostly lignite in the lower part of the Fashing Clay Member. Later, unoxidized ore from the Tordilla Sandstone Member was removed from the south and west portions of the mine. Siliceous cement, including clinoptilolite and cristobalite, apparently limited mineralization to the southwest along the trend (Figure 5). The siliceous "caprock" in the southwest end of the mine was broken up with explosives prior to mining.

Kellner Mine. Uranium-bearing waters from drainage of Catahoula terrane entered a porous channel deposit in the Fashing Clay Member, herein termed the Kellner channel (Figure 5), and traveled downdip southeastward to the depositional site where both medium-grained sandstone and underlying mudstone deposits were mineralized. The sandstone is well-sorted, medium-grained zeolitized arkose. This ore consisted of three separate bodies and did not conform to the ore-roll shape. Although the reductant is largely unknown, carbonized leaves and other plant matter were contained in the host rock.

Rosenbrock Mine. The Rosenbrock uranium ore body was deposited in the Kellner channel of the Fashing Clay Member about 2 mi. (3 km) east of the Kellner mine. The ore roll is at a depth ranging from 233 to 300 feet (70 to 90 m). The mine for this deposit was the deepest open-pit uranium mine in South Texas as of January 1, 1977, and at that time it was still being stripped. The oxidized side of the ore roll is to the north. The channel is eroded into and is at about the same stratigraphic position as the Tordilla Sandstone (Figure 6). The uranium-bearing water apparently entered the deposit from the Kellner channel, and the roll front may have migrated down this channel. Lineaments noted on aerial photographs intersect the deposit. They are believed to be joints or low-displacement faults that may have affected movement of ground water or reductants at the deposit. The deposit also lies in a slight down-flexed zone (Figure 6).

Brysch Mine. The Brysch deposit was apparently formed where uranium-bearing water of the Conquista Creek flows over lignite and sandstone beds in the Dubose Clay Member. The mine was completely filled with water at the time it was seen by the authors, and only the waste piles were available for study.

Mocszygemba-Manka Mine. The Mocszygemba-Manka deposit (Figure 5) was found in an area where the Catahoula unconformably overlies the lower part of the Fashing Clay and the Tordilla Sandstone Members. Channels at the base of the Catahoula were probably important in localizing uranium-bearing ground-water flow. A lignitic layer at the base of the Fashing and carbonaceous material in the Tordilla host rock probably provided the reductant.

Stoeltje Mine. The Tordilla Sandstone Member is the host rock for the Stoeltje deposit, which lies just north of the Hobson oil field (Figure 5). The Tordilla is overlain by the Fashing Clay Member, which, in turn, is overlain unconformably by fluvial deposits of the Catahoula Tuff. The deposit is transected by joints along which uranium-bearing water probably entered. One joint contains a clay deposit ranging from ¾ to 4 in. (2 to 10 cm) in thickness that reportedly predated and locally limited uranium emplacement. The Tordilla Sandstone Member contains grains of quartz, feldspar, and volcanic glass, and is weakly cemented with montmorillonite. The sandstone is mostly crossbedded and contains *Ophiomorpha* and clasts of lignite and clay. The mudstone unit overlying the basal lignitic layer of the Fashing Clay Member in the Stoeltje mine is saturated with water-soluble organic matter (J. Leventhal, oral communication, 1975) that may have been the reducing agent for this ore body. The organic material is leached out in the vicinity of the joints (Figure 4). The proximity of the Hobson oil field indicates a petrolic reductant, but the abundance of organic material in the host rock suggests that either or both could have been the reductant. The configuration of the ore roll is contorted and is not completely known to the authors.

Brown Mine. The Brown deposit is geologically similar to the Mosczygemba-Manka deposit. The Catahoula, with fluvial channels at its base, unconformably overlies the Fashing Clay Member, The channels in the base of the Catahoula seem to have been important in localizing the mineralization. The host rock, unlike that in most of the Karnes area deposits, consists of thinly interbedded sandstone or siltstone and claystone. The host rock may have been laid down under tidal-flat or lacustrine conditions.

Pawelek Mine. The uranium host rock in the Pawelek deposit (Figure 5) was mostly a lignite at the base of the Fashing Clay Member that directly overlies the Tordilla Sandstone Member. A small body of oxidized uranium ore was removed from the sandstone below the lignite. The average depth to the ore was about 15 m. The deposit was above the water table. Uranium-bearing water from the Catahoula terrane to the south apparently entered along the outcrop of the Fashing Clay Member, perhaps through the lignite itself.*

*This may have a significant impact on "frontier" exploration. See Campbell and Biddle, this volume: Chapter 1.

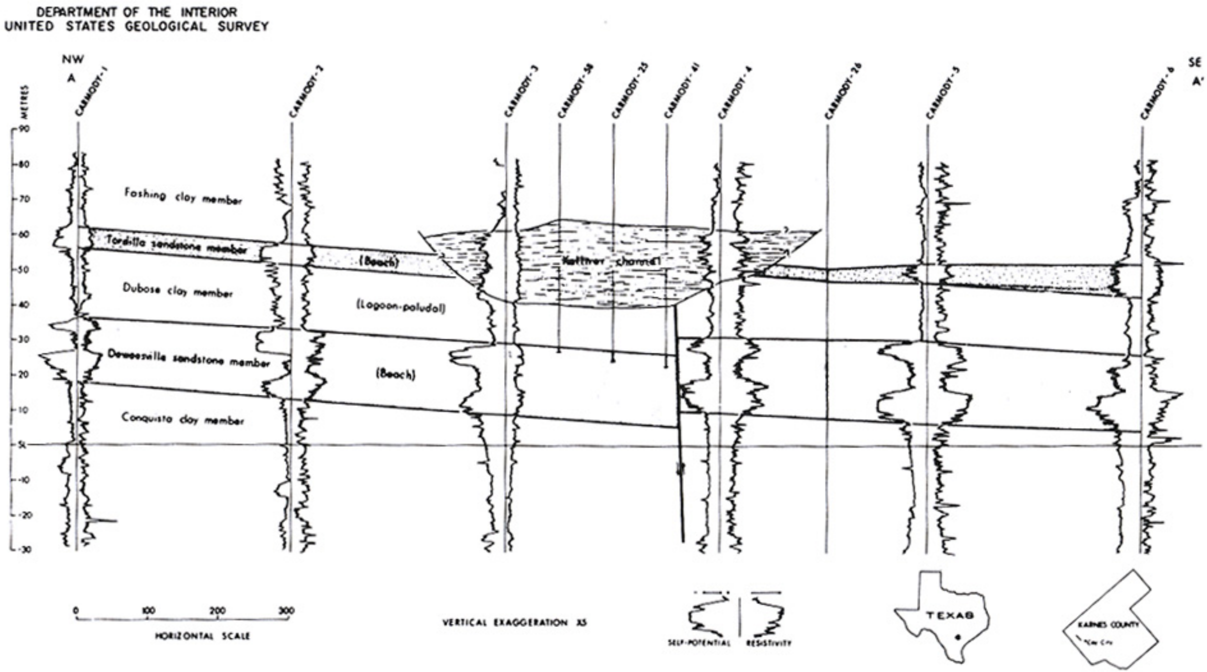

FIGURE 6. Electric-log section across Rosenbrock uranium deposit (profile A-A' on Figure 5). Deposit is in Kellner Channel of Fashing Clay Member and is eroded into Tordilla Sandstone and Dubose Clay Member of Whitsett Formation (see also Dickinson, 1976, Figure 3).

Lauw and Beiker Mines. The Lauw and Beiker deposits are discussed together, even though they are nearly 0.9 mi. (1½ km) apart (Figure 5), because the host rocks are both channel deposits believed to be part of the same channel. This channel is in the Dubose Clay Member and is herein termed the Lauw channel. It may have eroded in places into the underlying Deweesville Sandstone Member. The uranium-bearing water probably entered the channel deposit in the area east of Tordilla Hill, where the channel sandstone crops out. The channel deposit has not been definitely recognized in surface exposures owing to soil cover in the area, but a small outcrop of cross-bedded sandstone (*Twdc,* Figure 5) in a roadcut along highway FM 791 north of Tordilla Hill may be in this channel. The uranium was in a roll that is unoxidized on the northwest side, the opposite side from that of the other rolls in the Karnes area. The updip movement of the uranium-bearing water was probably caused by the movement of the ground water from the Lauw channel to the stratigraphically lower Deweesville Sandstone Member. The reductant in these deposits is probably the carbonized wood in the host rock. The channel sandstone is fine- to medium-grained, is cross-bedded, and contains *Ophiomorpha* burrows, suggesting that the channel was a distributary channel not far from a coast.

Searcy Mine. The Searcy deposit lies in the divide between Conquista and Scared Dog Creeks, just south of the Luckett deposit, an oxidized ore body in the Deweesville Member. The host rock for the Searcy is also the Deweesville, and the uranium-bearing water probably resulted from solution of uranium during weathering of deposits in the oxidized trend approximately 300 feet (100 m) to the northwest. The Deweesville Sandstone was deposited in a beach and back-beach environment. It contains abundant carbonized plant matter, an ample source of reductant. The configuration of the roll in this deposit is controlled by a thin mudstone unit believed to have been deposited within the beach sequence in a hurricane washover or tidal pond.

Live Oak Area

The Live Oak area includes most of Live Oak County. The main host rock is the Miocene Oakville Sandstone, although one deposit, the Mabel New Mine, 9 mi. (14 km) northwest of Three Rivers, was reported to be in basal fluvial sandstone of the Oligocene (?) Frio Clay (Eargle and Weeks, 1968). The source of the uranium in the Live Oak area deposits is believed to have been the underlying Catahoula Tuff.

Mabel New Mine. It contained the only known oxidized deposit in this area. According to Eargle and Weeks (1973), the host rock consists of lenses of fossiliferous sandstone as much as 6.5 feet (2.5 m) thick deposited in a channel near the base of a ferruginous, tuffaceous, gypsiferous clay unit 650 to 1000 feet (200 to 300 m) thick. The ore was scattered in irregular masses along the margins of a 900-ft (300-m)-wide channel. The ore minerals were boltwoodite and weeksite, which are rather unique for the South Texas deposits. The ore was generally out of equilibrium, and a few concretionary pyritic masses were very rich in uranium, containing several percent $_cU_3O_8$. An explanation for ores having relatively high $_cU_3O_8$ percentages is under investigation. These characteristics suggest that the near-surface deposit was being gradually destroyed by oxidizing surface waters, as was the case for deposits in the Karnes area.

The most important ores in the Live Oak area are unoxidized deposits in the margins of a major alluvial system that trends east-southeast (Eargle, 1975, Figure 7). The Felder, McClean, Kopplin, and Smith open-pit mines, and a new *in-situ* leaching plant about 1 mile (1½ km) east of the Felder mine are located along the northern margins of this fluvial system. Uranium is also being produced from two deposits, the Burns and the Clay West mines, along the southern margin of the system located 8 miles (13 km) southwest of George West (Eargle and others, 1975).

Felder Mine. It was described in detail by Klohn and Pickens (1970), and several important points from their work are summarized here. The Oakville Sandstone lacks sufficient carbonaceous material to have had an authigenic reductant; the reductant was allogenic, apparently petrolic H_2S gas introduced through faults. The deposit was in the form of a winged crescentic roll at a depth of about 50 feet (15 m). It was 2,433 feet (730 m) long, 150 feet (45 m) wide, and 27 to 40 feet (8 to 12 m) thick. The ore averaged 0.35 percent eU_3O_8. A radioactive anomaly produced by a broad halo of weak mineralization around the ore body extended about 2,500 feet (750 m) updip and about 1,000 feet (300 m) downdip. Anomalous concentrations of selenium and molybdenum were also associated with the ore body (Figure 4D). Pyrite was apparently formed from magnetite in the downdip, reduced part of the roll, and hematite and limonite were formed from pyrite in the oxidized tongue. Clay stringers localized uranium deposition and retarded oxidation of parts of the deposit.

Duval Area

The Duval area consists of Duval County, southwestern Live Oak and McMullen Counties, and a belt extending from Duval County to the Mexican border which is made up of southeastern Webb, eastern Zapata, and western Jim Hogg and Starr Counties (Figure 1). No open-pit mining has been undertaken in this area, but several deposits have been found and three *in-situ* leaching plants are in operation. These plants are located about 10 km north of Bruni, about 10 km east of Bruni, and at the Palagana salt dome.

All of the known deposits in the Duval area are in the Catahoula Tuff except for the one at the Palangana dome, for which the host rock is the Goliad Sand. In this area the Catahoula Tuff consists of porous sandstone and conglomerate sequences, fining-upward, which were deposited in channels, and finer mudstone and claystone units, which were deposited in inter-channel areas on the flood plain. The Catahoula sediment is composed mainly of quartz, feldspar, calcite, and montmorillonite, and rarely of zeolite and opal. Some samples contain volcanic glass, but in most it has been altered to clay. The Goliad Sand host rock at Palangana dome consists of light-gray, fine- to medium-grained, friable sandstone interbedded with clayball conglomerate (Weeks and Eargle, 1960). This rock consists of grains of feldspar and quartz lightly cemented with calcite. Over the dome the rock is greenish-gray, and contains pyrite; in scattered areas it is impregnated with oil (See Campbell and Biddle, this volume). Faults are present in the Duval area and are commonly marked by siliceous knobs 33 to 67 feet (10 to 20 m) high which have formed from chalcedony and calcite (Eargle and others, 1975).

The geologic controls for uranium deposition in the Duval area were very similar to those in the Live Oak Area. The uranium-bearing water derived from the Catahoula Tuff traveled through porous channel sandstone bodies enclosed in less porous, clayey flood-plain deposits until it reached a strong reductant. Lack of significant quantities of organic matter in the Catahoula or Goliad host rock and the abundance of oil and gas fields in the area suggest that the reductant was a petrolic gas probably containing H_2S. The gas traveled up the faults and to some extent through the porous sandstone bodies. Deposits are typically found at the intersections of faults and channel sandstone bodies.

All of the known deposits in the Duval area are unoxidized, and most are in the form of ore rolls. The deposits are calcareous and require alkaline leaching for uranium extraction (Hunkin, this volume).

Character of the Deposits

Most of the uranium deposits in South Texas are unoxidized ore rolls in porous fluvial-and beach-deposited sandstone units. Ore rolls are linear deposits elongate in a direction perpendicular to the direction of movement of the uranium-bearing solutions. The ore rolls are crescent-shaped in cross section, and the wings point in a direction opposite to that of fluid movement, which is generally downdip (see Campbell and Biddle, this volume, Figures 1, 17).

Exceptions to the ore-roll configuration are found in the oxidized deposits in Karnes and Live Oak Counties and in some unoxidized or reduced deposits, such as the one at the Kellner mine. In the Kellner deposit, the ore body was in the form of three discrete more or less tabular bodies, not in the roll shape. This deposit was apparently formed by partial precipitation of the uranium from the solution, which also continued further downdip and deposited the ore roll in the same channel sandstone in the Rosenbrock lease (Figure 6). Other exceptions to the common roll configuration are found in certain "re-reduced" deposits (McKnight, 1972). At these deposits the prior oxidation-reduction cell may have been engulfed in a second reducing environment, and the oxidized upstream portion of the former cell is reduced. The "re-reduction" is the result of dynamic equilibrium between the movement of oxidizing ground water through the front, on the one hand, and of mobile, probably gaseous, reductant on the other. Exceptions to the typical ore-roll orientation are found in the Lauw and Beiker mines, where ground water movement and roll migration were in an updip, northwesterly direction (Figure 5). This reversal in direction results from a hydrological condition in which paleochannels or faults permitted water flow across rather than parallel to the bedding planes, perhaps by artesian interaquifer transfer as indicated by Campbell and Biddle (this volume).

The oxidized deposits may originally have been roll deposits, but they have been altered by weathering. The deposits tend to be out of radioactive equilibrium in favor of eU_3O_8, suggesting geologically recent alteration. The shape of the oxidized uranium deposit at the F. Brysch mine suggests that the original deposit was a roll deposit that was subsequently altered (Dickinson and Sullivan, 1976).

In general, the Karnes area deposits are not calcareous and were processed by acid leaching, and the ore in the Live Oak and Duval areas is limey and is processed by alkaline leaching. Some uraniferous lignite, mined in the Karnes area, is mixed with sandstone ore or roasted prior to processing.

EXPLORATION TECHNIQUES

The original uranium discovery in South Texas was made using an aerial radiometric survey in 1955. Since that time, drilling, accompanied by gamma-ray and electric logging, has been the chief exploration tool. Gross-count aerial radiometric surveys, hand-held scintillometers, and geologic mapping using aerial photographs have also been used. Drilling has been extensively used because of the shallow depths (see discussion of standard exploration drilling techniques, Campbell and Biddle, this volume). As uranium deposits become even more difficult to locate, however, and as exploration extends deeper into the subsurface and drilling costs rise, more sophisticated exploration methods will be required.

Some aerial, surface, and in-hole techniques that show promise are discussed below.

Aerial Methods

Aerial exploration methods are attractive for regional evaluation because large areas can be covered quickly, the cost per unit area is low, they are not encumbered by land access problems, and they can collect geologic data in areas of poor outcrop. Although other aerial methods may be of value, only radiometrics and thermal infrared are evaluated here.

Aerial radiometric surveys are being improved largely through the use of better equipment that includes larger volume detectors; this equipment provides quality data, and less error, and permits the calculation of the eU/eTh ratio. These data also permit the use of more sophisticated data-analysis and data-presentation techniques (Figures 7-8).

Frequency distribution patterns—that is, the count rate plotted against the number of points having that count rate—can provide useful geologic data. Frequency distributions of potassium (K), equivalent (or radiometric) uranium (eU), and equivalent thorium (eTh) for three geologic formations were taken from an aerial survey in Duval, Live Oak, McMullen, and Webb Counties, Texas (Schulz, 1975) (Figure 7). In a geologic formation of uniform lithologic character, the frequency distributions of all three radioelements would be symmetrical about a mean value. If two or more of the radioelement distributions are

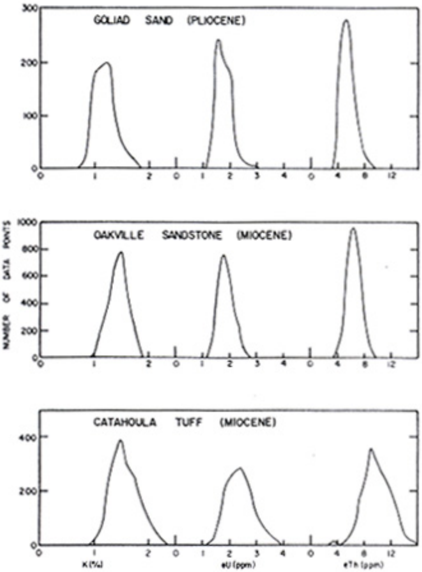

FIGURE 7. Frequency distributions of K, eU, and eTh for the Goliad Sand, Oakville Sandstone, and Catahoula Tuff taken from an aerial survey in Duval, Live Oak, McMullen, and Webb Counties, Texas.

asymmetric, the geologic formation as mapped at the surface is not uniform. If only the eU distribution is asymmetric, that formation may have a greater potential for uranium mineralization.

The frequency distributions of eU and eU/eTh shown in Figure 7 indicate that the formations are not homogeneous units as mapped in the area of the survey. In fact, on the basis of these data, certain areas mapped as Goliad Sand and as Catahoula Tuff more closely resemble areas mapped as Oakville Sandstone.

Simplified contour maps of the ratio eU/eTh and of eU are shown in Figure 8. An area of higher eU values trends northeast-southwest, whereas the area of high eU/eTh trend, not the eU trend, correctly reflects the trend of known uranium mineralization in the survey area. Gross-count radiometric data, even with qualitative spectrometric data, would not correctly outline the mineralized area.

Aerial thermal infrared surveys offer another means of delineating potential exploration targets. This technique produces images that show temperature contrasts on the ground surface. The contrasts are caused by differences in the physical properties of the surface—differences in density, thermal conductivity, specific heat, and reflectivity. Thermal images may discriminate various lithologic units, they may show silicified or water-saturated fault zones, and they may show alteration halos around uranium deposits. Examples of the use of thermal images for identifying rock types and for delineating structural features are given by Sabins (1969); Rowan and others (1970), and Wolfe (1971). Day and night thermal images of a small area centered along Texas Route 16 about 8 mi (13 km) north of Freer, Texas, are shown in Figures 9a and 9b. As described by Offield (1976), several features of geologic significance, such as warmer conglomerate-filled channels, can be seen on the night image in more detail than they are shown on geologic maps of the area. The day image by itself shows little of geologic interest. The conglomerate fill is warmer because it has a relatively high thermal inertia, which is a function of density, thermal conductivity, and specific heat. In other words, the conglomerate holds the solar heat longer after sunset than does the surrounding rock. The night image also shows a linear tonal change along the Piedra Lumbre fault and a warm lineament that marks a parallel fault. In the northeast part of the image area, Oakville Sandstone outliers on the Catahoula Tuff stand out as a train of small warm areas. Southeast of these outliers is a "warm" area believed to generally represent the outcrop area of the Oakville Sandstone, although the warm area is not in complete agreement with presently available geologic maps.

A temperature-difference (ΔT) map may be constructed by combining the day and night images (Figure 9c). This map directly indicates the amplitude of the diurnal heating cycle for each material and is basically a measure of thermal

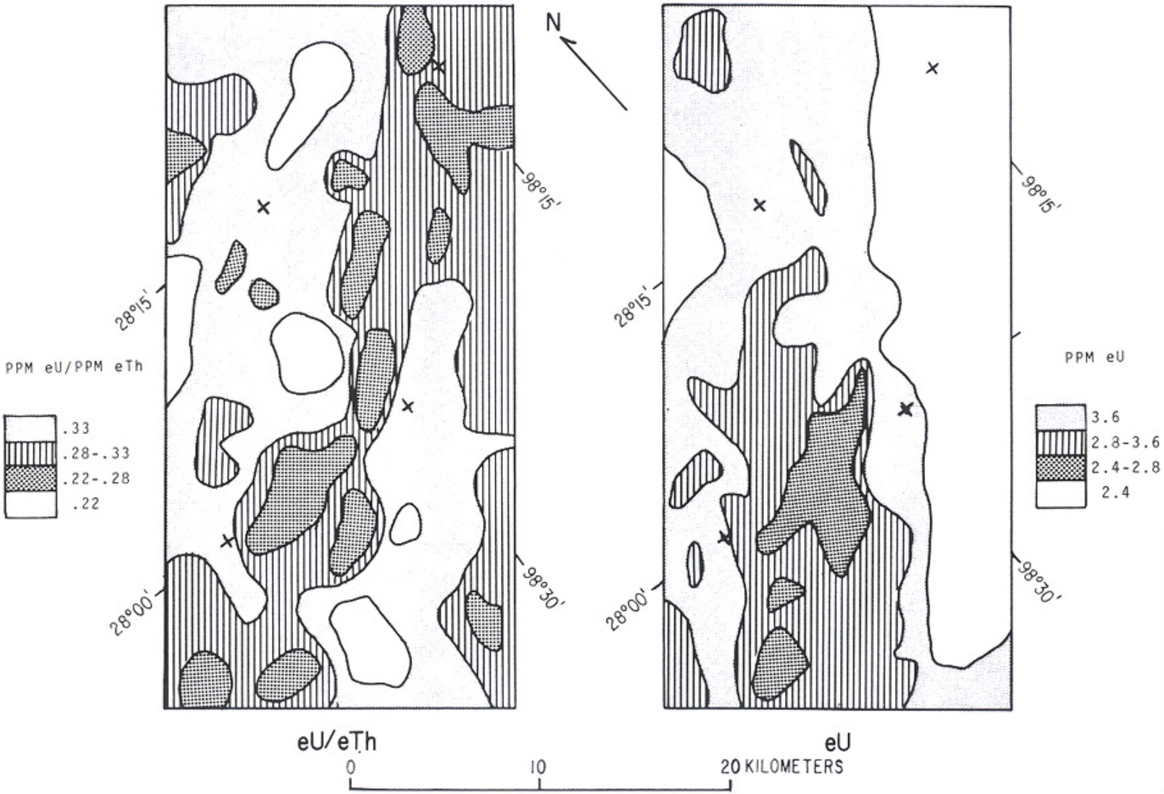

FIGURE 8. Simplified contour maps of eU/eTh and eU taken from an aerial survey in Duval, Live Oak, McMullen, and Webb Counties, Texas. The denser patterns represent higher values.

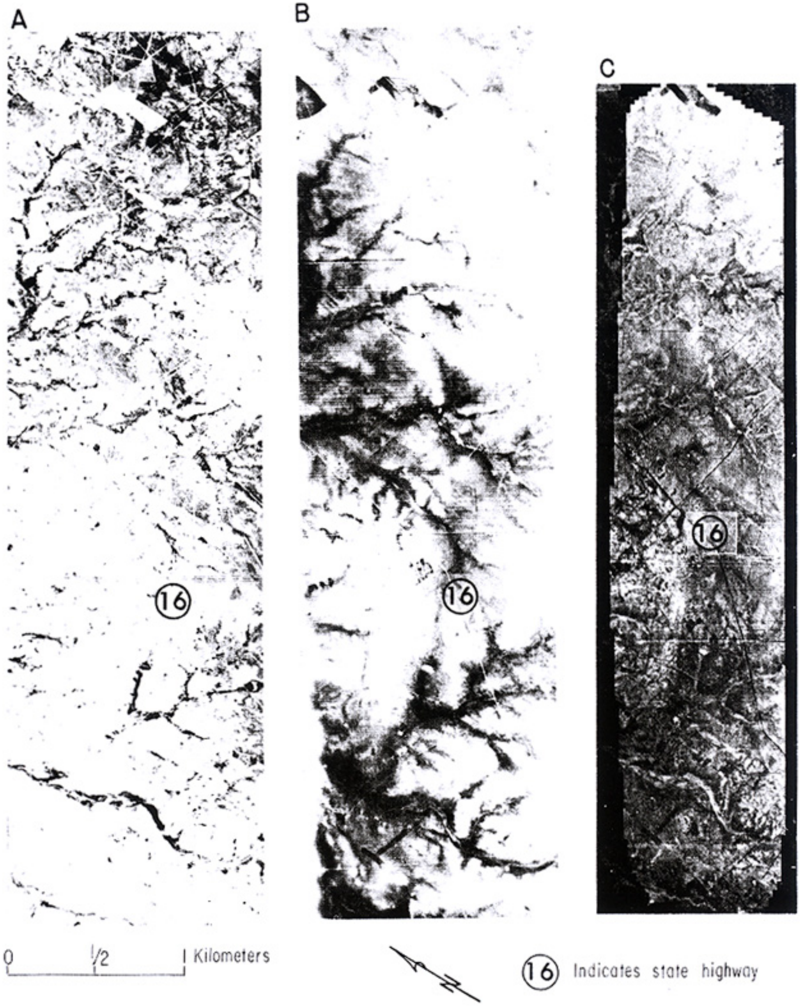

FIGURE 9. Thermal-infrared images of area north of Freer, Texas: A. Day image; B. Night image; bright tones are warm; dark tones are cool; sides of images of oriented N45E, C. Day-night temperature-difference (ΔT) image (slight scale difference: edge data best in image-registration process).

inertia. The ΔT image shows details within the channel fill and Oakville Sandstone areas that are different from those shown in the night image. These variations suggest minor lithologic differences within the units—probably differences in grain size, packing, or cementation.

Surface Methods

Surface geophysical techniques that may be useful at the intermediate and detailed reconnaissance stages of uranium exploration include gamma-ray spectrometry, radon and helium emanometry, magnetics, very low frequency (VLF) electromagnetic methods, and induced polarization (IP) measurements. Attempts to use gravity data at this scale have failed because of the extreme precision and detail required, but gravity studies may be relevant on a regional scale.

Surface gamma-ray spectrometry, which separates the radioactivity due to uranium and thorium, is an improvement over the older gross-count methods, which measure total radioactivity, and is the best way to locate eU/eTh ratio anomalies that do not have an associated gross-count anomaly. Suitable spectrometers may be portable or vehicle-mounted.

Radon emanometry has also been improved with the use of nuclear emulsions and solid state detectors. Measurement of the average radon emanation over a sufficiently long period of time to allow local meteorological effects to average out is now possible (Gingrich, 1975). Helium emanometry is still in the development stage, and the major difficulty is that the atmospheric background levels are high, which require very precise measurements (Reimer and others, 1976; Adkisson and Reimer, 1976). An interesting aspect of emanometry is that it has the potential for locating deeply buried deposits, although the radon transport mechanisms and the true sources of the detected radon have not yet been established.

Measurement of the total magnetic field can be useful if the local ore deposition process altered the distribution of magnetic minerals, or if the host rocks contrast magnetically with the surrounding rock. The ore-producing oxidation front frequently modifies the magnetic character of the host rock. The process of alteration may destroy magnetite in the oxidized rock and thus produce a relative magnetic low, or it may create magnetite and produce a magnetic high. The magnetic contrasts can be detected at depths of as much as 333 to 1,000 feet (100 to 300 m) using a sensitive magnetometer. A magnetic profile that clearly reveals a roll front in northern Colorado is shown in Figure 10.

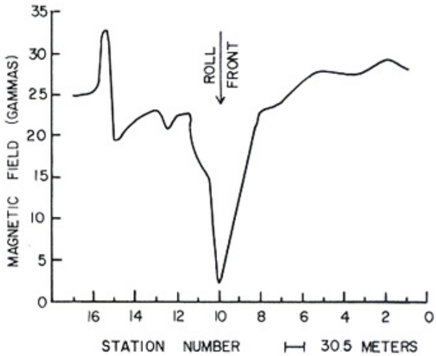

FIGURE 10. Total magnetic field measured across a roll front in northern Colorado (Smith and others, 1976).

Measurements of induced polarization (IP) provide data on the apparent resistivity and chargeability of the earth. Differences in these parameters may be caused by sulfide minerals, alteration of the clay minerals, or chemical differences in the ground water (See Campbell and Biddle, this volume). IP anomalies have been found within 133 ft. (40 m) of a known uranium deposit according to Smith and others (1976). They concluded, on the basis of core samples, that the anomalies are related to pyrite and montmorillonite in the host rock and that IP surveys could be useful in pinpointing drilling targets.

In-Hole Methods

As it becomes necessary to explore for deeper uranium deposits, in-hole methods become more important than surface or aerial methods. Various borehole methods currently in use or under study include direct uranium measurements, gamma-ray spectrometry, resistivity, spontaneous potential, magnetic susceptibility, and induced polarization. Spontaneous potential and resistivity allow lithologic interpretation, but uranium explorationists will need to consider other logs, such as density logs using scattered gamma rays or porosity logs using sonic and neutron-scattering tools to obtain additional lithologic information.

As briefly discussed by Campbell and Biddle (this volume), in some deposits the uranium is not in equilibrium with its daughter products and in these cases, techniques that measure the daughter products such as gross-count gamma-ray or even gamma-ray spectrometry, do not give an accurate measure of the uranium content. For such deposits two methods, both using neutron activation, are being studied. One method uses lithium-drifted or intrinsic germanium detectors, and the other uses neutron detection techniques. The germanium detectors measure gamma rays produced by radiative capture and delayed gamma-ray activation. These data also provide information on other elements. Various authors have discussed the use of germanium detectors (Moxham and others, 1972; Tanner and others, 1972a, 1972b). Givens and others (1976) discussed the measurement of delayed-fission neutrons and Bivens and others (1976) described the measurement of prompt-fission neutrons.

The gamma-ray sonde, even though subject to disequilibrium error, will continue to be a valuable exploration tool because it has a much lower detection limit than do the neutron activation methods. Furthermore, the gamma-ray techniques, when combined with the spontaneous potential and resistivity logs, provide data for lithologic interpretation.

Geochemical halos may be detected, as discussed by Scott and Daniels (1976), by the use of electrical resistivity, induced polarization, and magnetic susceptibility. These techniques may be applied between holes during exploration in order to reduce the number of holes needed to evaluate a deposit, and they would offer a great savings, especially for deep deposits.

URANIUM POTENTIAL OF THE AREA

What is the geologic potential for large new uranium resources in the Tertiary of the South Texas Coastal Plain? This important question is now facing uranium geologists in South Texas. Surface and near-surface areas may yet yield important uranium deposits, but intensive exploration has proceeded in this area for more than 20 years and most of these deposits have been found. The deeper subsurface, more than 300 feet (100 m) deep, is relatively unexplored and does offer potential for significantly increasing our uranium reserves. The mode of formation of uranium deposits in the deeper subsurface is nearly the same as for the present uranium-producing areas. Depth of burial is the chief difference, although the depth of burial at the time of uranium deposition is unknown. The Catahoula appears to have been a possible source rock about as far downdip to the southeast as the present coastline, where it grades into marine facies at depths of about 3,333 to 10,000 feet (1,000 to 3,000 m). Some doubt about the potential for this deep uranium results from lack of knowledge about the extent to which the formation of epigenetic uranium deposits depends on near-surface weathering. Campbell and Biddle (this volume) suggest that the proximity of ore deposits to the land surface is fortuitous and that uranium mineralization is controlled by geochemical and geological factors in the subsurface.

A little more than 14 million pounds (7,000 tons) of U_3O_8 concentrate have been produced from the South Texas uranium areas as of January 1, 1975 (Carl Applin, ERDA, oral communication). The National Uranium Resource Evaluation, Preliminary Report (ERDA, 1976) estimated about 100 million pounds of ore (50,000 tons) of "probable" *potential* resources in the central coast (Karnes County area) and 86 million pounds (43,000 tons) in Duval County. It also assigned 76 million pounds (38,000 tons) of "possible" *potential* resources to Duval County and 172 million pounds (86,000 tons) of "possible" *potential* resources to Starr County. It estimated 14 million pounds (7,000 tons) of "probable," 6 million pounds (3,000 tons) of "possible," and 62 million pounds (31,000 tons) of "speculative" *potential* resources in East Texas. It should be emphasized here that these estimates are in terms of *in-situ* ore, not produced yellowcake. Campbell and Biddle (this volume) discuss ERDA estimates of potential resources in East Texas and elsewhere in the South-Central United States. Definitions of ERDA potential resource categories follow:

"Probable *potential* resources" are those estimated to occur in known uranium districts and are further postulated to be:

1) in extensions of known deposits;
2) in new deposits within trends or areas of mineralization that have been identified by exploration.

"Possible" *potential* resources are those estimated to occur in new deposits in formations or geologic settings productive elsewhere:

1) within the same geologic province or subprovince under different geologic conditions;
2) within the same geologic province or subprovince under similar geologic conditions.

"Speculative" *potential* resources are those estimated to occur in new deposits:

1) in formations or geologic settings not previously productive within a productive geologic province or subprovince;
2) within a geologic province or subprovince not previously productive.

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