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The Geologic Parameters Affecting In Situ Leaching of Uranium Deposits

by

Robert A. Brooks

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Illustrations

THE GEOLOGIC PARAMETERS AFFECTING IN SITU LEACHING OF URANIUM DEPOSITS

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ABSTRACT

This report contains material presented at the Uranium Leach Conference, which was held in Vail, Colo., August 25-27, 1976. The purpose of the presentation was to summarize some important geological concepts to a largely nongeological audience involved in the in situ extraction of uranium from buried uranium ore deposits. The major geological feature affecting the leaching of sandstone-type deposits is permeability. Important permeability variations may be caused by sedimentary structures, texture, structure, composition, and lithology. The effects of these features on leaching uranium are discussed. The major uranium districts of the U.S. and the various factors that would affect permeability and, consequently, uranium extraction in these districts are also discussed.

INTRODUCTION

This paper contains the material presented by the author at the Uranium Leach Conference, which was sponsored by the American Association of Petroleum Geologists and the Society of Mining Engineers of AIME. The meeting was held in Vail, Colo., on August 25-27, 1976. This paper is not a transcript of the talk but has been constructed from notes used for the oral presentation. The talk was presented to a group composed largely of nongeologists and, as such, was merely intended to expose the audience to some geological features that may affect the leaching of uranium deposits. The material herein was derived from many published descriptions and from personal observation. The list of references included is not at all comprehensive; however, detailed descriptions of both the geological principles and the various described uranium districts can be found in most technical libraries.

In the United States, more than 95 percent of high-grade uranium resources are found in sandstones. Figure 1 shows the principal uranium producing areas of the United States. Except for the deposits (marked by circles) near Spokane, Wash., the Front Range of Colorado, all uranium deposits shown occur in sandtones. Most of the operating or planned uranium leaching operations are situated on sandstone deposits. This discussion will therefore be confined to sandstone-type uranium deposits and those geologic parameters that affect the leaching of sandstone-type uranium deposits. In the first part of this paper, some general principles of sandstones will be discussed. The manner in which these principles may be important in known uranium producing districts is described in the second part. Experience shows that ore recovery rates encountered in in situ leach operations average only about 65 percent of the ore present, and it is suggested that the features discussed here are largely responsible for these low recovery rates.

Understanding the composition and texture of sandstones is important simply because these features control both the ore deposition and ore extraction. The location of the ore within the sandstone is a function of the flow of ore-bearing fluid through the sandstone. More pertinent to this discussion, however, is fact that in situ leaching of uranium deposits depends on the flow of the lixivant (the leaching fluid) and the resulting pregnant liquor (the uranium-bearing solution) through the sandstone. The flow of these solutions should be thoroughly understood. Fortunately, much is known about the flow of fluids through sandstone bodies, and this knowledge is directly applicable to in situ leaching of uranium deposits.

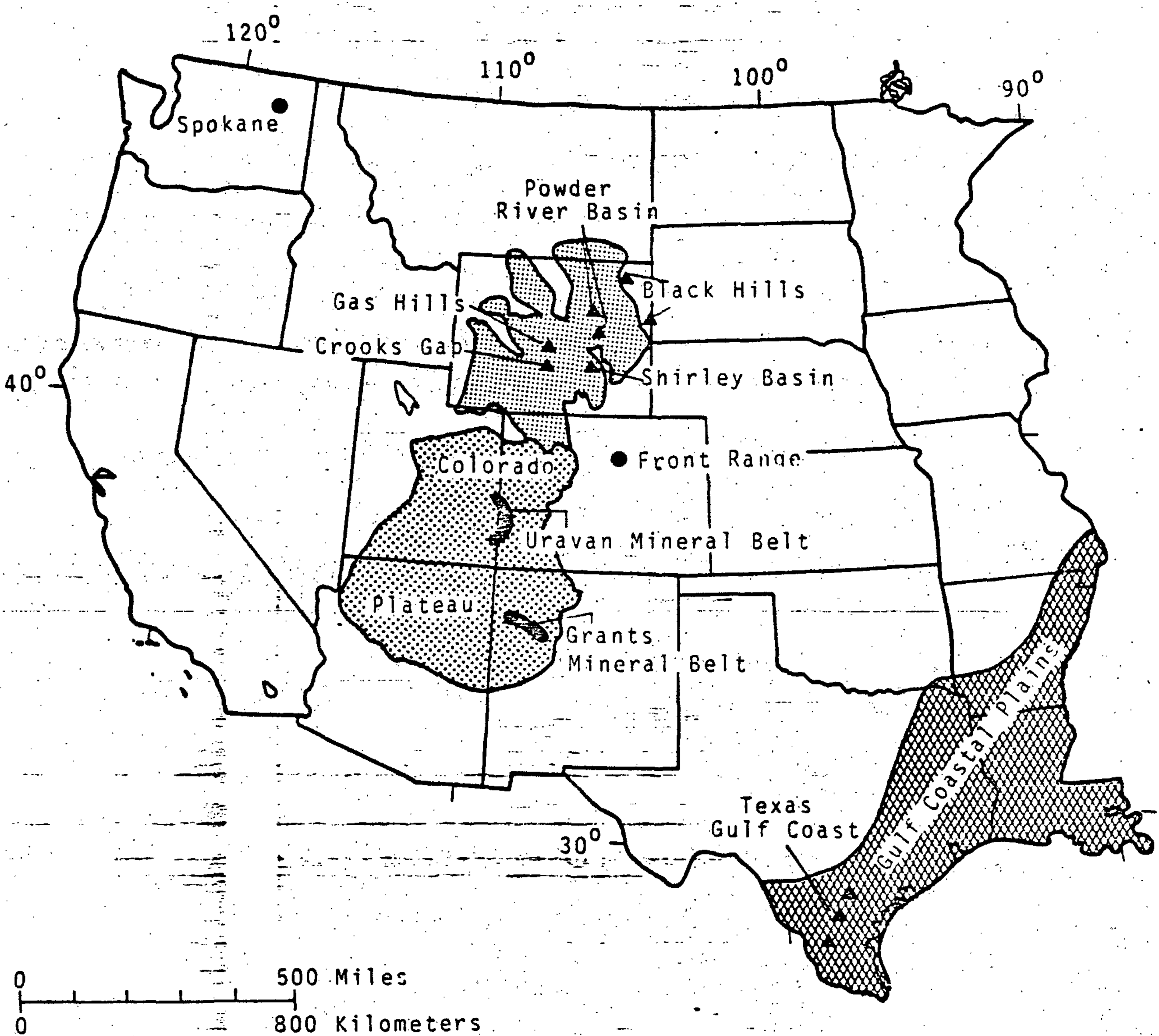


Figure 1.--Principal uranium districts of the United States.

PART 1

CHARACTERISTICS OF SANDSTONE BODIES

The main parameters controlling the in situ leaching of sandstone uranium bodies are those that alter the ability of the sandstone to act as a perfectly homogeneous body with equal permeability in all directions. Phenomena that can give rise to differential permeability in sandstones can be divided into five categories: textural differences, sedimentary structures, lithological differences, structural differences, and geochemical or compositional differences. These phenomena determine how closely a real sandstone will approximate an ideal one. In some cases, the categories overlap and may be largely indistinguishable; the categories are thus somewhat arbitrary.

Texture

The textural class includes those parameters that are influenced by the geometry and mutual relations among the component grains of the sandstone. For example, the grain size greatly influences the permeability of the rock (fig. 2). As the grain size becomes smaller, the permeability of the rock decreases. It should be recalled that although the permeability (which is the capacity for transmitting a fluid) decreases as the grain size decreases, the porosity (which is the ratio of the void volume to the total volume) remains the same. Permeability also decreases as the degree of sorting decreases (fig. 3), because the smaller particles occupy the pore spaces between larger particles. The degree of packing is also directly related to the permeability (fig. 4). In a loosely packed rock, permeability and porosity are both high; but a well packed configuration offers less permeability and porosity. The fabric (or orientation of the discrete particles or component grains) also affects the permeability. For example, the permeability in the direction of elongation is considerably greater than in other directions (fig. 5). In

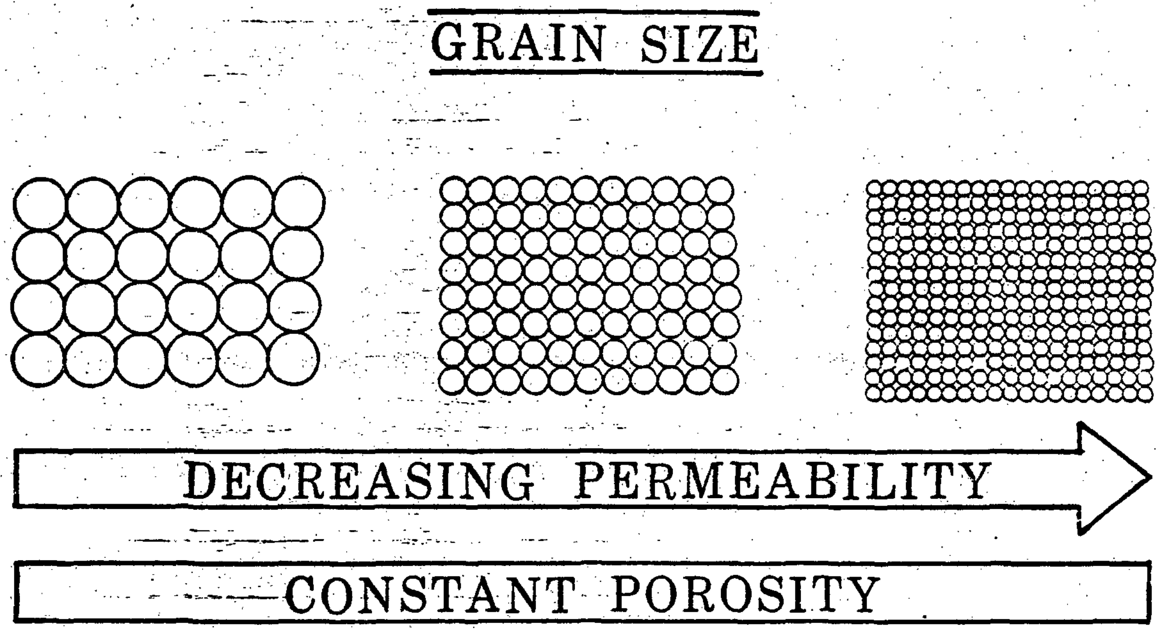


Figure 2.--The effect of grain size on permeability.

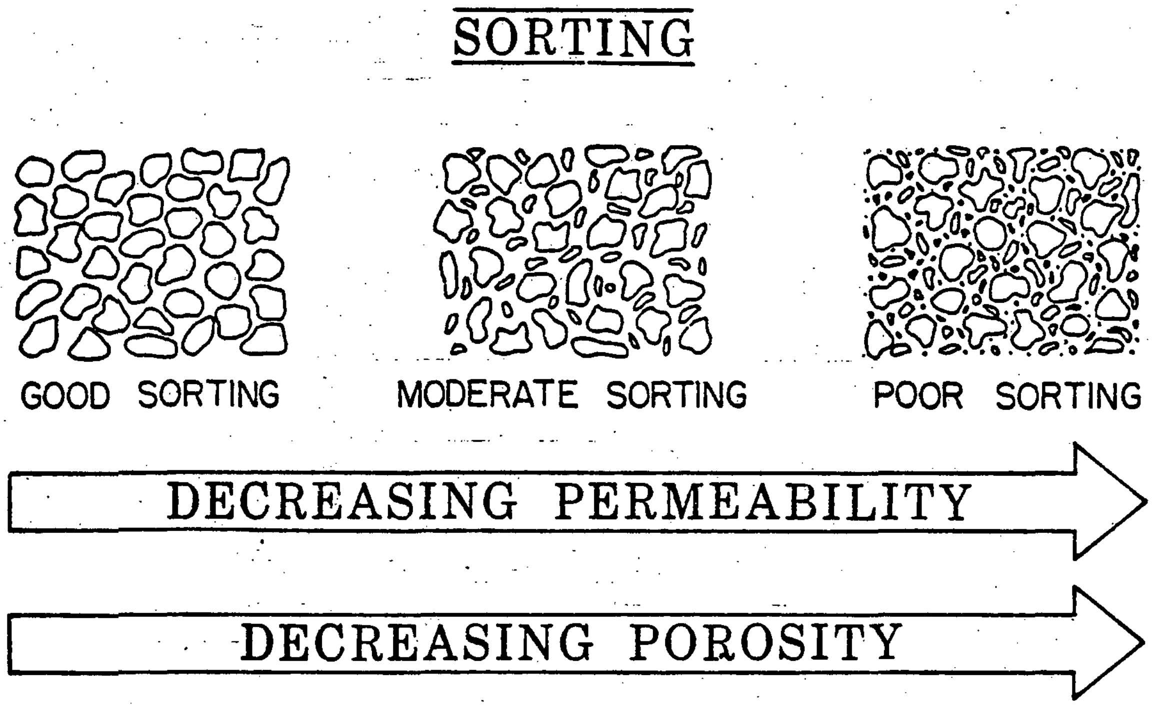


Figure 3.--The effect of sorting on permeability.

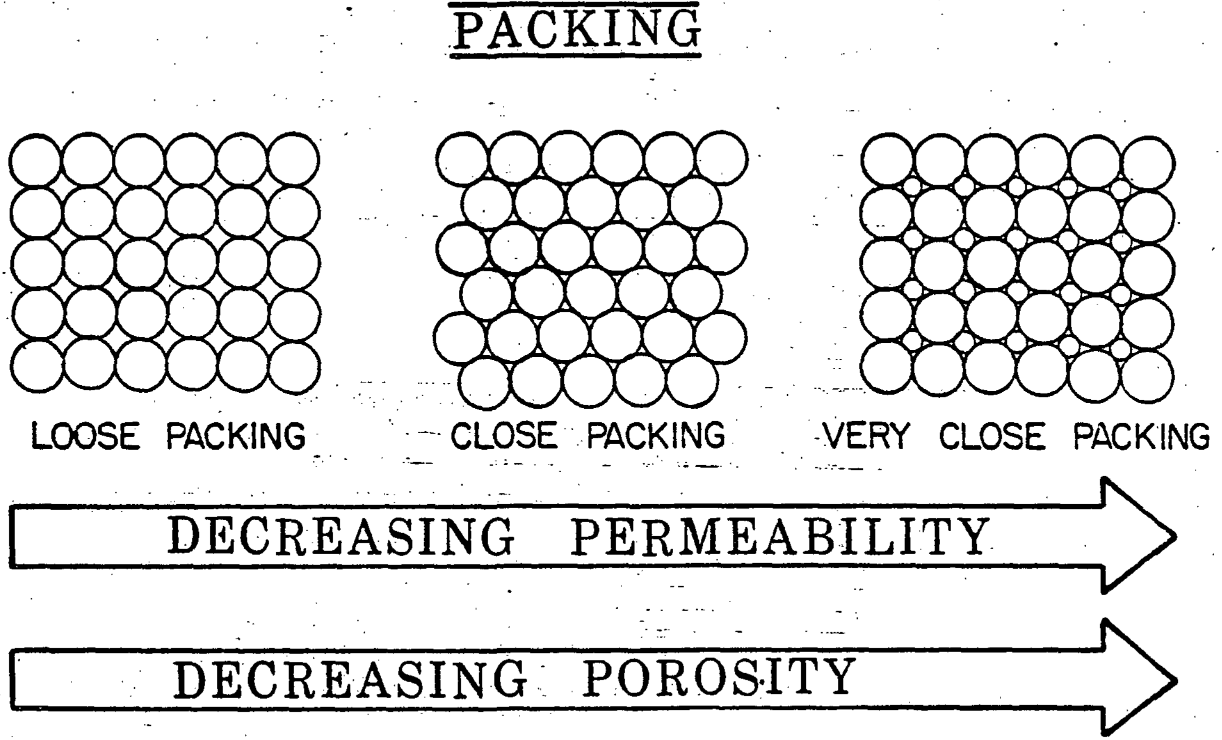


Figure 4.--The effect of packing on permeability.

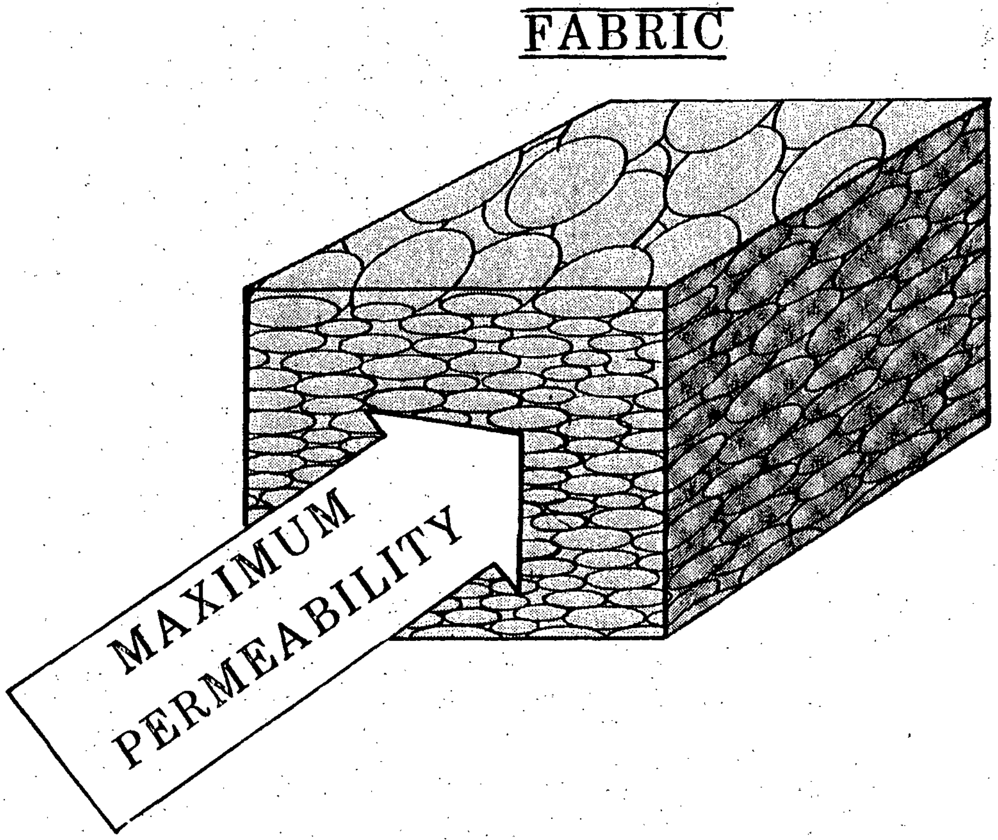


Figure 5.--The effect of fabric on permeability.

general, vertical permeabilities in sandstones are from 20 to 35 percent less than horizontal permeabilities, due to the orientation of the grains. As the degree of cementation increases, the permeability decreases (fig. 6). In most of the sandstone-type uranium districts in the U.S., ore occurs as grain coatings (fig. 7a), interstitial fillings (fig. 7b), or massive replacements of the detrital matrix (fig. 7c). The ore itself thus fills pore spaces and reduces the permeability of the sandstone.

Sedimentary Structures

There is a wide range of sedimentary structures that influence the permeability. These structures include crossbedding, ripple marks, bioturbation, slumps, and cut-and-fill structures. In general, these structures reduce permeability in proportion to the amount of lineation normal to or inclined to the direction of flow (fig. 8). Thus, horizontally bedded sandstones promote horizontal permeability, whereas inclined structures reduce it. Inasmuch as uranium ore occurs most commonly in fluvial and nearshore marine sediments, sedimentary structures common to these environments are the most important to understand. Several good books describing these structures are available. (See, for example, Bernard and others, 1970.)

Lithologic Differences

Lithologic differences also exert control over the permeability (fig. 9). Coarse sandstones are more permeable than silts, which are more permeable than clay. Equally important, though, is the arrangement of these lithologies. The incoroporation of minor silt layers in a sandstone can effectively compartmentalize permeability within the sandstone. Sandstones usually contain subtle but important permeability differences as a result of slightly different lithologies.

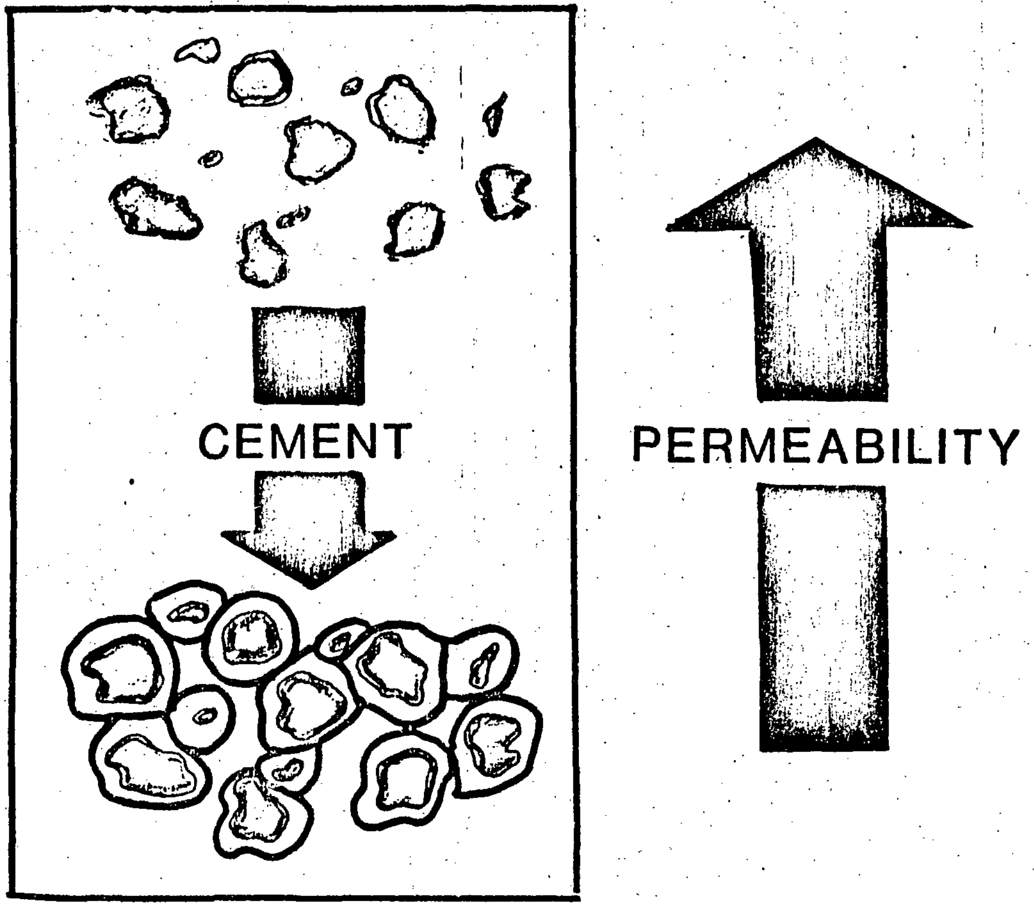


Figure 6.--The effect of cementation on permeability.

Figure 7.--Photomicrograph showing ore occurrences in sandstone. Ore appears dark.

a. Ore occurring as grain coatings

b. Ore occupying interstitial pore spaces

c. Ore that has replaced original detrital matrix, lower part of photo

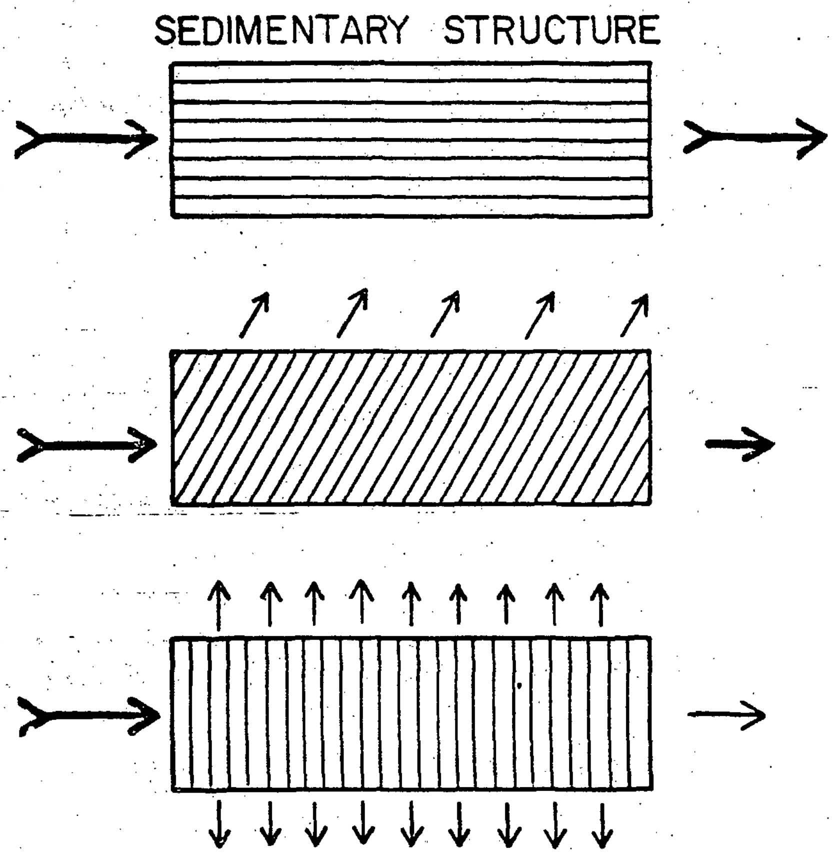


Figure 8.--The effect of sedimentary structure on permeability.

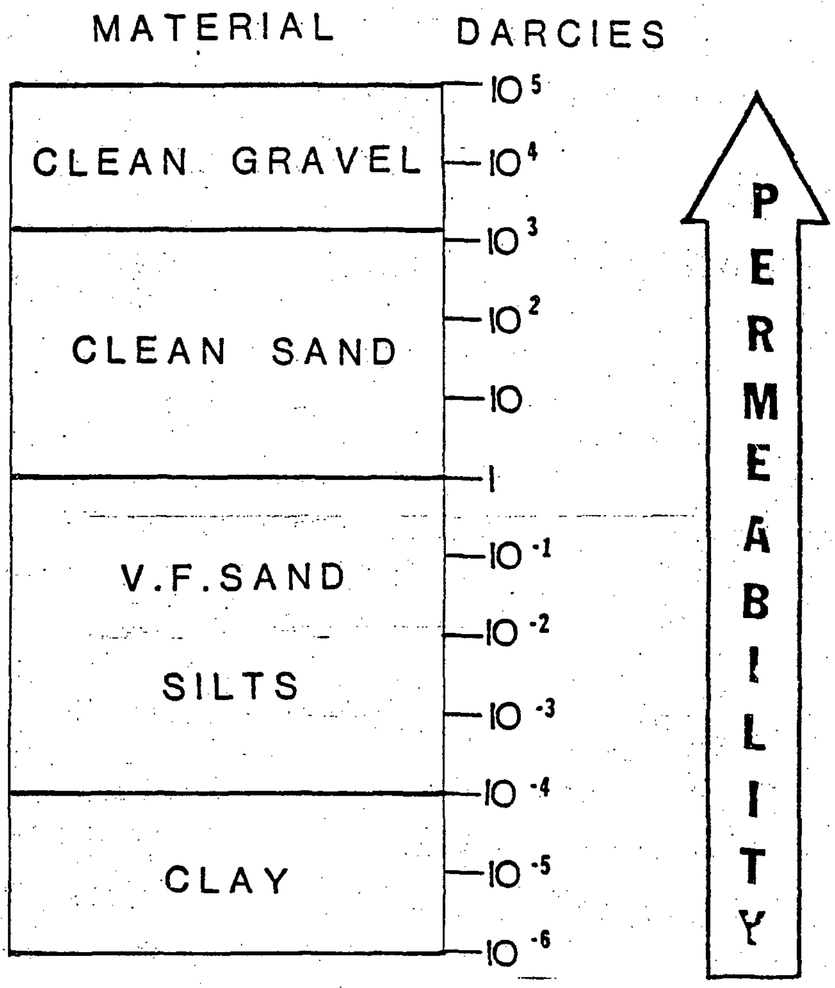


Figure 9.--Variation in permeability with lithologic type.

Structure

Structural features also can exert considerable control over the permeability of a sandstone. Major structural features such as faults and folds severely disrupt flow patterns (fig. 10). Minor structural features, which often cannot be seen from the surface, can also alter the flow. For example, figure 11 shows a vertical clay-filled dike which acted as a vertical permeability barrier in a uranium mine in Karnes County, Tex.

Composition

The final class of improtant features of sandstone is the geochemical class. The reactivity of the components of the sandstone affects the flow of the solutions. Because this aspect is the subject of a complementary geochemical paper presented at the meeting (Potter, 1976), it will not be discussed in detail in this report. However, a few points are worthy of mention because they relate directly to permeability. Injected fluids can dissolve framework sand grains. For example, acid leachates dissolve calcite grains and cement, which can result in secondary channelization. Organic material may also be removed by oxidants and alkaline leachates. Other reactive species can also use up or neutralize the reagents by various reactions and thereby reduce the effectiveness of the leach solution. Clay minerals swell as a result of sorption of a number of cations, resulting in severely reduced permeability. Zeolites and other materials can also act as ion exchange resins and alter the composition of the injected fluid.

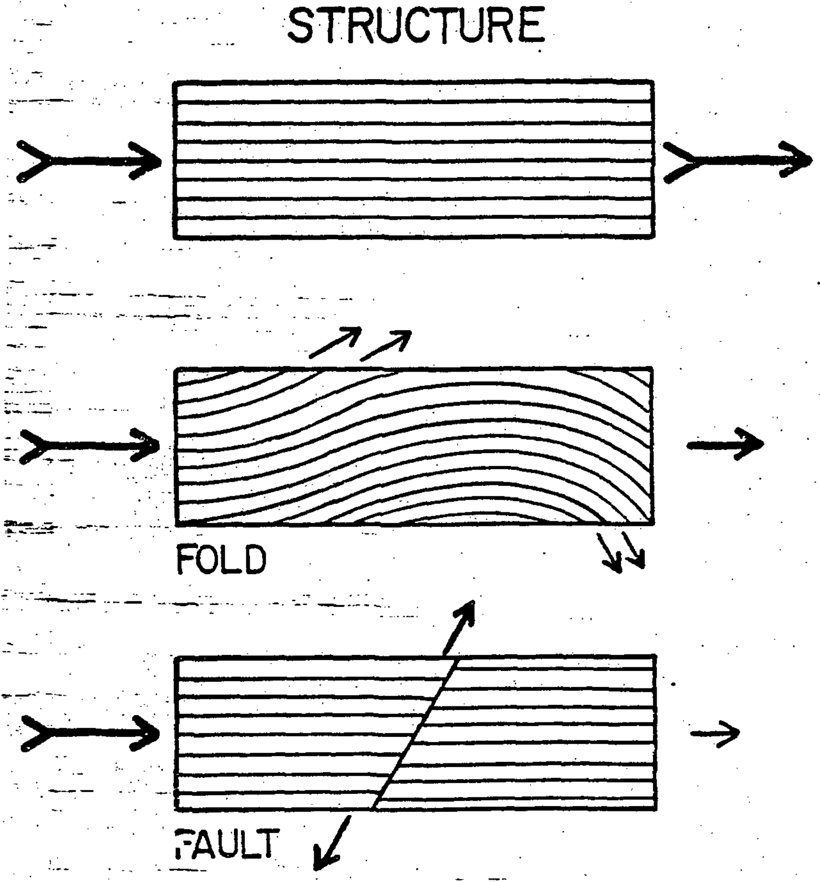


Figure 10.--The effect of structure on permeability.

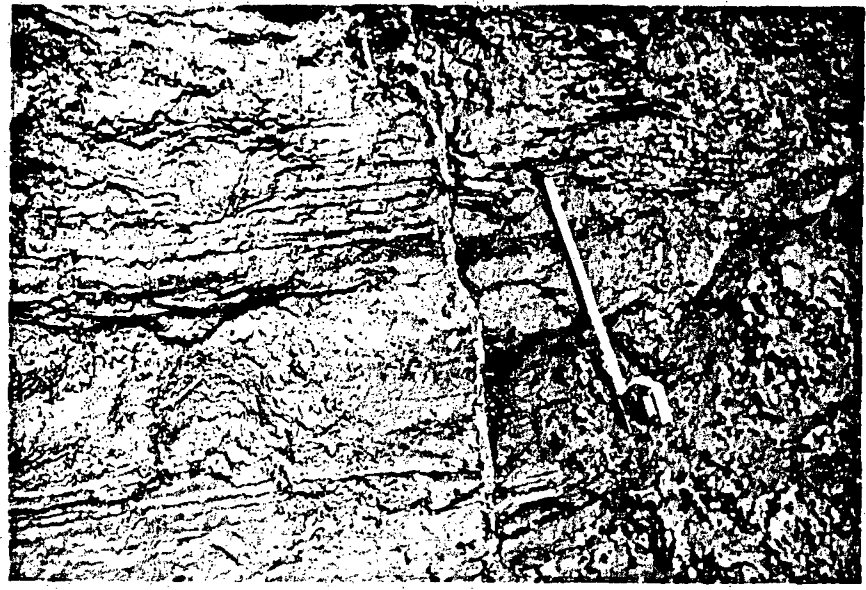


Figure 11.--Montmorillonite-filled joint separating ore-bearing sandstone on the right from barren sandstone on the left in a south Texas uranium mine. Note the accumulation of dark organic matter on the left side of the joint.

PART 2

IMPORTANT GEOLOGICAL PARAMETERS IN SOME URANIUM DISTRICTS

The geological characteristics of some sandstone-type uranium deposits illustrate how differences in these features of sandstones can affect permeability and in situ leaching operations. This summary relies on data gathered from deposits mined by conventional techniques; however, new deposits mined in the next few years will probably be very similar to the old ones, so the same principles will apply.

Texas

There are two major groups of uranium deposits in Texas: those in Eocene sediments in Karnes County and those in Miocene sediments in Live Oak County.

The Karnes County deposits occur in sandstones deposited in nearshore marine and fluvial environments. The most important nearshore marine environments are the barrier islands, which are elongate, podlike sand bodies about a mile in width and several miles in length and which lie parallel to the modern Gulf of Mexico shoreline. These barrier islands have been dissected by fluvial systems, and deltas have developed where rivers met the marine environment. The modern Galveston barrier island model applies to the Eocene barrier islands (fig. 12) (Bernard and others, 1970). Figure 13 shows a cross-sectional view of Galveston Island. The base of the unit is composed of mixed silt and clay; the upper layers consist of coarser sand. Figure 14 diagrammatically illustrates how the ore occurs in the Eocene barrier islands. Ore is present in an asymmetrical crescentic shape, which presumably results from a decreased flow rate of the mineralizing solution in the lower, fine-grained, less permeable portion of the sand pod.

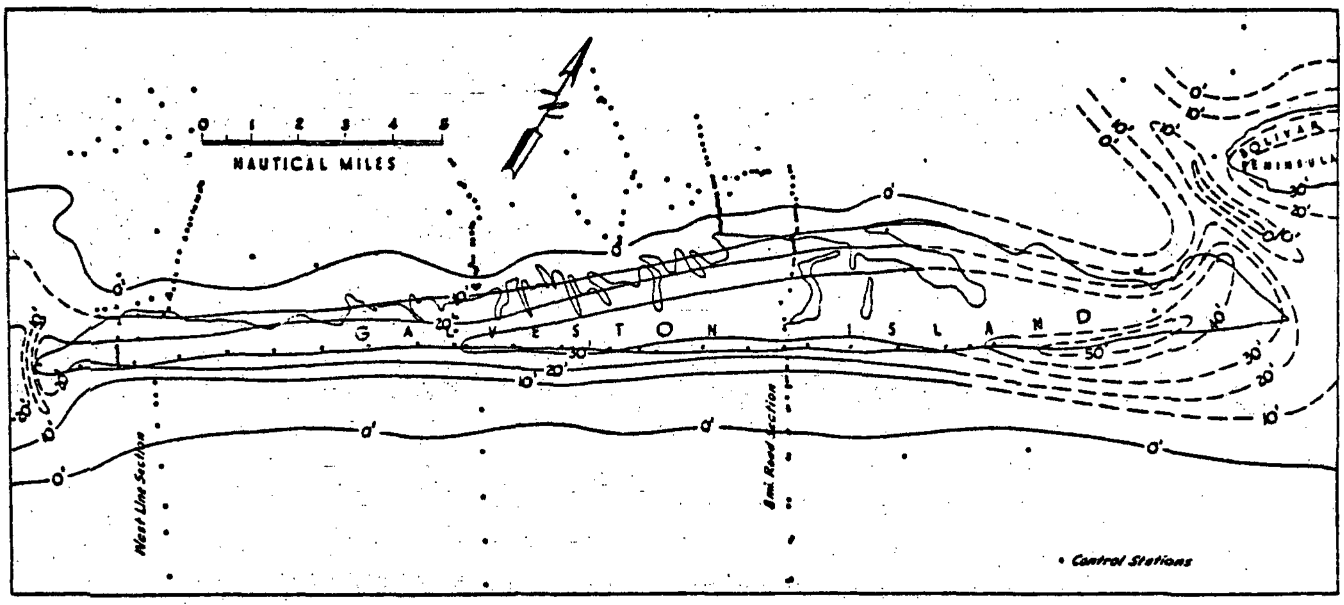


Figure 12.--Generalized isopach map of the clean, well-sorted Galveston barrier island sands. (From Bernard and others, 1970, fig. 50.)

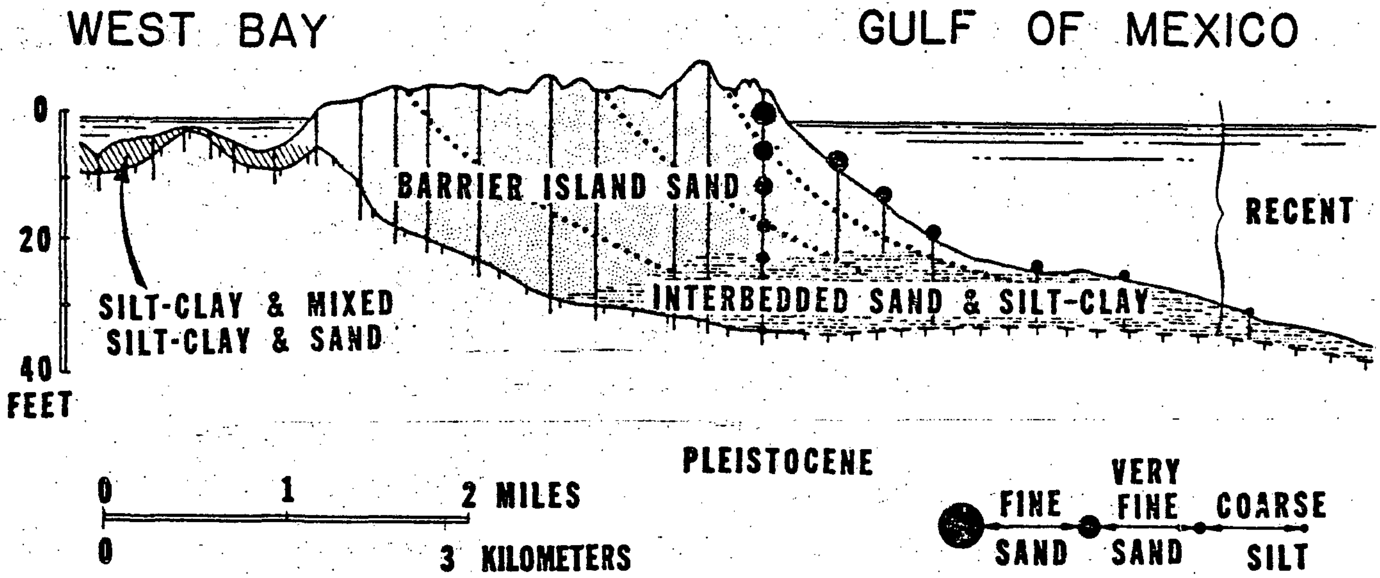


Figure 13.-- Schematic cross section of Galveston barrier island. (After Bernard and others, 1970, fig. 51.)

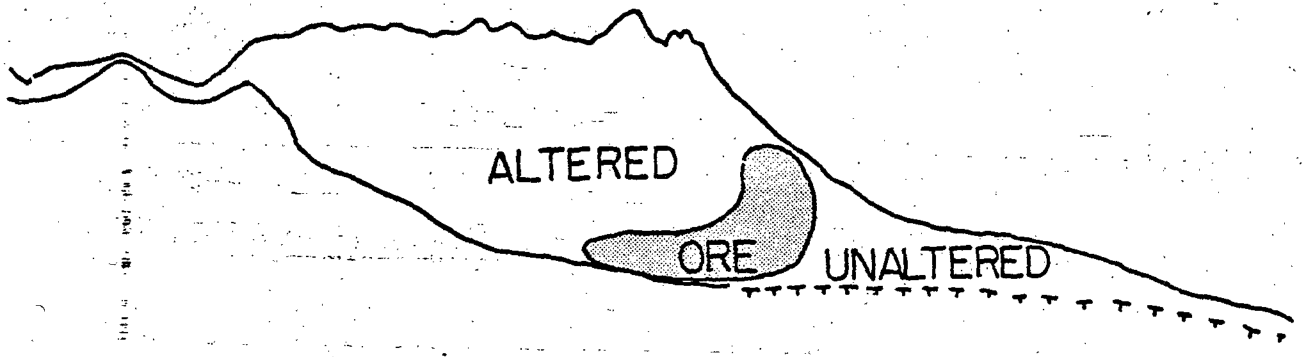


Figure 14.--Occurrence of ore in Eocene barrier island, Texas.

The sand is composed of quartz, feldspar, calcite, and clay. In addition, there is a large amount of volcanic ash. In some places the ash occurs as glassy shards, and in other places the zeolite clinoptilolite, which is an alteration product of ash, constitutes a large portion (>5 percent) of the sand. The zeolites may create special problems for leaching, inasmuch as they may have a very high cation exchange capacity and may absorb some of the lizivant. The ore minerals are reported to be uraninite and coffinite, but published accounts of the ore mineralogy may be incomplete; further characterization of the ore mineralogy should be undertaken. It might be noted that the published accounts of ore mineralogy in many uranium districts have been primarily derived from X-ray diffractometry, which can miss some of the subtle uranium phases, particularly in cases where the uranium species is poorly crystallized or where the uranium is bound to some cation exchange medium such as humates, clays, or zeolites.

The structural geology of the Karnes County deposits is generally uncomplicated. However, there are a number of joints tending approximately parallel to the strike. Often these joints are filled with montmorillonite (fig. 11). These dikes are generally less than an inch wide but may extend 1,000 feet horizontally and up to 80 feet vertically. They act as almost perfect vertical permeability barriers. These clay dikes could be dismissed as insignificant geological curiosities except that they will have profound effects in in situ leaching.

The uranium in Live Oak County lies on the flanks of a Miocene alluvial system (fig. 15). The sand was deposited as a point-bar sequence. Sandy point bars accumulated along the inside of meander loops, where the current was weak. Figure 16 illustrates some of the important features of a point-bar deposit. There is a decrease in grain size diameter and, consequently,

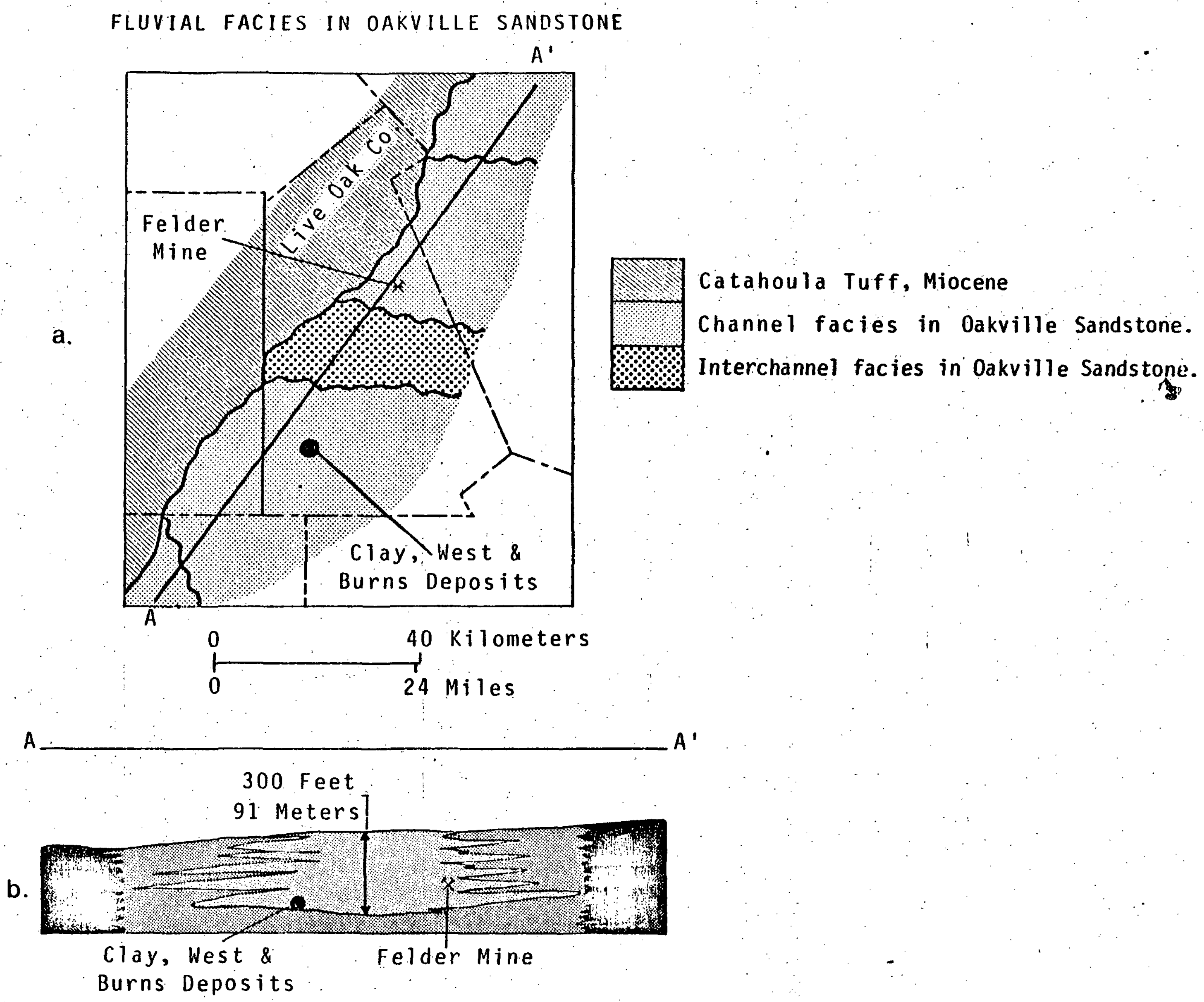


Figure 15.--Fluvial facies in Miocene Oakville Sandstone. a, Map showing areal extent. b, Schematic cross section. (Modified from Klohn and Pickens, 1970.)

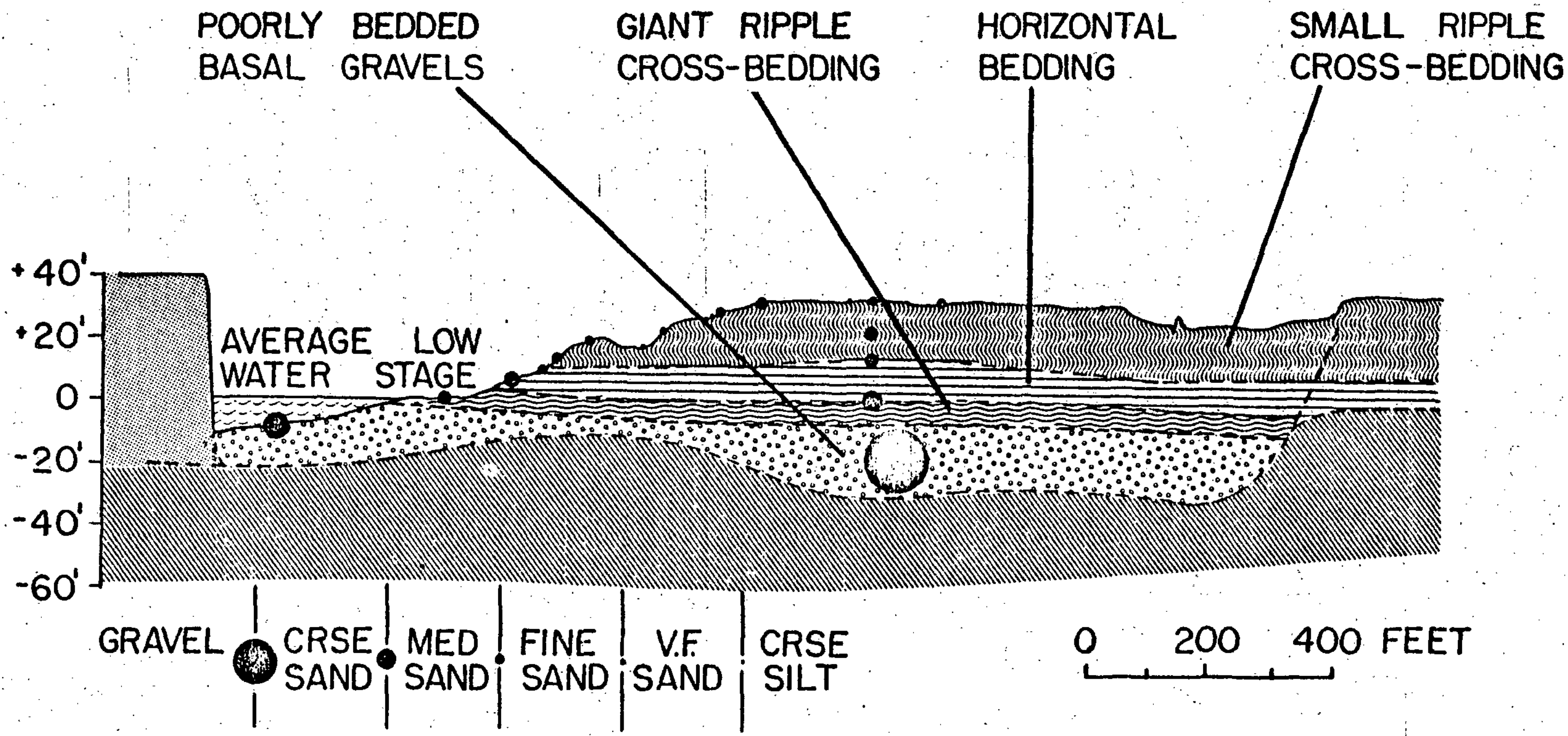


Figure 16.--Cross section of the Brazos point bar near Richmond, Tex. (After data in Barnard and others, 1970.)

permeability upward in the sequence. This contrasts with the coarsening upward sequence in the barrier islands.

To illustrate the importance of these differences in texture and sedimentary structure, a hypothetical ideal point bar is shown in figure 17. The sequence has permeabilities as high as 2,000 millidarcies (mD) in the lowermost zones and grades upward to permeabilities of 10 mD (fig. 17a). As an ore-bearing solution is introduced, ore is deposited in the zones of lower permeability and is transported through zones of high permeability resulting in an orebody like that shown in figure 17b. The ore, occurring in interstitial spaces, decreases the upper-zone permeability. If a leach fluid were injected in the left hole (fig. 17c) and withdrawn from the right, most of the leach fluid would flow through the highest permeability zones, bypassing the ore in the less permeable zones. The permeability relationships within real (non-ideal) point bars can be complicted, because point-bar sequences are often nested. Scouring and redeposition make permeability relations within point-bar sequences difficult to predict.

The structure in Live Oak County is straightforward. The beds dip gulfward at about 1°-2°, and no major folds are known to affect the Oakville system. There are, however, numerous faults in the area (fig. 18). Generally these strike parallel to the Gulf and are downthrown on the Gulf side. Some of these faults offset the Miocene rocks by as much as 300 feet and are assumed to be intimately connected with genesis of the ore deposits as shown on figure 19. In leaching uranium from fault controlled deposits, extreme care should be taken to understand the structure of the deposit.

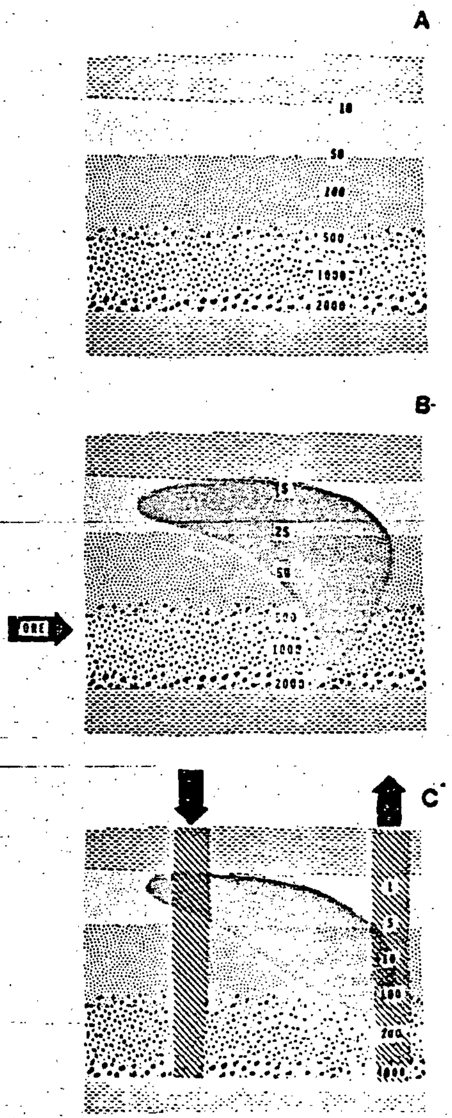


Figure 17.--Schematic illustration of the changes in permeability caused by introduction and subsequent leaching of ore.

a. Natural state permeability.
b. Permeability altered by ore deposition.
c. Permeability further altered by leaching.

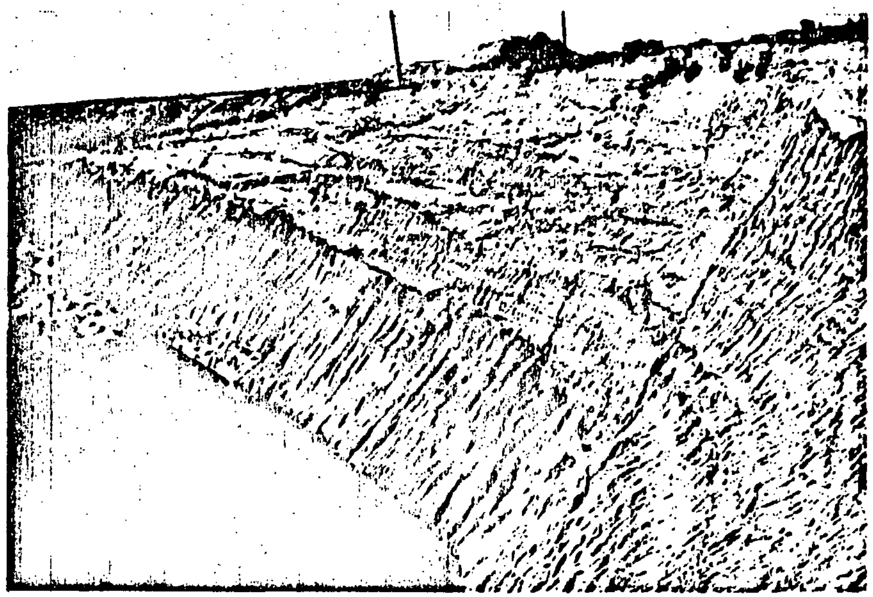
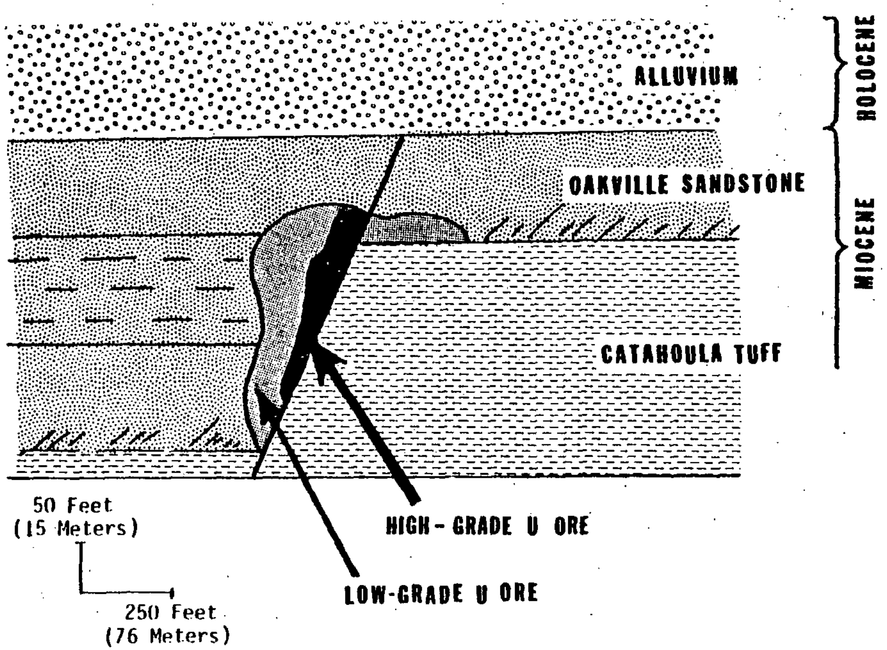


Figure 18.--Fault offsetting host sandstone, Koplin Mine, Live Oak County, Texas.



McLean 1, Live Oak Co.

Figure 19.--Distribution of ore along fault plane, Live Oak County, Tex.

Wyoming

Ore has been produced from four major basins in Wyoming--Wind River, Great Divide, Shirley, and Powder River Basins. All four basins produce ore from arkosic sandstones and conglomerates of Eocene age. The host rocks were derived from the erosion of Precambrian granites which were uplifted during the Eocene.

The Gas Hills district, which has produced about 12 percent of the total U.S. uranium ore, lies immediately north of the Granite Mountains Ore occurs in permeable arkosic sands of the Eocene Wind River Formation. Within the Wind River Formation, ore occurs primarily in the Puddle Springs Arkose Member, a coarse to very coarse arkose with minor amounts of other lithologies, including boulder conglomerate, fine sandstone, mudstone, and carbonaceous units. The source of sediments in the Puddle Springs was the nearby Granite Mountains. The Puddle Springs formed as an alluvial fan on the flanks of the Granite Mountains. Rapid deposition and proximity to the rising mountain resulted in an arkose in which the grains have undergone little chemical or mechanical weathering. The sediment is poorly sorted and not well cemented. Only incipient graded bedding occurs (fig. 20). The diverse lithologic types and poor sorting may result in problems with leaching. In the Gas Hills district there are several high-angle faults associated with the uplift of the Granite Mountains. These faults may act as vertical permeability barriers.

South of the Granite Mountains, in the Great Divide Basin, is the Crooks Gap district (fig. 21). The Crooks Gap ore occurs in the Eocene Battle Spring Formation, which is very similar to the Wind River Formation in the Gas Hills. It is also an alluvial fan with similar lithologies represented; the predominant rock type is granite fragments derived from the Granite

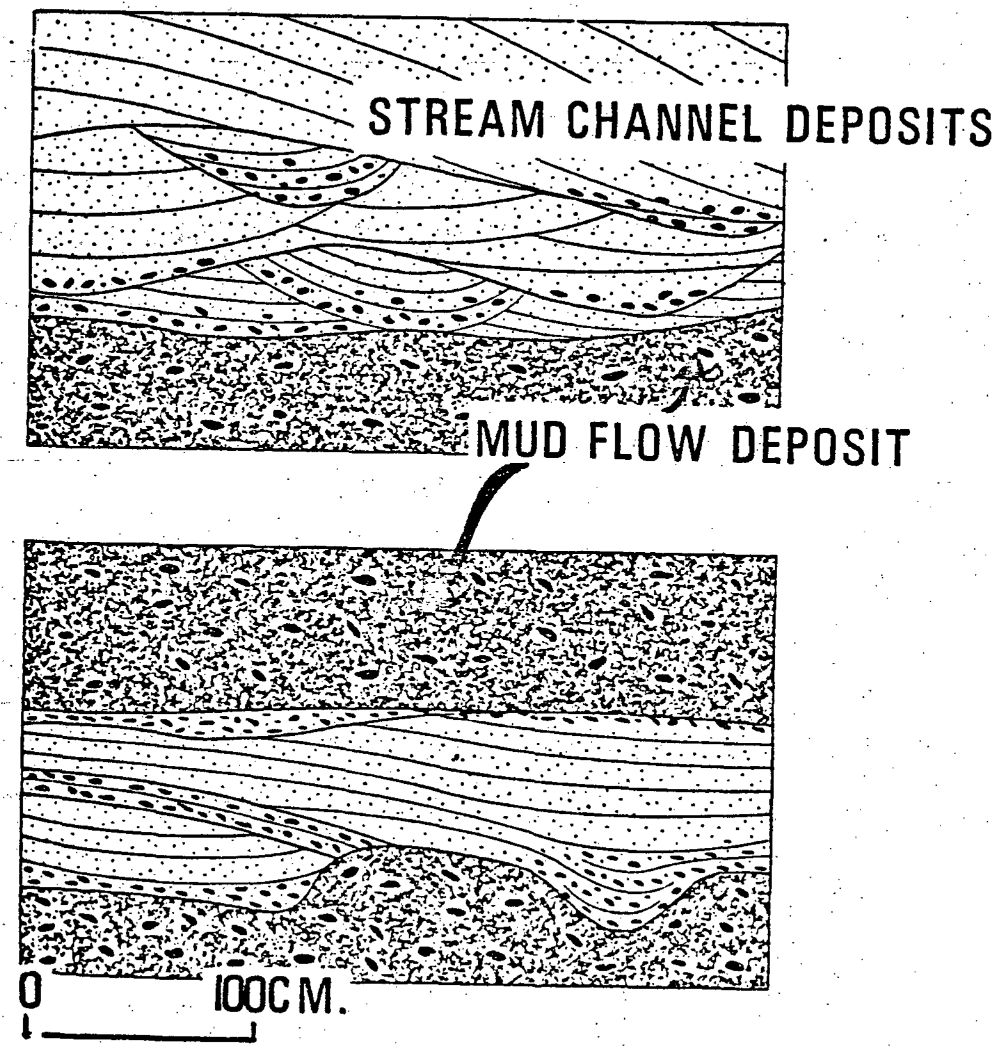


Figure 20.--Bedding in alluvial fan deposits.

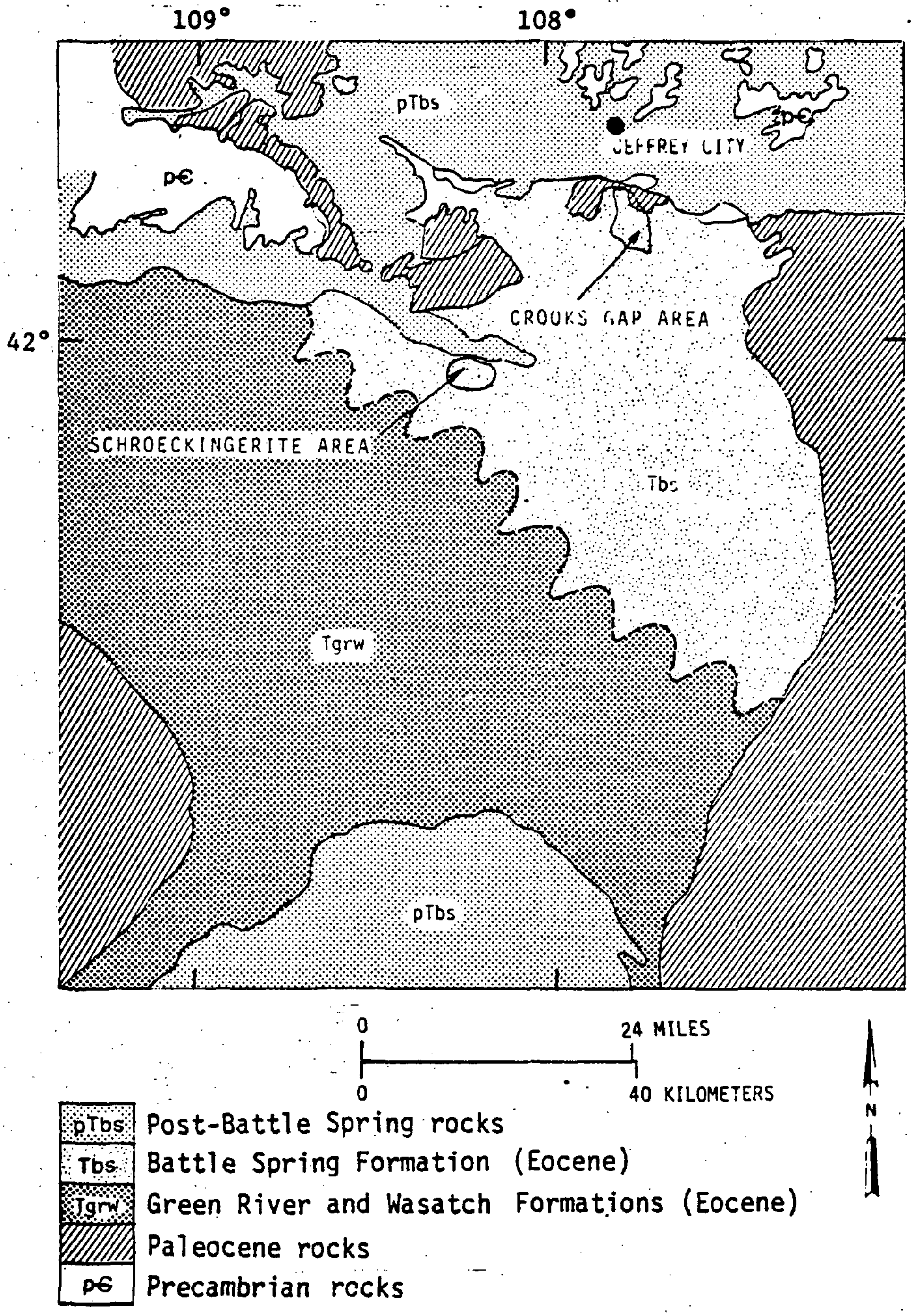


Figure 21.--Generalized geology of Great Divide Basin, Wyoming. (Modified from Bailey, 1963.)

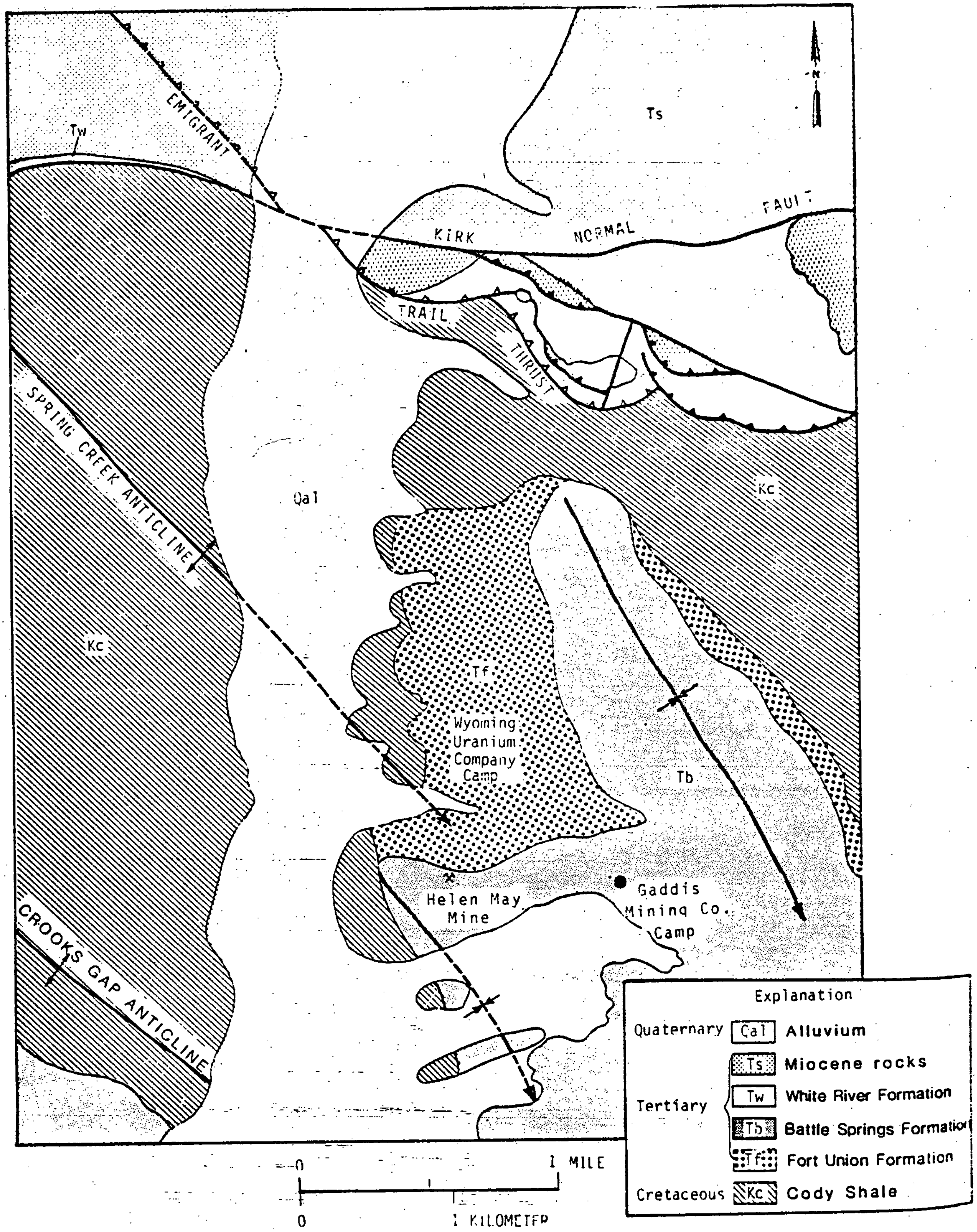


Figure 22.--Structure of Crooks Gap district, Wyoming. (Modified from Stephens, 1964.)

Mountains. The Crooks Gap district, however, has undergone more structural modification than most other uranium districts in Wyoming (fig. 22). Compressional folding occurred contemporaneously with the deposition of the Battle Spring Formation. Folding and faulting continued through late Eocene time, and the Battle Spring Formation was deformed extensively. Although this structural complexity has not greatly affected the conventional mining of uranium, it has implications with respect to in situ leaching.

Uranium deposits in the Shirley Basin, east of the Granite Mountains, also occur in the Eocene Wind River Formation. The mineralogy and stratigraphy of this formation here are very similar to those in other uranium districts. The Shirley Basin is a small Tertiary basin surrounded by Precambrian, Paleozoic, and Mesozoic rocks. Faults with small displacements are reported in the uranium pits, and many other major faults are present in the area. These faults did not affect open pit mining but will affect leaching.

The Powder River Basin, although larger than other uranium producing basins, is similar in many respects. The units known to contain uranium include the Paleocene Fort Union Formation, the Eocene Wasatch Formation, and the Oligocene White River Formation. The Highland mine of Exxon produces from the Fort Union, and many other deposits occur in the Wasatch Formation. The host rocks are finer grained here than in other Wyoming basins. Sand was derived from the Sweetwater arch to the south and spread north into the basin. Arkoses and sandstones were deposited in the basin by large slow-moving streams. Fluvial environments are better developed than in other producing basins. The rocks are composed of quartz, feldspar, rock fragments, clay, and calcite. Differential cementation by calcite has occurred, and some of the previously discussed problems are present, so the necessary precautions should be taken.

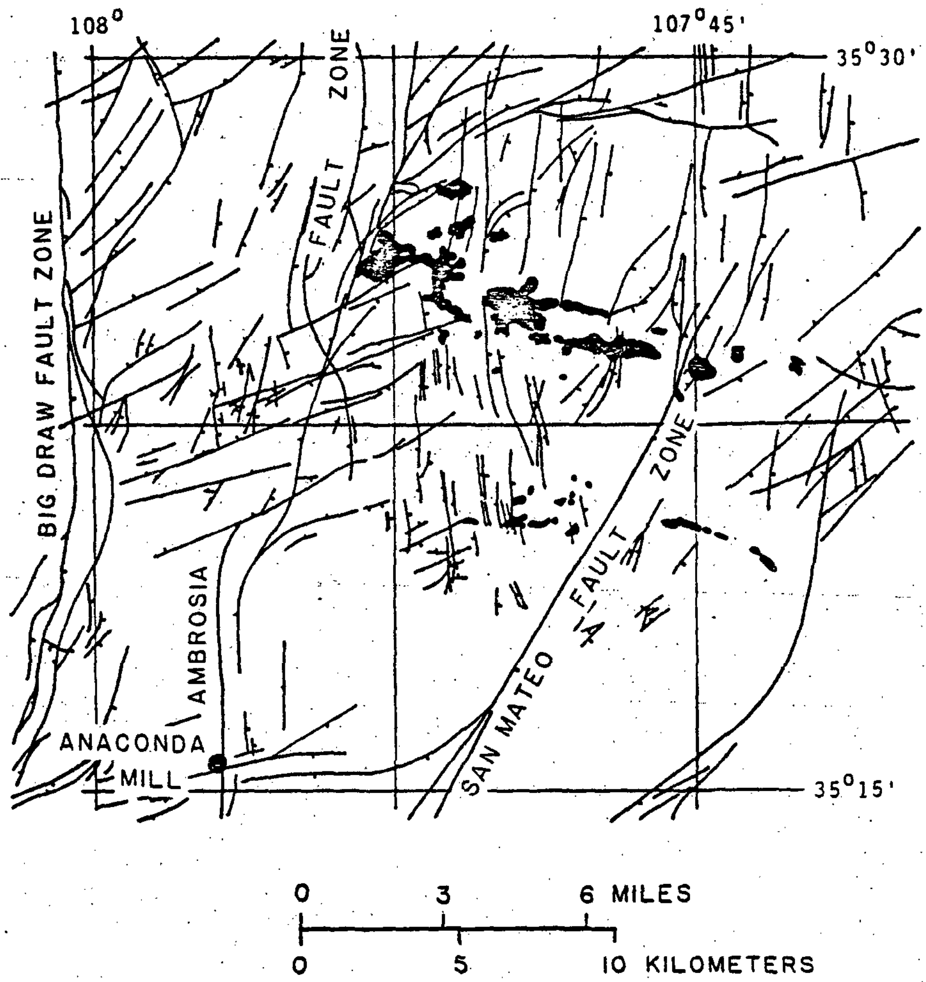


Figure 23.--Faults in the Ambrosia Lake district, New Mexico. (Modified from Thaden and Santos, 1963.)

Colorado Plateau

The largest resources of high-grade uranium found in the United States occur in the Grants mineral belt, in the southern Colorado Plateau. These deposits occur primarily in the Westwater Canyon Member and an informal unit, the Jackpile sandsone, of the Jurassic Morrison Formation. At Ambrosia Lake, the Westwater Canyon orebodies are as much as 3,000 feet long and extend intermittently many miles along trend. The host rock is a fluvial arkosic sandstone consisting of nests of disconformable fluvial systems. "The traceable extent of these unconformities is generally only a few tens of feet. The disconformities terminate either by being cut out by another disconformity or by dying out in surrounding crossbeds" (Granger and others, 1961, p. 1185). Thus the local permeabilities are quite heterogeneous and are related to local sedimentary structures. The Ambrosia Lake district also contains a good deal of faulting (fig. 23). One set of faults with large displacements trends northwest, and many smaller faults are present.

The grain size is quite variable, ranging from very fine to very coarse. The mineralogy is primarily quartz and feldspar, but lesser amounts of clay, calcite, chert, and organic matter are also present. The ore consists of coffinite and pitchblende which are quantitatively related to carbonaceous material or humate. This carbonaceous material formed by coagulation of humic acid and later acted as a permeability barrier to ore-bearing fluids. The ore is intimately associated with the material (fig. 24). The nature of the uranium-organic association is only partially understood. The carbonaceous material will affect the flow of leach solutions by acting as a permeability barrier and may alter the composition of leach solutions.

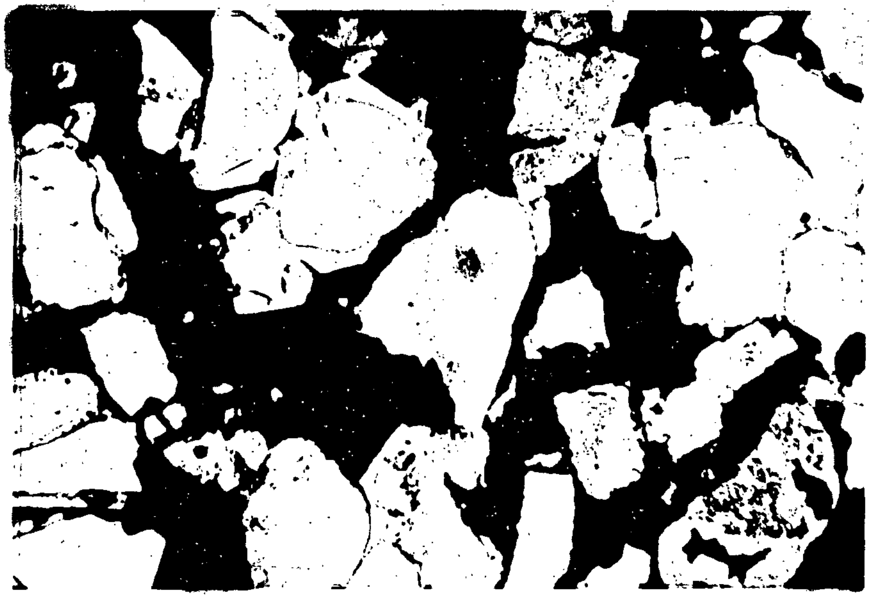


Figure 24.--Urano-organic material occupying interstitial pore space, Ambrosia Lake district, New Mexico. (Photo courtesy of John B. Squyres, Amoco Minerals Co.)

Another major deposit in the southern Colorado Plateau is the Jackpile-Paguate deposit (fig. 25). The Jackpile deposit occurs in the Jackpile sandstone, a local sandstone unit occurring primarily in sags on top of the Brushy Basin Member of the Morrison Formation. The Jackpile host rock is similar to that in the Westwater Canyon; it is a feldspathic sandstone with large quantities of volcanic, sedimentary, and metamorphic rock fragments. The sands are moderately well cemented with calcite and silica. The ore is predominantly an urano-organic complex containing coffinite, and it occurs as coatings, interstitial fillings, and massive replacements of the detrital matrix. Where the organic-uranium material has replaced the detrital matrix, the ore itself acts as a permeability barrier.

North of the Grants district, on the Colorado Plateau, the major producing unit is the Salt Wash Sandstone Member of the Morrison Formation. It was deposited as a large alluvial fan, whose apex lies near the area where the Colorado River crosses the Arizona-Utah border (fig. 26). The fan diverges radially from the apex, where it is some 300 feet thick, to the distal edge where it exists as a series of sandstone ledges 30 to 50 feet thick within finer-grained material. The important uranium districts seem to be localized within paleochannels along a zone at which the fan sediments change distally from dominantly sand to dominantly silt and clay.

The sandstone consists of sedimentary orthoquartzie, tuff, and rock fragments. Most of the sandtone is cemented with calcite and silica. The ore occurs as carnotite, montroseite, corvusite, uraninite, coffinite, and a variety of other secondary minerals. The ore minerals occur as grain coating and as massive replacements, and the ore zones are often the least permeable parts of the sandstones. In situ leaching of the Colorado Plateau uranium deposits will probably be more difficult than the leaching of deposits in

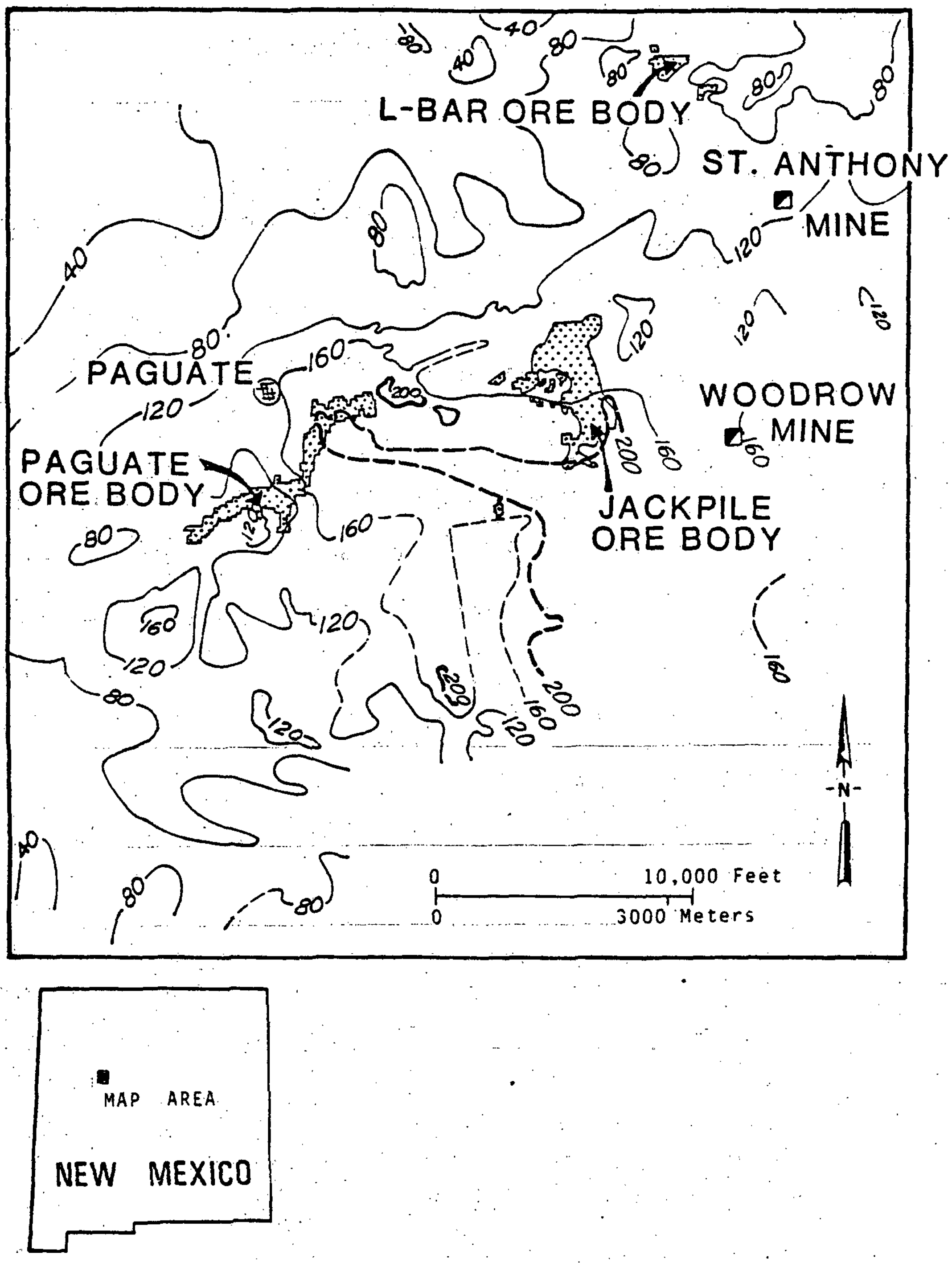


Figure 25.--Isopachous map of Jackpile sandstone, New Mexico. (After Kittel, 1963, fig. 3.)

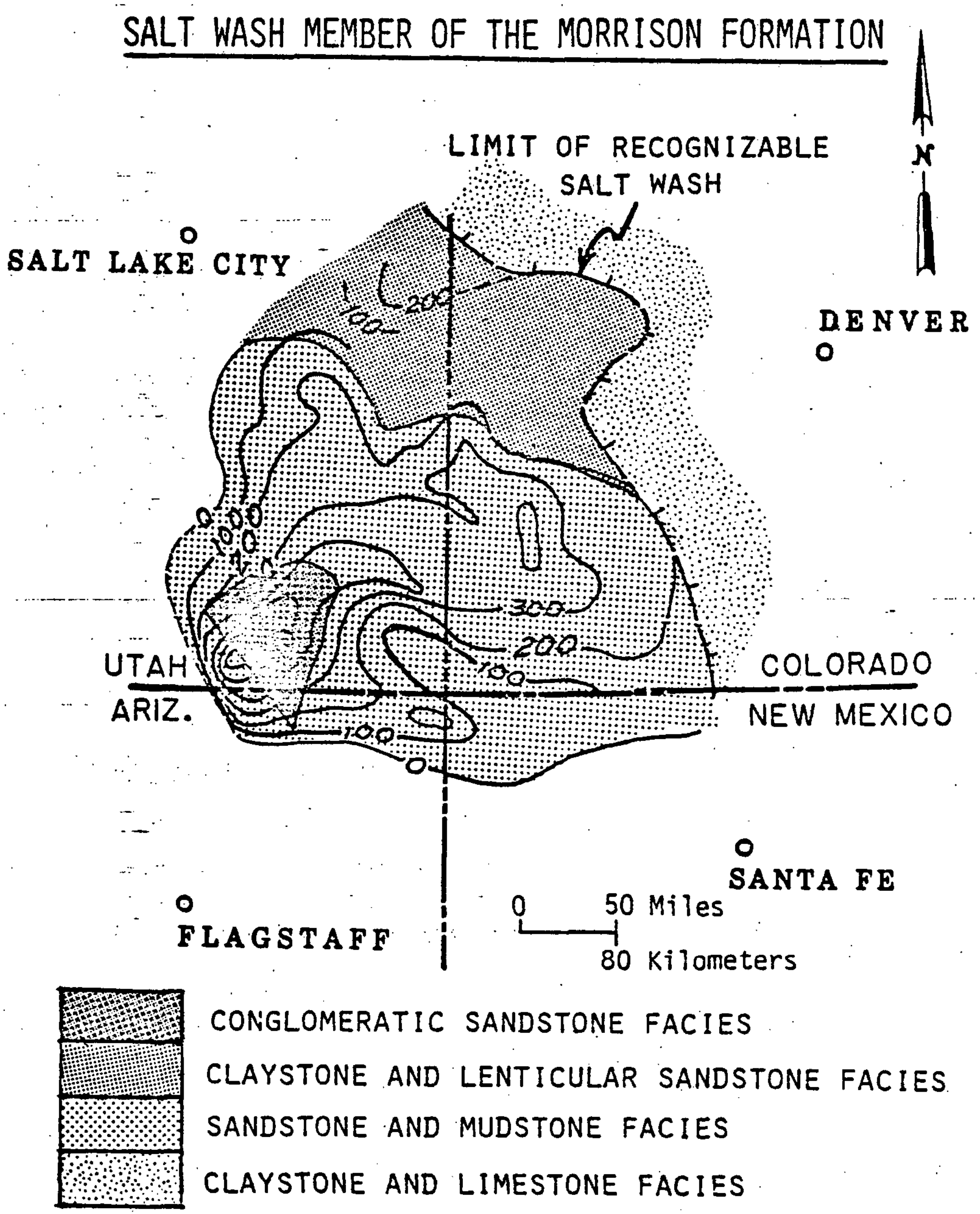


Figure 26.--Isopachous map of the Salt Wash Member of the Morrison Formation, Four Corners area. (After Craig and others, 1955.)

Wyoming or Texas for several reasons. First, many of the deposits contain as much or more vanadium than uranium, and the presence of vanadium will make the chemistry of the required leachate more complex. Second, the ore is more discontinuous and will require careful delineation. Third, the sandstone is less permeable than the Tertiary sandstones in the Wyoming and Texas uranium districts.

SUMMARY

Successful in situ leach mining of uranium deposits depends on an understanding the local permeability patterns, which will control the movement of leach fluids and pregnant liquors. Features that are trivial in conventional mining, such as porosity, clay matrix, cementation, mineralogy, and the reactivity of minerals, become vitally important in leaching. Differences in these features directly affect the ability to remove ore efficiently. Permeability is the most important control of the flow of the lixivant, and the permeability can be affected by textural differences, sedimentary structures, lithologic differences, structure, and composition. Often the presence of the ore itself is a major permeability-reducing feature.

Although these features may cause problems in in situ leaching, such problems can be discovered and appropriate measures taken before leaching begins. Aoiding these problems requires some special techniques and a more careful examination than is generally accorded geological features in open pit and underground mining. The results should prove to be worth the time and effort.

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