COMPARISON OF BRAIDED-STREAM DEPOSITIONAL ENVIRONMENT AND URANIUM DEPOSITS AT SAINT ANTHONY UNDERGROUND MINE

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Abstract

United Nuclear's Saint Anthony mine, located in the Laguna district, produces uranium ore from the Jackpile sandstone unit of the Morrison Formation. The Jackpile sediments were deposited in a fluvial environment characterized by aridity, gentle slope, distant source area, and limited flow volume. Resultant stratigraphy consists of an intricate assemblage of trough and tabular cross-stratification grading to near massive bedding at some locations. Interbedded with the Jackpile sands are green mudstones and siltstones that commonly display irregular thicknesses of less than 2 ft and that are laterally discontinuous. Major penecontemporaneous and postdepositional alteration of originally deposited sands, silts, and clays includes: 1) infiltration and filling of interstices by kaolinitic clays; 2) mobilization and relocation of organic carbonaceous material; and 3) geochemical alteration of mineral constituents and fixation of uranium ions in organic carbonaceous material. Mineralized zones of economic volume display a spatial relationship to bedding features indicative of loosely packed sand deposited in dune and trough foresets. This relationship indicates possible permeability control by initial stratigraphy upon the flow of mineralizing solutions. Additionally, the low-energy foreset environment facilitates the accumulation of low-specific-gravity carbonaceous material necessary for interaction with mineralizing solutions. Large volumes of loosely packed foreset sands accumulate in transverse bars in braided-stream environments. These structures have a great potential for conducting large volumes of mineralizing fluids and hosting economic quantities of uranium ore.

Introduction

This paper presents ideas formulated from three years' observation of the Saint Anthony underground mine and associated surface drilling. Most of the ideas resulted from hundreds of hours' observation of freshly excavated surfaces. Supplemental data were gathered from many binocular and hand-specimen examinations. Previous discussions of uranium trends in the Grants region do not emphasize correlation of palepenvironment bedding features to bedding features observed in economic concentrations of uranium ore. We have made this correlation for one orebody in the Saint Anthony mine in order to further understand the nature of sediments having an affinity for uranium mineralization. The analogy does not necessarily apply to other concentrations of ore occurring on the property.

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Stratigraphy

The Laguna district forms the southeastern end of the Grants uranium region, which extends northwestward about 80 mi from Laguna to Gallup and is described in detail by Hilpert and Moench (1960). Uranium deposits of the Laguna district, including the Saint Anthony deposit, are listed and described by Moench and Schlee (1967). The Laguna district is underlain by a sequence of exposed sedimentary strata ranging in age from Triassic to Late Cretaceous (Moench, 1963). Excavations at the Saint Anthony mine have exposed strata from Jurassic to Upper Cretaceous. This sequence (in ascending order) comprises the Jackpile sandstone unit (economic usage) of the Morrison Formation (Upper Jurassic), Dakota Sandstone (Cretaceous), and Mancos Shale (Upper Cretaceous). These units are relatively flat lying, dipping only 1½° NNW. Anomalous structural features occurring within these formations have not been observed on the property.

The mine workings now include two open pits and an underground mine (fig. 1). Ground was broken for the first surface excavation, Pit No. 1, near the Dakota-Mancos contact in November 1975. This excavation penetrated approximately 75 ft of the Jackpile. Ground was broken for Pit No. 2 in Mancos colluvium during the summer of 1976. Stripping operations first exposed the Dakota-Jackpile contact in the spring of 1977. Present mining operations in Pit No. 2 have also penetrated 75 ft of the Jackpile. Shaft construction for the underground mine began in January 1977. The mine shaft, collared in Mancos colluvium, is 357 ft deep and bottoms just above the Brushy Basin Member of the Morrison Formation.

The Brushy Basin Member contains the Jackpile sandstone, an informal unit of economic usage, which will be treated as a separate unit in this paper. Surface drilling indicates the Brushy Basin to be in excess of 250 ft thick at Saint Anthony. The Brushy Basin comprises a greenish-gray, sometimes silty, well-indurated mudstone. Oxidation of minute, very fine sand inclusions and fracture fills imparts a disseminated reddish coloration to the siltstones and mudstones in some areas.

The Jackpile sandstone unit of the Morrison Formation is well exposed in the open-pit walls and underground workings at Saint Anthony mine. Additionally, Jackpile outcrops occur south and east of Pit Nos. 1 and 2 (figs. 1 and 2). The average thickness of the Jackpile is 100 ft, varying from 80 to 120 ft. Variations in thickness result from the intertonguing nature of the Brushy Basin and Jackpile. The Jackpile lithology consists of a wide assortment of colors, grain sizes, and bedding forms. Generally, the unit is a very light gray, medium to coarse-grained, subrounded, moderately sorted, subarkosic sandstone (Folk, 1968).

The Dakota Sandstone unconformably overlies rocks of Jurassic age throughout the Laguna district (Moench and Schlee, 1967). The contact is well defined in the Willie P. orebody (fig. 3). The contact contrasts planar and cross-stratified beds of the Jackpile sandstone with the relatively massive, light-gray Dakota Sandstone containing thin laminae of black, carbonaceous shale. Examination of the contact shows higher concentrations of kaolinite in the Jackpile sandstone. Clusters of euhedral pyrite crystals often occur in the Dakota, replacing carbon masses. Pyrite occurs less commonly in the Jackpile and is not necessarily associated with carbon. Arkosic stringers of probable Jackpile sand occurring in the lower few centimeters of the Dakota were observed in two localities.

The Dakota Formation is relatively thin, ranging in thickness from 6 to 20 ft. The formation consists of nearly white to light-gray, fine- to medium-grained, well-sorted, angular to subrounded, quartz sandstone that is well cemented with clay and silica. A black carbonaceous shale, 3-6 ft thick, occurs interbedded in the Dakota Sandstone in some areas. In some locations, a thin bed of black shale marks the base of the formation.

The Mancos formation achieves a maximum thickness of

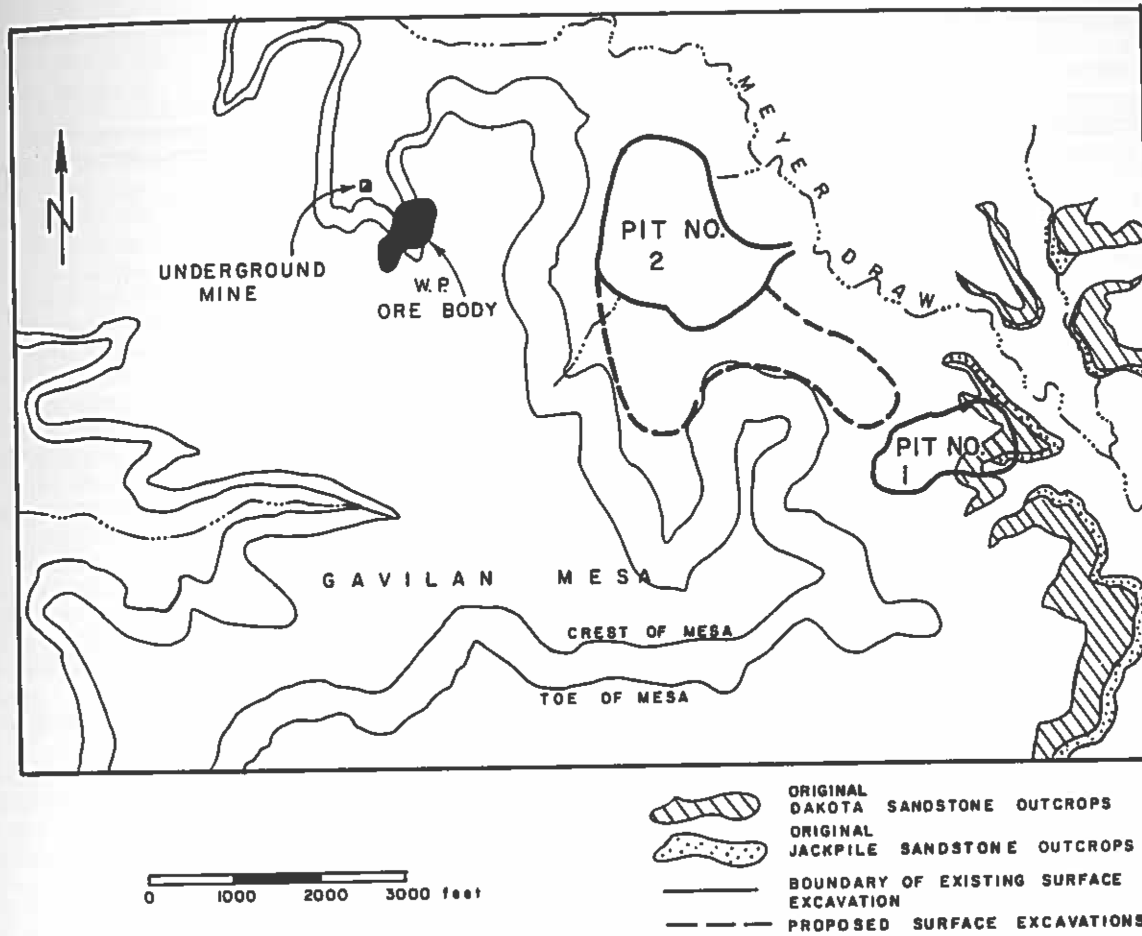

FIGURE 1—Location map for Saint Anthony underground mine and surface excavations.

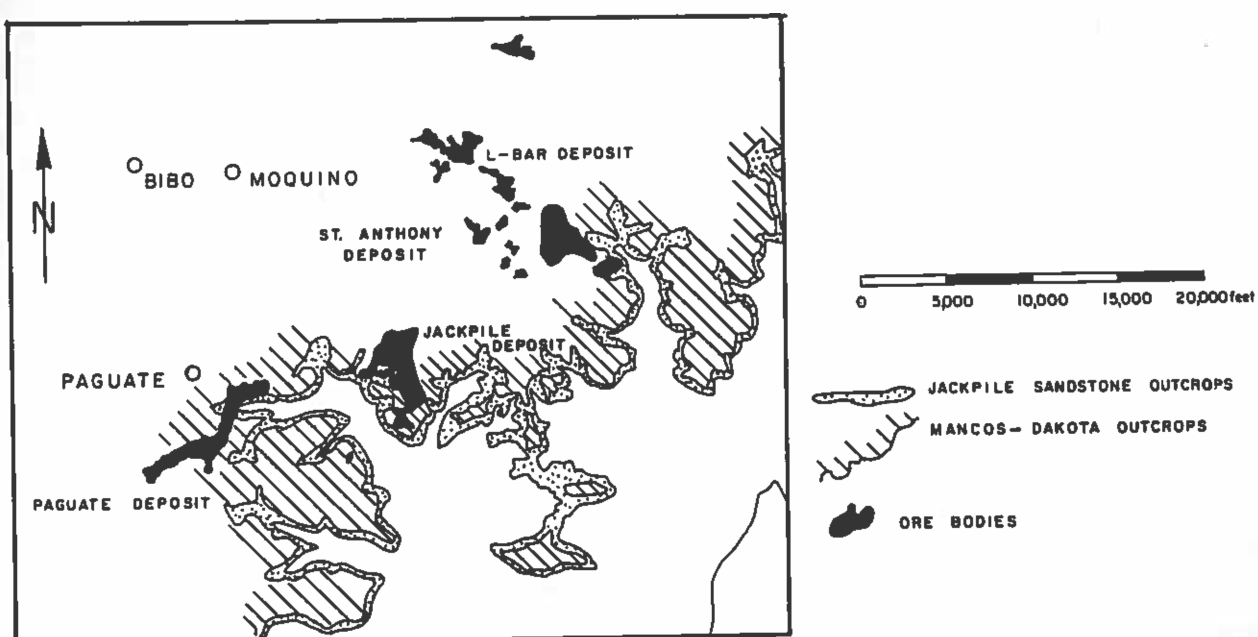

FIGURE 2—Location of uranium-production properties, Laguna district (after Moench and Schlee, 1967).

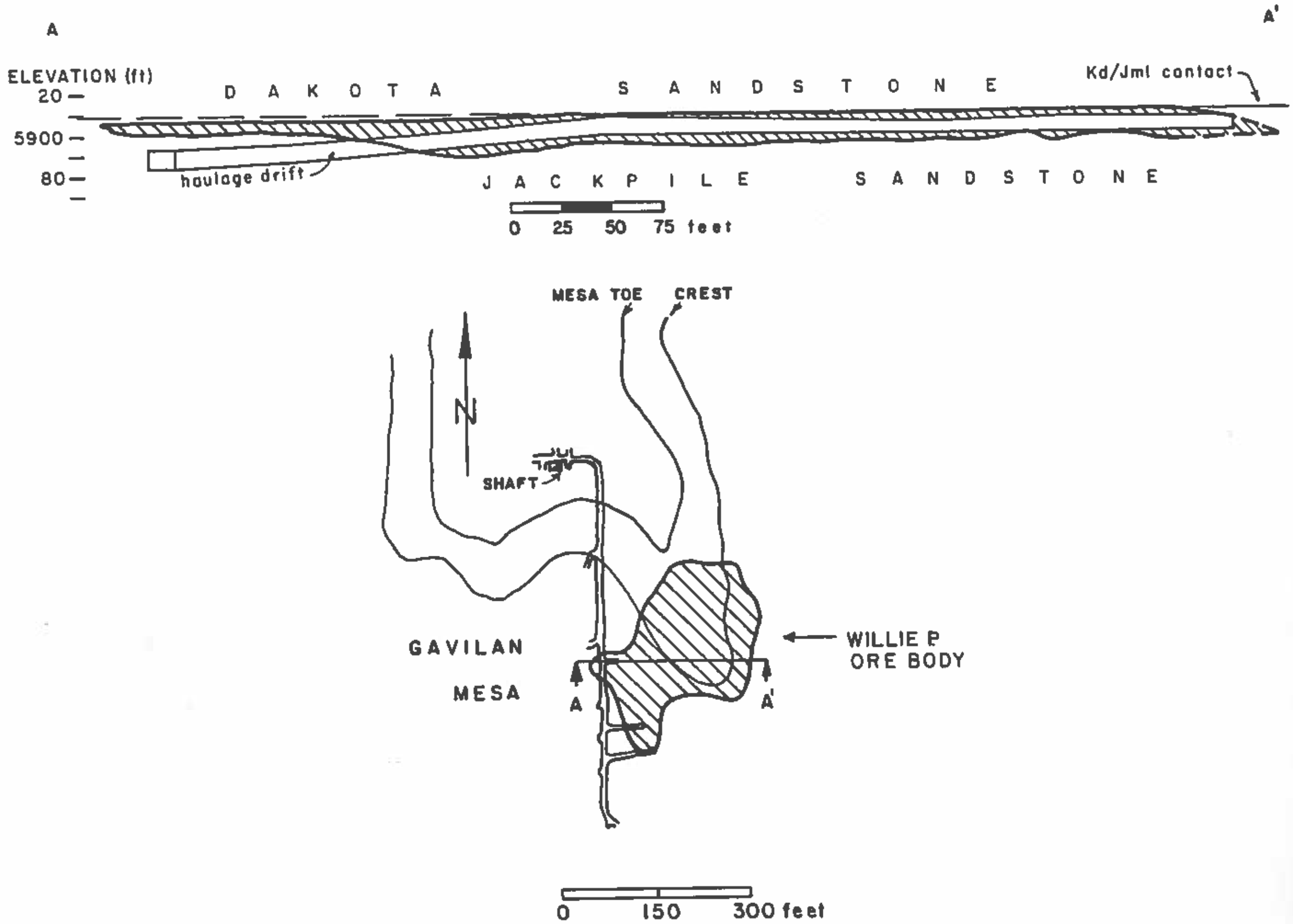

FIGURE 3—WILLIE P. OREBODY, SECTION AND PLAN VIEWS.

approximately 465 ft of Saint Anthony and comprises three prominent sandstone units and intervening shales. The three sandstones are in the lower Mancos and are identified by Moench and Schlee (1967) as the lower, middle, and upper sandstone units of the Mancos Shale. The middle sandstone unit, called the Tres Hermanos Sandstone Member, is the most extensive of the three sandstone units (Moench and Schlee, 1967). The sandstone units are more resistant than intervening shales and form prominent mesa bluffs. The sandstones typically are buff colored on weathered surfaces and consist of thick to thin, flat-bedded clean quartz sandstone. The upper sandstone unit is generally the thickest of the three units and forms a 50-ft cliff that caps Gavilan Mesa (fig. 1). The shale units between the sandstone units are gray to black on freshly exposed surfaces and buff colored on weathered surfaces. Nonresistant slopes consist of interbedded siltstones, shales, and thin limestone beds.

Petrology of sandstone

Petrologic information has been gathered from binocular examination of approximately 500 core, muckpile, and wall samples from the Jackpile sandstone. Detrital minerals and authigenic clays in 24 thin sections were examined for composition and habit. Additionally, the material from 14 samples smaller than two microns was x-rayed to identify and quantify clay species. With this limited amount of data, this paper offers only a basic understanding of Jackpile petrology.

Variations in the composition of the detrital fraction of the Jackpile sandstone at Saint Anthony are from quartz arenitic to arkosic (Folk, 1968). The average composition is:

quartz	86 percent
alkali feldspars	5 percent
plagioclase feldspars	5 percent
composite of detrital clay species (estimated from thin-section examination)	2-3 percent
rock fragments	1 percent
heavy minerals	trace

The detrital fraction is normally medium to coarse grained and rounded to subrounded. Sorting ranges from good in arenitic varieties to poor in arkosic varieties. Zircon is the only detrital heavy mineral observed in thin sections of 13 underground samples. Binocular examination of many samples from locations on the property seldom reveal heavy-mineral grains or opaques. Observed opaques are usually altering to iron oxides. Detrital pyrite is not present.

Silt- to clay-size material is often interbedded with the sand-size fraction, forming laminations less than 1 mm to several millimeters thick. In barren ground these laminations frequently appear as a color phenomenon only. Cross-stratified sandstone displaying alternating laminations of green and white were examined with a binocular microscope. No physical differences are apparent between laminations containing green interstitial clay and those containing bleached white interstitial clays. Mineralogic differences between the green clays and the bleached white clays have not been positively determined; however, the bleached white clays are believed to be principally kaolinite. Determination of how these laminations related to their original physical and chemical properties was not possible.

Binocular examination of moderately sorted sandstone specimens shows that approximately 80 percent of the detrital fraction consists of fine to coarse sand-size material. Very fine sand and coarse silt-size material that should be visible with the binocular microscope is not readily apparent. This observation has not been verified by sieve analysis. The grain-size distribution seems heavily skewed toward the sand-size fraction.

The principal cementing agent is authigenic clay. The authigenic nature of the clay cement was identified primarily by its textural relationship with adjacent detrital grains as observed in thin section. Silica or lime cements are rare.

Green silt- and clay-size material forms distinct bedding features up to several feet thick and from tens to hundreds of feet in plan view. Two mudstone channel fills were observed in the surface excavations. The dimensions of one are 12 ft deep by 50 ft wide. A thin extension of this mudstone spills over into an apparent overbank area. The channel appears to be continuous for several hundred feet.

Mudstone galls and blebs were observed as minor detrital constituents in the sandstone thin sections where they appear as masses much larger than neighboring grains and are usually deformed by postdepositional compaction.

Authigenic products comprise an assemblage of several generations of clay minerals (D. G. Brookins, personal communication, 1979), that constitute 12-22 percent of the whole-rock volume. X-ray diffraction of 13 samples revealed clay species occurring in the following approximate proportions to each other:

kaolinite	80 percent
illite-montmorillonite	10 percent
illite	5 percent
chlorite	5 percent
montmorillonite	not determined

The accuracy of x-ray-diffraction techniques for quantifying clays is rated at ±15 percent; the above data represent relative proportions only.

The dominant clay species is kaolinite, which makes up about 15 percent of the whole-rock volume in sandstone samples. The kaolinite occurs as infillings of altered feldspar grains, relict grains resulting from the complete replacement of detrital feldspar grains, and pore-fill nests resulting from the authigenesis of other associated clays and fine detrital fragments. Illite-montmorillonite is the next most abundant species, occurring as pore fill or a replacement product of altered detrital grains. Illite occurs as grain coatings or growths within fractures and as replacement of feldspar along grain boundaries. Montmorillonite is only a minor authigenic constituent and may have formed from the decomposition of volcanic ash (Adams and others, 1978). Authigenic chlorite was not seen in thin section.

Other authigenic constituents, including hematite, limonite, and goethite, occur as coatings on grains and interstitial material. The coatings are common but make up a very small percentage of the rock volume. Pyrite occurs as a rare authigenic constituent in barren ground. It is occasionally found in association with high concentrations of organic carbonaceous material and less frequently with interbedded mudstones. Quartz overgrowths are common and are occasionally observed in thin section enveloping detrital grains previously coated with illite. No attempt has been made to relate the location of abundant quartz overgrowths to areas of active feldspar destruction as was done by Adams and others (1978) at the Jackpile deposit.

Nature of mineralized organic carbonaceous material

The term *organic carbonaceous material* (OCM) after Lee (1976) describes vegetal material that has been coalified or liquified to a humic acid. The organic carbonaceous material occurs within the Jackpile sandstone in two forms: 1) One form is primary material representing the remains of vegetal material coalified in situ and occurring as sand-size particulate matter, or coalified laminations interstratified in crossbedding, and rounded to lensoid coalified masses that formed from twig and branch material. 2) The second form is mobilized material representing the remains of vegetal material liquified to a humic acid, which appears to have migrated through the sandstone, thereby forming pore fill and coating both grains and clay pore fill.

High concentrations of mobilized OCM occur as coatings of interstitial clay and detrital grains, and they also appear to fill interstices. This material, when mechanically disintegrated to a powder, is black to dark brownish gray; however, this phenomenon may result from the interlayer staining of clays. The formation of mobilized OCM is believed to be synchronous with the passage of uranium-mineralizing solutions (Lee, 1976).

Grain-size, particulate, primary OCM that apparently underwent partial remobilization over a distance of a grain diameter or two will stain adjacent detrital and interstitial material. This texture is common in low-grade massive sandstones and has been termed *speckled ore*. Staining of adjacent interstitial and detrital material occurred when primary OCM particles became soluble under alkaline conditions (Lee, 1976).

The cross-stratified sandstone hosts the OCM in a variety of relationships to bedding. Mobilized OCM often is distributed homogeneously throughout a particular crossbed set with thin interbedded laminations of coalified carbon. In the same area, this organic material will also occur discordant to bedding features and form clouds or halos that have no relationship to bedding or mineralogy. Variations in the occurrence of discordant OCM include a wide variety of irregular shapes and sizes. Notable are the ore rods or cones that occur in massive to poorly bedded sandstone. The rods are often found hanging below a perforated, thin mudstone or siltstone lamination that restricted the movement of mobilized OCM and mineralizing solutions.

Halo ore, common at Saint Anthony, is the occurrence of thin, highly mineralized concentrations of OCM in contact with the tops and/or bottoms of distinctly bedded mudstones or siltstones. In adjacent sands, this material has been concentrated along the mudstone or siltstone boundaries by adsorption. The adsorption phenomenon is enhanced by hydraulic drag along the boundaries, which increases the relative time that mineralized fluids are in contact with the clays. Occasionally the mudstones and siltstones will exhibit only an irregular coating of mineralized OCM. In this case, adsorption properties appear to be the dominant factor in the association of the mudstone and OCM. High-grade halo ore may enhance the gamma signature of weakly mineralized mudstones to the point that they are misinterpreted in gamma logs as an ore thickness equal to the thickness of the mudstone.

Geochemical observations

Three types of ground within the Jackpile sandstone may be distinguished on the basis of fundamental geochemical observations: 1) barren ground, 2) ground through which mineralizing solutions have passed (oxidized), and 3) well-mineralized ground (ore).

Barren ground occurs northwest of the Willie P. orebody in all development excavations. This sandstone is of a reduced geochemical nature, as indicated by the presence of: 1) interstitial authigenic clays that are usually bleached white; 2) interbedded green silts, mudstones, and mudstone galls; and 3) iron compounds in an unoxidized state. A majority of the barren sandstone is poorly indurated except where localized silica cementation occurs. This observation is in contrast to the nature of mineralized ground, which is invariably well indurated. Organic carbonaceous material is rare, occurring only in or around mudstones and siltstones. X-ray diffraction of clay separates from one sample of barren ground showed a higher ratio of illite-montmorillonite mixed-layer clay to kaolinite than averages obtained from x-ray data of oxidized and mineralized ground. The ratio is also higher than that obtained from thin-section examination. The greater illite-montmorillonite to kaolinite ratio suggests that barren ground is geochemically younger than ground subjected to mineralizing solutions—a smaller percentage of mixed-layer clays have had the opportunity to develop compositionally toward kaolinite. These data are compatible with expected barren-ground geochemistry; additional analyses are in progress to test this concept.

Ground to the south-southwest of the Willie P. orebody has been exposed to uranium-mineralizing solutions and is now oxidized. Nearly all of this sandstone has very weak red, orange, yellow, or brown-buff hues. Binocular examination of this material shows that colors originate principally from the color of interstitial clays that apparently underwent oxidation of interlayer cations (Adler, 1970). Interbedded mudstones and siltstones usually maintain their green color; only in areas of heavy oxidation do they acquire grayish-purple to grayish-red hues. Concentrations of carbonaceous material occur in isolated cross-stratified sets. These occurrences of mineralized organic material constitute satellite ore pods. Highly mineralized concentrations of organic carbonaceous material occurring in massively bedded sandstone are usually brown when associated with oxidized ground.

Well-mineralized ground occurring in the Willie P. orebody contains high concentrations of organic carbonaceous material conformable or discordant to bedding. Mild oxidation of host sandstone occurs within the orebody and is most prominent near its margins.

Ore trends in underground mine

Jackpile uranium occurrences being mined in the Laguna district are shown in fig. 2. Mineralization is locally present throughout the three producing properties owned separately by Anaconda Company, United Nuclear Corporation, and Sohio Natural Resources and Reserve Oil and Minerals. Original mineralization trends of the Laguna district have been obscured by a northwest retreat of the Jackpile outcrop. The deposits shown in fig. 2 are remnants of the original trends. Existing trends through the Saint Anthony and Sohio properties are north-northwest. Surface drilling at the Saint Anthony underground mine prior to production activities indicated a wide variety of plan-view orebody configurations. At that time, recognition of any kind of geochemical or stratigraphic model for the economic mineralization was impossible. After production activities had exposed a sufficient amount of ground, a relationship began to be seen between minable volumes of ore and their internal bedding features. Economic concentrations of uranium that are equidimensional in plan view occur in medium- to coarse-grained sandstones displaying a very high degree of large-scale tabular cross-stratification. This observation has not been documented statistically but stands out as an obvious relationship when comparing consistently heavily mineralized ground to barren or weakly mineralized ground. In barren ground northwest of the Willie P. orebody, cross-stratification occurs in a smaller percentage of the sandstone, and the average set size is larger than within the Willie P. orebody. Weakly mineralized ground southwest of the orebody contains large volumes of massively bedded sandstone. An example of consistently heavily mineralized ground is shown in fig. 3. The orebody is several hundred feet across and averages 12 ft thick at its interior. Near the margins, the ore zone gradually thins to about a foot except where mineralized beds have been truncated by fluvial erosion features. The upper surface is truncated by the Dakota unconformity in the central portion of the orebody. Peripheral to the Willie P. orebody are many small concentrations of ore, often high grade and occurring in isolated large-scale cross-stratified sets (fig. 4). No lateral continuity exists between these satellite pods and the adjacent orebody. Massively bedded sandstone in intervening areas is often weakly mineralized. The satellite pods in oxidized ground are probably representative of destructive processes occurring behind the advancing geochemical cell that mineralized portions of the Jackpile sandstone.

Relationship between economic concentrations of ore and braided-stream bedding configurations

Descriptions of fluvial sediments by Smith (1970) and Harms and Fahnestock (1965) illustrate the variety of bedding features common to arid stream environments. We stress the importance

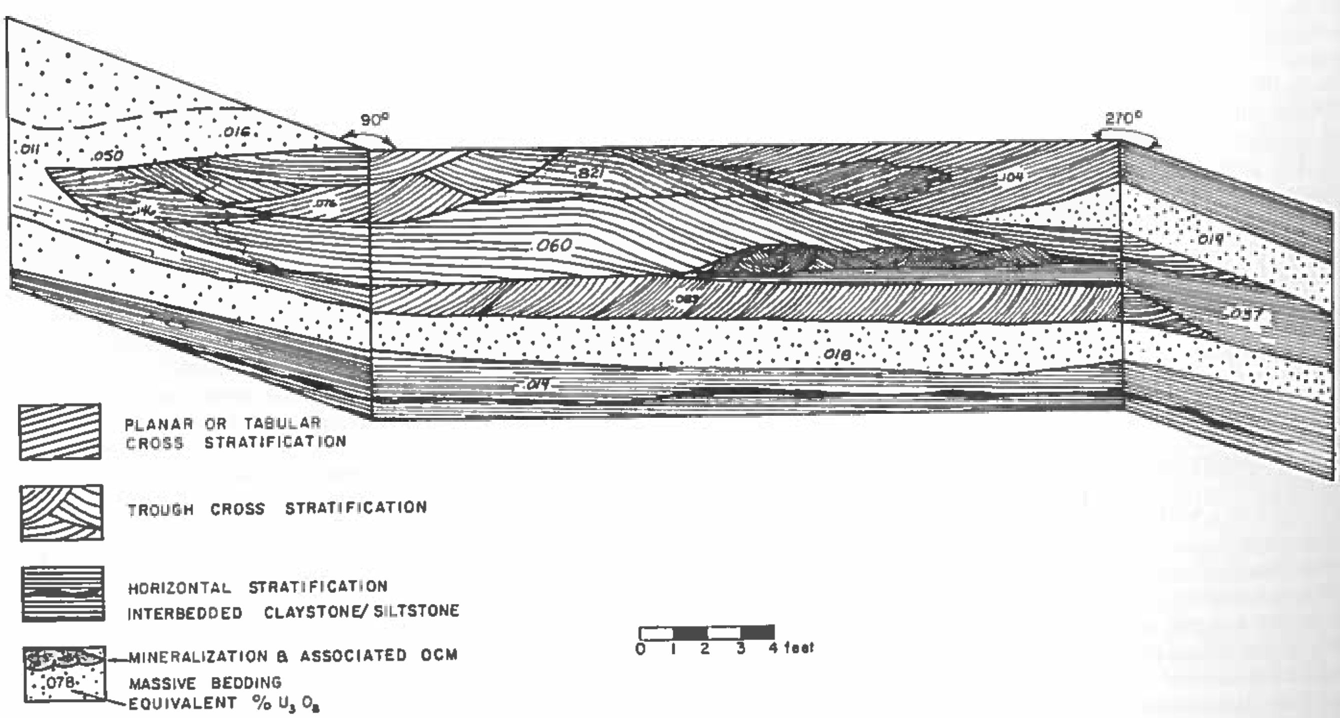

FIGURE 4—Cross-stratification in vertical exposures, Saint Anthony underground mine (view looking southeast).

of associating the term *arid* with the Jackpile paleoenvironment because of the effect vegetation stabilization in humid fluvial environments has on channel configurations. Development of the braided-stream pattern is retarded by vegetation in overbank areas within the active channel zone. Sinuous, meander-belt features common in humid fluvial environments cannot be seen in the Jackpile sandstone. For analysis of the Jackpile depositional environment with respect to features observed in the Willie P. orebody, a fluvial lithosome must be postulated that contains a volume of sediment comparable in size to the orebody and that hosts similar bedding features. Since the mobilized organic carbonaceous material does not appear to have traveled farther than several times its longest dimension, it must also be present in the lithosome for reaction with uranium. The occurrence of primary organic material within the host lithosome would create a source for mobilized carbonaceous material if quantities were sufficient. Original sandstone permeability must be suitable for transmission of mineralizing solutions. As mentioned in the petrologic discussion, the detrital-clay fraction of whole-rock samples constitutes 12-22 percent and averages 17 percent of the sandstone by volume. The time relationship between interstitial plugging by authigenic clays and the movement of mineralizing solutions will be considered later.

The classification of stratification types and bedforms in the braided-stream environment is an attempt to model a very complex set of depositional variables. This complexity is particularly evident in the field, where longitudinal- and transverse-bar forms often interfinger (Smith, 1970) and make resulting configurations difficult to classify. However, the basic bedding characteristics of the transverse bar frequently maintain its identity and make it distinguishable in the field. The transverse bar is composed of sand-sized material, as opposed to the longitudinal bar which contains high concentrations of coarse-sand- to pebble-sized material (Smith, 1970). Transverse bars form by aggradation of foreset beds on the downstream slip face. Stratification forms created by this phenomenon were first called planar cross-stratification by Jopling (1966), and the name was adopted by Smith (1970). Harms and Fahnestock (1965), working with the Rio Grande sediments, have not described bar features as extensively as Smith (1970). They describe bars as being composed predominately of dune trough cross-stratification. Large-scale tabular cross-stratification analogous to Smith's planar cross-stratification occurs in shallow channel fills and on bar margins (Harms and Fahnestock, 1965). The difference in cross-stratification forms and lack of emphasis on bar deposits in the Harms and Fahnestock article is probably a result of greater stream gradients and topographic restrictions to lateral channel development along the Rio Grande.

Harms and Fahnestock describe the dune foresets as "yielding afoot" and attribute this to a loose packing of sand grains. This description is in contrast to close packing of sand deposited in horizontal stratification often found capping bar deposits. The abundance of large-scale cross-stratification, whether tabular or trough shaped, forming on the downstream slip face of an aggrading bar, would form a suitable accumulation of porous sand with the potential to act as a conduit for mineralizing solutions.

During their investigation of the Rio Grande sediments, Harms and Fahnestock found leaves and twigs forming layers several inches thick in the fills of a few troughs. Rapid burial of low-specific-gravity material in the foreset avalanche face by upslope reverse eddies is a plausible means of accumulating organics in stream sediments. Quite possibly, under the right conditions transverse bars would contain suitable quantities of vegetal debris to act as a source of mobile organic carbonaceous material. Remnants of primary carbonaceous material interbedded in large-scale cross-stratification are well documented in Saint Anthony underground ore concentrations.

The maximum bar thickness, as observed by Smith and by Harms and Fahnestock, is 2.5 ft. Their observations were limited to a depth of 5 ft by ground water in trench excavations. This maximum is a measurement of active transverse and longitudinal bar forms. Other forms such as point bars may also occur in the braided-stream environment (Smith, 1970). The thickness of a point bar will be controlled by the depth of the associated channel. The thickness of a transverse bar is similarly controlled by the depth of water in the depression immediately preceding the aggrading bar. Full faces of ore in the underground mine contain multiple generations of superimposed cross-stratified sets. Since many of these accumulations are thicker than bar deposits observed in the field, they may represent an assemblage of superimposed or stacked bar deposits.

Studies of bar deposits in existing literature describe many features that occur in the Willie P. orebody. The average grain size of cross-stratified sandstone in the orebody is comparable to the average grain sizes observed in present-day fluvial bar deposits. The plan-view configuration of the orebody is tabular, as are transverse-bar deposits observed in the Platte River. Stratification forms occur in the Willie P. orebody in the same relative proportions as in transverse-bar deposits. Channel-erosion features that breach transverse bars are found in the orebody. Not mentioned in the literature examined for this paper but commonly observed in the Willie P. orebody are rip-up clasts and clay galls embedded in the crossbeds. These features are common during higher discharge rates which occur when spring runoff increases overbank sloughing and lateral channel migration.

The ratio of quartz to less-stable detrital constituents (feldspar) and physical properties of the sandstone grains (sorting and roundness) suggest that the Jackpile is a relatively mature sediment. This degree of maturity would be expected of sediment occurring in the lower reaches of the Platte River, where Smith (1970) has observed increasing occurrence of transverse bars as a function of distance from the source area. However, this conclusion would be incorrect if the Jackpile sediments included and/or consisted of reworked Morrison sediments. Sedimentological work is necessary to clarify the origin of Jackpile sediments.

Massively bedded, medium-grained sandstone increases in frequency of occurrence toward the peripheral margins of the Willie P. orebody. Massive bedding in a fluvial environment may form under several conditions. The massively bedded sandstone here does not seem to have formed under conditions of flood bed-load dumping because of the absence of clay- and silt-size material, mudstone galls, and rip-up clasts. Additionally, the massive sandstone does not seem to have formed from bioturbation because of its complete homogeneity. Massive bedding near the Willie P. orebody apparently formed under upper-flow-regime conditions where turbulence is sufficient to winnow silt and clay fractions, depositing larger sizes homogeneously. Low-specific-gravity carbonaceous material will not be deposited in this environment. The deposition occurs when heavy sediment loads are being transported in the upper flow regime and deposited in features such as pools. This phenomenon creates significant volumes of porous sand devoid of OCM. Concentrations of high-grade ore do not form in massive sandstone except when they occur near high concentrations of primary, mobilized OCM.

The interstitial plugging of originally deposited sand-sized material by infiltrating and authigenic clays occurred sometime after deposition. Mechanically infiltrating clays penetrate freshly deposited alluvium, randomly filling voids and coating grains with platelets oriented parallel to grain surfaces (Wilson and Pittman, 1977). Authigenic clays formed from the alteration of the feldspar constituents and detrital-clay fraction. The time relationship between the formation of authigenic clays and sediment diagenesis is not understood; however, some degree of interstitial plugging by authigenic clays must have occurred prior to the mobilization of OCM and the impingement of mineralizing solutions in order to coat existing interstitial clays. The geochemical environment in which OCM is mobile generates organic acids that readily break down clay minerals (Lee, 1976). Under these conditions, sandstone porosity would be rejuvenated by the resolution of portions of the authigenic-clay fraction.

Conclusions

Bedforms in the braided-stream depositional environment resemble bedding features observed in the Willie P. orebody at the Saint Anthony underground mine. Prominent bedding styles include large-scale cross-stratification with tabular varieties predominating over trough forms. The tabular cross-stratification occurs on the downstream slip face of aggrading transverse bars. Concentrations of organic material become interbedded in these foresets, creating a source for mobilized OCM internal to the transverse-bar deposit. During diagenesis, authigenic clays form from the alteration of detrital clays and begin the slow process of plugging original rock porosity. Later geochemical events which mobilize OCM and introduce uranium ions partially rejuvenate rock porosity by redissolving authigenic clays. The mobilized carbonaceous material moves for short distances, probably not more than one or two times the size of the crossbed set within which it exists. Large accumulations of transverse-bar sediments or sediments of a similar genetic nature form a suitable environment for the accumulation of economic concentrations of uranium ore.

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